Thermal Effects on Spin Currents in Non-Local Metallic Spin Valves

Alex Hojem
University of Denver

Follow this and additional works at: https://digitalcommons.du.edu/etd

Part of the Condensed Matter Physics Commons

Recommended Citation
Hojem, Alex, "Thermal Effects on Spin Currents in Non-Local Metallic Spin Valves" (2016). Electronic Theses and Dissertations. 1198.
https://digitalcommons.du.edu/etd/1198

This Dissertation is brought to you for free and open access by the Graduate Studies at Digital Commons @ DU. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of Digital Commons @ DU. For more information, please contact jennifer.cox@du.edu,dig-commons@du.edu.
THERMAL EFFECTS ON SPIN CURRENTS IN NON-LOCAL METALLIC SPIN VALVES

A Dissertation
Presented to
the Faculty of Natural Sciences and Mathematics
University of Denver

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

by
Alex Hojem
August 2016
Advisor: Barry L. Zink
© Copyright by Alex Hojem 2016
All Rights Reserved
Abstract

The study of non-local spin valves (NLSVs) has recently proven to be a fertile area for both applied and fundamental research in nanomagnetism due to the unique ability to separate charge currents and spin currents. NLSVs may also prove essential for a new class of high-density hard disk read heads due to their favorable scalability. Recent studies have shown thermal effects created by high current densities play a significant role in the response of NLSVs. These thermal effects also provide the opportunity to create a pure spin current from thermal gradients via a mechanism call the spin dependent Seebeck effect (SDSE). Due to the challenges in control and measurement of thermal gradients in nanoscale structures, both the fundamental physics and materials dependencies of thermally-driven spin transport in nanoscale structures remains largely unexplored.

In the dissertation I present measurements of thermal and electrical spin injection in nanoscale metallic non-local spin valve (NLSV) structures. Informed by measurements of the Seebeck coefficient and thermal conductivity of representative films made using a micromachined Si-N thermal isolation platform, we use simple analytical and finite element thermal models to determine limits on the thermal gradient driving thermal spin injection and calculate the spin-dependent Seebeck coefficient that is comparable in terms of the fraction of the absolute Seebeck coefficient to previous results, despite dramatically
smaller electrical spin injection signals. Since the small electrical spin signals are likely caused by interfacial effects, we conclude that thermal spin injection is less sensitive to the FM/NM interface, and possibly benefits from the presence of oxidized ferromagnet, which further stimulates interest in thermal spin injection for applications in sensors and pure spin current sources. To investigate contact resistance further we also present work comparing NLSVs with permalloy oxide contacts and devices with an alumina capping layer to prevent to formation of the magnetic oxide. The resulting devices show reduced thermal spin injection compared to initial results but overall increase electrical injection in both cases. Notably, the alumina capped devices present greater electrical injection spin resistance but lower thermal injection spin signal than the magnetic oxide devices. Performing measurements from 78 K to 300 K show an overall decrease in spin resistance signals in both injection configurations as device operation approaches room temperature. Along with reduced spin resistance a parasitic signal appears that we attribute to the Anomalous Nernst Effect (ANE), the thermoelectric analogue of the anomalous Hall effect. This ANE creates a voltage in the detection ferromagnet from a thermal gradient produced by the driving current in the injection ferromagnet. We also describe measurements that demonstrate and quantify both thermoelectric effects on electrical spin injection and purely thermal spin injection, as well as the ANE in NLSVs. Since the ANE is a result of thermal gradients only on detector ferromagnet the spin resistance signal can be enhancement or hindered depending on the device geometry.
Acknowledgements

I would like to first thank C. Leighton, and L. O’Brien for helpful discussions on fabrication and physics of NLSVs, J. Aumentado for advice on EBL, G. C. Hilton, J. Beall, and J. Neibarger for advice and assistance on RF surface preparation and Al deposition, and J. Nogan and the IL staff at CINT for guidance and training. I gratefully acknowledge support from the DU PROF program for their support near the end of completing this thesis. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Los Alamos National Laboratory and Sandia National Laboratories.

I would also like to thank the former members of the Zink lab group, Sarah Mason, Dain Bassett, Azure Avery and Jason Underwood for guidance and instruction. Lastly I would like to acknowledge Devin Wesenberg for both technical advice on fabrication and thermal simulation as well as his work on helping to fabricate devices covered in this thesis.

Lastly, I would like to dedicate this work first to my parents for always encouraging my pursuit of science, to every physics and astronomy teacher I’ve ever had and lastly to my partner Aaron, for putting up with me while I completed my work.
## Contents

Acknowledgements .................................................. iv
List of Figures ......................................................... viii

1 Background .......................................................... 1
   1.1 Spin Polarized Current ........................................ 1
   1.1.1 Spin Valves .................................................. 2
   1.2 Pure Spin Current .............................................. 3
   1.2.1 Theory of Non-Local Spin Valves ......................... 4
   1.3 Thermal Effects ............................................... 6
   1.3.1 Joule Heating ............................................... 6
   1.3.2 Seebeck Effect .............................................. 6
   1.3.3 Peltier Effect .............................................. 7
   1.3.4 Spin Dependent Seebeck Effect ........................... 8
   1.3.5 Anomalous Nernst Effect ................................. 10
   1.4 Summary ....................................................... 12

2 Thermal spin injection and interface insensitivity in permalloy/aluminum metallic non-local spin valves 13
   2.1 Introduction ................................................... 13
   2.2 Experiment ..................................................... 17
   2.2.1 Device Fabrication ......................................... 17
   2.2.2 Transport Measurements ................................... 18
   2.3 Results ......................................................... 20
   2.4 Discussion ..................................................... 29
   2.5 Conclusions .................................................... 42

3 Anomalous Nernst effects and thermally altered spin injection from high temperature gradients in nonlocal spin valves 44
   3.1 Introduction ................................................... 44
   3.2 Experimental Details ......................................... 47
   3.2.1 Fabrication ................................................ 47
   3.2.2 Measurement Technique ................................... 48
3.3 Results and Discussion ........................................ 49
  3.3.1 IV Curve Measurements and Contact Temperatures ..... 49
  3.3.2 Thermally Affected Electrical Injection ............... 54
  3.3.3 Anomalous Nernst Effects .............................. 56
  3.3.4 Thermal Modeling ........................................ 60
  3.4 Conclusions .................................................. 62

4 Effect of Oxides on the Performance of Non-Local Spin Valves 63
  4.1 Introduction .................................................. 63
  4.2 Experimental Detail ......................................... 64
    4.2.1 Fabrication ............................................ 64
    4.2.2 Measurement Techniques ............................... 65
  4.3 Results and Discussion ................................... 67
    4.3.1 Background Measurements and Temperature Projections 67
    4.3.2 Subtracted Spin Resistance ........................... 70
    4.3.3 Anomalous Nernst Effects ............................ 74
  4.4 Conclusion .................................................. 76

5 Conclusion ...................................................... 77

Bibliography ....................................................... 78

A Appendix A: Analytic Thermal Modeling of NLSVs 94

B Appendix B: IV Measurements From Differential Conduction 98
  B.1 Comments on Differential Conductance and Establishing Error
      Values ...................................................... 98
  B.2 Delta Method Resistance and Higher Order Fits ............ 99

C Appendix C: Multiple Configuration Measurement Technique101

D Appendix D: Magnetic Oxide and Aluminum Oxide Device
  Data for Other Separations .................................. 104
  D.1 MagneticOx 900nm ......................................... 105
    D.1.1 IV Curve Regression .................................. 105
    D.1.2 P-AP .................................................. 106
    D.1.3 ANE .................................................. 107
  D.2 MagneticOx 1300nm ....................................... 108
    D.2.1 IV Curve Regression .................................. 108
    D.2.2 P-AP .................................................. 109
    D.2.3 ANE .................................................. 110
  D.3 AluminiumOx 900nm ....................................... 111
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.3.1</td>
<td>IV Curve Regression</td>
<td>111</td>
</tr>
<tr>
<td>D.3.2</td>
<td>P-AP</td>
<td>112</td>
</tr>
<tr>
<td>D.3.3</td>
<td>ANE</td>
<td>113</td>
</tr>
<tr>
<td>D.4</td>
<td>AluminiumOx 1300nm</td>
<td>114</td>
</tr>
<tr>
<td>E</td>
<td>Appendix E: Data Taking and Analysis Code</td>
<td>115</td>
</tr>
<tr>
<td>E.1</td>
<td>LabVIEW VIs</td>
<td>115</td>
</tr>
<tr>
<td>E.1.1</td>
<td>NLSVBoxFullControlV1.vi</td>
<td>116</td>
</tr>
<tr>
<td>E.1.2</td>
<td>IVCurveMultiChannelMultiField.vi</td>
<td>116</td>
</tr>
<tr>
<td>E.1.3</td>
<td>IVCurveMultiChannel.vi</td>
<td>117</td>
</tr>
<tr>
<td>E.1.4</td>
<td>DifferentialConductance_IVCurve.vi</td>
<td>117</td>
</tr>
<tr>
<td>E.1.5</td>
<td>NLSVBoxAMRMultiChannel.vi</td>
<td>118</td>
</tr>
<tr>
<td>E.1.6</td>
<td>NLSV_AMR_Film_WithField_DeltaV4.vi</td>
<td>118</td>
</tr>
<tr>
<td>E.1.7</td>
<td>NLSVBoxR2AMRMultiChannel.vi</td>
<td>119</td>
</tr>
<tr>
<td>E.1.8</td>
<td>NLSVBoxIVvsH.vi</td>
<td>119</td>
</tr>
<tr>
<td>E.1.9</td>
<td>NLSVIVcurvesHSingle.vi</td>
<td>119</td>
</tr>
<tr>
<td>E.1.10</td>
<td>FieldSetBZv3.vi</td>
<td>119</td>
</tr>
<tr>
<td>E.1.11</td>
<td>Set6211DO_oldstyle.vi</td>
<td>119</td>
</tr>
<tr>
<td>E.1.12</td>
<td>Read6211DI_oldstyle.vi</td>
<td>120</td>
</tr>
<tr>
<td>E.1.13</td>
<td>Set6211AO_oldstyle.vi</td>
<td>120</td>
</tr>
<tr>
<td>E.1.14</td>
<td>Read6211AI_oldstyle.vi</td>
<td>120</td>
</tr>
<tr>
<td>E.1.15</td>
<td>NLSVChangeSRSChan.vi</td>
<td>120</td>
</tr>
<tr>
<td>E.2</td>
<td>MATLAB Scripts</td>
<td>120</td>
</tr>
<tr>
<td>E.2.1</td>
<td>NLSVLoading</td>
<td>120</td>
</tr>
<tr>
<td>E.2.2</td>
<td>NLSVPlotingPsuBAPAlFormsWithSavefixed</td>
<td>126</td>
</tr>
<tr>
<td>E.2.3</td>
<td>NLSVHSweepsPlotingWithSave</td>
<td>131</td>
</tr>
<tr>
<td>E.2.4</td>
<td>NLSVPloting</td>
<td>133</td>
</tr>
<tr>
<td>E.2.5</td>
<td>NLSVRegressionFixed</td>
<td>136</td>
</tr>
<tr>
<td>E.2.6</td>
<td>RegressionJustSave</td>
<td>149</td>
</tr>
<tr>
<td>E.2.7</td>
<td>SDSECalcsOneShot</td>
<td>154</td>
</tr>
<tr>
<td>E.2.8</td>
<td>ContactTemps</td>
<td>159</td>
</tr>
<tr>
<td>E.2.9</td>
<td>NLSVRegressionFixedMem</td>
<td>160</td>
</tr>
<tr>
<td>E.2.10</td>
<td>SDSECalcsOneShotMem</td>
<td>175</td>
</tr>
<tr>
<td>E.2.11</td>
<td>NLSVRegressionDifConFixed</td>
<td>183</td>
</tr>
<tr>
<td>E.2.12</td>
<td>NLSVDeviceSummation</td>
<td>196</td>
</tr>
</tbody>
</table>
List of Figures

1.1  a) A cartoon of the electron scattering for spin-up and spin-down populations for parallel and antiparallel orientations. b) The resistor model for parallel and antiparallel orientations. If the magnets are aligned the majority spin, spin-up, will have a low resistance path while the minority spin, spin-down, will have a higher resistance path. If the magnets are antiparallel both paths are roughly equally resistive in this cartoon.  

1.2  a) A cartoon of a NLSV. b) A sketch of the electrochemical potential from the injection FM/NM contact to the detection FM/NM contact. c) A cartoon of NLSV function as external field is sweep up and down.  

1.3  a) Cartoon of the spin dependent Seebeck effect (SDSE). The thermal gradient in the FM injector drives a spin accumulation at the FM/NM contact. The resulting spin accumulation in the NM diffuses through the NM like in regular NLSV spin injection. b) The longitudinal spin Seebeck effect (LSSE). The LSSE is mediated by thermally exited magnons in a ferromagnetic insulator that create a spin current in a paramagnetic material. This spin current is produces an electrical current via the inverse spin hall effect to that allows for spin accumulation detection.  

1.4  Cartoons of the Hall effect, the anomalous Hall effect and the anomalous Nernst effect.
2.1 a) Schematic layout of the NLSV under electrical spin injection, where a large charge current driven through a FM nanowire creates a spin accumulation and pure spin current in a NM channel that is detected with a second FM. b) The non-local resistance $R_{\text{NLSV}} = V_{\text{NLE}}/I$ for a $L = 900$ nm device at 78 K, where the relative alignments of the two FM contacts are indicated with paired arrows. c) Thermal spin injection is achieved by passing current $I$ only through FM1, creating a thermal gradient at the NM/FM interface that injects spin into the NM. d) False-color SEM micrograph of the nanoscale circuit defining the NLSV. Sizes given indicate the designed widths of nanowires, measured geometries appear in Table A.1.

2.2 $V_{\text{channel}}$ vs. $I$ characteristics for the NM channel (contacts made as shown schematically in the inset) are highly linear across the entire range of applied $I$ in contrast to both the three-terminal contact resistance (Fig. 2.6 e)) and non-local resistance measurements (Figs. 2.5a) and 2.6c)). Measurements for two NLSVs are shown for two temperatures. Dashed lines show linear fits.

2.3 Non local resistance signals $R_{\text{NLE}} = V_{\text{NLE}}/I$ in electrical (a) and (b)) and $R_{\text{NLT}} = V_{\text{NLT}}/I$ in thermal (c) and (d)) spin injection for both 500 nm and 1300 nm nominal FM spacing. e) The electrical spin signal $\Delta R_{\text{NLE}}$ vs. $L$ with the fit to the 1d spin diffusion equation. This fit gives $\lambda_{nm} = 760 \pm 50$ nm.

2.4 a) Comparison of electrically-driven spin signal $\Delta R_{\text{NLE}}$ (blue spheres) to various models based on the 1d spin diffusion equation. Matching of the electrical signal is only possible using a strongly reduced value of interfacial spin polarization, regardless of the model employed. b) Comparison of $\Delta R_{\text{NLE}}$ reported here (blue spheres) to similar Py-based NLSV with various NM channels. In each case the lines represent a 1d spin diffusion model that explains the signal size. Relevant parameters and spin resistances are also given. Note especially the large signal that matches predictions of the transparent interface model for the Py/Cu device originally used to observe the SDSE. NLSV used in this study have much reduced electrical signal, but maintain the same thermally-driven spin signal.
2.5  a) IV characteristic for the electrical spin injection configuration (Fig. 3.2a) measured separately for parallel and antiparallel states of the FM nanowires for the $L = 500$ nm device at 78 K. b) The corresponding IV characteristic for the thermal spin injection configuration (Fig. 3.2c). c) Subtraction of the parallel and antiparallel curves in a) gives the highly linear response of electrical spin injection, while the corresponding subtraction for thermal injection yields a spin signal dominated by the $I^2$ term indicating thermal generation of a spin accumulation in the NM. In both c) and d), data for both $L = 500$ nm and $L = 1300$ nm are shown. Fitted values of spin signal are also shown.

2.6  a-b) Two-body thermal models used to analytically model the $T$ profile in the devices. c-d) Resulting IV curves show significant curvature as a result of heating and thermoelectric effects. Data is shown for the $L = 1300$ nm NLSV at 78 K, but similar curvature is seen at room $T$ and for other devices. Inset: The simplified thermal profile used to estimate a maximum possible $\nabla T$ of 33 K/micron from our data. e) The three-terminal contact resistance (shown schematically in upper inset) IV characteristic shows small but clearly measurable non-linearity (lower inset).

2.7  Measured Seebeck coefficients for the constituent thin films vs. $T$. Each film was deposited on a thermal isolation platform, and the measured Seebeck coefficient is relative to Cr/Pt leads. The estimated lead contribution has been subtracted here, so that this plot compares estimated absolute Seebeck coefficients. Inset: Scanning electron micrograph of the thermal isolation platform we use for thermal properties measurements.

2.8  a) 2d geometry and mesh used for FEM thermal calculations. b) Thermal profile resulting from heat dissipated in FM1 chosen to give the correct $\Delta T$ at FM2. Inset: Dashed red line shows the region of the 2d cross-sectional slice used for the FEM model. c-d) Resulting $T$ and $dT/dx$ profiles for the $L = 1300$ nm NLSV at the height $\approx 50$ nm above the substrate at the peak of the broad maximum in $dT/dx$.

3.1  A cartoon crosssection of a SiN coated Si chip and a SiN suspended membrane along with an optical photo of the membrane area on chip. The red square shows the fabrication area for the NLSV.
3.2 A cartoon of the 3 main wiring configurations compared on the devices. Electrical injection is standard operation of NLSV, where current is injected in NM channel but shunted away from the second NM/FM contact. Thermal injection is Joule heating of the FM injection strip only, no net current flows down the NM channel in either direction. The contact measurement is a 3-terminal resistance measurement of the injection contact.

3.3 IV measurements for electrical injection on the substrate and membrane devices. Large signal represents the background signal produced by the thermoelectric characteristics of the device.

3.4 a) IV measurement with both second and forth order fits along with the corresponding equations as well as the effective second order fit equation at 1 mA. b) The R vs H measurement for 78 K on the membrane device. The background “effective” first order resistance here is $\sim 1.52 \mu \Omega$. The effective second order resistance, I term coefficient, is in better agreement in both value and sign than the original second order fit I term.

3.5 A plot of the injection FM/NM contact temperature, $T_1$, and the temperature difference between injection and detection contact, $T_t$ for both the substrate and membrane device.

3.6 Parallel minus antiparallel IV curves for spin resistance signal for electrical spin injection (a) and thermal spin injections (b) on the substrate and membrane devices at 78 K.

3.7 a) and b) show electrical injection delta method resistance measurements at 300 K for the 500 nm device from chapter 2 in both orientation 1 and 2 (see chapter 4 for more about this significance). c) Shows R2 vs H at 300 K for thermal spin injection in orientation 1. Here, R2 is measured by taking differential conductance measurements at $\sim 10$ Oe.

3.8 a) Shows the IV measurement of the positive parallel saturation, Pp, minus the negative parallel saturation, Pn, for both the membrane device (blue) and substrate device(green) at 78 K. b) represents the R2 regression value from the Pp-Pn curves for electrical and thermal spin injection for the substrate and membrane devices compared to temperature from 78 K to 200 K. At 250 K and above the membrane NLSV background spin resistance began to drift too much to successfully measure repeatable behavior. c) is a cartoon of the cross section of the detector contact showing the assumed direction of the thermal gradient. d) is a cartoon showing labeling conventions used for the magnetization directions.
3.9 R vs H sweeps for substrate, a), and membrane, c). b) Seebeck coefficients for Al and Py from thin film measurement. d) Peltier produced at the FM/NM injection contact. 59
3.10 a) The temperature map of the membrane device at 200 K and 1 mA thermal injection. b) The thermal gradient along the NM channel from the temperature map. The injection and detection FM locations are indicated. 60

4.1 The wiring configuration for the electrical injection measurement for Orientation 1 and 2. 65
4.2 In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the device with magnetic oxide are shown. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis. d) shows the projected contact temperatures from the 1-dimensional analytic model for both orientations in thermal injection, what should be the hottest orientation. 68
4.3 In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the device with aluminum oxide are shown. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis. d) shows the projected contact temperatures from the 1-dimensional analytic model for both orientations in thermal injection, what should be the hottest wiring configuration. 69
4.4 Parallel minus antiparallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d). First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis. 71
4.5 Parallel minus antiparallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d). First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis. 72
4.6 Positive minus negative parallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d). First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis. 

A-1 An circuit diagram for the grounding circuit is shown above. This circuit is repeated for every line that is going to be grounded together, i.e. every line connected to the NLSV. At no point does a line remain unconnected while everything is plugged in so there should be less of a chance of built up charge.

A-1 In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the 900 nm magnetic oxide devices. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis.

A-2 Parallel minus antiparallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d) for the 900 nm magnetic oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.

A-3 Positive minus negative parallel IV curve fit values for first and second order coefficients for thermal, b), and electrical injection, a) for orientation 1 and 2 for the 1300 nm magnetic oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.

A-4 In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the 1300 nm aluminum oxide devices. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis.
A-5 Parallel minus antiparallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d) for the 1300 nm aluminum oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis. 

A-6 Positive minus negative parallel IV curve fit values for first and second order coefficients for thermal, b), and electrical injection, a) for orientation 1 and 2 for the 900 nm aluminium oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.

A-7 In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the 900 nm aluminum oxide devices. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis.

A-8 Parallel minus antiparallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d) for the 900 nm aluminum oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.

A-9 Positive minus negative parallel IV curve fit values for first and second order coefficients for thermal, b), and electrical injection, a) for orientation 1 and 2 for the 900 nm aluminum oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.
Chapter 1

Background

In this chapter information is presented to provide a scientific framework necessary to understand the results presented in the following chapters.

1.1 Spin Polarized Current

The basis for understanding spin-polarized current comes from the pioneering work of Mott[1, 2] where he realized that below the Curie point current flow in a ferromagnetic metal (FM) the majority spin, spin-up, and minority spin, spin-down, do not mix in their scattering processes. This results in different conductivities and thermoelectric properties for the two currents. When current is injected from a FM into a nonmagnetic metal (NM) the electrochemical potentials for the spin-up and spin-down populations are not continuous at the interface, however the current densities for the populations must be continuous as $J_\uparrow + J_\downarrow = J = \text{const}$. This creates a nonequilibrium state of an unequal population of spin-up and spin-down populations in a normal metal.
1.1.1 Spin Valves

In 1987 the giant magnetoresistance effect (GMR) was independently discovered by Fert and Grünberg [3, 4]. They noticed that the resistance of a multilayer ferromagnet device had a $\sim 100\%$ increase in resistance if the magnets were aligned antiparallel instead of parallel. As the spin-up and spin-down electrons scattering processes are separate. An up-spin electron will have more scatterings in a down magnetized FM than in an up magnetized on. The GMR effect allowed the creation of a spin-valve, a device the changes it’s operation based on the orientation of two ferromagnets. The spin valves high $\frac{\Delta R}{R}$ value made it an attractive tool to use in hard disk hard drive read head for non-volatile memory read out. Because of this significance Fert and Grünberg earned the Nobel prize in physics for their discovery in 2007.

After GMR’s implementation in 2001 (as Current in Plane, or CIP geometry) HDD read heads have transitioned to TMR and now current perpendicular plane, CPP, GMR geometry to achieve an ever decreasing read head
size to accommodate higher bit densities in the media. A fundamental challenge in reducing the read head size is the increased spin valve resistance from the reduction in size as design must balance signal to noise ratio, SNR, with bandwidth and \( \Delta R/R \). In general, lower device resistance improves the SNR and increases bandwidth. Nonlocal spin valves have been suggested as a low resistance alternative to GMR read heads[5].

1.2 Pure Spin Current

A pure spin current differs from a spin polarized current in that it requires that is no net charge flow. This can be understood as two different phenomena. In one way this can be seen as an equal flow of up spin electrons flowing one direction and down spin electrons in the opposite direction. The net charge flow is 0 but the net angular momentum flow of the system is a addition of the angular momentum flow of both. The other way to think about pure spin transport would be spin diffusion in a material. If there is a nonequilibrium accumulation of spins in a paramagnetic material, or nonmagnetic metal (NM), at a given location the diffusion of electrons through the material will result in a net flow of spin. Again there is no net flow of current but there is a flow of angular momentum away for a source of accumulation.

The relaxation distance for the spin polarization in the NM material is determined by the spin diffusion length, the average distance traveled by an electron before a spin-flip event. The electrons are assumed to ballistically travel between scatter events and at each scatter even there is a certain probability that the electron will lose it’s angular momentum. At higher tempera-
Figure 1.2: a) A cartoon of a NLSV. b) A sketch of the electrochemical potential from the injection FM/NM contact to the detection FM/NM contact. c) A cartoon of NLSV function as external field is sweep up and down.

tures this scattering is dominated by impurities and phonons in the material as described by the Elliott-Yafet mechanism. Each scattering event has a probability of changing the angular momentum of the electron, relaxing the polarization in the material. Typically diffusion lengths, $\lambda$, can vary from a few nanometers in FMs ($Py \sim 5 \text{ nm}$) up to on order of a micron in NM ($Al \sim 700 \text{ nm}$) [6].

### 1.2.1 Theory of Non-Local Spin Valves

Much like a regular spin valve works by detecting a change in resistance due to a spin polarized current a non-local spin valve (NLSVs) or lateral spin valve, is a tool in measuring a pure spin current. The NLSV, first conceived of by Johnson and Silsbee in 1985 [7] consists of two FM nanowires contacted by a NM channel. Like in the regular spin valve a current, $I$, is passed through one FM into the NM material. This injects a nonequilibrium spin acumulation into the NM channel material. After the injection of a spin polarized
current into the channel material the electric current is shunted away from the second FM. The spin accumulation will then diffuse down the channel as a pure spin current. The spin current creates a spin accumulation at the second FM/NM contact. Because the electrochemical potentials of both the up and down states must remain continuous across the FM/NM junction the spin accumulation will cause a gradient to form in the total electrochemical potential. This creates a gradient in the electrical potential, a measurable voltage difference as shown in equation 1.2.1.

\[ \mu = \mu_{ch} - eV \]  

To have reliable signal to noise the separation distance between the FM contacts in NLSVs should be \( \approx \lambda \). Materials like copper and aluminum have relatively long spin diffusion lengths on order of \( 1 \sim \mu m \), making them ideal candidate materials for the NM channel. The relaxation distance has been modeled for NLSVs in the seminal work by Takahashi and Maekawa where they considered devices with tunnel junction NM/FM contacts and transparent NM/FM contacts[8]. In this work all devices are produced with an oxide barrier in between the FM and NM channel which, as discussed in chapter 2, result in a simple exponential decay function to explain the spin relaxation distance dependence as shown in Eq 2.3.1.

Since the size of the NLSV is limited by the spin diffusion length in the NM channel much the device it’s self must have features that are nanoscale. Typical operational currents in the NLSV are on order of 1 mA. With the reduced geometry this creates a current density of \( \geq 10^{10} \text{A/m}^2 \). These high
current densities can dissipate a relatively large amount of heat that drives a thermoelectric background signal in the detection of spin currents.

1.3 Thermal Effects

1.3.1 Joule Heating

Resistive heating was discovered by James Prescott Joule in 1841[9]. In his experiment Joule measured the temperature rise in a fixed mass of water due to running a current through a submerged length of wire. He determined that the heat produced was proportional to the square of the current applied. This is now defined as $P_J = I^2 R$.

1.3.2 Seebeck Effect

Discovered by Thomas Johann Seebeck in 1921 the Seebeck effect is an electrical current produced from a temperature difference. The Seebeck effect is an intrinsic property of the material and therefore the thermopower coefficient, or Seebeck coefficient, $S$ describes the electrical response to an applied thermal gradient. We can define this Seebeck coefficient by writing a coupled matrix of electric field and thermal gradient in a metal:

$$
\begin{pmatrix}
\dot{J} \\
\dot{Q}
\end{pmatrix} = \sigma \begin{pmatrix} 1 & S \\ \Pi & k/\sigma \end{pmatrix} \begin{pmatrix} \nabla V \\ -\nabla T \end{pmatrix}
$$

where $\dot{Q}$ is the heat current density, $\dot{J}$ is the electrical current density, $\sigma$ is the electrical conductivity and $k$ is the thermal conductivity. Boundary conditions
can now be applied to build a deeper understanding of these relations. In the case of \( \vec{J} = 0 \) the thermal gradient produces an parallel electric potential across the material, \( S \nabla T = \nabla V \). Functionally this effect is used in digital thermometers called thermocouples. Two leads of dissimilar Seebeck coefficients are joined together at a junction. If this junction is heated or cooled as compared to the ends of the leads the thermal gradient in both leads will produce a voltage proportional to the temperature difference and the difference in Seebeck coefficients between the two leads. In NLSVs the detector FM/NM contact is a junction of two materials with different Seebeck coefficients making the spin accumulation detector also a thermometer by definition.

### 1.3.3 Peltier Effect

The Peltier effect was discovered by Jean Charles Peltier in 1834 and is the conjugate of the Seebeck effect. In the Peltier effect an electrical current flowing in a material will create a thermal gradient dependent on the direction of current flow, effectively transferring heat from one end of the material to another. The direction of this thermal gradient is governed by the direction of current and the sign of the Peltier coefficient, \( \Pi \). To understand the Peltier coefficient, \( \Pi \) we use the boundary condition \( \nabla T = 0 \) in the heat expression of equation 1.3.1. Dividing the thermal current by the charge density gives:

\[
\frac{\dot{Q}}{\dot{I}} = \frac{\Pi \sigma \nabla V}{\sigma \nabla V} = \Pi
\]  

(1.3.2)

Therefore \( \Pi \) is the heat transferred per unit area per charge transferred per unit area or, more succinctly, the amount of heat transferred per charge transferred.
Figure 1.3: a) Cartoon of the spin dependent Seebeck effect (SDSE). The thermal gradient in the FM injector drives a spin accumulation at the FM/NM contact. The resulting spin accumulation in the NM diffuses through the NM like in regular NLSV spin injection. b) The longitudinal spin Seebeck effect (LSSE). The LSSE is mediated by thermally exited magnons in a ferromagnetic insulator that create a spin current in a paramagnetic material. This spin current is produces an electrical current via the inverse spin hall effect to that allows for spin accumulation detection.

Reversing the current reverses the Peltier effect from heating(cooling) to cooling(heating) but has no effect on the heat generated through the Joule effect. Experiments probing the Seebeck and Peltier effects can directly test the relationship between $\alpha$ and $\Pi$ ($\Pi = \alpha T$) [10] predicted by the Onsager symmetry theorem for which Lars Onsager won the 1968 Nobel prize in chemistry [11].

1.3.4 Spin Dependent Seebeck Effect

There can be a great deal of misunderstanding about what the Spin Dependent Seebeck effect (SDSE) as this can be easily confused with the longitudinal spin Seebeck effect (LSSE)[12]. The SDSE is a result of the difference in spin-up and spin-down electron populations Seebeck coefficients. A thermal gradient then will drive a pure spin current proportional to $S_\uparrow - S_\downarrow$ through the FM. This spin current results in a nonequilibrium spin accumulation at
a FM/NM contact that decays at the spin diffusion length in both materials. The SDSE coefficient, \( S_s \), is defined as:

\[
S_s = \frac{V_s}{\nabla T \lambda_{FM} R_{mis}}
\]

(1.3.3)

where \( V_s = \mu_{s/e} \) is the spin accumulation at the injection junction (FM1), and

This effect also exhibits Onsager reciprocity as a spin accumulation can drive a heat current[14]. In the practice of NLSVs this effect is used by only Joule heating a ferromagnet and letting the spin polarization to travel along with the heat current into the normal metal[13, 15, 16, 17, 18, 19, 20].

The LSSE also is caused by a thermal gradient in a ferromagnet material but results from a different phenomenon. The LSSE is the result of incoherent magnons, spin waves, thermally excited in a ferromagnet insulator that produce a pure spin current in paramagnetic metal in contact with the FM. This spin current is then typically detected via the inverse spin hall effect (ISHE). The ISHE effect is caused by shifting electron orbits based on whether they are spin up or down. This creates movement of up and down electrons in the opposite directions that is normal to the bulk current flow. The splitting of the up and down electron populations result in a large voltage difference in some heavy metals such as Pt.

In a practical sense the difference between the two are as follows. First, as the SDSE is the result of moving charges, though without net current, with a thermoelectric effect. The coherence of a spin accumulation is limited by the spin diffusion length of a ferromagnet. In the case of Py this is about \( \sim 5 \) nm. In the LSSE this effect is carried by spin waves that deposit their angular
Figure 1.4: Cartoons of the Hall effect, the anomalous Hall effect and the anomalous Nernst effect.

momentum into electrons scattered at the FMI/NM interface. These spin waves have a much longer coherence length, typically $\sim 1 \mu m$. This means that any investigation of the SDSE is going to try to investigate thermal gradients on a much shorter length scale than that of the SSE. The other difference between SDSE and SSE is that the SSE does not require a current flow from the FM to the NM. Instead, the spin current is mediated by the magnons from the ferromagnetic insulator. Conversely, the SDSE works by driving a thermoelectric spin accumulation in a FM that diffuses into a NM.

### 1.3.5 Anomalous Nernst Effect

The final thermal effect that we must go over is the anomalous Nernst effect (ANE). When a thermal gradient is applied to a ferromagnet that is orthogonal to the magnetization with will produce an electric potential that is orthogonal to both magnetization and applied thermal gradient. This effect is often referred to as a thermal analogue to the anomalous Hall effect[21].

The Hall effect is caused by an electric current that traveling in a magnetic field. According to the Lorentz force charges moving through a perpendicular magnetic field will experience a force orthogonal to both the current and the
direction of current. As the total force must be 0 this magnetic force results in an electric field.

\[ F = q[\vec{E} + \vec{v} \times \vec{B}] = 0 \rightarrow E_y = v_x B_z \]  

(1.3.4)

Here, \( F \) is a force, \( E \) is the electric field, \( B \) is the magnetic field and \( v \) is the charge velocity. In the anomalous Hall effect the magnetic field, \( H \), is replaced with a magnetization produced the ferromagnetic conductor the current is traveling down[22]. Strong spin-orbit interactions such as skew scattering are often larger than their counterparts generated through the Lorentz force result in spin-up and spin-down electrons being preferentially deflected by phonons and impurities to opposite edges. Thus an electric current through a magnetic material can drive a spin imbalance along the edges as shown in 1.4.

The ANE then arise from replacing the electric current in the AHE with a thermal gradient. The thermal gradient will drive charge flow via the Seebeck effect.

\[ \vec{\nabla}V_N = -S_N \vec{m} \times \vec{\nabla}T \]  

(1.3.5)

where \( \vec{m} \) is the unit vector pointing in the direction of magnetization, \( \vec{\nabla}T \) is the thermal gradient, \( \vec{\nabla}V \) is the voltage gradient and \( S_N = R_N S \) is the transverse Seebeck coefficient of the effect, a fraction of the material’s total Seebeck coefficient. In NLSVs the ANE has been observed in cases of induced thermal gradient of the FM detector[23, 24].
1.4 Summary

In this chapter we discussed briefly spin polarized currents, spin valves, pure spin currents and NLSVs. We also discussed thermoelectric effects and how manifestation can change electrical properties. Finally we also addressed spin caloritronic effects and did a brief overview of how they are connected to NLSVs. We will be drawing on this material when discussing the thermal effects in the operation of metallic NLSVs in the following few chapters.
Chapter 2

Thermal spin injection and interface insensitivity in permalloy/aluminum metallic non-local spin valves

2.1 Introduction

The non-local spin valve (NLSV), also called a lateral spin valve or spin accumulation sensor, plays an essential role in modern spintronics because of the unique ability to separate charge current from pure spin current [25, 26, 27, 28, 29]. The NLSV is formed from two ferromagnetic (FM) nanowires connected by a non-magnetic (NM) channel material with a length $L$ on the order of the spin diffusion length. As shown schematically in Fig. 3.2a), when a (charge) current $I$ is driven from the left FM contact and extracted from the
nearby end of the NM channel, the spin polarization of the electrons flowing into the channel causes a transfer of angular momentum, or spin, into the NM. This spin accumulation diffuses, decaying exponentially with distance with a spin diffusion length $\lambda_{nm}$. Note that in the ideal case no charge current is present in the NM channel where the spin accumulation leads to a pure spin current. Because of the difference in chemical potential for up and down spins, the potential difference $V_{\text{NLE}}$ measured between the right FM contact and the right side of the NM channel depends on the relative alignment of the magnetization in the two FM contacts. Here the subscript NLE specifies the non local voltage under conditions of electrical spin injection. Dividing $V_{\text{NLE}}$ and $I$ in this nonlocal geometry gives the non-local resistance resulting from electrical spin injection, $R_{\text{NLE}}$, which then has the dependence on applied magnetic field, $H$, shown in Fig. 3.2b). This electrically-driven NLSV allows powerful probes of spin injection, spin accumulation, and spin transport in a wide variety of material systems [30, 31].

Despite decades of study, spin transport and injection even in supposedly simple metallic systems still holds open questions and surprising results, including the role of size and material effects and nature of the injection mechanisms [32, 33, 34]. These open questions become more urgent as industrial use of NLSV sensors for demanding magnetic field sensing applications such as read heads in magnetic recording rapidly approaches reality [5]. Recently, thermal effects on the NLSV have proven a critical area of study, with some authors suggesting that the dominant physics driving the background resistance of the NLSV originates in thermoelectric effects [35, 36, 37], and others observing that significant Joule heating plays an important role in spin injection.
A few groups have even shown that spin accumulation and transport in a metallic NLSV is possible by driving heat current, rather than charge current [13, 15, 39, 40, 20, 19, 18]. Such a thermal injection is shown schematically in Fig. 3.2c), where current is passed only through the FM contact in order to provide a local heat source at the FM/NM interface. If the resulting thermal gradient generates a spin accumulation in the NM and resulting spin current in the channel, the potential difference $V_{\text{NLT}}$ shows a characteristic switching pattern similar to Fig. 3.2b). Here the subscript NLT specifies a non local voltage under conditions of thermal spin injection. This thermal generation of pure spin current, usually called the spin-dependent Seebeck effect (SDSE)[12], is still largely unexplored, and often difficult to quantify due to the need to accurately determine the thermal gradient in nanoscale structures. There is a great deal of interest in the SDSE for applications in sensors and as a source for pure spin currents in possible spin-based logic [41, 42, 43, 44, 45], as well as for its role in spin-torque switching in response to fast or ultrafast laser fluence [18].

In this paper we present measurements of thermal and electrical spin injection and transport in all-metallic NLSVs made using permalloy (Py, the Ni-Fe alloy with 80% Ni) FM and aluminum NM. In addition to quasi-dc measurements using the equivalent of the lock-in amplifier techniques common in the field, we fully characterize the voltage-current characteristics of the NLSV in both electrical and thermal spin injection configurations. As discussed in detail below, this allows description of each device using a simple analytic thermal model that includes Joule heating and Peltier heating or cooling. With knowledge of the thermal conductivity and Seebeck coeffi-
Figure 2.1: **a)** Schematic layout of the NLSV under electrical spin injection, where a large charge current driven through a FM nanowire creates a spin accumulation and pure spin current in a NM channel that is detected with a second FM. **b)** The non-local resistance $R_{NLSV} = V_{NLE}/I$ for a $L = 900$ nm device at 78 K, where the relative alignments of the two FM contacts are indicated with paired arrows. **c)** Thermal spin injection is achieved by passing current $I$ only through FM1, creating a thermal gradient at the NM/FM interface that injects spin into the NM. **d)** False-color SEM micrograph of the nanoscale circuit defining the NLSV. Sizes given indicate the designed widths of nanowires, measured geometries appear in Table A.1.
cients of representative films that we measure using our technology for thin film thermal measurements [46, 47, 48, 49, 10, 50, 51], we determine an upper limit on the thermal gradient driving spin injection without recourse to complicated simulations or assumptions of bulk thermal properties. We also use a 2d finite element approach based on purely diffusive heat flow, though again informed by measured values of thermal conductivity and Seebeck coefficients, to approach a more realistic estimate of the thermal gradient and the SDSE. The resulting SDSE coefficient for the Py/Al system at 78 K that we report here is smaller in absolute value than previous reports using typical ferromagnets, though very comparable as a fraction of the absolute Seebeck coefficient [13, 52] despite a very low efficiency of electrical injection. This suggests that thermal spin injection is far less sensitive to the nature of the FM/NM interface than its electrical counterpart and motivates broader study of the materials- and interface-dependence of thermal spin injection.

2.2 Experiment

2.2.1 Device Fabrication

We fabricate NLSVs via a two-step e-beam lithography lift-off process. Starting with silicon-nitride coated 1 cm × 1 cm Si chips with pre-patterned Au or Pt leads and bond pads, we spin an ≈ 150 nm thick layer of PMMA that is baked for 30 min. at 180° C. After exposure of the FM nanowire pattern using a 40 kV SEM with the NPGS package[53] at a dose of ∼ 600 µC/cm² and a 45 s development in a 1:3 MIBK:IPA solution, we deposited 100 nm of Py from a single Ni-Fe alloy source in a load-locked UHV e-beam evaporation
system at growth rates of $\sim 0.15$ nm/s. After removal of the resist, we spin an $\approx 380$ nm PMGI spacer layer that is baked at 250° for 30 min, followed by an $\approx 100$ nm thick PMMA imaging layer. After e-beam exposure of the NM channel and lead pattern and a two-step development (1 : 3 : MIBK for 45 s, followed by a 35 s soak in 1 : 30 solution of 2% TMAH: IPA to form the undercut in the PMGI), we deposited a 110 nm Al layer in a HV e-beam evaporation system at 0.2 – 0.5 nm/s using a water cooled stage after a 2 minute, 50 W, -580 V RF clean process in 10 mT of Ar intended to desorb moisture from the exposed FM surface (to promote adhesion during lift-off) and potentially remove the native oxide formed on the Py nanowires. We then remove the PMGI/PMMA resist stack via a 45 min soak in 80° C MicroChem Remover PG. A scanning electron micrograph showing an example NLSV is shown in Fig. 3.2d).

## 2.2.2 Transport Measurements

Measurements are carried out after bolting the NLSV chip to a fully radiation-shielded gold-coated high-purity Cu sample mount installed in a sample-in-vacuum LN2 cryostat. An open bore split-coil electromagnet allows application of fields in excess of 1000 Oe in the plane of the chip. For the measurements described here the field is applied as shown in Fig. 3.2a). Simple resistance or non-local resistance measurements are made using the “delta mode” function of a linked Keithley 2128a nanovoltmeter and 6220 high precision current source. This measurement is functionally equivalent to a first-harmonic lock-in amplifier measurement [54]. We determine IV characteristics of the NLSV in various configurations by numerically integrating differential conductance.
Figure 2.2: $V_{\text{channel}}$ vs. $I$ characteristics for the NM channel (contacts made as shown schematically in the inset) are highly linear across the entire range of applied $I$ in contrast to both the three-terminal contact resistance (Fig. 2.6 e)) and non-local resistance measurements (Figs. 2.5a) and 2.6c)). Measurements for two NLSVs are shown for two temperatures. Dashed lines show linear fits.

measurements made with the same system. Fig. 2.2 shows an example IV measurement of the the NM channel for the $L = 900$ nm and $L = 1300$ nm devices at both $T = 78$ K and 300 K. Since no FM/NM couple is in the current path in this measurement, no thermoelectric contributions are expected and indeed $V_{\text{channel}}$ is highly linear for the entire range of applied $I$, as seen by the excellent agreement with linear fits shown with dashed lines. After all measurements are completed on a NLSV, we measure the FM and NM film thicknesses via AFM contact profilometry and the actual lateral geometry of the nanowires using SEM micrographs (see Table A.1). For the devices described here, this revealed somewhat wider NM channels than intended, with widths reaching $400 - 450$ nm. These measured values are used wherever geometry is needed in model calculations.
Figure 2.3: Non local resistance signals $R_{\text{NLE}} = V_{\text{NLE}}/I$ in electrical (a) and b)) and $R_{\text{NLT}} = V_{\text{NLT}}/I$ in thermal (c) and d)) spin injection for both 500 nm and 1300 nm nominal FM spacing. e) The electrical spin signal $\Delta R_{\text{NLE}}$ vs. $L$ with the fit to the 1d spin diffusion equation. This fit gives $\lambda_{nm} = 760 \pm 50$ nm.

2.3 Results

Fig. 2.3 shows the nonlocal resistance as a function of applied field for two NLSVs with different FM spacing, $L$. Panels a) and b) result from electrical spin injection using a bias current of $I = 1$ mA (Fig. 3.2a)), while panels c) and d) current ($I = 2$ mA) flows only in the FM, causing no net charge current to pass into either arm of the NM channel, but heating the FM such that a heat current forms at the FM/NM interface. The characteristic switching clearly shows that this heating generates a spin accumulation in the NM channel that is detected after diffusing to the location of FM2. Note however, that this quasi-dc $R$ measurement is sensitive to terms linear in $I$, where heating effects
are proportional to $I^2$. The apparent sign change in $\Delta R_\text{NLT} = R_\text{NLT}(\uparrow\uparrow) - R_\text{NLT}(\uparrow\downarrow)$ is peculiar, but as is discussed in more detail below does not indicate a sign change in the SDSE.

As shown in Fig. 2.3e), we use $\Delta R_\text{NLE} = R_\text{NLE}(\uparrow\uparrow) - R_\text{NLE}(\uparrow\downarrow)$ to determine the spin diffusion length in the Al, $\lambda_{\text{nm}}$. As discussed further below, this device does not clearly meet the criterion for any of the three limits typically used to analyze signals in NLSVs, but is closest to the case of tunnel contacts. In this tunneling limit, the form of the 1d spin diffusion equation is \[8\],

$$\Delta R_\text{NLE} = P^2 I R_{\text{NM}} e^{-L/\lambda_{\text{NM}}}, \quad (2.3.1)$$

and this equation can safely be used at least to determine $\lambda_{\text{NM}}$. The fit shown by the dashed line in the Fig. 2.3b) inset gives $\lambda_{\text{NM}} = 760 \pm 50$ nm, which is in line with previous results for Al \[6, 33\].

To better understand the signal size in this series of Py/Al NLSVs, in Fig. 2.4a we compare the experimental $\Delta R_\text{NLE}$ as a function of FM separation, $L$, on a semi-log plot to expectation of various models described by Takahashi and Maekawa.\[8\] If spin flip scattering at the interfaces is ignored, the NLSV signal is predicted to follow

$$\Delta R_\text{NLE} = 4 R_{\text{NM}} e^{-L/\lambda_{\text{NM}}} \prod_{i=1}^{2} \left( \frac{P_I R_i}{R_{\text{NM}}} \left( 1 - P_I^2 \right) + \frac{\alpha R_{\text{PM}}}{1 - \alpha^2} \right) \times \left[ \prod_{i=1}^{2} \left( 1 + \frac{2 R_i}{1 - P_I^2} + \frac{2 R_{\text{PM}}}{1 - \alpha^2} \right) - e^{-2L/\lambda_{\text{nm}}} \right]^{-1}. \quad (2.3.2)$$

Here $R_i$ is the contact resistance of the $i^{th}$ FM/NM interface, $\alpha = (\sigma_\uparrow - \sigma_\downarrow)/(\sigma_\uparrow + \sigma_\downarrow)$ is the spin polarization of the FM nanowire, $P_I = (G_\uparrow - G_\downarrow)/(G_\uparrow + G_\downarrow)$ is the spin polarization of the contact, and $R_{\text{PM}}$ is the spin-flip conductance of the FM nanowire.

Here $R_i$ is the contact resistance of the $i^{th}$ FM/NM interface, $\alpha = (\sigma_\uparrow - \sigma_\downarrow)/(\sigma_\uparrow + \sigma_\downarrow)$ is the spin polarization of the FM nanowire, $P_I = (G_\uparrow - G_\downarrow)/(G_\uparrow + G_\downarrow)$ is the spin polarization of the contact, and $R_{\text{PM}}$ is the spin-flip conductance of the FM nanowire.
\( G_\uparrow \) is the spin polarization of the interfacial current with \( G_\uparrow \) \((G_\downarrow)\) giving the interfacial conductance of the two spin channels, and

\[
\mathcal{R}_{\text{FM}} = \rho_{\text{Py}}\lambda_{\text{Py}}/w_{\text{FM}}w_{\text{nm}} \tag{2.3.3}
\]

and

\[
\mathcal{R}_{\text{NM}} = \rho_{\text{Al}}\lambda_{\text{NM}}/t_{\text{NM}}w_{\text{NM}} \tag{2.3.4}
\]

are the spin resistances of the ferromagnet and normal metal, respectively. Takahashi and Maekawa use reduction of the \( P_I \) term to phenomenologically take interfacial spin-flips into account, though others have considered this issue directly.[55]

Eq. 2.3.2 is commonly simplified for the three limits often, but not always, relevant to particular NLSV fabrication techniques. It is also common to assume a single contact resistance value for both FM/NM junctions, \( R_i = R_c \).

With this notation the three limits are the transparent limit, where \( R_c \ll \mathcal{R}_{\text{FM}} \):

\[
\Delta R_{\text{NLE}} = 4\frac{\alpha^2 \mathcal{R}_{\text{FM}}^2}{(1 - \alpha^2)^2 \mathcal{R}_{\text{NM}}} \frac{e^{-L/\lambda_{\text{NM}}}}{\left[ 1 + \left( \frac{2 \mathcal{R}_{\text{FM}}}{(1 - \alpha^2) \mathcal{R}_{\text{NM}}} \right)^2 - e^{-2L/\lambda_{\text{NM}}} \right]^2 - e^{-2L/\lambda_{\text{NM}}}} \tag{2.3.5}
\]

the intermediate limit \((\mathcal{R}_{\text{NM}} \gg R_c \gg \mathcal{R}_{\text{FM}})\):

\[
\Delta R_{\text{NLE}} = 4\frac{P_i^2}{(1 - P_i^2)^2} \frac{R_c^2}{\mathcal{R}_{\text{NM}}} \frac{e^{-L/\lambda_{\text{NM}}}}{1 - e^{-2L/\lambda_{\text{NM}}}} \tag{2.3.6}
\]

and the Tunneling limit, \( R_c \gg \mathcal{R}_{\text{NM}} \), given in Eq. 2.3.1 above.

Following common practice, we estimate the contact resistance from a transport measurement as shown schematically in the inset to Fig. 2.6e. The
linear slope of this measurement provides $R_c$ for this set of devices. Despite the RF clean step between the FM and NM depositions, we measure a fairly large contact resistance, such that at 78 K, $R_c \approx 40$ mΩ. The value of the contact resistance area product, $R_c A = 4$ mΩμm² (from the $L = 1300$ nm NLSV), is roughly an order of magnitude higher than seen in transparent contacts[33], and on par with the lowest values seen in MgO tunnel barriers capable of strongly enhancing $\Delta R_{NLE}$[56]. However, in our devices $R_{FM} \approx 14$ mΩ, and $R_{NM} \approx 0.28$ Ω. This indicates that $R_{NM} > R_c > R_{FM}$, meaning that the NLSV is far from the limit of transparent interfaces defined by $R_c \ll R_{FM}$. Since $R_c$ is only $\approx 2R_{NM}$, these devices do not belong to any of the simpler limits, though they are nearest to the intermediate limit. In Fig. 2.4a we compare the predictions of the model for our geometry and resistances. Though reports vary, for Py/Al NLSVs, $\alpha = 0.38$ and $P_I = 0.2$ are fairly common values for Py/Al junctions. The solid black line in Fig. 2.4a) gives the expected $\Delta R_{NLE}$ calculated from Eq. 2.3.2 using these parameters and our measured geometry and $R_c$. Note that this calculation is nearly linear above 500 nm, suggesting single exponential behavior as seen in the tunneling model. However, as is the case for similar predictions of the transparent and intermediate models (Eqs. 2.3.5 and 2.3.6), the theory assuming no interfacial spin flip scattering predicts much larger $\Delta R_{NLE}$ than we observe. The full theory does match the measured data well if $P_I$ is strongly reduced to $\approx 0.01$, as shown in the solid navy blue curve. Note that we must also somewhat reduce $\alpha$ to match the observed values, and here we choose $\alpha = 0.32$, a reduction of 15 percent motivated by a similar reduction in $M_s$ for Py grown from this source in our chamber.[57] We clarify that these predictions are not fits and there is
obviously not enough data here to determine all the possible parameters. We can also roughly match the measured data using the intermediate model, but only using a significantly reduced $P_I = 0.11$. We interpret this reduced signal as evidence of a high degree of interfacial spin-flip scattering in our NLSVs. As noted above, the simple single-exponential tunneling model can also fit the data well with a low value of $P_I = 0.02$. Such a fit is more convenient, if less obviously physical than use of the full equation where the spin polarization of the FM itself provides the difference in spin potentials that determine the signal, with a significant drop of electrochemical potential at the interfaces that has very low spin polarization and does not increase the signal. A fit with poor $\chi^2$ and large error bars on parameters is also possible using the transparent equation, though there is little physical justification for use of this model considering the relative values of $R_c$ and $R_{FM}$.

Fig. 2.4b compares our NLSV to a range of other devices reported in the literature using Py ferromagnetic elements. Perhaps most importantly, we first point out the large signal size reported by Slachter, et al. in the initial report of the SDSE indicated by the orange star.[13] The transparent spin diffusion model prediction of this signal is also shown as a dashed line. This prediction is at least $10 \times$ greater than the values we measure for all $L$. We also compare our results to some of the earliest reports on Py/Au devices, where similarly small overall signal size was observed at 10 K using a Au normal metal channel.[27] This set of devices also showed a similar pattern of contact and spin resistance as our NLSV, and can be explained with the same reduction of $P_I$ as a result of likely interfacial spin-flip scattering. One can also fit the tunneling equation to the data from Ji, et al., which gives a very low value of $P_I = 0.03$. Because
of the short $\lambda_{NM}$ of Au in comparison to Cu or Al, the transparent model can also be tuned to match the Ji data, though again the contact resistance is far higher than $R_{FM}$ and there is little physical justification for use of the transparent model.

Fig. 2.4b also compares data from Isasa, et al. on polycrystalline Ag channels where the full equation is the only reasonable match for the signal size,[58] as well as for a Py/Ag NLSV that was exposed to atmosphere over a long period of time by Mihaijlovic, et al.[59] This exposure caused diffusion of oxygen through grain boundaries in the Ag overlayer, allowing increased oxidation of the underlying Py. In this case, the additional oxide increased $\Delta R_{NLE}$ dramatically, such that the device that matched expectations of the transparent limit converged to the tunneling prediction (though no measurements of contact resistance were included so the match to models remains approximate).

Though we cannot truly specify the physical mechanism responsible for low electrically-driven spin signals and low $P_I$ in the NLSV we used here, it is clear that oxidation of the Py nanowires followed by the RF sputter-clean before Al deposition resulted in an imperfect interface. Here some amount of the native oxide most likely remains, and the resulting disordered magnetic environment scatters spins as they are electrically driven through the interface into the NM.

Fig. 2.5 details the extraction of spin accumulation signals from the full IV characteristics measured in both electrical and thermal spin injection configurations. Fig. 2.5a) plots $V_{NLE}$ vs. $I$ for $L = 500$ nm at 78 K measured for two different fields, chosen based on the $R_{NLE}$ vs. $H$ patterns in Fig. 2.3a) to give the parallel (labeled $\uparrow\uparrow$) and antiparallel ($\uparrow\downarrow$) states of the FM nanowires.
Figure 2.4: a) Comparison of electrically-driven spin signal $\Delta R_{NLE}$ (blue spheres) to various models based on the 1d spin diffusion equation.[8] Matching of the electrical signal is only possible using a strongly reduced value of interfacial spin polarization, regardless of the model employed. b) Comparison of $\Delta R_{NLE}$ reported here (blue spheres) to similar Py-based NLSV with various NM channels.[13, 59, 58, 27] In each case the lines represent a 1d spin diffusion model that explains the signal size. Relevant parameters and spin resistances are also given. Note especially the large signal that matches predictions of the transparent interface model for the Py/Cu device originally used to observe the SDSE.[13]. NLSV used in this study have much reduced electrical signal, but maintain the same thermally-driven spin signal.
Figure 2.5: a) $IV$ characteristic for the electrical spin injection configuration (Fig. 3.2a) measured separately for parallel and anti-parallel states of the FM nanowires for the $L = 500$ nm device at $78$ K. b) The corresponding $IV$ characteristic for the thermal spin injection configuration (Fig. 3.2c). c) Subtraction of the parallel and antiparallel curves in a) gives the highly linear response of electrical spin injection, while the corresponding subtraction for thermal injection yields a spin signal dominated by the $I^2$ term indicating thermal generation of a spin accumulation in the NM. In both c) and d), data for both $L = 500$ nm and $L = 1300$ nm are shown. Fitted values of spin signal are also shown.
Both curves show obvious terms $\propto I$ and $\propto I^2$. The striking non-linearity is a clear indication of the importance of thermal and thermoelectric effects in this NLSV. However, subtracting the two curves gives the very linear response shown in Fig. 2.5c) for both $L = 500$ nm and $L = 1300$ nm, where the slope matches the spin signal seen in $R_{\text{NLE}}$ vs. $H$. Fig. 2.5b) and d) show similar plots for thermal spin injection ($V_{\text{NLT}}$) measured at the same temperature over a wider $I$ range. As expected $V_{\text{NLT}}$ is predominantly $\propto I^2$, and the difference between parallel and antiparallel configurations (Fig. 2.5d) retains a large $\propto I^2$ component. Lines in Fig. 2.5d) are fits to $V_{P-AP} = R_1^s I + R_2^s I^2$. As discussed further below, the $R_2^s$ provides the same information as the second-harmonic lock-in signal in previous work [13], and is the evidence of thermally-generated spin accumulation in the NLSV. The physics of the $R_1^s$ term is less clear, though this term was also seen in the original report of the SDSE [13]. In fact, the size of $R_1^s$ and $R_2^s$ shown in Fig. 2.5d) for $L = 500$ nm is nearly the same as the results in [13]. However, this does not necessarily imply a similar SDSE coefficient, since the thermal profile in the NLSV must be determined and will certainly depend on the detailed geometry and materials in each device. We also point out that the difference in sign in $R_1^s$ between the 500 nm and 1300 nm devices entirely explains the sign change of $\Delta R_{\text{NLT}}$ apparent in Figs. 2.3c) and d) and clarifies that this is not related to the SDSE. Recent electrical injection experiments in the wiring configuration of Fig. 3.2b for a Py/Cu NLSV with Al$_2$O$_3$ tunnel barriers showed a spin accumulation signal that was interpreted as evidence of a non-uniform spin injection across the contact.[60] A similar mechanism could well explain our $R_1^s$, but requires further study to conclusively discuss.
2.4 Discussion

Accurately determining the thermal gradient generated in any nanoscale metallic device is a serious challenge. Even if complicated 3d finite element analysis (FEM) is used, having accurate values of thermal properties for the thin film constituents of the devices is important, and the role of interfaces for electron, phonon, and spin transport is difficult to quantify without great effort [61, 62]. Furthermore, typical codes describe only diffusive heat transport, ignoring ballistic or quasi-ballistic phonon transport that is known to play a role in nanoscale metallic features on insulating substrates [63]. In fact the previously common view that only phonons of quite short wavelength and mean-free-path dominate heat transport in bulk materials at room temperature is now understood to be incorrect, with more and more quantitative measurements showing large contributions to heat flow from parts of the phonon spectrum ignored in typical FEM simulations [64, 65, 66, 50, 67, 68]. These issues suggest that truly quantitative determination of the SDSE coefficient will be challenging and some level of disagreement between experimental groups should be expected, a situation familiar to the spintronics community.

We therefore clarify that the main result of this study requires no complicated or controversial calculations of thermal gradients. First consider that the spin signal due to electrical spin injection in the NLSV first used for the SDSE measurement by Slachter, et al. was (as shown in Fig. 2.4b above) \( \Delta R_{\text{NLE}} \approx 10 \, \text{m}\Omega \) where the thermal injection signal as discussed earlier was \( R_2^s = -16 \, \text{nV}\/\text{mA}^2 \). In the NLSV devices described here we achieved the same thermal spin signal \( R_2^s \) despite an electrical spin signal of only \( \Delta R_s \approx 70 \, \mu\Omega \), a
factor of more than 100 smaller. We can also use a simple 1d Valet-Fert model for spin diffusion to make a more fair comparison of spin accumulation at the injection site between devices and injection techniques. This suggests that Slachter et al.’s \( L = 100 \text{ nm} \) asymmetric NLSV where ion milling was used to remove Py oxide at the interfaces showed thermal spin accumulation of \(< 0.2 \% \) of electrical spin accumulation at the same applied current. Our NLSVs, where Py oxide likely remains at the interface, show similar thermal spin accumulation but dramatically smaller electrical spin accumulation so that the ratio is \( > 0.15 \% \). As discussed further below, this suggests that thermal spin injection is much more tolerant of imperfect interface quality, and in fact may be enhanced by the presence of an oxidized Py layer.

We now consider two techniques for estimating the thermal gradient driving the SDSE in our NLSVs. The first is a simple analytic technique using the two-body thermal models shown in Fig. 2.6a) and b). Here we assume the two FM/NM junctions equilibrate to two different temperatures in steady state, \( T_1 \) and \( T_2 \), that both junctions are connected to thermal ground (the substrate held at \( T_0 \)) via the same thermal conductance \( K_{\text{sub}} \), and that heat can flow between the two junctions via thermal conductance \( K_{\text{nm}} \). This model is shown schematically for electrical spin injection in Fig. 2.6a). Note that truly ascribing physical meaning to the parameters in this simple model is difficult. For example one would normally expect that the NM channel in a typical NLSV would be coupled to the bath (substrate) with approximately the same thermal conductance as the junctions, though all these features are on the size scale where decoupling from the phonons responsible for heat-sinking
Figure 2.6: **a-b)** Two-body thermal models used to analytically model the $T$ profile in the devices. **c-d)** Resulting $IV$ curves show significant curvature as a result of heating and thermoelectric effects. Data is shown for the $L = 1300$ nm NLSV at 78 K, but similar curvature is seen at room $T$ and for other devices. **Inset:** The simplified thermal profile used to estimate a maximum possible $\nabla T$ of 33 K/µm from our data. **e)** The three-terminal contact resistance (shown schematically in upper inset) $IV$ characteristic shows small but clearly measurable non-linearity (lower inset).
the metal structures can lead to larger heating effects and counterintuitive behavior [63].

As already noted by other groups [37, 35, 38], when current is driven into the injector FM and out of one arm of the NM channel, Joule heating in this current path is accompanied by either cooling or heating due to the Peltier effect. Whereas Joule heating, \( P_{J,i} = I^2 R_{\text{eff}} \), is always positive, the Peltier term, \( P_{\Pi_{\text{rel}}} = I \Pi_{\text{rel}} \), is either positive or negative. The sign of the Peltier term depends on the direction of applied current, the geometric arrangement of the two metals with respect to this current flow, and the difference in the absolute Peltier coefficients of the two materials (written here simply as the relative coefficient \( \Pi_{\text{rel}} \)). Furthermore, via Onsager reciprocity\([69, 10]\), \( \Pi_{\text{rel}} = S_{\text{rel}} T_0 \) with the relative Seebeck coefficient \( S_{\text{rel}} \), where we use the substrate temperature since deviation in \( T \) even by several Kelvin makes a negligible change in the Peltier power at the \( T \) studied here.

The schematics in Fig. 2.6a) and b) for electrical and thermal spin injection, in addition to a three terminal contact resistance measurement shown in Fig. 2.6e) with voltage \( V_C \), lead to a coupled system of equations that can be compared to fits of the full \( IV \) characteristics in the configurations shown in Figs. 3.2a) and b) and Fig. 2.6e). Each of these measurements contains terms proportional to \( I \) and to \( I^2 \) and are fit to:

\[
V_{\text{NLE}} = A_1 I + A_2 I^2 \tag{2.4.1}
\]
\[
V_{\text{NLT}} = B_1 I + B_2 I^2 \tag{2.4.2}
\]
\[
V_C = C_1 I + C_2 I^2 \tag{2.4.3}
\]
Figure 2.7: Measured Seebeck coefficients for the constituent thin films vs. $T$. Each film was deposited on a thermal isolation platform, and the measured Seebeck coefficient is relative to Cr/Pt leads. The estimated lead contribution has been subtracted here, so that this plot compares estimated absolute Seebeck coefficients. Inset: Scanning electron micrograph of the thermal isolation platform we use for thermal properties measurements.

Collecting terms in the corresponding thermal model that are proportional to $I$ and $I^2$ and solving these systems of equations yields expressions for the thermal parameters (as shown in Appendix A). With certain assumptions listed below we can then calculate the temperature difference between the heated region of junction 1 and the substrate in thermal spin injection, $\Delta T_t^1$. This is the critical value needed to calculate the SDSE coefficient, $S_s$. First we assume that the parameter $K_{nm}$ is given by the thermal conductance of the normal metal nanowire itself (ignoring any heat transported by the underlying substrate) and use the Wiedemann-Franz law to determine this $K_{nm}$ from the measured resistance of the channel, $R_{nm}$,

$$K_{nm} = \frac{L_A T_0}{R_{nm}}.$$  (2.4.4)
Here we take the value of the Lorenz number, \( L_{Al} = 2.0 \times 10^{-8} \, \text{W} \Omega/\text{K}^2 \) from a measurement of a similar Al thin film made using our micromachined thermal isolation platform [51]. Next we assume that both the injection and detection FM/NM arms of the NLSV have the same value of \( S_{rel} \). Though thermopower is often assumed to be independent of geometry, this is only strictly true in the case where thermal gradient is simply aligned with the sample and in the regime where size effects cannot play a role. Nanoscale metal features are not always in this simple limit [70, 71], so our model could be improved using actual measurements of Seebeck effects in nanowires of the same dimension as used in the NLSV. Since these measurements are not possible for the current devices, we instead take a value of the relative Seebeck coefficient at 78 K again from measurements of representative films made using thermal isolation platforms.

Seebeck coefficient data is shown in Fig. 2.6f), where we present estimated absolute Seebeck coefficient as a function of \( T \) for both Al and Py films. These measurements are made on thin films deposited on a patterned 500 nm thick suspended silicon-nitride membrane with integrated heaters, thermometers, and electrical contacts. Application of a temperature difference \( \Delta T = T_H - T_c \) generates a voltage across the film due to the Seebeck effect, \( V \), giving the relative Seebeck coefficient, \( S_{rel} = V/\Delta T = S_{abs} - S_{\text{lead}} \). Note that both measurements are made with the same lead material, so the determination of \( S_{abs} \) (which adds some uncertainty) is not necessary to determine the value needed for NLSV modeling, \( S_{rel} = S_{Al} - S_{Py} \). More details about Seebeck measurements made with our thermal isolation platforms are available elsewhere [48, 49, 10, 72].
Table 2.1: Fitting parameters as defined in Eqs. 2.4.1-2.4.3 and resulting temperature difference, and absolute values of thermal gradient from the analytic thermal model, ( $\Delta T^t_1$ and $\nabla T^t_1$) and resulting lower limit on SDSE coefficient, $S_s$ compared to temperature difference, thermal gradient, and SDSE coefficient from FEM modeling, ( $\Delta T^{\text{FEM}}_1$, $\nabla T^{\text{FEM}}_1$, and $S_{s,\text{FEM}}$) . †: Value calculated from model assuming the same value of $K_{\text{sub}}$ for both devices.

With these assumptions we can write,

$$K_{\text{sub}} = \left( \frac{C_2}{A_1} \frac{S_{\text{rel}} T_0}{R_{\text{eff}}} - 1 \right) K_{\text{nm}},$$

where here we use $R_{\text{eff}} = S_{\text{rel}} T_0 (A_2/A_1)$ for the contact resistance measurement to determine $K_{\text{sub}}$. The temperature rise at the injector junction is then

$$\Delta T_1^t = \left( \frac{B_2}{S_{\text{rel}}} \frac{(K_{\text{sub}} + 2K_{\text{nm}})}{K_{\text{nm}}} \right) \left[ 1 - \frac{A_1 K_{\text{sub}}}{S_{\text{rel}}^2 T_0} \right] I^2.$$  

(2.4.6)

The $B_2$ term enters from use of $R_{\text{eff}} = S_{\text{rel}} T_0 (B_2/A_1)$ to account for the different effective resistance when current flows only through FM1.

<table>
<thead>
<tr>
<th></th>
<th>500 nm</th>
<th>1300 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>3.9 $\mu$Ω</td>
<td>39.34 $\mu$Ω</td>
</tr>
<tr>
<td>$A_2$</td>
<td>$-0.984 \text{ V/A}^2$</td>
<td>$-0.586 \text{ V/A}^2$</td>
</tr>
<tr>
<td>$B_1$</td>
<td>$-146.95 \mu$Ω</td>
<td>$-11.43 \mu$Ω</td>
</tr>
<tr>
<td>$B_2$</td>
<td>$-1.498 \text{ V/A}^2$</td>
<td>$-1.112 \text{ V/A}^2$</td>
</tr>
<tr>
<td>$C_1$</td>
<td>-</td>
<td>$-36.76 \text{ m$\Omega$}$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>$-1.76^3 \text{ V/A}^2$</td>
<td>$-1.66 \text{ V/A}^2$</td>
</tr>
<tr>
<td>$\Delta T^t_1$ (2 mA)</td>
<td>5.3 K</td>
<td>3.3 K</td>
</tr>
<tr>
<td>$\nabla T^t_1$ (2 mA)</td>
<td>53 K/µm</td>
<td>33 K/µm</td>
</tr>
<tr>
<td>$S_s$</td>
<td>$-0.46 \mu$V/K</td>
<td>$-0.53 \mu$V/K</td>
</tr>
<tr>
<td>$\Delta T^{\text{FEM}}_1$ (2 mA)</td>
<td>3.9 K</td>
<td>5.4 K</td>
</tr>
<tr>
<td>$\nabla T^{\text{FEM}}_1$ (2 mA)</td>
<td>15 K/µm</td>
<td>23 K/µm</td>
</tr>
<tr>
<td>$S_{s,\text{FEM}}$</td>
<td>$-1.6 \mu$V/K</td>
<td>$-0.77 \mu$V/K</td>
</tr>
</tbody>
</table>
\( \Delta T_1 \) for the two NLSVs for two different currents are shown in Table 2.1, and indicate the NLSV junctions heat by several Kelvin during operation in thermal injection. The SDSE coefficient, \( S_s \), following [13] is

\[
S_s = \frac{V_s}{\nabla T \lambda_{FM} R_{mis}},
\]

where \( V_s = -\mu_s/e \) is the spin accumulation at the injection junction (FM1), and \( R_{mis} = R_{NM}/(R_{NM} + (R_{FM}/1 - P_1^2) \) is always \( \approx 1 \) for these metallic NLSVs. To estimate the SDSE Coefficient, \( S_s \), we need to determine a thermal gradient at the injection site from our temperature difference. For the analytic model we assume the highly simplified situation shown schematically inset in Fig. 2.6d), where the temperature \( T_1 = T_0 + \Delta T_1 \) is the effective temperature of the interface between FM and NM, and apply the 1d heat flow equation across the FM with the boundary conditions of \( T_0 \) and \( T_1 \), which gives a linear thermal gradient in the FM. The resulting \( \nabla T_1 \) for two applied currents is also shown in Table 2.1, and is comparable to that calculated in other work for large \( I \) [13, 15, 39]. Note that this simple assumption amounts to the limit where the NM channel can only exchange heat with the top surface of each FM contact, and is most likely not physically accurate. However, it does provide an estimate for the largest absolute value of gradients possible in our structure because it ignores heat-sinking by the NM channel which will lower \( \nabla T \) at the interface.

The opposite limit is described by a purely diffusive heat flow model that allows exchange of energy between elements in the real geometry of the device. 3d finite-element modeling (FEM) calculations that couple the heat, charge,
Figure 2.8: a) 2d geometry and mesh used for FEM thermal calculations. b) Thermal profile resulting from heat dissipated in FM1 chosen to give the correct $\Delta T$ at FM2. Inset: Dashed red line shows the region of the 2d cross-sectional slice used for the FEM model. c-d) Resulting $T$ and $dT/dx$ profiles for the $L = 1300$ nm NLSV at the height $\approx 50$ nm above the substrate at the peak of the broad maximum in $dT/dx$. 

37
and spin degrees of freedom to calculate $\nabla T$ in this limit have already been demonstrated [14, 13, 37]. The second thermal modeling approach we take is a simple FEM calculation focusing only on the thermal degrees of freedom, and taking 2d “slices” through the device structure in critical areas. Similar 2d FEM codes have been frequently used to describe heat flow in micro- and nanomachined calorimeters [73, 74, 75, 76]. We performed 2d FEM using a common commercially available software package [77]. This allows solution of the 2d heat flow equation (for our purposes limited to steady-state):

$$
\frac{\partial}{\partial x} \left( k_{2D}(x, y) \frac{\partial T(x, y)}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{2D}(x, y) \frac{\partial T(x, y)}{\partial y} \right) = P_{2D}(x, y), \quad (2.4.8)
$$

where $k_{2D} = k \cdot t$ with $k$ the thermal conductivity (in W/mK) of the constituent materials shown in Fig. 2.8a) and $t$ is a uniform thickness (here 450 nm) of the hypothetical cross-section. As long as the heat flow is dominated by the bulk substrate so that in-plane thermal transport is negligible on long length scales, such a model gives a reasonable estimate of the thermal gradient at the FM/NM interface. To match our experimental conditions (sample in vacuum, with substrate clamped at the bottom to a thermal bath), we choose the Dirichlet boundary condition at the base of the Si substrate (fixing $T = 78$ K), and Neumann boundary conditions elsewhere with no radiative or convective heat flow.

Values of the thermal conductivity of the metallic nanowires are determined in the same fashion as for the analytic model (the WF law with modified $L$ for Al and using measured values for similar thickness of Py). For the Si-N underlayer, which is critical for realistic modeling, we take the value $\sim 3$ W/mK.
that we measure frequently for this Si-N using the suspended Si-N platforms [50], and use literature values for Si thermal conductivity (2000 W/mK at 78 K) [78]. For simplicity we use temperature-independent thermal conductivity (since most of these materials have $k$ that varies slowly if at all over the few-kelvin range of heating we expect), and also make the simplifying assumption that all Joule heat is dissipated in the FM1 nanowire. In the case of Py (a high electrical resistivity alloy) and Al (a potentially low conductivity metal) with a truly clean interface and bulk-like values of $\rho$ this would likely be a poor assumption. However, the reduced size, impurity and roughness, and likelihood of less-than ideal contact all suggest that modeling this limit could be more realistic. Any spreading of the applied current to FM1 into the NM channel would cause some amount of the dissipated power to occur also in the NM, which would serve to reduce the thermal gradient calculated at the FM/NM interface. This would then increase the value of $S_s$ estimated from the FEM model. Overall, this challenge falls in the realm of the difficulty all groups have with taking interface heat flow and thermal properties correctly into account when performing thermal modeling.

We set $P_{2d}$ dissipated in FM1 by matching the temperature difference to that required to generate the measured voltage response at the FM2/NM thermocouple. The FEM problem is then solved using an adaptive mesh with $> 5000$ nodes (as shown in Fig. 2.8a). The resulting solution for $T(x, y)$ is shown in Fig. 2.8b), and this solution is plotted for the height midpoint of the NM channel as a function of length along the channel in Fig. 2.8c). The numerical derivative of this curve gives the thermal gradient $dT/dx$ as a function of $x$ as shown in Fig. 2.8d). As expected this indicates somewhat
smaller thermal gradients in the FM within one spin diffusion length of the interface compared to the analytic model. Note also that the thermal gradient vector at the FM/NM channel interface points toward the FM (in the negative $x$ direction) for this device. The same operating conditions discussed above for the $L = 1300$ nm device at 78 K give $\nabla T_{\text{FEM}} = 23$ K/$\mu$m. The same procedure applied to the 500 nm geometry gives a yet lower thermal gradient, which most likely indicates breakdown in the assumptions, and possibly that the relative Seebeck coefficients or thermal conductivities are in fact not the same between these devices.

To calculate $S_s$ we then assume a value of $\lambda_{\text{FM}} = 5$ nm for Py for easiest comparison to other work, though note that variation in this value directly affects $S_s$ and that our results would be best discussed as the product $S_s\lambda_{\text{FM}}$. Finally, we determine $V_s$ via solution of the Valet-Fert equation using measured $V_s = R_s^2I^2$ at the detector junction, $\lambda_{\text{nm}}$, and $L$ for each NLSV. The result (for $L = 1300$ nm) is $S_s = -0.5$ $\mu$V/K (from the analytic method) and $S_s = -0.77$ $\mu$V/K (from the FEM method) for our Py/Al at 78 K. This absolute value is somewhat smaller than other reports, which range from $S_s = -3.8$ $\mu$V/K for Py/Cu at 300 K in the original report [13], to as large as $S_s = -72$ $\mu$V/K for CoFeAl/Cu also at 300 K where the strong enhancement is believed to relate to formation of a half-metallic phase in the CoFeAl film [39]. However, viewed as a fraction of the T-dependent total absolute Seebeck coefficient of Py, $S_{\text{abs}}^{Py}$, in order to compare across the different measurement temperatures, our value $S_s/S_{\text{abs}}^{Py} = 0.12 - 0.3$ is closer to (and perhaps even in excess of) that seen in other Py devices $S_s/S_{\text{abs}}^{Py} = 0.19$ [13].
It is quite remarkable that the size of the thermal spin injection signals corresponds to this very significant degree of polarization of the Seebeck coefficient when the interfacial current polarization, \( P_I = 0.02 \), determined from the size and \( L \) dependence of the electrical spin signal is so low. As stated above, we attribute the low electrical injection signals and \( P_I \) to a high degree of interfacial spin-flip scattering. Some reduction of the spin polarization \( \alpha \) of the bulk of the Py itself could also contribute, though films made from this source in this chamber have historically not shown dramatically reduced values of \( M_s \), AMR, or of course Seebeck coefficient [57, 79, 48]. The most likely cause for the reduced electrical spin injection is the formation of oxidized permalloy at the FM/NM junction that was not fully removed by the RF cleaning step before Al deposition. Native permalloy oxides can be complicated chemically and magnetically [80], though typically are not seen to develop long-range magnetic order above \( \sim 30 \) K [81, 82, 83]. However, the permalloy oxide is a likely source of intermediate energy states in the barrier with random local magnetic environments that could easily contribute to loss of spin fidelity as initially spin-polarized electrons transport from Py to Al. Importantly, our large \( S_s/\alpha_{\text{abs}}^{Py} \) values indicate that thermal injection suffers much less from this loss of signal due to interfacial effects.

Though it is not possible to clearly identify a physical origin of this reduced sensitivity to the interface based on results presented here, we point out that the physical processes involved in electrical and thermal injection are potentially quite different. This is particularly true when the clean interface limit is not achieved. While electrical spin injection in the limit of high \( R_c \) invokes tunneling of spin-polarized electrons, thermal injection in the tunneling limit
could proceed by incoherent spin pumping as seen in the longitudinal spin Seebeck effect [84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95]. In this picture, the magnetic oxide could increase the effective interfacial spin mixing conductance or allow transport of spin via (non-electronic) collective spin excitations [96, 97, 98, 57, 99]. Though the current devices are in an intermediate limit, these effects from excitation of collective magnetization could still contribute to the SDSE signal measured here. Further experiments exploring thermal spin injection in a range of materials and with more carefully controlled and characterized interfaces are required to clarify the potential advantages of thermal spin injection for a wide range of potential spintronic applications.

2.5 Conclusions

In summary, we presented evidence of thermally generated pure spin currents in permalloy/aluminum non-local spin valve structures. Electrical spin injection, combined with contact resistance and using the actual geometry of the nanoscale devices determined from SEM images, indicated relatively high resistance junctions and low values of interfacial spin polarization that we attribute to presence of oxidized permalloy that remains at the FM/NM interface. Surprisingly, thermal spin injection remains efficient, suggesting that the oxidized permalloy participates in converting heat in the metallic FM into pure spin current in the NM, presumably via excitation of a collective magnetization. We also briefly discussed challenges in quantifying thermal gradients in nanoscale structures, and described two methods for estimating thermal gradients in the NLSV. We used these to quote a spin-dependent Seebeck co-
efficient in this Py/Al structure at 78 K near 1 μV/K, which agrees well with previous reports on Py/Cu structures at 300 K when compared as a fraction of the total absolute Seebeck coefficient.
Chapter 3

Anomalous Nernst effects and thermally altered spin injection from high temperature gradients in nonlocal spin valves

3.1 Introduction

Non-local Spin Valves (NLSV) has become a vital tool in modern spintronics because of the unique ability to separate a pure spin current from a charge current. While the thermoelectric effects in nanoscale devices are typically regarded as small it has been recently shown that they can dominate signals in lateral heterostructure like NLSVs. In fact, recently studies have shown that it is possible to produce a pure spin current from a thermal gradient[13, 15, 16, 17, 20, 100, 18]. In an attempt to quantify the temperature
profile and thermal spin injection in NLSVs we developed the 1 dimensional analytic model shown in chapter 2. Here we present work that tries to push the limits of the analytic model by reducing the thermal conductance of the substrate to study the effect on thermally injected spin resistance. Thermal gradients in NLSVs also bring rise to the Anomalous Nernst Effect (ANE), an thermoelectric analog to the Anomalous Hall Effect[21, 23, 24]. Here we also focus on the effect of anomalous Nernst effect and how it can affect measurement of spin injection in NLSVs.

Previous studies show that changing the substrate, and therefore the thermal conductance to the bath, of the NLSV can effect the thermoelectric background resistance[35]. To study the effect of poor substate conductance we developed two devices, one on a SiN-Si substrate while the other on a 500 nm thick SiN suspended membrane. Both devices consist of two permalloy ferromagnets (FM) connected by an aluminum nonmagnetic channel (NM). The membrane device should have reduced thermal conductance to the bath allowing the device to reach a higher temperature relative to bath during operation. We also assume that in the membrane device the thermal gradients become entirely in-plane, as we have made the entire device out of thin films.

We have been able able to inject spin accumulation into a NM channel via heat alone using thermal spin injection in similar NLSV devices as shown in chapter 2. By Joule heating the injection FM we create a thermal gradient in the NM channel as well as a thermally generated spin accumulation at the site of the contact that will diffuse down the NM channel. This spin accumulation is created by the spin dependent Seebeck effect (SDSE), the difference in the Seebeck coefficients between up and down spin electrons in
the FM[13, 12]. The SDSE results in a spin accumulation on the length scale of the spin diffusion length away from the interface with another material. For thermal spin injection to occur the thermal gradient in the FM on the length of order of the spin diffusion length would have to be appreciable. In the case of permalloy this length scale is $\sim 5\text{nm}$. We show that the higher temperatures in the NLSV conversely produce lower thermal gradients for thermal spin injection.

In the ANE, when a thermal gradient is applied to a ferromagnet an electric potential gradient is formed orthogonal to both the magnetization and thermal gradient. This voltage gradient is related to the thermoelectric effect by the Nernst coefficient, $R_N$, as show below.

$$\vec{\nabla}V_N = -S_N\vec{m} \times \vec{\nabla}T \quad (3.1.1)$$

where $\vec{m}$ is the unit vector pointing in the direction of magnetization, $\vec{\nabla}T$ is the thermal gradient, $\vec{\nabla}V$ is the electric field and $S_N = R_N S$, a fraction of the material’s total Seebeck coefficient. We show it is possible for thermal gradients caused by the large current density required for operation in NLSVs to be sufficient for the ANE signal to be significant relative to the spin signal. A diagram showing the directionality of the thermal gradient and the induced electric field are shown in figure 3.8c
Figure 3.1: A cartoon crosssection of a SiN coated Si chip and a SiN suspended membrane along with an optical photo of the membrane area on chip. The red square shows the fabrication area for the NLSV.

<table>
<thead>
<tr>
<th>Device</th>
<th>$L$ (nm)</th>
<th>$w_{FM_1}$ (nm)</th>
<th>$w_{FM_2}$ (nm)</th>
<th>$w_{NM}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>770</td>
<td>235</td>
<td>235</td>
<td>285</td>
</tr>
<tr>
<td>Membrane</td>
<td>760</td>
<td>240</td>
<td>240</td>
<td>245</td>
</tr>
</tbody>
</table>

Table 3.1: NLSV geometries as measured by scanning electron micrography. Each dimension has an estimated error of 30 nm.

### 3.2 Experimental Details

#### 3.2.1 Fabrication

The devices were fabricated on the same silicon-nitride coated 1 cm $\times$ 1 cm Si chips with pre-patterned Cr-Pt leads and bond pads. Areas of intended membrane devices have been backside etched with a 80% TMAH to free the SiN from the underlying Si. A cartoon and photo of the membrane structure are shown in figure 3.1. Both NLSV devices are then fabricated via the same a two-step ebeam lithography lift-off process described in chapter 2 except with a reduced ebeam dosage of $\sim 250 \ \mu$C/cm$^2$ to improve the design resolution. The device design was altered from chapter 2 in an effort to create the similar contact sizes for the injector and detector FM/NM contacts. The actual geometry values for both devices are shown in table 3.1.
3.2.2 Measurement Technique

Measurements are carried out after clipping the NLSV chip to a fully radiation-shielded gold-coated high-purity Cu sample mount installed in a sample-in-vacuum LN2 cryostat. An open bore split-coil electromagnet swepted fields of ±400 Oe in the plane of the chip. For the measurements described here the field is applied as shown in Fig. 3.2a). Simple resistance or non-local resistance measurements are made using the “delta mode” function of a linked Keithley 2128a nanovoltmeter and 6220 high precision current source. As stated in chapter 1, this measurement is functionally “equivalent” to a first-harmonic lock-in amplifier measurement [54]. This resistance is measured with respect to a sweep of the external field to establish parallel and antiparallel orientations of the FM leads.
Also like in chapter 2 we determine IV characteristics of the NLSV in multiple configurations by numerically integrating differential conductance measurements made with the same system. By taking IV measurements in multiple configurations we are able to derive values for the temperatures of the contacts. Both devices were tested in a total of four configurations measured at different fields to characterize the thermoelectric responses of the junctions. As shown in Fig. 3.2 the device has 3 measurements of the FM/NM junctions: electrical injection, thermal injection and a 3-wire injection contact measurement. A fourth curve is a 4-wire resistance measurement of the NM channel shown in 3.2 d). IV measurements for electrical and thermal spin injection are repeated at both full field saturations and antiparallel orientations established from the “delta mode” function.

3.3 Results and Discussion

3.3.1 IV Curve Measurements and Contact Temperatures

The four IV curve measurements are combined to understand the temperature dependence of the device. Normally, these curves are fit to second order polynomials to extract the different thermoelectric effects. We assume the linear response, I dependence, of the non local resistance is resulting from the Peltier effect and the parabolic response, \( I^2 \) dependent, is from Joule heating. These measurements are carried out at a variety of temperatures between 78 K and 300 K to understand the temperature dependence of the device. In fig-
Figure 3.3: IV measurements for electrical injection on the substrate and membrane devices. Large signal represents the background signal produced by the thermoelectric characteristics of the device.

Figure 3.6 we show an example of the background nonlocal IV for electrical injection at 78 K for both the substrate and membrane device. The linear component remains comparable between devices but the second order component is a factor of $\sim 20$ times larger. This is consistent with the reduced thermal conductance to the base temperature of the membrane device increasing the temperature of the injector and detector contacts.

However, the membrane device’s response is so large that second order polynomials are not sufficient to fit the large background signal. As seen in figure 3.4, the thermoelectric response for standard electrical injection does not fit a second order fit very well. This fitting difference is large enough to create significant changes in what our analytic model predicts for NLSV.
Figure 3.4: a) IV measurement with both second and forth order fits along with the corresponding equations as well as the effective second order fit equation at 1 mA. b) The R vs H measurement for 78 K on the membrane device. The background “effective” first order resistance here is $\sim 1.52 \, \mu\Omega$. The effective second order resistance, I term coefficient, is in better agreement in both value and sign than the original second order fit I term.
response. Indeed, as shown by the fits in figure 3.4 the difference is large enough at 78 K to change the expected sign of the I dependent term.

These changes are not unexpected in the membrane device as we know there are temperature dependencies for resistance and Seebeck values for the materials that comprise the NLSVs. As the NLSV increases in temperature from Joule heating, an $I^2$ dependent term, the Peltier effect and the Joule heating effect coefficients will change with temperature creating $I^3$ and $I^4$ terms respectively. The sources can still divided in the electric background into odd terms coming from Peltier effects and even terms from Joule heating effects. To fit these 4 parameters into our second order thermal model we can write effective first and second order terms for a given applied current.

$$R_{1}^{eff} = R_1 + R_3 I^2, \quad R_{2}^{eff} = R_2 + R_4 I^2$$

(3.3.1)

We can compare this new effective term to the background resistance from the R vs H plots and see that the $A_{1}^{eff}$ is in closer agreement with the measured equivalent first order “equivalent” from the “delta method” resistance.

Using the effective fitted values from the IV measurements in our thermal model we are able to derive expected temperature differences between the contacts and the bath temperature in the device from the 1-dimensional analytic model from chapter 1. These injector temperature difference, $T_1$ and the temperature difference between the injector and detector contacts, $T_t$ are shown in figure 3.5. The results for this modeling show a factor of $\sim 5$ increase in the in the temperature differences between the membrane device and the substrate device.
Figure 3.5: A plot of the injection FM/NM contact temperature, $T_1$, and the temperature difference between injection and detection contact, $T_t$, for both the substrate and membrane device.

However, there are some limitations to applying the analytic model to the membrane device. First, we assume that the substrate conductance at both injector and detector contacts are identical. As the membrane conductance is significantly reduced most of the excess heat is conducted through the leads of the device. The structural differences of the contacts would result in a difference in the substrate conductance term in our model. Another assumption we make is that the FM s are at some point along their structure at the bath temperature. As the thermal conductance is reduced it is possible for this to no longer be true. This can reduce the thermoelectric background detected at the detection FM/NM contact.
3.3.2 Thermally Affected Electrical Injection

As discussed in detail in chapter 2 we are able to isolate the the spin resistance signal of NLSVs by subtracting the antiparallel IV measurement form the parallel measurement. The devices in chapter 1, much like the substrate device data shown in figure 3.6, show a very linear spin resistance when being used for electrical injection. The membrane device however shows a very strong parabolic component. This component is roughly the same when compared to the thermal spin injection P-AP curve on the membrane while the substrate device show a much smaller response. This might be indicative of thermally injected spin accumulation enhancement in both electrical and thermal spin injection orientations in the membrane device but this violates the in plane thermal gradient assumption we make for this device. The mechanism behind thermal spin injection, the spin dependent Seebeck effect, operates on the length scale of the spin diffusion length in a FM. As the thermal conductivity is reduced this should reduce the thermal gradient at the interface because everything in the device is becoming hotter. One likely alternative is that the effective thermal spin injection signal is from the change of thermal conductivity at the FM/NM detection interface resulting from the different spin orientations. The heat carrying electrons in the NM at this interface will have a different thermal conductivity based on their electrical conductivity based on whether they are parallel or antiparallel to the detector FM.
Figure 3.6: Parallel minus antiparallel IV curves for spin resistance signal for electrical spin injection (a) and thermal spin injections (b) on the substrate and membrane devices at 78 K.
3.3.3 Anomalous Nernst Effects

In our measurements for the spin injection signal we observed a difference between P-AP IV curves, particularly in R2, of the same device if we compare parallel and antiparallel device states with different detector magnetization. We discovered that P-AP is consistent only if comparing P and AP with the same detector magnetization. This would indicate an added background signal that would be dependent only on the orientation of detection FM. The large thermal background present in NLSVs leading us to believe that this added background signal is from the ANE.

![Graphs showing electrical injection delta method resistance measurements](image)

Figure 3.7: a) and b) show electrical injection delta method resistance measurements at 300 K for the 500 nm device from chapter 2 in both orientation 1 and 2 (see chapter 4 for more about this significance). c) Shows R2 vs H at 300 K for thermal spin injection in orientation 1. Here, R2 is measured by taking differential conductance measurements at $\sim 10$ Oe.

We first noticed this phenomenon in the devices from Chapter 2 at 300 K with electrical injection in two device orientations (3.7 a and b) (device
orientations are discussed at length in Chapter 4.2.2). The two orientations are typically similar in switching signal size but here the hystereses is reversed in sign. This sign difference corresponds with the reversed direction of the thermal gradient across the detector FM caused by the other, injector, FM. It is difficult to discern the four distinct switches expected in electrical injection in both device orientations but this is only limited to R1. The R2 vs H plot in 3.7 c) confirms this to be a detector based phenomenon. The thermal spin injection signal is nonexistence in this measurement however there is a clear hystereses loop that corresponds weaker FM strip, the detector FM. The lack of a signal from the injection FM switch indicates that it plays little thermal role at this point other than providing a consistent thermal gradient to the detector FM/NM contact.

In the substrate and membrane devices, as the base temperature of NLSVs approach room temperature the ANE becomes a significant source of background signal on both substrate and membrane devices. As shown in figure 3.8a and b, both devices exhibit a difference in the second order background resistance. Similar to comparing P-AP IV measurements, by comparing positive and negative full saturations of applied field states of the devices, Pp and Pn respectively, we are able to isolate the ANE signal produced in the devices. The membrane device shows significantly higher R2 values than the substrate device, consistent with the increased background R2 resistances and the thermal gradients predicted by our analytic model.

We also see the hysteresis signal at higher temperatures in the R1 vs H measurements coincides with the change in magnetization of the detector strip. Examples of the R vs H measurements are shown in figure 3.7 a and b and 3.8
a and b. We believe this can be attributed to the increased Peltier component in the contact temperatures as the base temperature is increased. This is similar to the ANE that resulted from a lateral thermal gradient produced in the FM detector strip similar to effects seen by other groups. An example of the nonlocal hysteresis loop and a cartoon of the Nernst effect are shown if figure 3.8 a and b.

Figure 3.8: a) Shows the the IV measurement of the positive parallel saturation, Pp, minus the negative parallel saturation, Pn, for both the membrane device (blue) and substrate device(green) at 78 K. b) represents the R2 regression value from the Pp-Pn curves for electrical and thermal spin injection for the substrate and membrane devices compared to temperature from 78 K to 200 K. At 250 K and above the membrane NLSV background spin resistance began to drift too much to successfully measure repeatable behavior. c) is a cartoon of the cross section of the detector contact showing the assumed direction of the thermal gradient. d) is a cartoon showing labeling conventions used for the magnetization directions.
Figure 3.9: R vs H sweeps for substrate, a), and membrane, c). b) Seebeck coefficients for Al and Py from thin film measurement. d) Peltier produced at the FM/NM injection contact.

The Peltier component of all ANE curves remains small enough to remain below the noise threshold on the IV measurements at lower temperatures but nearer to room temperature this can result in the hysteresis loop shown in figure 3.9 a and b. This effect is consistent with the increased magnitude of the relative Seebeck coefficient of the injector contact near room temperature, injection Peltier power, and the increased magnitude of the Seebeck coefficient of the detecting FM strip.
3.3.4 Thermal Modeling

While our 1-dimensional analytic model can provide some idea of contact temperature we ultimately are concerned with what the thermal gradient is across the FM detector strip. We are able to model the membrane device using the Matlab PDE tool box for 2-dimension finite element analysis (FEM). We assume that there is no out of plane thermal gradient on the membrane device and that the thermal conductivities of the materials are additive when they overlap. From direct 4-wire resistance measurements on both the injection FM and NM channel to measure electrical resistivities of the materials from which we can derive thermal conductivities using the Wiedemann-Franz law. The temperature gradient plot in figure 3.10 b) shows the thermal gradients relevant for thermal injection and the ANE.

![Temperature Map](image)

Figure 3.10: a) The temperature map of the membrane device at 200 K and 1 mA thermal injection. b) The thermal gradient along the NM channel from the temperature map. The injection and detection FM locations are indicated.

The SDSE drives a spin accumulation from a thermal gradient within 1 spin diffusion length of the FM/NM contact. In the case of permalloy we assume a spin accumulation length of \( \sim 5 \) nm. From the 2-dimensional simulation
the gradient at the injection interface is only $\sim 0.2 \, K/m$. This is two orders of magnitude lower than the 23 K/µm thermal gradient produced from the 2 dimension cross section simulation from chapter 2. The thermal injection spin resistance for the membrane device is large compared to the miniscule thermal gradient confirms that the SDSE is not responsible for what is observed in the P-AP measurement in the membrane device. This effect could be present in both electrical and thermal injection and could result in the altered electrical spin injection we observed.

The thermal gradient produced at the detector FM is responsible for the ANE detected. Using the gradient of 0.5 K/m at 200 K in permalloy with a Seebeck coefficient of -12 V/K and the thickness of the FM of 35 nm we expect to see a 210 nV signal. At 200 K and 1 mA injection the measured signal for Pp-Pn, which should add the Nernst signal from the two magnetization together, was $\sim 200$ nV. This results in a Nernst coefficient of $R_n \approx 0.5$. This is larger than the 0.13 value seen in [23] and so we must entertain the idea that we have underestimated the thermal gradient. While we assume that the membrane device has the thermal gradient entirely inplane with such large temperature differences involved it is possible for some of the gradient to be three dimensional at the interfaces. If there was a thermal gradient across the FM/NM junction, in the z-direction, then it would produce a voltage laterally across the FM detector. In this second gradient direction the produced voltage would add to the already produced voltage in the z-direction.
3.4 Conclusions

In summary, we present evidence of significantly increased thermoelectric background resistance produced from reduced thermal conductance of NLSV fabricated on self suspended membranes. Applying our 1-dimensional analytic model predicts an injector temperature but fails to predict a realistic temperature difference at the detector contact. Thermal simulation of the device suggests that it has higher operation temperature but lower thermal gradients than a device made on substrate, disagreeing with the detector contact temperature found from the analytic model. The injector thermal gradient on the membrane is small relative to the large thermal injection spin resistance detected. Thermal injection signal is then likely cause by some other phenomenon than the SDSE. Lastly thermal gradients produced at the detection FM in operation of NLSVs can provide added signal from the ANE based on alignment of the detector. The higher temperatures on the membrane device, while decrease the temperature gradients at the injector, increase the gradient across the detector providing a larger thermally associated spin signal.
Chapter 4

Effect of Oxides on the Performance of Non-Local Spin Valves

4.1 Introduction

In chapter 2 we discussed how the presence of a native oxide on the permalloy ferromagnetic injector nanowires might enhance thermal spin injection in NLSVs. The hypothesis is that inhomogeneous thermal magnons excited in oxide could add to the spin current already produced by the spin dependent Seebeck effect (SDSE) via the longitudinal spin Seebeck effect (LSSE)[101, 84, 85, 86, 87, 88, 89, 90, 91, 92]. Here we present our work to investigate this phenomenon further by comparing magnetic oxide to non-magnetic oxide between similar NLSVs presented in chapter 2.
Table 4.1: NLSV geometries as measured by scanning electron micrography. Each dimension has an estimated error of 30 nm.

### 4.2 Experimental Detail

#### 4.2.1 Fabrication

We produce two sets of NLSVs of varying separations simultaneously using the recipe and design described in chapter 2 with two differences. First, we grew the ferromagnet, FM, to be 35 nm thick. Next, after the deposition of the permalloy for the FM injector and detector nanowires while still in vacuum we cap half of them with a $\sim 2$ nm thick layer of alumina, aluminum oxide, to act as an oxidation barrier. We deposit this layer using e-beam evaporation from an Al2O3 source in a single crucible, at a rate of $\sim 1\,\text{Å/s}$ after pumping to a base pressure of $\sim 5 \times 10^{-8}$ torr. This layer was deposited about 30 minutes after the deposition of the Py and so we do not believe it contributed to the formation of any magnetic oxide. We then completed the rest of the recipe both both chips, allowing a permalloy oxide, PyOx, to form on half of the devices. If the presence of magnetic oxide enhances thermal spin injection, then the alumina capped, magnetic oxide free, NLSVs should show reduced thermal injection as compared to native magnetic oxide control. Devices were intended on having 35 nm thick, 200 nm and 400 nm wide FM strips connected by a 250 nm wide and 110 nm thick NM channel. Measured geometries for 500 nm devices are show in table 4.1.
4.2.2 Measurement Techniques

Here we use the same techniques described in chapters 2 and 3 to characterize the NLSVs. First, we are able to combine the thermoelectric background IV measurements for the electrical spin injection, thermal spin injection and the 3-wire contact measurements along with the 4-wire resistance of the normal metal (NM) channel using our 1-dimensional analytic model to attempt to quantify the average temperatures between the FM/NM contacts of the NLSV. This is necessary to try to understand the thermal gradient that might drive the SDSE in the thermal spin injection. Next we can compare the IV response associated with spin-dependent processes from parallel magnetizations of the FM to antiparallel magnetizations in both electrical injection and thermal injection to isolate the IV curve for the spin resistance. Lastly we can test for the anomalous Nernst effect by comparing the two parallel magnetization configurations similarly to how the parallel and antiparallel configurations are compared.

Figure 4.1: The wiring configuration for the electrical injection measurement for Orientation 1 and 2
To further understand the effects of contact resistance as well as developing a more complete characterization of the device we use the designed device symmetry to allow for a second set of device orientations. This device design has 2 wires running to each FM and the NM channel giving 6 total leads. We are able to switch leads to make the FMs swap roles in the operation of the NLSV. In this chapter orientation 1 is the original orientation, driving current down FM1, the thin FM, and detecting with the wider FM2. Orientation 2 then is driving current down the wider FM2 and detecting with FM1. As the FMs are designed to have different widths to create a difference in coercivity they therefor have a difference in injection area. This allows us to compare the operation contact temperature, spin efficiency and the ANE between the two FM/NM injection contacts.

We are also able to change the background temperature to probe any temperature dependencies on the measured effects. As there are a large number of IV measurements to take we automate many of these measurements using custom written LabVIEW™ scripts and a custom designed switch box as described in Appendix C to switch between multiple measurement configurations and device orientations. Measurements are carried out at 6 temperatures from 78 K to 300 K over a period of a few days per device. Measurement error was determined from confidence intervals from first order fits of resistance vs current from differential conductance. This is discussed further in appendix B.1
4.3 Results and Discussion

Because there is a large amount of information gathered from the NLSVs for all of the measurements orientations, configurations, separations and temperatures to focus the analysis we will present here only data from two devices, the 500 nm separation magnetic oxide devices and the 500 nm alumina capped devices. The remaining data is tabulated in Appendix D.

4.3.1 Background Measurements and Temperature Projections

As in chapters 2 and 3, the IV measurements are fit to second order polynomials. We assume that for the thermoelectric background the linear dependence to $I$ is the result of Peltier heating or cooling of the contact and the $I^2$ dependence is the result of Joule heating. Figures 4.2 and 4.3 show the respective magnetic oxide and aluminum oxide first and second order fit parameters for a variety of temperatures for both electrical and thermal spin injection configurations.

Both devices see an increase in $A_1$, the linear component of electrical spin injection IV response, with temperature, a sign of increasing linear dependence of the background signal with temperature. This is likely due to the increasing Peltier power at the FM/NM injection interface caused by the increased magnitude of both both in the relative Seebeck coefficient of the injector and the absolute coefficient of the detector. This provides increased heating/cooling at the injector from the Peltier effect as well as sensitivity to detecting heat at the detector from both Joule heating and the Peltier effect of the injector.
Figure 4.2: In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the device with magnetic oxide are shown. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis. d) shows the projected contact temperatures from the 1-dimensional analytic model for both orientations in thermal injection, what should be the hottest orientation.

As both devices have the same lead material and roughly the same geometry the A1 values are expected to be very similar between the devices. There is also a linear dependence in the thermal injection but it is about an order of magnitude smaller than in electrical injection. This is because the Peltier effect does not produce as much heat at the contact due to current only running through the FM.
Figure 4.3: In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the device with aluminum oxide are shown. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis. d) shows the projected contact temperatures from the 1-dimensional analytic model for both orientations in thermal injection, what should be the hottest wiring configuration.

The second order signal in thermal and electrical injection, A2 and B2, are similar but thermal injection always larger. This is expected because the resistance of the FM is higher than the NM so thermal injection should produce more Joule heating than electrical injection. We do not have measurements for the resistance of either aluminum oxide or the magnetic oxide but based on the size of the A2 and B2 values it appears that the aluminum oxide is higher resistance.
Like the devices in chapter 2 the 3-wire contact measurement are difficult to understand on it’s own. The C1 dependence is opposite sign of normal resistance and the Peltier effect shown in A1. However, the C2 value is similar to the A2 value for each device for all temperatures suggesting that the Joule heating in both cases is the same as they have the same current path. As C2 is larger in the aluminum oxide devices like A2 this is further proof that the contact resistance for the aluminum oxide devices is likely higher.

Lastly we apply the 1-dimensional analytic model to the three measurements for both devices in both orientations to derive projections for contact temperatures of the device during operation in the thermal injection configuration, figures 4.2 d) and 4.3 d). In both devices show roughly the same temperature difference between the contacts, $T_{t}$, in both orientations. However, in both devices there is a larger injector contact temperature, $T_{1}$, in orientation 2. We believe this to be unlikely to be true as in thermal injection the heat produced is from Joule heating of just the injector strip at the contact and orientation 2 has a wider, and therefore less resistive, injector strip. This poor prediction is likely due to a poor assumption made in our analytic model.

### 4.3.2 Subtracted Spin Resistance

As in Chapters 2 and 3 we are able to isolate the spin resistance by subtracting the antiparallel IV measurement from the parallel measurement, $P-AP$. Figures 4.4 and 4.5 show both parallel minus antiparallel configurations for the two devices. To ensure elimination of ANE we compared parallel and antiparallel states with the same detector magnetization. By displaying the
two P-AP states for each orientation together expected commonalities and differences emerge from the devices.

Both orientations for each device have nearly identical R1 values for electrical injection. As the two contacts involved in the device remain the same this is consistent with the prediction of the spin resistance from the Takahashi Maekawa equations[8]. The notable difference between devices is the increased R1 signal in the aluminum oxide devices. It has been suggested that the presence of a more resistive contact might prevent spin backflow from the NM back into the injector FM[102]. While both devices have an oxide at the NM/FM
Figure 4.5: Parallel minus antiparallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d). First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.

Barrier it seems clear from the larger C2 measured value, the second order coefficient for the 3-wire contact measurement, in the aluminum oxide device that the contact is more resistive. This could be consistent with reduced back flow via higher contact resistance. Another group has suggested that the aluminum oxide might also help sit the resistive matching of the current path, improving the spin injection[103].

In thermal injection all current is intended to flow only through the FM injector. There does appear to be an appreciable R1 measurement along with thermal injection much like the small B1 signal in the thermal background.
This R1 signal in thermal injection appears to be greater in orientation 2 rather than orientation 1 in both devices. It has been proposed by some that the current required for Joule heating may split and flow through the NM channel when traveling parallel to the injection contact\[60]. There would then have to be some spin flip mechanism that some of the spin polarized current would undergo in the NM to accumulate spin with and first order dependence seen here. The higher R1 in orientation 2 is consistent with this theory as the injector strip in this case is wider, increasing the contact area, allowing for more current splitting.

Comparing the R2 values for thermal injection shows larger signals in P-AP in the magnetic oxide samples as compared to the Al oxide however both of these signals are smaller than the thermal injection shown in chapter 2. Without thermal simulations it is difficult to quantify the SDSE between the device rounds as we need a fine understanding of the thermal gradient at the contacts. There is some variance in the R2 measurement over different temperatures and between orientations. We believe that some of this can be attributed to slow thermal drift of the room temperature while taking data. Even with the drift a clear trends emerge as the thermal injection changes with temperature. The AlOx device has reduced signal in both orientations and does not seem to vary with base temperature. The Magnetic Ox device has an increasing R2 with temperature starting negative and later becoming positive. This sign change, while surprising, is not unrealistic. The spin dependent Seebeck effect drives a spin accumulation based on the difference in the Seebeck coefficient between the two spin states. This difference might vary with temperature. Another possibility is that the thermal characteristics of the device might change. As
the size of the spin accumulation is driven the size of the thermal gradient at the FM/NM interface changes in the thermal conductivity of the materials might also contribute to drive the sign change in R2.

### 4.3.3 Anomalous Nernst Effects

![Graphs showing anomalous Nernst effects](image)

Figure 4.6: Positive minus negative parallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d). First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.

In measuring the spin resistance we find that there is a difference between the spin signals when comparing different parallel and antiparallel configurations. Specifically there is a larger R2 signal when comparing parallel and antiparallel orientations with different detector magnetization. As much of
the signal is NLSVs is thermoelectrically driven it is possible that the thermal
gradients produced in operation might driven an anomalous Nernst effect in
the detection FM [21, 23, 24]. To isolate this effect we compare the IV mea-
surement for both parallel orientations of the device. Figure 4.6 shows the R1
and R2 measurements for both orientations and both devices.

The key signature of ANE is the change in sign in the R1 and R2 co-
efficients between the orientation 1 and orientation 2. When changing the
device orientations the magnetization direction remains the same but because
the direction of heat flow in the NM channel changes directions the electrical
potential in the detection FM will change sign. The change in thermal gra-
dient direction changes the sign of the induced as shown in equation 3.1.1.
This is clearly illustrated in the diverging blue lines showing the R2 values for
both orientations in each plot. In both orientations R2 is larger in thermal
configuration than electrical configuration, consistent with more heat being
produced. In fact, the R2 signal from the ANE here is larger than the mea-
sured SDSE signal from the thermal injection configuration for either device in
either orientation. Without knowing the thermal gradient across the detector
from thermal simulations it is not possible to compare the signal to theory and
derive a Nernst coefficient.

While the general sign of R2 terms are of opposite sign the values them-
selves are not equal and opposite. In both orientations there are increased R1
magnitude with temperature in electrical configuration than thermal, consist-
tent with larger heat being moved by the increased Peltier coefficient at higher
temperatures. While ideally the power created by the Peltier effect should be
the same for both orientations the power dissipated towards the bath and ge-
ometries of the detectors can create the discrepancies seen between both R1 and R2 in both orientations and configurations.

4.4 Conclusion

From the background measurements we see signs of larger magnitude second order terms in the aluminum oxide devices than the magnetic oxide devices. This is consistent with higher contact resistance in the FM/NM injector interface. However, temperatures we derive from our 1-dimensional analytic model do not seem to be realistic based on comparing values for orientations 1 and 2 in both devices. The isolated spin resistance, P-AP, shows an increase in R1 but a decrease R2 signal that is indicative to increased electrical injection efficiency from aluminum oxide but likely reduced thermal injection efficiency from the removal of the magnetic oxide.

The presence of the ANE in both devices provides an interesting addition to the measured spin resistance. We isolated spin injection and the ANE effect from each other by carefully choosing which parallel and antiparallel states to compare. By choosing the opposite pairing, comparing P and AP with the same injector state, the ANE signal can be added to the spin resistance to further change the P-AP signal. This is likely the configuration the NLSV would operate in as a read head for a HDD[5]. While careful measurements of the material characteristics and modeling of the thermal gradients are still needed to properly quantify both the ANE and the SDSE in these devices this work can provide a proof of concept that these two effects can work together.
Chapter 5

Conclusion

In summary I have presented a group of experiments designed to investigate thermal effects present in the operation of metallic nonlocal spin valves (NLSV). In the first experiment I presented evidence of thermally generated pure spin currents in permalloy/ aluminum NLSVs. These devices’ contact resistance and electrical spin injection resistance indicate high resistance junctions with low interfacial spin polarization that can be attributed to a magnetic oxide formed at the FM/NM interfaces. Surprisingly, thermal spin injection remains efficient, suggesting that oxidized permalloy participates in converting heat in the metallic FM into pure spin current in the NM. In the second experiment I presented evidence of significantly increased thermoelectric background resistance produced from reduced thermal conductance of NLSV fabricated on self suspended membranes compared to NLSVs produced on a substrate. Based on simulation, the injector thermal gradient on the membrane is small relative to the large thermal injection spin signal detected indicating that this is likely caused by some other phenomenon than the SDSE. I also show that
thermal gradients produced at the detection FM in operation of NLSVs can provide added signal from the ANE based on alignment of the detector. The higher temperatures on the membrane device decrease the temperature gradients at the injector, increase the gradient across the detector providing a larger thermally associated spin signal. In the last experiment I present data from NLSVs with native permalloy oxide contacts and alumina capped contacts. The background resistance measurements show larger magnitude second order resistance terms in the aluminum oxide devices than the magnetic oxide devices that is consistent with higher contact resistance in the FM/NM injector interface. The isolated spin resistance shows an increase in first order spin resistance but a decrease in the second order resistance that is indicative of increased electrical injection efficiency from aluminum oxide but likely reduced thermal injection efficiency from the removal of the magnetic oxide. The presence of the ANE in both devices provides an interesting addition to the measured spin signal. In all experiments we try to quantifying thermal gradients in nanoscale structures using both analytic modeling and finite element simulations. This remains an extremely difficult task as the thermal conductivity and absolute Seebeck coefficients for nanoscale structures are not well known. While careful measurements of the material characteristics and modeling of the thermal gradients are still needed to properly quantify both the ANE and the SDSE in these devices, this work can provide a proof of concept that these two effects can work together.
Bibliography


[64] K. T. Regner, J. P. Freedman, and J. A. Malen. Advances in Studying Phonon Mean Free Path Dependent Contributions to Thermal


[70] C. Strunk, M. Henny, C. Schönenberger, G. Neuttiens, and C. Van Hae-

[71] G. P. Szakmany, A. O. Orlov, G. H. Bernstein, and W. Porod. Single-


Appendix A

Appendix A: Analytic Thermal Modeling of NLSVs

For the case of electrical spin injection (Fig. 3.2a) in steady state with $I$ applied to junction 1, we can write two coupled equations for heat flow:

\begin{align*}
P_J + P_{\Pi} &= K_{\text{Sub}}(T_1^e - T_0) + K_{\text{nm}}(T_1^e - T_2^e) \quad \text{(A-1)} \\
0 &= K_{\text{Sub}}(T_2^e - T_0) + K_{\text{nm}}(T_2^e - T_1^e). \quad \text{(A-2)}
\end{align*}

Where $T_1^e$ ($T_2^e$) indicate the temperature of junction 1 (2) in response to power applied to junction 1 in the electrical spin injection configuration (Fig. 3.2a). These can be solved to give the temperature differences between the junctions
and the substrate:

\[ T_2^e - T_0 = \frac{K_{nm}(P_J + P_{II})}{K_{sub}(K_{sub} + 2K_{nm})}, \quad (A-3) \]

\[ \Delta T_2^e = \frac{K_{nm}(I^2R_{eff} + IS_{rel}T_0)}{K_{sub}(K_{sub} + 2K_{nm})}, \quad (A-4) \]

and

\[ T_1^e - T_0 = \frac{P_J + P_{II}}{K_{Sub}} - \Delta T_2^e, \quad (A-5) \]

\[ \Delta T_1^e = \frac{I^2R_{eff} + IS_{rel}T_0}{K_{sub}} - \Delta T_2^e. \quad (A-6) \]

This combination of Joule and Peltier power applied to junction 1 will lead to a voltage contribution from purely thermoelectric effects at junction 2, \( V_{NLE} = S_{rel}\Delta T_2^e \). Eq. A-4 clearly shows that this voltage will have terms \( \propto \) both I and \( I^2 \), as seen in Figs. 2.5a) and 2.6b).

Similar expressions describe the device in the thermal spin injection configuration (Fig. 3.2c). Here only Joule heating is expected, as shown in the thermal model schematic inset in Fig. 2.6c), so that when current is driven through FM1:

\[ P_J = K_{Sub}(T_1^d - T_o) + K_{nm}(T_1^d - T_2^d) \quad (A-7) \]

\[ 0 = K_{Sub}(T_2^d - T_o) + K_{nm}(T_2^d - T_1^d). \quad (A-8) \]

Here \( T_1^d (T_2^d) \) indicate the temperature of junction 1 (2) in response to power applied to FM1 in the thermal spin injection orientation (Fig. 3.2c).
Again these can be solved to give the temperature differences between the junctions and the substrate:

\[ T_{2}^{t} - T_{0} = \frac{K_{nm}(P_{J})}{K_{sub}(K_{sub} + 2K_{nm})}, \quad (A-9) \]

\[ \Delta T_{2}^{t} = \frac{K_{nm}(I^{2}R_{eff}^{t})}{K_{sub}(K_{sub} + 2K_{nm})}, \quad (A-10) \]

and

\[ T_{1}^{t} - T_{0} = \frac{P_{J}}{K_{Sub}} - \Delta T_{2}^{t}, \quad (A-11) \]

\[ \Delta T_{1}^{t} = \frac{I^{2}R_{eff}^{t}}{K_{sub}} - \Delta T_{2}^{t}. \quad (A-12) \]

The Joule power applied to FM1 will again lead to a voltage contribution from purely thermoelectric effects at junction 2, \( V_{NLT} = S_{rel}\Delta T_{2}^{t} \). As expected, the model predicts only \( \propto I^{2} \) terms for \( V_{NLT} \), and the measurements (Figs. 2.5b and 2.6c) are indeed nearly perfect parabolas.

Finally, we note that the “contact resistance” measurement, where the voltage is measured at the FM strip used for current injection as shown in Fig. 2.6e) will give the sum of potentially three voltages: a voltage drop caused by current flow across the actual interface between NM and FM1 (the traditional understanding of a contact resistance), a potential difference due to geometrical current spreading in the nanoscale circuit[33], and a voltage from thermoelectric effects due to the temperature gradients produced in the structure. This sum is then:

\[ V_{C} = IR_{C} + V\text{spread} + S_{rel}\Delta T_{1}^{e}. \quad (A-13) \]
<table>
<thead>
<tr>
<th>Device</th>
<th>$L$</th>
<th>$w_{FM_1}$(nm)</th>
<th>$w_{FM_2}$(nm)</th>
<th>$w_{NM}$(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 nm</td>
<td>475</td>
<td>190</td>
<td>400</td>
<td>510</td>
</tr>
<tr>
<td>900 nm</td>
<td>850</td>
<td>230</td>
<td>415</td>
<td>485</td>
</tr>
<tr>
<td>1300 nm</td>
<td>1260</td>
<td>225</td>
<td>425</td>
<td>460</td>
</tr>
</tbody>
</table>

Table A.1: NLSV geometries as measured by scanning electron micrography. Each dimension has an estimated error of 30 nm.

The thermoelectric voltage includes both $I$ and $I^2$ terms, and as seen in Fig. 2.6e) these IV curves show clear non-linearity. It will also be important to consider the size of the thermoelectric term $\propto I$ relative to the average apparent resistance in using these effective 3-terminal measurements to judge which form of the 1d spin diffusion equation to choose for analysis of the spin transport in the NLSV [8]. In the NLSV devices shown here, the thermoelectric $\propto I$ term is small compared to the total signal (on order of 100 nV for the measurement shown in Fig. 2.6e).

This model therefore provides expressions for three voltage measurements as a function of applied current with terms proportional to $I$ and to $I^2$ as shown in Eqs. 2.4.1-2.4.3, where the $A_i$, $B_i$, and $C_i$ coefficients result from fits to the measured $V$ as a function of $I$ as shown in Fig. 2.6. Measurements and fitting of these three voltages allows determination of the temperature profile in the device.
Appendix B

Appendix B: IV Measurements

From Differential Conduction

B.1 Comments on Differential Conductance and Establishing Error Values

A key part of our analysis is determining the V(I) response of the NLSV from differential conductance. Differential conductance steps through a range of current from low to high and alternates adding a delta current to the applied current step. This effectively creates a “delta method” quasi-dc measurement on top of a changing dc bias. The raw measurement is in $\Delta V$ vs I and so dividing by the delta current can give the R vs I curve. The V vs I curve can then be created by numerically integrating the R vs I curve. However, fitting the integrated V vs I curve can be deceiving as small data discrepancies in R vs I can create large jumps in an V vs I curve through integration. By fitting the R vs I in third order and converting to the expected V vs I forth order
through integration we can accurately measure the V(I) for a given wiring configuration. The accurate fitting of R vs I also gives correct errors on the fit that a poorly integrated curve might not take into account. It is important to note that the error bars on the Pp-Pn and P-AP measurements in chapter 4 are derived in this fashion and that these error bars are smaller than the error for each unsubtracted IV measurement. This points to a systematic error present in the differential conductance that is removed by subtracting two IV measurements.

Another important point is that the established error values are taken from the 95 % confidence interval in MatLab™ regression. Matlab does not do standard deviation in regression so I derived the standard error from the difference in the confidence intervals divided by 2.

B.2 Delta Method Resistance and Higher Order Fits

Our group as well as others[38] have assumed that the “delta method” resistance measurement is a measure of the first order term in V(I). This is typically an ok assumption as NLSVs are nominally only measured up to second order in V vs I. However, as we noted in chapter, under large thermal gradients the thermoelectric response in the NLSV can push V(I) to have significant forth order terms. As the delta method resistance is a quasi-dc measurement it is measuring slow enough that it’s measurement is off all odd order terms in V vs I, not just the first. Taking the first and third order terms into account we were able to directly recreate the delta method resistance from
the V vs H plot on the membrane device as shown in chapter 3. While devices on substrates did not appear to show significant difference between the delta method measurement and the first order term in V vs I it is not unreasonable to assume that discrepancies between these two measurements might be the result of not taking into account higher order terms.
Appendix C

Appendix C: Multiple Configuration Measurement Technique

Due to their nanoscale sizes NLSV are very electrostatic sensitive. Charges built up on normal laboratory objects, such as rubber gloves, or, more importantly, the leads of a voltmeter are enough to blow up one of the leads. To ensure no excess charge can build up across the NLSV leads the outside wiring must be shorted together before anything else is connected. When wire bonding the device we had to take care to wear a grounding wrist strap that is tied to the bonder ground as well as no wearing rubber gloves. When bonding we would start by shorting all of the mount wiring together at the chip mount ground (which then is grounded directly at the bonder’s table). After attaching the wire bonds to the NLSV we would then pull the shorting bonds before attaching the device to the grounded cryostat. On the warm
end of the cryostat we attach a shorting box that uses two single pull four throw switches that tie each voltage line to ground. A diagram of one line of the grounding circuit is shown in figure ?? and is the basis for all grounding circuits used. An alternate design could be to use single pole double throw switches but one must make certain to use make-then-brake switches rather than brake-then-make.

Figure A-1: An circuit diagram for the grounding circuit is shown above. This circuit is repeated for every line that is going to be grounded together, i.e. every line connected to the NLSV. At no point does a line remain unconnected while everything is plugged in so there should be less of a chance of built up charge.

The data taken in chapter 2 was made with a version 1 box that had 1 BNC connector for voltage connections and 1 BNC for current connections. This left a total of four leads running to the device at a time. As we discovered that we wanted to measure the device in multiple configurations having to rewire the device after each measurement became time consuming and dangerous for the the NLSV. With each wiring and handling there is a change that a device will fail due to undesired charge build up. In order to make measurements in multiple configurations we designed and build a grounding box to accompany an SRS eight channel multiplexing box.
The grounding box is designed to use the same switch design from the version 1 grounding box, connecting each line to ground, through a digitally control single pull single throw switch. On a custom designed PCB six of these digital switches are joined together on the same control lines allowing them to only switch together, grounding all of the signal lines together. The PCB also connects each line to a predetermined input configuration for the SRS multiplexor. The input configurations are designed to capture each of the 3 measurement configurations for each device orientation as well as a channel resistance measurement as described in chapter 4. The digital grounding box allows for each lead attached to the NLSV to be shorted together, test configuration changed by the SRS module, and then unshort each lead autonomously, quickly, and safely. The version 1 grounding box was also changed to be connected to the digital grounding box. The now version 1.5 box still ties all lines to ground but is only is needed when connecting the digital grounding box.

Control of the digital grounding box was handled by a suite of LabVIEW scripts, or virtual interfaces, (VI) controlling a National Instruments 6002 USB digital and analog control box. The NI-6002 provides digital power, ground and signal to the SPST switches on the PCB as well as senses what state the switches are expected to be in.
Appendix D

Appendix D: Magnetic Oxide and Aluminum Oxide Device Data for Other Separations

In this section we display the IV measurement data taken from the other separations of magnetic oxide and aluminum oxide devices. In total the magnetic oxide devices had intended separations of 500 nm, 900 nm and 1300 nm. The aluminum oxide devices only 500 nm and 900 nm remained consistent. The 1300 nm aluminum oxide devices had a significantly lower channel resistance than their 900 nm counterparts making us believe that their responses would be too different to compare to the other separations. It should be noted that preliminary contact temperature analysis that is too incomplete to include suggests lower injection temperatures with increased contact separation. This seems counter intuitive and is likely a sign of a poor assumption in our analytic model.
D.1 MagneticOx 900nm

D.1.1 IV Curve Regression

Figure A-1: In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the 900 nm magnetic oxide devices. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis.
Figure A-2: Parallel minus antiparallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d) for the 900 nm magnetic oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.
Figure A-3: Positive minus negative parallel IV curve fit values for first and second order coefficients for thermal, b), and electrical injection, a) for orientation 1 and 2 for the 1300 nm magnetic oxide devices First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.
D.2 MagneticOx 1300nm

D.2.1 IV Curve Regression

Figure A-4: In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the 1300 nm aluminum oxide devices. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis.
Figure A-5: Parallel minus antiparallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2, c) and d) for the 1300 nm aluminum oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.
D.2.3 ANE

Figure A-6: Positive minus negative parallel IV curve fit values for first and second order coefficients for thermal, b), and electrical injection, a) for orientation 1 and 2 for the 900 nm aluminium oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.
D.3 AluminiumOx 900nm

D.3.1 IV Curve Regression

Figure A-7: In a), b) and c) first and second order fit coefficients for electrical injection, A1 and A2, thermal injection, B1 and B2, and 3-wire contact measurement, C1 and C2, in both orientation 1 and 2 for the 900 nm aluminum oxide devices. All first order terms are green and correspond to the left axis, all second order terms are blue and correspond to the right axis.
D.3.2 P-AP

Figure A-8: Parallel minus antiparallel IV curve fit values for first and second order coefficients for thermal, b) and d) and electrical injection, a) and c) for orientation 1, a) and b), and orientation 2. c) and d) for the 900 nm aluminum oxide devices. First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.
D.3.3 ANE

Figure A-9: Positive minus negative parallel IV curve fit values for first and second order coefficients for thermal, b), and electrical injection, a) for orientation 1 and 2 for the 900 nm aluminum oxide devices First order terms are in green and correspond to left axis, second order terms are in blue and correspond to right axis.
D.4 AluminiumOx 1300nm

Data is not included because we believe that this device is too different from the other AluminiumOx devices. The key signifier is a dramatically reduced channel resistance, without much change in lateral dimensionality. Perhaps the channel got thicker on this part of the chip?
Appendix E

Appendix E: Data Taking and Analysis Code

In this section we provide a brief description of LabVIEW VIs written for data taking as well as including published html versions of Matlab scripts for data analysis.

E.1 LabVIEW VIs

Labview is a visual programing “language” that allows for easy data taking scripts to be constructed without the need to understand a proper coding language. Here I list all of the VIs I wrote and/or alter to accomplish my task. Some of this has been based on the VIs described in Azure Avery’s Thesis [104]. The general layout was to design a suite of VIs that would work under one superVI that would control all data taking for standard runs. Individual pieces of data can be taken using the more base-level VIs.
Some VIs are written to control our NI-USB 6001 control box. This box controls the applied magnetic field and the grounding box via analog and digital outputs respectively.

E.1.1 NLSVBoxFullControlV1.vi

This is the Super VI. It will control the three main data taking types: Delta method resistance vs H, IV curve measurement, and R2 vs H via IV curve measurement. Note, the vs H measurements are often called AMR, though not really AMR measurements, simple because it was based on the AMR data taking code written by Azure Avery and Barry L. Zink. For this VI there are multiple array inputs to allow for multiple sets to be taken where each set is a given temperature. There are buttons (green/red) to activate or deactivate certain data taking sections as not all types of data need to be taken at once. The user can enter positive and negative field saturation points, expected AP points, temperature to regulate at as well as control all of the finer tooling capable on the data taking VIs listed below. This is done via the settings arrays for each experiment.

E.1.2 IVCurveMultiChannelMultiField.vi

This VI takes IVCurveMultiChannel.vi and measures at 4 field locations (in this order): positive saturation, negative antiparallel, negative saturation, positive antiparallel.
E.1.3 IVCurveMultiChannel.vi

This VI uses NLSVChangeSRSChan.vi to switch between an array of channels and run the DifferentialConductance_IVCurve.vi. This VI also allows some channels to be skipped if it is being taken at an antiparallel location.

E.1.4 DifferentialConductance_IVCurve.vi

This VI performs the differential conductance. It is really a heavily modified provided VI with the drivers VIs we can download for the Keithley 6221 current source and 2282a nano-voltmeter. In conjunction they can perform the differential conductance with their preprogramed firmware. The idea is that differential conductance is performing a delta method measurement while sweeping through a current range. Each step is offset via a delta current, alternating positive and negative with each step, to determine the change in voltage for each step. The general settings are I min, I max, Delta pulse size, Delay time, Step size and number of averages. The min and max variables set the range and the numbers are in whole units, so 1 mA is .001. Delta size determines the change in current for each current step. Delay time is the amount of time waited at each step before measuring. Having a faster wait time on this will improve noise, but too fast and it will not be able to function (.001-.002 s do not seem to work here. I’ve gone with .005 s to be safe). The step size should be self explanatory. Number of averages is how many times the procedure is run. With 100 averages the picture is very low noises but this takes about 1 hour to complete. I’ve run with 10 here to balance speed and error.
The output for this VI is stored as a text file containing data for current, dV, R and then integrated V (using the Labview integration). The VI it’s self will display plots for the 3 current dependent variables. Along with that the VI it also displays the the resistance regression values up to third order of the averaged resistance. This was meant for local verification for fourth order terms in the voltage plot. Error is also displayed and not saved for R2 and R4. Lastly there are plots of R2 and R4 vs run number to observe drift over the IV curve taking process.

E.1.5  NLSVBoxAMRMultiChannel.vi

This VI is designed to measure “AMR” style measurements for multiple channels based using NLSVChangeSRSChan.vi and an array of inputs for NLSV_AMR_Film_WithField_DeltaV4.vi.

E.1.6  NLSV_AMR_Film_WithField_DeltaV4.vi

This VI is designed to measure AMR in a previous iteration. I modified it to give me equal step size but a complete forward and back sweep. This performs a delta method resistance measurement continuously. Starting at positive saturation at each field point the program measures a set number of averages and records this value. At 2000 averages the VI will sweep from +400 to -400 Oe and back in about half an hour. The settings here also include a delay timer, how long to wait before each measurement. Again, this should be low(.005 s), but too low fails(.001-.002 s).
E.1.7  NLSVBoxR2AMRMultiChannel.vi

This program is designed to run R2 vs H measurements on multiple channels in order. I rarely used this feature because one good scan took overnight.

E.1.8  NLSVBoxIVvsH.vi

This program sweeps out H and performs IV measurements via Differential-Conductance_IVCurve.vi at each H step. It will take the recorded R2 value from labview regression on the resistance measurement and display this vs H. Averaging is set from 4-10. This program also has the feature of taking half sweeps. ie sweeps away from 0 field that might show interesting things. I will always start the sweep at full saturation before going to 0 to start the sweep.

E.1.9  NLSVIVcurvevsHSingle.vi

E.1.10  FieldSetBZv3.vi

This is a slight modification used in [104]. I replaced the sensitive current source running the power supply for the magnet with the voltage output of the NI USB 6001 box. It is capable of ± 10 V analog at good precision. There is some capacitance on the long leads so I added wait timers to slow down the feedback mechanism.

E.1.11  Set6211DO_oldstyle.vi

This VI sets the digital output for the grounding box, controlling the switch to ground for all channels at once.
E.1.12  Read6211DI_oldstyle.vi

This VI reads to see what state the digital output is in.

E.1.13  Set6211AO_oldstyle.vi

This VI sets the analog output used for FieldSetBZv3.vi

E.1.14  Read6211AI_oldstyle.vi

This detects the voltage of the analog output lines.

E.1.15  NLSVChangeSRSChan.vi

This VI grounds the grounding box via Set6211DO_oldstyle.vi and then switches the SRS channel before ungrounding again.

E.2  MATLAB Scripts

Code here is published via MatLab publishing feature using LaTex translation. I edited out the formatting changes and error codes to clean it up. Code will be available on demand in standard m files.

E.2.1  NLSVLoading

- NLSVLoading
- Loading Files
- Subscripts
NLSVLoading

This script is designed to load a set of data files from the second generation NLSV grounding box and NLSV Master control labview VI. All that should be changed for each set is the file name, starting in YearMonthDay, the NLSV device name, the AP locations in Oe, and the temperature. *NOTE: much of the data is saved in the active folder via the subscripts. You must make sure you are in the right folder for the device before running otherwise the files go in places you don’t want.***

%S e t t i n g Name Variables

Pp='400Oe’;
Pn='−400Oe’;
AP1='−160Oe’; %Change for each Temp
AP2='160Oe’; %Change for each Temp
T='78K’; %Change for each Temp

% The files should all then have the same root name below. However, if data % taking runs past midnight, the dates will need to be changed to fit into % the code as the labview VIs will right the data for each subVI itteration

name='160405Run9bMem800nm’; %This should change for each data set
DeviceName='Run9bMem800nm'; %This changes with each device

% file name constants, I'm not sure I ever used the Short version, but I'm
% too afraid to get rid of it now incase I break things
TestName={'II-VVElec.txt' 'II-VVTher.txt' 'II-VVCont.txt'
'ChanRest.txt' 'IV-VIElec.txt' 'IV-VITher.txt' 'IV-VICont.txt'};
TestNameShort={'II-VVElec' 'II-VVTher' 'II-VVCont'
'ChanRest' 'IV-VIElec' 'IV-VITher' 'IV-VICont'};

Loading Files

This will now load files based on the parameters above and pre-established naming conventions

%II-VVElec
PpIIVVElec=importdata(strcat(name,T,Pp,TestName{1}));
PnIIVVElec=importdata(strcat(name,T,Pn,TestName{1}));
AP1IIVVElec=importdata(strcat(name,T,AP1,TestName{1}));
AP2IIVVElec=importdata(strcat(name,T,AP2,TestName{1}));

%II-VVTher
PpIIVVTher=importdata(strcat(name,T,Pp,TestName{2}));
PnIIIVVTher=importdata ( strcat (name, T, Pn, TestName{2}))
AP1IIIVVTher=importdata ( strcat (name, T, AP1, TestName{2}))
AP2IIIVVTher=importdata ( strcat (name, T, AP2, TestName{2}))

%II-VVECont
PpIIIVVCont=importdata ( strcat (name, T, Pp, TestName{3}))
PnIIIVVCont=importdata ( strcat (name, T, Pn, TestName{3}))

%IV-VIElec
PpIVVIElec=importdata ( strcat (name, T, Pp, TestName{5}))
PnIVVIElec=importdata ( strcat (name, T, Pn, TestName{5}))
AP1IVVIElec=importdata ( strcat (name, T, AP1, TestName{5}))
AP2IVVIElec=importdata ( strcat (name, T, AP2, TestName{5}))

%IV-VITher
PpIVVITher=importdata ( strcat (name, T, Pp, TestName{6}))
PnIVVITher=importdata ( strcat (name, T, Pn, TestName{6}))
AP1IVVITher=importdata ( strcat (name, T, AP1, TestName{6}))
AP2IVVITher=importdata ( strcat (name, T, AP2, TestName{6}))

%IV-VICont
PpIVVICont=importdata ( strcat (name, T, Pp, TestName{7}))
PnIVVICont=importdata ( strcat (name, T, Pn, TestName{7}))

123
%Chan_Rest
PpChanRest=importdata ( strcat (name, T, Pp, TestName{4}) );
PnChanRest=importdata ( strcat (name, T, Pn, TestName{4}) );
%

%HSweeps Files
%II−VV Elec
IIVVElecHSweepUp=importdata ( strcat (name, T, 'AMR', TestNameShort{1}, 'Up.txt') );
IIVVElecHSweepDown=importdata ( strcat (name, T, 'AMR', TestNameShort{1}, 'Down.txt') );

%II−VV Ther
IIVVTherHSweepUp=importdata ( strcat (name, T, 'AMR', TestNameShort{2}, 'Up.txt') );
IIVVTherHSweepDown=importdata ( strcat (name, T, 'AMR', TestNameShort{2}, 'Down.txt') );
%
%IV−VI Elec
IVVIElecHSweepUp=importdata ( strcat (name, T, 'AMR', TestNameShort{5}, 'Up.txt') );
IVVIElecHSweepDown=importdata ( strcat (name, T, 'AMR', TestNameShort{5}, 'Down.txt') );
%IV–VI Ther

IVVITherHSweepUp=importdata(strcat(name,T,'AMR',
    TestNameShort{6},'Up.txt'));

IVVITherHSweepDown=importdata(strcat(name,T,'AMR',
    TestNameShort{6},'Down.txt'));

Subscripts

Each subscript will load plot and/or save data. These lines are usually commented out as I only want to run a few of these at a time. Note, some of these conflict with one another or just versions that are different

% These do basic plotting of all data before regression
NLSVHsweepsPloting
NLSVHsweepsPlotingWithSave;
NLSVPloting;
NLSVPlotingPsubAPAlFormsWithSave_fixedFast;
NLSVPlotingPsubAPAlFormsWithOutSave_fixedFast;

% Regression subscripts, DifCon has it’s own save code, otherwise use
% Regression_fixed with RegressionJustSave.
NLSVRegressionDifCon_Fixed;
NLSVRegression_Fixed;

125
RegressionJustSave;

% Code to apply our 1–D Model and find contact temps
SDSECalcsOneShot;
ContactTemps;

E.2.2 NLSVPloitingPsubAPAIFormsWithSavefixed

P-AP Subtraction and Ploting

This script takes the parallel IV measurement and subtracts the appropriate antiparallel measurement, ie the one without the ANE signal added in. This is then plotted, labeled and saved for each of the eight P-AP measurement (2x for each thermal and electrical injection for each device orientation.)

mkdir(strcat(T,'/Plots/PsubAP'))
%This script is meant to fix the issue I noted 3/4/16 where I should have
%been using Pp–AP2 for IIIV and Pn–AP2 for IVVI (and following pairing for
%other orientation. There is some background signal in
the DETECTOR not the
%INJECTOR that adds to a background signal.
%% Electricals

%% Pp–AP2 II–VV Elec

PpsubAP2IIVVElec = PpIIVVElec(:,1);
PpsubAP2IIVVElec(:,2) = PpIIVVElec(:,4) – AP2IIVVElec(:,4);

figure
plot(PpsubAP2IIVVElec(:,1), PpsubAP2IIVVElec(:,2))
title(strcat(DeviceName, ’ Pp–AP2 II–VV Elec ’, T))
xlabel(’I (Amps)’)  
ylabel(’V(V)’)  
saveas(gcf, strcat(T, ’ / Plots /PsubAP/ ’, DeviceName, ’ Pp–AP2 II–VV Elec ’, T, ’.png’))

%% Pp–AP1 IV–VI Elec

PpsubAP1IVVIElec = PpIVVIElec(:,1);
PpsubAP1IVVIElec(:,2) = PpIVVIElec(:,4) – AP1IVVIElec(:,4);

figure
plot(PpsubAP1IVVIElec(:,1), PpsubAP1IVVIElec(:,2))
title(strcat(DeviceName, ’ Pp–AP1 IV–VI Elec ’, T))
xlabel(’I (Amps)’)  
ylabel(’V(V)’)  
saveas(gcf, strcat(T, ’ / Plots /PsubAP/ ’, DeviceName, ’ Pp–AP1 IV–VI Elec ’, T, ’.png’))
%%Pn–AP1 II–VV Elec
PnsubAP1IIIVVElec=PnIIIVVElec(:,1);
PnsubAP1IIIVVElec(:,2)=PnIIIVVElec(:,4)–AP1IIIVVElec(:,4);

figure
plot(PnsubAP1IIIVVElec(:,1),PnsubAP1IIIVVElec(:,2))
title(strcat(DeviceName, ' Pn–AP1 II–VV Elec ',T))
xlabel('I (Amps)')
ylabel('V(V)')
saveas(gcf,strcat(T, '/Plots/PsubAP/ ',DeviceName, ' Pn–AP1 II–VV Elec ',T, '.png'))

%%Pn–AP2 IV–VI Elec
PnsubAP2IVVIElec=PnIVVIElec(:,1);
PnsubAP2IVVIElec(:,2)=PnIVVIElec(:,4)–AP2IVVIElec(:,4);

figure
plot(PnsubAP2IVVIElec(:,1),PnsubAP2IVVIElec(:,2))
title(strcat(DeviceName, ' Pn–AP2 IV–VI Elec ',T))
xlabel('I (Amps)')
ylabel('V(V)')
saveas(gcf,strcat(T, '/Plots/PsubAP/ ',DeviceName, ' Pn–AP2 IV–VI Elec ',T, '.png'))

%%%%%%% Thermals

128
%%Pp–AP2 II–VV Ther
PpsubAP2IIVVTHER=PpIIVVTHER(:,1);
PpsubAP2IIVVTHER(:,2)=PpIIVVTHER(:,4)–AP2IIVVTHER(:,4);

figure
plot(PpsubAP2IIVVTHER(:,1),PpsubAP2IIVVTHER(:,2))
title(strcat(DeviceName,’ Pp–AP2 II–VV Ther ’,T))
xlabel(’I (Amps)’)
ylabel(’V(V)’)
saveas(gcf,strcat(T,’/Plots/PsubAP/’,DeviceName,’ Pp–AP2 II–VV Ther ’,T,’.png’))

%%Pp–AP1 IV–VI Ther
PpsubAP1IVVIITHER=PpIVVIITHER(:,1);
PpsubAP1IVVIITHER(:,2)=PpIVVIITHER(:,4)–AP1IVVIITHER(:,4);

figure
plot(PpsubAP1IVVIITHER(:,1),PpsubAP1IVVIITHER(:,2))
title(strcat(DeviceName,’ Pp–AP1 IV–VI Ther ’,T))
xlabel(’I (Amps)’)
ylabel(’V(V)’)

129
saveas(gcf,strcat(T,'/Plots/PsubAP/','DeviceName,' Pp–AP1 IV–VI Ther ',T,'.png'))

% Pn–AP1 II–VV Ther

PnsubAP1IIVVTher=PnIIVVTher(:,1);
PnsubAP1IIVVTher(:,2)=PnIIVVTher(:,4)–AP1IIVVTher(:,4);

figure
plot(PnsubAP1IIVVTher(:,1),PnsubAP1IIVVTher(:,2))
title(strcat(DeviceName,' Pn–AP1 II–VV Ther ',T))
xlabel('I (Amps)')
ylabel('V(V)')
saveas(gcf,strcat(T,'/Plots/PsubAP/','DeviceName,' Pn–AP1 II–VV Ther ',T,'.png'))

% Pn–AP2 IV–VI Elec

PnsubAP2IVVITher=PnIVVITher(:,1);
PnsubAP2IVVITher(:,2)=PnIVVITher(:,4)–AP2IVVITher(:,4);

figure
plot(PnsubAP2IVVITher(:,1),PnsubAP2IVVITher(:,2))
title(strcat(DeviceName,' Pn–AP2 IV–VI Ther ',T))
xlabel('I (Amps)')
ylabel('V(V)')
E.2.3 NLSVHsweepsPlotingWithSave

**H Sweep Ploting**

This subscript plots the H sweep data, that I called AMR data in the raw files, for both down and up sweeps. The data is NOT AMR data but this is using legacy labview VIs originally meant for AMR data taking.

```matlab
mkdir(strcat(T,'/Plots/HSweep'))
figure
plot(IIVVElecHSweepUp(:,1),IIVVElecHSweepUp(:,2),
     IIVVElecHSweepDown(:,1),IIVVElecHSweepDown(:,2))
title(strcat(DeviceName,' V vs H II−VV Elec ',T))
xlabel('H (Oe) ')
ylabel('V(V) ')
legend('up','down')
saveas(gcf,strcat(T,'/Plots/HSweep/',DeviceName,' V vs H II−VV Elec ',T,'.png'))
```

```matlab
figure
plot(IIVVTherHSweepUp(:,1),IIVVTherHSweepUp(:,2),
     IIVVTherHSweepDown(:,1),IIVVTherHSweepDown(:,2))
title(strcat(DeviceName,' V vs H II−VV Ther ',T))
```
xlabel('H (Oe)')
ylabel('V(V)')
legend('up', 'down')
saveas(gcf, strcat(T,'/Plots/HSweep/','DeviceName',' V vs H II–VV Ther ','T',' .png'))

figure
plot(IVVIElecHSweepUp(:,1),IVVIElecHSweepUp(:,2),
     IVVIElecHSweepDown(:,1),IVVIElecHSweepDown(:,2))
title(strcat(DeviceName, ' V vs H IV–VI Elec ','T'))
xlabel('H (Oe)')
ylabel('V(V)')
legend('up', 'down')
saveas(gcf, strcat(T,'/Plots/HSweep/','DeviceName',' V vs H IV–VI Elec ','T',' .png'))

figure
plot(IVVITherHSweepUp(:,1),IVVITherHSweepUp(:,2),
     IVVITherHSweepDown(:,1),IVVITherHSweepDown(:,2))
title(strcat(DeviceName, ' V vs H IV–VI Ther ','T'))
xlabel('H (Oe)')
ylabel('V(V)')
legend('up', 'down')
saveas(gcf, strcat(T,'/Plots/HSweep/','DeviceName',' V vs H IV–VI Ther ','T',' .png'))
E.2.4 NLSVPloting

Plots

This subscript will plot IV curve data except the P-P and P-AP values. This focus on only Pp and Pn data taken. If these values do not match then there was an issue taking data. The AP data is too similar to notice on these scale lengths so I left it off. Plots are saved in a new directory in the active folder

```matlab
mkdir(fullfile(T, '/Plots/IVCurves'))

figure
plot(PpIVVElec(:,1), PpIVVElec(:,4), 'b', PnIVVElec(:,1), PnIVVElec(:,4), 'r')
title(fullfile(DeviceName, ' Pp(b) Pn(r) II-VV Elec ', T))
xlabel('I (Amps)')
ylabel('V(V)')
saveas(gcf, fullfile(T, '/Plots/IVCurves/', DeviceName, ' Pp(b) Pn(r) II-VV Elec ', T, '.png'))
```

```matlab
figure
plot(PpIVVTher(:,1), PpIVVTher(:,4), 'b', PnIVVTher(:,1), PnIVVTher(:,4), 'r')
title(fullfile(DeviceName, ' Pp(b) Pn(r) II-VV Ther ', T))
```

133
xlabel('I (Amps)')

ylabel('V(V)')

saveas(gcf, strcat(T, '/Plots/IVCurves/', DeviceName, ' Pp(b) Pn(r) II−VV Ther ', T, '.png'))

%Pp II−VV Cont

figure

plot(PpIIVVCont(:,1), PpIIVVCont(:,4), 'b', PnIIVVCont(:,1), PnIIVVCont(:,4), 'r')
title(strcat(DeviceName, ' Pp(b) Pn(r) II−VV Cont ', T))
xlabel('I (Amps)')
ylabel('V(V)')

saveas(gcf, strcat(T, '/Plots/IVCurves/', DeviceName, ' Pp(b) Pn(r) II−VV Cont ', T, '.png'))

%Pp IV−VI Elec

figure

plot(PpIVVIElec(:,1), PpIVVIElec(:,4), 'b', PnIVVIElec(:,1), PnIVVIElec(:,4), 'r')
title(strcat(DeviceName, ' Pp(b) Pn(r) IV−VI Elec ', T))
xlabel('I (Amps)')
ylabel('V(V)')

saveas(gcf, strcat(T, '/Plots/IVCurves/', DeviceName, ' Pp(b) Pn(r) IV−VI Elec ', T, '.png'))
%%Pp IV–VI Ther

figure
plot(PpIVVITher(:,1), PpIVVITher(:,4), 'b', PnIVVITher(:,1), PnIVVITher(:,4), 'r')
title(strcat(DeviceName, ' Pp(b) Pn(r) IV–VI Ther ', T))
xlabel('I (Amps)')
ylabel('V(V)')
saveas(gcf, strcat(T, '/ Plots/IVCurves/', DeviceName, ' Pp(b Pn(r) IV–VI Ther ', T, '.png'))

%%Pp IV–VI Cont

figure
plot(PpIVVICont(:,1), PpIVVICont(:,4), 'b', PnIVVICont(:,1), PnIVVICont(:,4), 'r')
title(strcat(DeviceName, ' Pp(b) Pn(r) IV–VI Cont ', T))
xlabel('I (Amps)')
ylabel('V(V)')
saveas(gcf, strcat(T, '/ Plots/IVCurves/', DeviceName, ' Pp(b Pn(r) IV–VI Cont ', T, '.png'))

%%Pp Chan Rest

figure
plot(PpChanRest(:,1), PpChanRest(:,4), 'b', PnChanRest(:,1), PnChanRest(:,4), 'r')
title(strcat(DeviceName, ' Pp(b) Pn(r) ChanRest ', T))
xlabel('I (Amps)')

ylabel('V(V)')

saveas(gcf, strcat(T, '/Plots/IVCurves/', DeviceName, ' Pp(b Pn(r) ChanRest ', T, '.png'))

E.2.5 NLSVRegressionFixed

Regression

All parts are second order fits on the integrated IV curves. This is column 4 in the raw difcon variables, column 2 in the P-AP/P-P files. The "error" here is not the best way to handle this. Matlab gives out confidence intervals rather than Std Dev or Std Err. Here I am using 95% confidence intervals (standard), and essentially taking the difference divided by 2 to get a poor approximation of the Std Err. Note 7/19/16: Last minute thesis comments, this is not the right way to handle this as the integration removes a fair amount of the error from the data. I'm keeping this in the thesis because I did use to for data saving earlier, I just didn't do anything with the std err values from these calculations

```matlab
f=fit(PpIIVVElec(:,1),PpIIVVElec(:,4),'poly2');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/2),(abs(cf(1,2)-cf(2,2))/2)];
PpIIVVElecFit=[coeffvalues(f) cdf];
```
f = fit (PpIVVTher(:,1), PpIVVTher(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
PpIVVTherFit = [coeffvalues(f) cdf];

f = fit (PpIVVCont(:,1), PpIVVCont(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
PpIVVContFit = [coeffvalues(f) cdf];

f = fit (PpIVVIElec(:,1), PpIVVIElec(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
PpIVVIElecFit = [coeffvalues(f) cdf];

f = fit (PpIVVITher(:,1), PpIVVITher(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
PpIVVITherFit = [coeffvalues(f) cdf];

f = fit (PpIVVICont(:,1), PpIVVICont(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
PpIVVIContFit = [coeffvalues(f) cdf];
f = fit (PpChanRest(:,1), PpChanRest(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/2), (abs(cf(1,2) - cf(2,2))/2)];
PpChanRestFit = [coeffvalues(f) cdf];

%Pn
f = fit (PpIIVVElec(:,1), PnIIVVElec(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/2), (abs(cf(1,2) - cf(2,2))/2)];
PnIIVVElecFit = [coeffvalues(f) cdf];

f = fit (PpIIVVTher(:,1), PnIIVVTher(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/2), (abs(cf(1,2) - cf(2,2))/2)];
PnIIVVTherFit = [coeffvalues(f) cdf];

f = fit (PpIIVVCont(:,1), PnIIVVCont(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/2), (abs(cf(1,2) - cf(2,2))/2)];
PnIIVVContFit = [coeffvalues(f) cdf];

f = fit (PpIVVIElec(:,1), PnIVVIElec(:,4), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/2), (abs(cf(1,2) - cf(2,2))/2)];
PnIVVIElecFit = [coeffvalues(f) cdf];

f = fit (PpIVVITher(:, 1), PnIVVITher(:, 4), 'poly2');
cf = confint(f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
PnIVVITherFit = [coeffvalues(f) cdf];

f = fit (PpIVVICont(:, 1), PnIVVICont(:, 4), 'poly2');
cf = confint(f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
PnIVVIContFit = [coeffvalues(f) cdf];

f = fit (PpChanRest(:, 1), PnChanRest(:, 4), 'poly2');
cf = confint(f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
PnChanRestFit = [coeffvalues(f) cdf];

% AP1
f = fit (AP1IIVVElec(:, 1), AP1IIVVElec(:, 4), 'poly2');
cf = confint(f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
AP1IIVVElecFit = [coeffvalues(f) cdf];

f = fit (AP1IIVVTher(:, 1), AP1IIVVTher(:, 4), 'poly2');
cf = confint(f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
AP1IVVTherFit = [coeffvalues(f) cdf];

f = fit(AP1IVVIElec(:,1), AP1IVVIElec(:,4), 'poly2');
 cf = confint(f, .64);
 cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
 AP1IVVIElecFit = [coeffvalues(f) cdf];

f = fit(AP1IVVITher(:,1), AP1IVVITher(:,4), 'poly2');
 cf = confint(f, .64);
 cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
 AP1IVVITherFit = [coeffvalues(f) cdf];

% AP2

f = fit(AP2IVVIElec(:,1), AP2IVVIElec(:,4), 'poly2');
 cf = confint(f, .64);
 cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
 AP2IVVIElecFit = [coeffvalues(f) cdf];

f = fit(AP2IVVITher(:,1), AP2IVVITher(:,4), 'poly2');
 cf = confint(f, .64);
 cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2)];
 AP2IVVITherFit = [coeffvalues(f) cdf];

f = fit(AP2IVVIElec(:,1), AP2IVVIElec(:,4), 'poly2');
cf = confint(f, .64);
cdf = [(abs(cf(1,1)− cf(2,1))/2), (abs(cf(1,2)− cf(2,2))/2)];
AP2IVVIElecFit = [coeffvalues(f) cdf];

f = fit(AP2IVVITher(:,1), AP2IVVITher(:,4), 'poly2');

% % P−AP Stuff
% II−VV
% Pp−AP2

f = fit(PpsubAP2IIVVElec(:,1), PpsubAP2IIVVElec(:,2), 'poly2');

% Pn−AP1

f = fit(PpsubAP2IIVVTher(:,1), PpsubAP2IIVVTher(:,2), 'poly2');

PpsubAP2IIVVElecFit = [coeffvalues(f) cdf];
PpsubAP2IIVVTherFit = [coeffvalues(f) cdf];
f = fit (PnsubAP1IIVVElec (: , 1), PnsubAP1IIVVElec (: , 2), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1, 1) - cf(2, 1))/2), (abs(cf(1, 2) - cf(2, 2))/2)];
PnsubAP1IIVVElecFit = [coeffvalues(f) cdf];

f = fit (PnsubAP1IIVVTher (: , 1), PnsubAP1IIVVTher (: , 2), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1, 1) - cf(2, 1))/2), (abs(cf(1, 2) - cf(2, 2))/2)];
PnsubAP1IIVVTherFit = [coeffvalues(f) cdf];

% IV–VI
% Pp–AP1
f = fit (PpsubAP1IVVIElec (: , 1), PpsubAP1IVVIElec (: , 2), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1, 1) - cf(2, 1))/2), (abs(cf(1, 2) - cf(2, 2))/2)];
PpsubAP1IVVIElecFit = [coeffvalues(f) cdf];

f = fit (PpsubAP1IVVITher (: , 1), PpsubAP1IVVITher (: , 2), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1, 1) - cf(2, 1))/2), (abs(cf(1, 2) - cf(2, 2))/2)];
PpsubAP1IVVITherFit = [coeffvalues(f) cdf];
\%
Pn–AP2

\texttt{f=fit(PnsubAP2IVVIElec(:,1),PnsubAP2IVVIElec(:,2), '}
\texttt{poly2 '');}
\texttt{cf=confint(f,.64);}
\texttt{cdf=[(abs(cf(1,1)-cf(2,1))/2),(abs(cf(1,2)-cf(2,2))/2)];}
\texttt{PnsubAP2IVVIElecFit=[coeffvalues(f) cdf];}

\texttt{f=fit(PnsubAP2IVVITher(:,1),PnsubAP2IVVITher(:,2), '}
\texttt{poly2 ' });}
\texttt{cf=confint(f,.64);}
\texttt{cdf=[(abs(cf(1,1)-cf(2,1))/2),(abs(cf(1,2)-cf(2,2))/2)];}
\texttt{PnsubAP2IVVITherFit=[coeffvalues(f) cdf];}

\%
Pp–Pn
\%
IIVV

\texttt{f=fit(PpIIVVElec(:,1),(PpIIVVElec(:,4)-PnIIVVElec(:,4)), '}
\texttt{poly2 ');}
\texttt{cf=confint(f,.64);}
\texttt{cdf=[(abs(cf(1,1)-cf(2,1))/2),(abs(cf(1,2)-cf(2,2))/2)];}
\texttt{PpsubPnIIVVElecFit=[coeffvalues(f) cdf];}

\texttt{f=fit(PpIIVVTher(:,1),(PpIIVVTher(:,4)-PnIIVVTher(:,4)), '}
\texttt{poly2 ');}
\texttt{cf=confint(f,.64);}

143
cdf = [(abs(cf(1,1) - cf(2,1)) / 2), (abs(cf(1,2) - cf(2,2)) / 2)];
PpsubPnIIIVVITherFit = [coeffvalues(f) cdf];

%%IVVI
f = fit(PpIVVIElec(:,1), (PpIVVIElec(:,4) - PnIVVIElec(:,4)), 'poly2');
 cf = confint(f, 0.64);
cdf = [(abs(cf(1,1) - cf(2,1)) / 2), (abs(cf(1,2) - cf(2,2)) / 2)];
PpsubPnIVVIElecFit = [coeffvalues(f) cdf];

f = fit(PpIVVITher(:,1), (PpIVVITher(:,4) - PnIVVITher(:,4)), 'poly2');
 cf = confint(f, 0.64);
cdf = [(abs(cf(1,1) - cf(2,1)) / 2), (abs(cf(1,2) - cf(2,2)) / 2)];
PpsubPnIVVITherFit = [coeffvalues(f) cdf];

{%
%commented out 4/14/16, Replaced with stand alone script to save. This
%allows me to record regression locally w/o perhaps saving over a good file
%with a bad file.

%FileWrite

144
Output={’PpIIIVElec’ , PpIIIVElecFit (3) , PpIIIVElecFit (2) ,
PpIIIVElecFit (1) , PpIIIVElecFit (5) , PpIIIVElecFit (4) ;
’PpIIIVTher’ , PpIIIVTherFit (3) , PpIIIVTherFit (2) ,
PpIIIVTherFit (1) , PpIIIVTherFit (5) , PpIIIVTherFit (4) ;
’PpIIIVVCont’ , PpIIIVVContFit (3) , PpIIIVVContFit (2) ,
PpIIIVVContFit (1) , PpIIIVVContFit (5) , PpIIIVVContFit (4) ;
’PpIVVIElec’ , PpIVVIElecFit (3) , PpIVVIElecFit (2) ,
PpIVVIElecFit (1) , PpIVVIElecFit (5) , PpIVVIElecFit (4) ;
’PpIVVITher’ , PpIVVITherFit (3) , PpIVVITherFit (2) ,
PpIVVITherFit (1) , PpIVVITherFit (5) , PpIVVITherFit (4) ;
’PpIVVICont’ , PpIVVIContFit (3) , PpIVVIContFit (2) ,
PpIVVIContFit (1) , PpIVVIContFit (5) , PpIVVIContFit (4) ;
’PpChanRest’ , PpChanRestFit (3) , PpChanRestFit (2) ,
PpChanRestFit (1) , PpChanRestFit (5) , PpChanRestFit (4) ;
’PnIIIVElec’ , PnIIIVElecFit (3) , PnIIIVElecFit (2) ,
PnIIIVElecFit (1) , PnIIIVElecFit (5) , PnIIIVElecFit (4) ;

'AP1IVVIElec', AP1IVVIElecFit(3), AP1IVVIElecFit(2),
AP1IVVIElecFit(1), AP1IVVIElecFit(5),
AP1IVVIElecFit(4);

'AP1IVVIPTher', AP1IVVIPTherFit(3), AP1IVVIPTherFit(2),
AP1IVVIPTherFit(1), AP1IVVIPTherFit(5),
AP1IVVIPTherFit(4);

'AP2IIVVElec', AP2IIVVElecFit(3), AP2IIVVElecFit(2),
AP2IIVVElecFit(1), AP2IIVVElecFit(5),
AP2IIVVElecFit(4);

'AP2IIVVTher', AP2IIVVTherFit(3), AP2IIVVTherFit(2),
AP2IIVVTherFit(1), AP2IIVVTherFit(5),
AP2IIVVTherFit(4);

'AP2IVVIElec', AP2IVVIElecFit(3), AP2IVVIElecFit(2),
AP2IVVIElecFit(1), AP2IVVIElecFit(5),
AP2IVVIElecFit(4);

'AP2IVVIPTher', AP2IVVIPTherFit(3), AP2IVVIPTherFit(2),
AP2IVVIPTherFit(1), AP2IVVIPTherFit(5),
AP2IVVIPTherFit(4);

'PpsubAP2IIVVElec', PpsubAP2IIVVElecFit(3),
PpsubAP2IIVVElecFit(2), PpsubAP2IIVVElecFit(1),
PpsubAP2IIVVElecFit(5), PpsubAP2IIVVElecFit(4);

'PpsubAP2IIVVTher', PpsubAP2IIVVTherFit(3),
PpsubAP2IIVVTherFit(2), PpsubAP2IIVVTherFit(1),
PpsubAP2IIVVTherFit(5), PpsubAP2IIVVTherFit(4);
'PpsubAP1IVVIElec', PpsubAP1IVVIElecFit(3),
PpsubAP1IVVIElecFit(2), PpsubAP1IVVIElecFit(1),
PpsubAP1IVVIElecFit(5), PpsubAP1IVVIElecFit(4);

'PpsubAP1IVVITher', PpsubAP1IVVITherFit(3),
PpsubAP1IVVITherFit(2), PpsubAP1IVVITherFit(1),
PpsubAP1IVVITherFit(5), PpsubAP1IVVITherFit(4);

'PnsubAP1IIVVElec', PnsubAP1IIVVElecFit(3),
PnsubAP1IIVVElecFit(2), PnsubAP1IIVVElecFit(1),
PnsubAP1IIVVElecFit(5), PnsubAP1IIVVElecFit(4);

'PnsubAP1IIVVTher', PnsubAP1IIVVTherFit(3),
PnsubAP1IIVVTherFit(2), PnsubAP1IIVVTherFit(1),
PnsubAP1IIVVTherFit(5), PnsubAP1IIVVTherFit(4);

'PnsubAP2IVVIElec', PnsubAP2IVVIElecFit(3),
PnsubAP2IVVIElecFit(2), PnsubAP2IVVIElecFit(1),
PnsubAP2IVVIElecFit(5), PnsubAP2IVVIElecFit(4);

'PnsubAP2IVVITher', PnsubAP2IVVITherFit(3),
PnsubAP2IVVITherFit(2), PnsubAP2IVVITherFit(1),
PnsubAP2IVVITherFit(5), PnsubAP2IVVITherFit(4);

'PpsubPnIIVVElec', PpsubPnIIVVElecFit(3),
PpsubPnIIVVElecFit(2), PpsubPnIIVVElecFit(1),
PpsubPnIIVVElecFit(5), PpsubPnIIVVElecFit(4);

'PpsubPnIIVVTher', PpsubPnIIVVTherFit(3),
PpsubPnIIVVTherFit(2), PpsubPnIIVVTherFit(1),
PpsubPnIIVVTherFit(5), PpsubPnIIVVTherFit(4);
\[
\text{OutputTable} = \text{cell2table} (\text{Output}, \text{'VariableNames'}, \text{['Test', 'YCept', 'R1', 'R2', 'R1STD', 'R2STD']})
\]

\[
\text{Filename1} = \text{strcat} (\text{DeviceName}, T, '.txt')
\]
\[
\text{Filename2} = \text{strcat} (\text{DeviceName}, T, '.csv')
\]
\[
\text{writetable} (\text{OutputTable}, \text{Filename1})
\]
\[
\text{writetable} (\text{OutputTable}, \text{Filename2})
\]

E.2.6 RegressionJustSave

FileWrite

This works in conjunction with NLSVRegression_Fixed, it can be commented out as needed

\[
\text{Output} = \{'PpIIIVVElec', \text{PpIIIVVElecFit}(3), \text{PpIIIVVElecFit}(2), \text{PpIIIVVElecFit}(1), \text{PpIIIVVElecFit}(5), \text{PpIIIVVElecFit}(4)\}
\]
'PpIVVTher', PpIVVTherFit (3), PpIVVTherFit (2),
    PpIVVTherFit (1), PpIVVTherFit (5), PpIVVTherFit (4);

'PpIVVCont', PpIVVContFit (3), PpIVVContFit (2),
    PpIVVContFit (1), PpIVVContFit (5), PpIVVContFit (4);

'PpIVVI Elec', PpIVVI ElecFit (3), PpIVVI ElecFit (2),
    PpIVVI ElecFit (1), PpIVVI ElecFit (5), PpIVVI ElecFit (4);

'PpIVVI Ther', PpIVVI TherFit (3), PpIVVI TherFit (2),
    PpIVVI TherFit (1), PpIVVI TherFit (5), PpIVVI TherFit (4);

'PpIVVI Cont', PpIVVI ContFit (3), PpIVVI ContFit (2),
    PpIVVI ContFit (1), PpIVVI ContFit (5), PpIVVI ContFit (4);

'PpChanRest', PpChanRestFit (3), PpChanRestFit (2),
    PpChanRestFit (1), PpChanRestFit (5), PpChanRestFit (4);

'PnII VV Elec', PnII VV ElecFit (3), PnII VV ElecFit (2),
    PnII VV ElecFit (1), PnII VV ElecFit (5), PnII VV ElecFit (4);

'PnII VV Ther', PnII VV TherFit (3), PnII VV TherFit (2),
    PnII VV TherFit (1), PnII VV TherFit (5), PnII VV TherFit (4);
'PnIIIVVCont’, PnIIIVVContFit (3), PnIIIVVContFit (2),
   PnIIIVVContFit (1), PnIIIVVContFit (5), PnIIIVVContFit (4);

'PnIVVIIElec’, PnIVVIIElecFit (3), PnIVVIIElecFit (2),
   PnIVVIIElecFit (1), PnIVVIIElecFit (5), PnIVVIIElecFit (4);

'PnIVVIITher’, PnIVVIITherFit (3), PnIVVIITherFit (2),
   PnIVVIITherFit (1), PnIVVIITherFit (5), PnIVVIITherFit (4);

'PnIVVICont’, PnIVVIContFit (3), PnIVVIContFit (2),
   PnIVVIContFit (1), PnIVVIContFit (5), PnIVVIContFit (4);

'PnChanRest’, PnChanRestFit (3), PnChanRestFit (2),
   PnChanRestFit (1), PnChanRestFit (5), PnChanRestFit (4);

'AP1IIIVVElec’, AP1IIIVVElecFit (3), AP1IIIVVElecFit (2),
   AP1IIIVVElecFit (1), AP1IIIVVElecFit (5),
   AP1IIIVVElecFit (4);

'AP1IIIVVTher’, AP1IIIVVTherFit (3), AP1IIIVVTherFit (2),
   AP1IIIVVTherFit (1), AP1IIIVVTherFit (5),
   AP1IIIVVTherFit (4);

'AP1IVVIIElec’, AP1IVVIIElecFit (3), AP1IVVIIElecFit (2),
   AP1IVVIIElecFit (1), AP1IVVIIElecFit (5),
   AP1IVVIIElecFit (4);
'AP1IVVIITher', AP1IVVIITherFit (3), AP1IVVIITherFit (2),
    AP1IVVIITherFit (1), AP1IVVIITherFit (5),
    AP1IVVIITherFit (4);
'AP2IIIVVElec', AP2IIIVVElecFit (3), AP2IIIVVElecFit (2),
    AP2IIIVVElecFit (1), AP2IIIVVElecFit (5),
    AP2IIIVVElecFit (4);
'AP2IIIVVTher', AP2IIIVVTherFit (3), AP2IIIVVTherFit (2),
    AP2IIIVVTherFit (1), AP2IIIVVTherFit (5),
    AP2IIIVVTherFit (4);
'AP2IVVIElec', AP2IVVIElecFit (3), AP2IVVIElecFit (2),
    AP2IVVIElecFit (1), AP2IVVIElecFit (5),
    AP2IVVIElecFit (4);
'AP2IVVIITher', AP2IVVIITherFit (3), AP2IVVIITherFit (2),
    AP2IVVIITherFit (1), AP2IVVIITherFit (5),
    AP2IVVIITherFit (4);
'PpsubAP2IIIVVElec', PpsubAP2IIIVVElecFit (3),
    PpsubAP2IIIVVElecFit (2), PpsubAP2IIIVVElecFit (1),
    PpsubAP2IIIVVElecFit (5), PpsubAP2IIIVVElecFit (4);
'PpsubAP2IIIVVTher', PpsubAP2IIIVVTherFit (3),
    PpsubAP2IIIVVTherFit (2), PpsubAP2IIIVVTherFit (1),
    PpsubAP2IIIVVTherFit (5), PpsubAP2IIIVVTherFit (4);
'PpsubAP1IVVIElec', PpsubAP1IVVIElecFit (3),
    PpsubAP1IVVIElecFit (2), PpsubAP1IVVIElecFit (1),
    PpsubAP1IVVIElecFit (5), PpsubAP1IVVIElecFit (4);
'PpsubAP1IVVITher', PpsubAP1IVVITherFit (3),
PpsubAP1IVVITherFit (2), PpsubAP1IVVITherFit (1),
PpsubAP1IVVITherFit (5), PpsubAP1IVVITherFit (4);

'PnsubAP1IIVVElec', PnsubAP1IIVVElecFit (3),
PnsubAP1IIVVElecFit (2), PnsubAP1IIVVElecFit (1),
PnsubAP1IIVVElecFit (5), PnsubAP1IIVVElecFit (4);

'PnsubAP1IIVVTher', PnsubAP1IIVVTherFit (3),
PnsubAP1IIVVTherFit (2), PnsubAP1IIVVTherFit (1),
PnsubAP1IIVVTherFit (5), PnsubAP1IIVVTherFit (4);

'PnsubAP2IVVIElec', PnsubAP2IVVIElecFit (3),
PnsubAP2IVVIElecFit (2), PnsubAP2IVVIElecFit (1),
PnsubAP2IVVIElecFit (5), PnsubAP2IVVIElecFit (4);

'PnsubAP2IVVITher', PnsubAP2IVVITherFit (3),
PnsubAP2IVVITherFit (2), PnsubAP2IVVITherFit (1),
PnsubAP2IVVITherFit (5), PnsubAP2IVVITherFit (4);

'PpsubPnIIVVElec', PpsubPnIIVVElecFit (3),
PpsubPnIIVVElecFit (2), PpsubPnIIVVElecFit (1),
PpsubPnIIVVElecFit (5), PpsubPnIIVVElecFit (4);

'PpsubPnIIVVTher', PpsubPnIIVVTherFit (3),
PpsubPnIIVVTherFit (2), PpsubPnIIVVTherFit (1),
PpsubPnIIVVTherFit (5), PpsubPnIIVVTherFit (4);

'PpsubPnIVVIElec', PpsubPnIVVIElecFit (3),
PpsubPnIVVIElecFit (2), PpsubPnIVVIElecFit (1),
PpsubPnIVVIElecFit (5), PpsubPnIVVIElecFit (4);

153
'PpsubPnIVVITher', PpsubPnIVVITherFit(3),
PpsubPnIVVITherFit(2), PpsubPnIVVITherFit(1),
PpsubPnIVVITherFit(5), PpsubPnIVVITherFit(4);
}

OutputTable=cell2table (Output,'VariableNames',{ 'Test','
YCept','R1','R2','R1STD','R2STD'});
Filename1=strcat(DeviceName,T,'.txt');
Filename2=strcat(DeviceName,T,'.csv');
writetable (OutputTable,Filename1);
writetable (OutputTable,Filename2);

\section*{E.2.7 SDSECalsOneShot}

\textbf{SDSE One Shot Calculations}

This script figures out what data temp was loaded in th NLSV Loading
script and takes variables from the NLSVregression script and runs the val-
ues through our 1-D analytic model. The SDSE is from the lateral thermal
gradient, not one of the limits established in Chapter 2, but a really poor
approximation of what the FEM would tell us.

if strcmp(T,'300K')
    Srel=-9.83E-6;
    TScale=300;
else if strcmp(T,'250K')

154
Srel = -9.35E-6;
TScale = 250;
else if strcmp(T,'200K')
Srel = -7.96E-6;
TScale = 200;
else if strcmp(T,'150K')
Srel = -6.14E-6;
TScale = 150;
else if strcmp(T,'100K')
Srel = -3.87E-6;
TScale = 100;
else if strcmp(T,'78K')
Srel = -2.77E-6;
TScale = 78;
end

%Srel = cell2mat([-2.77E-6; -3.87E-6; -6.14E-6; -7.96E-6; -9.35E-6; -9.83E-6]);
%TScale = cell2mat([78; 100; 150; 200; 250; 300]);
L = 2E-8;
I = .001;
RmisIIVV = 1;
RmisIVVI = 1;

%II - VV Positive Saturation
%PpIIVVElecFit(2)
KnmIIVVp = TScale.* L./ PpChanRestFit(2);
RefEIIVVP=Srel .* TScale .* PpIIVVElecFit(1) ./ PpIIVVElecFit(2);
RefTIIVVP=TScale .* PpIIVVTHERFit(1) ./ PpIIVVElecFit(2) .* Srel;
KsubIIIVP=((Srel.*PpIIVVContFit(1)./ PpIIVVElecFit(2) ) .* (TScale ./ RefEIIVVP)−1).*KnmIIIVP;

PJIIIVP=I^2*RefEIIVVP;
PJTIIVVP=I^2*RefTIIVVP;
PPiEIIIVP=I^2*Srel .* TScale;

DeltaT2tIIIVP=PJTIIVP.* KnmIIIVP ./ (KsubIIIVP.* (KsubIIIVP+2*KnmIIIVP)));
DeltaT1tIIIVP=(PJTIIVP ./ KsubIIIVP)−DeltaT2tIIIVP;
DeltaTttIIIVP=DeltaT1tIIIVP−DeltaT2tIIIVP;

SDSIIIVP=(PpsubAP2IIVVTHERFit(1)*I^2) ./ (DeltaTttIIIVP *.001*RmisIIIVV);

%II–VV Negative Saturation
KnmIIIVN=TScale .* l. ./ PnChanRestFit(2);
RefEIIVVN=Srel .* TScale .* PnIIVVElecFit(1) ./ PnIIVVElecFit(2);
RefTIIVVN=TScale .* PnIIVVTHERFit(1) ./ PnIIVVElecFit(2) .* Srel;
\[ K_{subIIVVn} = \left( (S_{rel} \cdot P_{nIIVVContFit(1)}) / P_{nIIVVElecFit(2)} \right) \cdot \left( T_{scale} / RefE_{IIVVn} \right) - 1 \cdot Knm_{IIVVn}; \]

\[ PJ_{EIIIVVn} = I^2 \cdot RefE_{IIVVp}; \]
\[ PJ_{TIIIVVn} = I^2 \cdot RefT_{IIVVp}; \]
\[ PP_{EIIIVVn} = I^2 \cdot S_{rel} \cdot T_{scale}; \]

\[ \Delta T_{2tIIVVn} = PJ_{TIIIVVn} \cdot Knm_{IIVVn} / (K_{subIIVVn} \cdot (K_{subIIVVn} + 2 \cdot Knm_{IIVVn})); \]
\[ \Delta T_{1tIIVVn} = (PJ_{TIIIVVn} / K_{subIIVVn}) - \Delta T_{2tIIVVn}; \]
\[ \Delta T_{ttIIVVn} = \Delta T_{1tIIVVn} - \Delta T_{2tIIVVn}; \]

\[ SD_{SEIIVVn} = (P_{nsubAP1IIVVTherFit(1)} \cdot I^2) / (\Delta T_{ttIIVVn} \cdot 0.001 \cdot R_{misIIVV}); \]

%IV–VI Positive Saturation
\[ Knm_{IIVVIp} = T_{scale} \cdot L / P_{pChanRestFit(2)}; \]
\[ RefE_{IIVVIp} = S_{rel} \cdot T_{scale} \cdot P_{pIVVIElecFit(1)} / P_{pIVVIElecFit(2)}; \]
\[ RefT_{IIVVIp} = T_{scale} \cdot P_{pIVVITherFit(1)} / P_{pIVVIElecFit(2)} \cdot S_{rel}; \]
\[ K_{subIIVVIp} = ((S_{rel} \cdot P_{pIVVIContFit(1)}) / P_{pIVVIElecFit(2)}) \cdot (T_{scale} / RefE_{IIVVIp}) - 1 \cdot Knm_{IIVVIp}; \]

\[ PJ_{EIVVIp} = I^2 \cdot RefE_{IIVVIp}; \]
\[ PJ_{TIVVIp} = I^2 \cdot RefT_{IIVVIp}; \]
PPiEIVVIp=I^2*Srel.*TScale;

DeltaT2tIVVIp= PJTIVVIp.* KnnmIVVIp ./ (KsubIVVIp.* (KsubIVVIp+2*KnnmIVVIp));
DeltaT1tIVVIp=(PJTIVVIp ./ KsubIVVIp)−DeltaT2tIVVIp;
DeltaTttIVVIp=DeltaT1tIVVIp−DeltaT2tIVVIp;

SDSEIVVIp=(PpsubAP1IVVITherFit(1)*I^2)/( DeltaTttIVVIp*.001*RmisIVV);

%IV−VI Negative Saturation
KnnmIVVIn=TScale.* L./ PnChanRestFit(2);
RefEIVVIn=Srel .* TScale .* PnIVVIElecFit(1) ./ PnIVVIElecFit(2);
RefTIVVIn=TScale .* PnIVVITherFit(1) ./ PnIVVIElecFit(2) .* Srel;
KsubIVVIn=((Srel.*PnIVVIContFit(1)./ PnIVVIElecFit(2)) *(TScale ./RefEIVVIn)−1).*KnnmIVVIn;

PJEIVVIn=I^2*RefEIVVIn;
PJTIVVIn=I^2*RefTIVVIn;
PPiEIVVIn=I^2*Srel.*TScale;

DeltaT2tIVVIn=PJTIVVIn.* KnnmIVVIn ./ (KsubIVVIn.* (KsubIVVIn+2*KnnmIVVIn));
DeltaT1tIVVIn=(PJTIVVIn ./ KsubIVVIn)−DeltaT2tIVVIn;
\[ \Delta T_{tt}^{IV} \text{In} = \Delta T_{1t}^{IV} \text{In} - \Delta T_{2t}^{IV} \text{In} ; \]

\[ \text{SDSE}^{IV} \text{In} = (P_{nsub \cdot AP2} \cdot \text{TherFit}(1) \cdot I^2) / (\Delta T_{tt}^{IV} \text{In} \cdot 0.01 \cdot R_{mis^{IV}}) ; \]

E.2.8 ContactTemps

Contact Temp File write

This file quickly dumps the contact temp data from SDSECalsOneShot and saves a file with these few data points. It could probably save more but I don’t know what to do with all of that data yet.

\[ \text{OutputTemps} = \{ '\Delta T_{2t}^{IIVV}p' , \Delta T_{2t}^{IIVV}p ; \]
\[ '\Delta T_{1t}^{IIVV}p' , \Delta T_{1t}^{IIVV}p ; \]
\[ '\Delta T_{tt}^{IIVV}p' , \Delta T_{tt}^{IIVV}p ; \]
\[ 'SDSE^{IIVV}p' , SDSE^{IIVV}p ; \]
\[ '\Delta T_{2t}^{IIVV}n' , \Delta T_{2t}^{IIVV}n ; \]
\[ '\Delta T_{1t}^{IIVV}n' , \Delta T_{1t}^{IIVV}n ; \]
\[ '\Delta T_{tt}^{IIVV}n' , \Delta T_{tt}^{IIVV}n ; \]
\[ 'SDSE^{IIVV}n' , SDSE^{IIVV}n ; \]
\[ '\Delta T_{2t}^{IVV}Ip' , \Delta T_{2t}^{IVV}Ip ; \]
\[ '\Delta T_{1t}^{IVV}Ip' , \Delta T_{1t}^{IVV}Ip ; \]
\[ '\Delta T_{tt}^{IVVIP} , \Delta T_{tt}^{IVVIP} ; \]
\[ 'SDSE^{IVV}Ip' , SDSE^{IVV}Ip ; \]
'DeltaT2tIVVIn', DeltaT2tIVVIn;
'DeltaT1tIVVIn', DeltaT1tIVVIn;
'DeltaTttIVVIn', DeltaTttIVVIn;
'SDSEIVVIn', SDSEIVVIn;}

OutputTable = cell2table(OutputTemps);
Filename3 = strcat(DeviceName, T, 'Temps.txt');
Filename4 = strcat(DeviceName, T, 'Temps.csv');
writeTable(OutputTable, Filename3);
writeTable(OutputTable, Filename4)

E.2.9 NLSVRegressionFixedMem

Mem Regression

%This script performs third order regression on the differential
% conductance R vs I values from the locally stored IV measurements from
% NLSVLoading and is specifically meant for the membrane devices. The fit
% parameters along with fit confidence intervals are then converted to the
% expected second order fit parameters and standard deviations of the
% integrated V vs I plot. These values are calculated for all IV measurements and subtracted IV measurements.

\[ f = \text{fit}(\text{PpIIVVElec}(:,1),\text{PpIIVVElec}(:,3),'poly3'); \]
\[ \text{cf} = \text{confint}(f, .64); \]
\[ \text{cdf} = [(\text{abs}(\text{cf}(1,1) - \text{cf}(2,1))/2), (\text{abs}(\text{cf}(1,2) - \text{cf}(2,2))/2), (\text{abs}(\text{cf}(1,3) - \text{cf}(2,3))/2), (\text{abs}(\text{cf}(1,4) - \text{cf}(2,4))/2)]; \]
\[ \text{PpIIVVElecFit} = [\text{coeffvalues}(f) \text{ cdf}]; \]

\[ f = \text{fit}(\text{PpIIVVTher}(:,1),\text{PpIIVVTher}(:,3),'poly3'); \]
\[ \text{cf} = \text{confint}(f, .64); \]
\[ \text{cdf} = [(\text{abs}(\text{cf}(1,1) - \text{cf}(2,1))/2), (\text{abs}(\text{cf}(1,2) - \text{cf}(2,2))/2), (\text{abs}(\text{cf}(1,3) - \text{cf}(2,3))/2), (\text{abs}(\text{cf}(1,4) - \text{cf}(2,4))/2)]; \]
\[ \text{PpIIVVTherFit} = [\text{coeffvalues}(f) \text{ cdf}]; \]

\[ f = \text{fit}(\text{PpIIVVCont}(:,1),\text{PpIIVVCont}(:,3),'poly3'); \]
\[ \text{cf} = \text{confint}(f, .64); \]
\[ \text{cdf} = [(\text{abs}(\text{cf}(1,1) - \text{cf}(2,1))/2), (\text{abs}(\text{cf}(1,2) - \text{cf}(2,2))/2), (\text{abs}(\text{cf}(1,3) - \text{cf}(2,3))/2), (\text{abs}(\text{cf}(1,4) - \text{cf}(2,4))/2)]; \]
\[ \text{PpIIVVContFit} = [\text{coeffvalues}(f) \text{ cdf}]; \]
f = fit (PpIVVIElec(:,1), PpIVVIElec(:,3), 'poly3');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2), (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PpIVVIElecFit = [coeffvalues(f) cdf];

f = fit (PpIVVITher(:,1), PpIVVITher(:,3), 'poly3');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2), (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PpIVVITherFit = [coeffvalues(f) cdf];

f = fit (PpIVVICont(:,1), PpIVVICont(:,3), 'poly3');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2), (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PpIVVIContFit = [coeffvalues(f) cdf];

f = fit (PpChanRest(:,1), PpChanRest(:,3), 'poly3');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2), (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PpChanRestFit = [coeffvalues(f) cdf];

% Pn

162
f = fit(PpIVVElec(:,1), PnIVVElec(:,3), 'poly3');
cf = confint(f, 0.64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2),
      (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PnIVVElecFit = [coeffvalues(f) cdf];

f = fit(PpIVVTHER(:,1), PnIVVTHER(:,3), 'poly3');
cf = confint(f, 0.64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2),
      (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PnIVVTHERFit = [coeffvalues(f) cdf];

f = fit(PpIVVCONT(:,1), PnIVVCONT(:,3), 'poly3');
cf = confint(f, 0.64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2),
      (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PnIVVCONTFit = [coeffvalues(f) cdf];

f = fit(PpIVVIELEC(:,1), PnIVVIELEC(:,3), 'poly3');
cf = confint(f, 0.64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2),
      (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PnIVVIELECFit = [coeffvalues(f) cdf];
cf = confint(f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/2), (abs(cf(1,2) - cf(2,2))/2), (abs(cf(1,3) - cf(2,3))/2), (abs(cf(1,4) - cf(2,4))/2)];

PnIVVI TherFit = [coeffvalues(f) cdf];

f = fit(PpIVVI Cont(:, 1), PnIVVI Cont(:, 3), 'poly3');
cf = confint(f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/2), (abs(cf(1,2) - cf(2,2))/2), (abs(cf(1,3) - cf(2,3))/2), (abs(cf(1,4) - cf(2,4))/2)];

PnIVVI ContFit = [coeffvalues(f) cdf];

f = fit(PpChanRest(:, 1), PnChanRest(:, 3), 'poly3');
cf = confint(f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/2), (abs(cf(1,2) - cf(2,2))/2), (abs(cf(1,3) - cf(2,3))/2), (abs(cf(1,4) - cf(2,4))/2)];

PnChanRestFit = [coeffvalues(f) cdf];

%AP1
f = fit(AP1 IIIV Elec(:, 1), AP1 IIIV Elec(:, 3), 'poly3');
cf = confint(f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/2), (abs(cf(1,2) - cf(2,2))/2), (abs(cf(1,3) - cf(2,3))/2), (abs(cf(1,4) - cf(2,4))/2)];

AP1 IIIV ElecFit = [coeffvalues(f) cdf];

f = fit(AP1 IIIV Ther(:, 1), AP1 IIIV Ther(:, 3), 'poly3');
\text{cdf} = \left[ \left( \frac{\text{abs}(\text{cf}(1,1) - \text{cf}(2,1))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,2) - \text{cf}(2,2))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,3) - \text{cf}(2,3))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,4) - \text{cf}(2,4))}{2} \right) \right] ; \\
\text{AP1IVVTherFit} = \text{coeffvvalues}(f) \; \text{cdf} ; \\
\text{f} = \text{fit}(\text{AP1IVVIElec(:,1),}\; \text{AP1IVVIElec(:,3)}, \text{'}\text{poly3}' \text{)} ; \\
\text{cf} = \text{confint}(f, .64) ; \\
\text{cdf} = \left[ \left( \frac{\text{abs}(\text{cf}(1,1) - \text{cf}(2,1))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,2) - \text{cf}(2,2))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,3) - \text{cf}(2,3))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,4) - \text{cf}(2,4))}{2} \right) \right] ; \\
\text{AP1IVVIElecFit} = \text{coeffvvalues}(f) \; \text{cdf} ; \\
\text{f} = \text{fit}(\text{AP1IVVITher(:,1),}\; \text{AP1IVVITher(:,3)}, \text{'}\text{poly3}' \text{)} ; \\
\text{cf} = \text{confint}(f, .64) ; \\
\text{cdf} = \left[ \left( \frac{\text{abs}(\text{cf}(1,1) - \text{cf}(2,1))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,2) - \text{cf}(2,2))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,3) - \text{cf}(2,3))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,4) - \text{cf}(2,4))}{2} \right) \right] ; \\
\text{AP1IVVITherFit} = \text{coeffvvalues}(f) \; \text{cdf} ; \\
\% \text{AP2} \\
\text{f} = \text{fit}(\text{AP2IIVVElec(:,1),}\; \text{AP2IIVVElec(:,3)}, \text{'}\text{poly3}' \text{)} ; \\
\text{cf} = \text{confint}(f, .64) ; \\
\text{cdf} = \left[ \left( \frac{\text{abs}(\text{cf}(1,1) - \text{cf}(2,1))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,2) - \text{cf}(2,2))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,3) - \text{cf}(2,3))}{2} \right), \left( \frac{\text{abs}(\text{cf}(1,4) - \text{cf}(2,4))}{2} \right) \right] ; \\
\text{AP2IIVVElecFit} = \text{coeffvvalues}(f) \; \text{cdf} ; \\
\text{f} = \text{fit}(\text{AP2IVVITher(:,1),}\; \text{AP2IVVITher(:,3)}, \text{'}\text{poly3}' \text{)} ;
\text{cf} = \text{confint}(f, .64);
\text{cdf} = [(\text{abs}\ (\text{cf}(1,1) - \text{cf}(2,1))/2), (\text{abs}\ (\text{cf}(1,2) - \text{cf}(2,2))/2),
(\text{abs}\ (\text{cf}(1,3) - \text{cf}(2,3))/2), (\text{abs}\ (\text{cf}(1,4) - \text{cf}(2,4))/2)];
\text{AP2IIIVVTherFit} = [\text{coeffvalues}(f) \ cdf];

\text{fit}\ (\text{AP2IVVIElec}( :, 1), \text{AP2IVVIElec}( :, 3), \text{'poly3'});
\text{cf} = \text{confint}(f, .64);
\text{cdf} = [(\text{abs}\ (\text{cf}(1,1) - \text{cf}(2,1))/2), (\text{abs}\ (\text{cf}(1,2) - \text{cf}(2,2))/2),
(\text{abs}\ (\text{cf}(1,3) - \text{cf}(2,3))/2), (\text{abs}\ (\text{cf}(1,4) - \text{cf}(2,4))/2)];
\text{AP2IVVIElecFit} = [\text{coeffvalues}(f) \ cdf];

\text{fit}\ (\text{AP2IVVITher}( :, 1), \text{AP2IVVITher}( :, 3), \text{'poly3'});
\text{cf} = \text{confint}(f, .64);
\text{cdf} = [(\text{abs}\ (\text{cf}(1,1) - \text{cf}(2,1))/2), (\text{abs}\ (\text{cf}(1,2) - \text{cf}(2,2))/2),
(\text{abs}\ (\text{cf}(1,3) - \text{cf}(2,3))/2), (\text{abs}\ (\text{cf}(1,4) - \text{cf}(2,4))/2)];
\text{AP2IVVITherFit} = [\text{coeffvalues}(f) \ cdf];

% % P - AP Stuff
% II - VV
% Pp - AP2
\text{fit}\ (\text{PpsubAP2IIIVVElec}( :, 1), \text{PpsubAP2IIIVVElec}( :, 2), \text{'poly2'});
\text{cf} = \text{confint}(f, .64);
\text{cdf} = [(\text{abs}\ (\text{cf}(1,1) - \text{cf}(2,1))/2), (\text{abs}\ (\text{cf}(1,2) - \text{cf}(2,2))/2)];
\text{PpsubAP2IIIVVElecFit} = [\text{coeffvalues}(f) \ cdf];
f = fit (PpsubAP2IIVVTher (: , 1), PpsubAP2IIVVTher (: , 2), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)−cf(2,1))/2), (abs(cf(1,2)−cf(2,2))/2)];
PpsubAP2IIVVTherFit = [coeffvalues(f) cdf];

%Pn–AP1
f = fit (PnsubAP1IIVVElec (: , 1), PnsubAP1IIVVElec (: , 2), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)−cf(2,1))/2), (abs(cf(1,2)−cf(2,2))/2)];
PnsubAP1IIVVElecFit = [coeffvalues(f) cdf];

f = fit (PnsubAP1IIVVTher (: , 1), PnsubAP1IIVVTher (: , 2), 'poly2');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)−cf(2,1))/2), (abs(cf(1,2)−cf(2,2))/2)];
PnsubAP1IIVVTherFit = [coeffvalues(f) cdf];

%IV–VI
%Pp–AP1
f = fit (PpsubAP1IVVIElec (: , 1), PpsubAP1IVVIElec (: , 2), 'poly2');
cf = confint (f, .64);
cdf = \left[ \frac{\text{abs}(cf(1,1) - cf(2,1))}{2}, \frac{\text{abs}(cf(1,2) - cf(2,2))}{2} \right];

PpsubAP1IVVIElecFit = \text{coeffvalues}(f)\text{cdf};

f = \text{fit}(\text{PpsubAP1IVVITher}( :, 1), \text{PpsubAP1IVVITher}( :, 2), \ 'poly2');

\text{cf} = \text{confint}(f, .64);

cdf = \left[ \frac{\text{abs}(cf(1,1) - cf(2,1))}{2}, \frac{\text{abs}(cf(1,2) - cf(2,2))}{2} \right];

PpsubAP1IVVITherFit = \text{coeffvalues}(f)\text{cdf};

\%Pn–AP2

f = \text{fit}(\text{PnsubAP2IVVIElec}( :, 1), \text{PnsubAP2IVVIElec}( :, 2), \ 'poly2');

\text{cf} = \text{confint}(f, .64);

cdf = \left[ \frac{\text{abs}(cf(1,1) - cf(2,1))}{2}, \frac{\text{abs}(cf(1,2) - cf(2,2))}{2} \right];

PnsubAP2IVVIElecFit = \text{coeffvalues}(f)\text{cdf};

f = \text{fit}(\text{PnsubAP2IVVITher}( :, 1), \text{PnsubAP2IVVITher}( :, 2), \ 'poly2');

\text{cf} = \text{confint}(f, .64);

cdf = \left[ \frac{\text{abs}(cf(1,1) - cf(2,1))}{2}, \frac{\text{abs}(cf(1,2) - cf(2,2))}{2} \right];

PnsubAP2IVVITherFit = \text{coeffvalues}(f)\text{cdf};

\%Pp–Pn

\%IIVV

168
f = fit (PpIVVElec(:,1), (PpIVVElec(:,3) - PnIVVElec(:,3)), 'poly3');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2),
      (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PpsubPnIVVElecFit = [coeffvalues(f) cdf];

f = fit (PpIVVTher(:,1), (PpIVVTher(:,3) - PnIVVTher(:,3)), 'poly3');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2),
      (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PpsubPnIVVTherFit = [coeffvalues(f) cdf];

%IVVI
f = fit (PpIVVIElec(:,1), (PpIVVIElec(:,3) - PnIVVIElec(:,3)), 'poly3');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)-cf(2,1))/2), (abs(cf(1,2)-cf(2,2))/2),
      (abs(cf(1,3)-cf(2,3))/2), (abs(cf(1,4)-cf(2,4))/2)];
PpsubPnIVVIElecFit = [coeffvalues(f) cdf];

f = fit (PpIVVITher(:,1), (PpIVVITher(:,3) - PnIVVITher(:,3)), 'poly3');
cf = confint (f, .64);
cdf = [(abs(cf(1,1)−cf(2,1))/2), (abs(cf(1,2)−cf(2,2))/2), 
      (abs(cf(1,3)−cf(2,3))/2), (abs(cf(1,4)−cf(2,4))/2)];
PpsubPnPnIVVITherFit=[coeffvalues(f) cdf];

{%
%commented out 4/14/16, Replaced with stand alone script to save. This allows me to record regression locally w/o perhaps saving over a good file with a bad file.

%FileWrite
Output={’PpIVVElec’, PpIVVElecFit(3), PpIVVElecFit(2), PpIVVElecFit(1), PpIVVElecFit(5), PpIVVElecFit(4); ’PpIVVTHER’, PpIVVTHERFit(3), PpIVVTHERFit(2), PpIVVTHERFit(1), PpIVVTHERFit(5), PpIVVTHERFit(4); ’PpIVVCont’, PpIVVContFit(3), PpIVVContFit(2), PpIVVContFit(1), PpIVVContFit(5), PpIVVContFit(4); ’PpIVVIElec’, PpIVVIElecFit(3), PpIVVIElecFit(2), PpIVVIElecFit(1), PpIVVIElecFit(5), PpIVVIElecFit(4);
'PpIVVITher’, PpIVVITherFit (3), PpIVVITherFit (2),
PpIVVITherFit (1), PpIVVITherFit (5), PpIVVITherFit (4);

'PpIVVICont’, PpIVVIContFit (3), PpIVVIContFit (2),
PpIVVIContFit (1), PpIVVIContFit (5), PpIVVIContFit (4);

'PpChanRest’, PpChanRestFit (3), PpChanRestFit (2),
PpChanRestFit (1), PpChanRestFit (5), PpChanRestFit (4);

'PnIIVVElec’, PnIIVVElecFit (3), PnIIVVElecFit (2),
PnIIVVElecFit (1), PnIIVVElecFit (5), PnIIVVElecFit (4);

'PnIVVITher’, PnIVVITherFit (3), PnIVVITherFit (2),
PnIVVITherFit (1), PnIVVITherFit (5), PnIVVITherFit (4);

'PnIVVIVTher’, PnIVVIVTherFit (3), PnIVVIVTherFit (2),
PnIVVIVTherFit (1), PnIVVIVTherFit (5), PnIVVIVTherFit (4);

'PnIIVVCont’, PnIIVVContFit (3), PnIIVVContFit (2),
PnIIVVContFit (1), PnIIVVContFit (5), PnIIVVContFit (4);

'PnIVVIElec’, PnIVVIElecFit (3), PnIVVIElecFit (2),
PnIVVIElecFit (1), PnIVVIElecFit (5), PnIVVIElecFit (4);

'PnIVVITher’, PnIVVITherFit (3), PnIVVITherFit (2),
PnIVVITherFit (1), PnIVVITherFit (5), PnIVVITherFit (4);

171
'PnIVVICont' , PnIVVIContFit (3) , PnIVVIContFit (2) , PnIVVIContFit (1) , PnIVVIContFit (5) , PnIVVIContFit (4) ;

'PnChanRest' , PnChanRestFit (3) , PnChanRestFit (2) , PnChanRestFit (1) , PnChanRestFit (5) , PnChanRestFit (4) ;

'AP1IIVVElec' , AP1IIVVElecFit (3) , AP1IIVVElecFit (2) , AP1IIVVElecFit (1) , AP1IIVVElecFit (5) , AP1IIVVElecFit (4) ;

'AP1IIVVTher' , AP1IIVVTherFit (3) , AP1IIVVTherFit (2) , AP1IIVVTherFit (1) , AP1IIVVTherFit (5) , AP1IIVVTherFit (4) ;

'AP1IVVIElec' , AP1IVVIElecFit (3) , AP1IVVIElecFit (2) , AP1IVVIElecFit (1) , AP1IVVIElecFit (5) , AP1IVVIElecFit (4) ;

'AP1IVVITher' , AP1IVVITherFit (3) , AP1IVVITherFit (2) , AP1IVVITherFit (1) , AP1IVVITherFit (5) , AP1IVVITherFit (4) ;

'AP2IIVVElec' , AP2IIVVElecFit (3) , AP2IIVVElecFit (2) , AP2IIVVElecFit (1) , AP2IIVVElecFit (5) , AP2IIVVElecFit (4) ;

'AP2IIVVTher' , AP2IIVVTherFit (3) , AP2IIVVTherFit (2) , AP2IIVVTherFit (1) , AP2IIVVTherFit (5) , AP2IIVVTherFit (4) ;

172
\text{'PnsubAP2IVVIElec'}, \text{PnsubAP2IVVIElecFit (3)}, \\
\text{PnsubAP2IVVIElecFit (2)}, \text{PnsubAP2IVVIElecFit (1)}, \\
\text{PnsubAP2IVVIElecFit (5)}, \text{PnsubAP2IVVIElecFit (4)}; \\
\text{'PnsubAP2IVVITher'}, \text{PnsubAP2IVVITherFit (3)}, \\
\text{PnsubAP2IVVITherFit (2)}, \text{PnsubAP2IVVITherFit (1)}, \\
\text{PnsubAP2IVVITherFit (5)}, \text{PnsubAP2IVVITherFit (4)}; \\
\text{'PpsubPnIIVVElec'}, \text{PpsubPnIIVVElecFit (3)}, \\
\text{PpsubPnIIVVElecFit (2)}, \text{PpsubPnIIVVElecFit (1)}, \\
\text{PpsubPnIIVVElecFit (5)}, \text{PpsubPnIIVVElecFit (4)}; \\
\text{'PpsubPnIIVVTher'}, \text{PpsubPnIIVVTherFit (3)}, \\
\text{PpsubPnIIVVTherFit (2)}, \text{PpsubPnIIVVTherFit (1)}, \\
\text{PpsubPnIIVVTherFit (5)}, \text{PpsubPnIIVVTherFit (4)}; \\
\text{'PpsubPnIVVIElec'}, \text{PpsubPnIVVIElecFit (3)}, \\
\text{PpsubPnIVVIElecFit (2)}, \text{PpsubPnIVVIElecFit (1)}, \\
\text{PpsubPnIVVIElecFit (5)}, \text{PpsubPnIVVIElecFit (4)}; \\
\text{'PpsubPnIVVITher'}, \text{PpsubPnIVVITherFit (3)}, \\
\text{PpsubPnIVVITherFit (2)}, \text{PpsubPnIVVITherFit (1)}, \\
\text{PpsubPnIVVITherFit (5)}, \text{PpsubPnIVVITherFit (4)}; \\
}\); \\
\text{OutputTable} = \text{cell2table (Output, 'VariableNames', { 'Test', 'YCept', 'R1', 'R2', 'R1STD', 'R2STD'})}; \\
\text{Filename1} = \text{strcat (DeviceName, T, '.txt')}; \\
\text{Filename2} = \text{strcat (DeviceName, T, '.csv')}; \\
\text{writetable (OutputTable, Filename1)}; \\
\text{writetable (OutputTable, Filename2)}
E.2.10  SDSECalsOneShotMem

SDSE One Shot Mem

Like the non-"mem" script, this takes the locally saved regression data saved and inputs those values into our 1-dimensional analytic model. We calculate substrate and channel thermal conductances from the Wiedemann-Franz law, establish effective resistances and computes contact temperatures given assumed relative Seebeck coefficient for a given temperature and maximum input injection current. To fit the third and forth order terms into the first and second order we multiply them by the assumed current squared.

```matlab
if strcmp(T, '300K')
    Srel=−9.83E−6;
    TScale=300;
elseif strcmp(T, '250K')
    Srel=−9.35E−6;
    TScale=250;
elseif strcmp(T, '200K')
    Srel=−7.96E−6;
    TScale=200;
elseif strcmp(T, '150K')
    Srel=−6.14E−6;
    TScale=150;
```

175
elseif strcmp(T,'100K')
    Srel=-3.87E-6;
    TScale=100;
elseif strcmp(T,'78K')
    Srel=-2.77E-6;
    TScale=78;
end
%Srel=cell2mat ([-2.77E-6; -3.87E-6; -6.14E-6; -7.96E-6; -9.35E-6; -9.83E-6]);
%TScale=cell2mat ([78; 100; 150; 200; 250; 300]);
L=2E-8;
I=.001;
RmisIIVV=1;
RmisIVVI=1;

%II–VV Positive Saturation
%PpIIVVElecFit (2)
KnmIIVVp=TScale.* L./ (PpChanRestFit(4)+(I.^2/3).*
    PpChanRestFit(2));
RefIIVVp=Srel .* TScale .* (PpIIVVElecFit(3)/2+(I.^2/4).*
    PpIIVVElecFit(1)) ./ (PpIIVVElecFit(4)+(I.^2/4).*
    PpIIVVElecFit(2));
RefTIVVp=TScale .* (PpIIVVTherFit(3)/2+(I.^2/4).*
    PpIIVVTherFit(1)) ./ (PpIIVVElecFit(4)+(I.^2/4).*
    PpIIVVElecFit(2)) .* Srel;

176
\[ K_{sub\text{IIIVVp}} = ((S_{rel} \cdot (P_{IIIVVContFit(3)}/2 + (l^{2}/4) \cdot P_{IIIVVContFit(1)}) \cdot (T_{Scale} \cdot / RefEIIIVVp) - 1) \cdot KnmIIIVVp); \]

\[ PJ_{EIIIVVp} = l^{2} \cdot RefEIIIVVp; \]
\[ PJ_{TIIIVVp} = l^{2} \cdot RefTIIIVVp; \]
\[ PP_{IIEIIIVVp} = I^{2} \cdot S_{rel} \cdot T_{Scale}; \]

\[ \Delta T_{2tIIVVp} = PJ_{TIIIVVp} \cdot KnmIIIVVp \cdot (K_{subIIIVVp} \cdot (K_{subIIIVVp} + 2 \cdot KnmIIIVVp)); \]
\[ \Delta T_{1tIIVVp} = (PJ_{TIIIVVp} \cdot K_{subIIIVVp}) - \Delta T_{2tIIVVp}; \]
\[ \Delta T_{ttIIVVp} = \Delta T_{1tIIVVp} - \Delta T_{2tIIVVp}; \]

\[ SD_{SEIIVVp} = (P_{psubAP2IIVVTherFit(1)} \cdot I^{2}) \cdot (\Delta T_{ttIIVVp} \cdot 0.01 \cdot RmisIIIVV); \]

%II–VV Negative Saturation

\[ KnmIIIVVn = T_{Scale} \cdot L. \cdot (P_{nChanRestFit(4)} + (l^{2}/3) \cdot P_{nChanRestFit(2)}); \]
\[ RefEIIIVVn = S_{rel} \cdot T_{Scale} \cdot (P_{nIIIVVElecFit(3)}/2 + (l^{2}/4) \cdot P_{nIIIVVElecFit(1)}) \cdot (P_{nIIIVVElecFit(4)} + (l^{2}/4) \cdot P_{nIIIVVElecFit(2)}); \]
\[ RefTIIIVVn = T_{Scale} \cdot (P_{nIIIVVTherFit(3)}/2 + (l^{2}/4) \cdot P_{nIIIVVTherFit(1)} \cdot (P_{nIIIVVElecFit(4)} + (l^{2}/4) \cdot P_{nIIIVVElecFit(2)}) \cdot S_{rel}; \]
\[
K_{\text{subIVVn}} = ((S_{\text{rel}} \ast (P_{\text{IVVContFit}}(3)/2 + (I^2/4) \ast \\
P_{\text{IVVContFit}}(1))/(P_{\text{IVVElecFit}}(4) + (I^2/4) \ast \\
P_{\text{IVVElecFit}}(2))) \ast (\text{TScale} \ast \text{RefEIIVVn}) - 1) \ast KnmIVVn
\]

\[
K_{\text{nmIVVn}} = \text{TScale} \ast \text{L} / P_{\text{ChanRestFit}}(2);
\]

\[
\text{RefEIIVVn} = S_{\text{rel}} \ast \text{TScale} \ast \text{P}_{\text{IVVElecFit}}(1) / \\
P_{\text{IVVElecFit}}(2);
\]

\[
\text{RefTIIVVn} = \text{TScale} \ast \text{P}_{\text{IVVTherFit}}(1) / P_{\text{IVVElecFit}}(2) \ast \\
S_{\text{rel}};
\]

\[
K_{\text{subIVVn}} = ((S_{\text{rel}} \ast \text{P}_{\text{IVVContFit}}(1)) / \text{P}_{\text{IVVElecFit}}(2)) \ast \\
(\text{TScale} / \text{RefEIIVVn}) - 1) \ast KnmIVVn;
\]

\[
P_JEIIVVn = I^2 \ast \text{RefEIIVVp};
\]

\[
P_JTIIVVn = I^2 \ast \text{RefTIIVVp};
\]

\[
PP_iEIIVVn = I^2 \ast S_{\text{rel}} \ast \text{TScale};
\]

\[
\Delta T_{2tIIVVn} = P_JTIIVVn \ast \text{KnmIVVn} / (K_{\text{subIVVn}} \ast (K_{\text{subIVVn}} + 2 \ast \text{KnmIVVn}));
\]

\[
\Delta T_{1tIIVVn} = (P_JTIIVVn / K_{\text{subIVVn}}) - \Delta T_{2tIIVVn};
\]

\[
\Delta T_{ttIIVVn} = \Delta T_{1tIIVVn} - \Delta T_{2tIIVVn};
\]

\[
\text{SDSEIIVVn} = (\text{P}_{\text{subAP1IIVVTherFit}}(1) \ast I^2) / \left(\Delta T_{ttIIVVn} \ast .001 \ast R_{\text{misIVV}}\right);
\]

178
% IV–VI Positive Saturation

\[ \text{KnmIVVIp} = T\text{Scale} \cdot \frac{L}{(Pp\text{ChanRestFit}(4)+(I^{2}/3) \cdot (Pp\text{ChanRestFit}(2))} \]

\[ \text{RefEIVVIp} = S_{\text{rel}} \cdot T\text{Scale} \cdot \frac{Pp\text{IVVIElecFit}(1)}{(Pp\text{IVVIElecFit}(4)+(I^{2}/4) \cdot (Pp\text{IVVIElecFit}(2))} \]

\[ \text{RefTIVVIp} = T\text{Scale} \cdot \frac{(Pp\text{IVVITherFit}(3)/2+(I^{2}/4) \cdot (Pp\text{IVVITherFit}(1))}{(Pp\text{IVVIElecFit}(4)+(I^{2}/4) \cdot (Pp\text{IVVIElecFit}(2))} \cdot S_{\text{rel}} \]

\[ \text{KsubIVVIp} = ((S_{\text{rel}} \cdot (Pp\text{IVVIContFit}(3)/2+(I^{2}/4) \cdot (Pp\text{IVVIContFit}(1))}{(Pp\text{IVVIElecFit}(4)+(I^{2}/4) \cdot (Pp\text{IVVIElecFit}(2))} \cdot (T\text{Scale} \cdot \text{RefEIVVIp})-1) \cdot \text{KnmIVVIp} \]

{%
\[ \text{KnmIVVIp} = T\text{Scale} \cdot \frac{L}{Pp\text{ChanRestFit}(2)} \]
\[ \text{RefEIVVIp} = S_{\text{rel}} \cdot T\text{Scale} \cdot \frac{Pp\text{IVVIElecFit}(1)}{Pp\text{IVVIElecFit}(2)} \]

\[ \text{RefTIVVIp} = T\text{Scale} \cdot \frac{Pp\text{IVVITherFit}(1)}{Pp\text{IVVIElecFit}(2)} \cdot S_{\text{rel}} \]

\[ \text{KsubIVVIp} = ((S_{\text{rel}} \cdot Pp\text{IVVIContFit}(1)}{Pp\text{IVVIElecFit}(2)}) \cdot (T\text{Scale} \cdot \text{RefEIVVIp})-1) \cdot \text{KnmIVVIp} \]
{%}
PJIEIVVIp=I \cdot 2 \cdot \text{RefEIVVIp};

PJTIVVIp=I \cdot 2 \cdot \text{RefTIVVIp};

PPiEIVVIp=I \cdot 2 \cdot \text{Srel} \cdot \text{TScale};

\Delta T_{2tIVVIp}=\text{PJTIVVIp} \cdot \text{KnmIVVIp} ./ (\text{KsubIVVIp} \cdot (\text{KsubIVVIp}+2\cdot \text{KnmIVVIp}));

\Delta T_{1tIVVIp}=(\text{PJTIVVIp} ./ \text{KsubIVVIp})-\text{DeltaT}_{2tIVVIp};

\Delta T_{ttIVVIp}=\text{DeltaT}_{1tIVVIp} - \text{DeltaT}_{2tIVVIp};

\text{SDSEIVVIp}=(\text{PpsubAP1IVVITherFit(1)} \cdot I \cdot 2)/ (\text{DeltaT}_{ttIVVIp} \cdot .001 \cdot \text{RmisIVV});

\% IV−VI Negative Saturation

\text{KnmIVVIn}=\text{TScale} \cdot \text{L} ./ (\text{PnChanRestFit(4)}+(I \cdot 2/3) \cdot \text{PnChanRestFit(2)});

\text{RefEIVVIn}=\text{Srel} \cdot \text{TScale} \cdot (\text{PnIVVIElecFit(3)}/2+(I \cdot 2/4) \cdot \text{PnIVVIElecFit(1)}) ./ (\text{PnIVVIElecFit(4)}+(I \cdot 2/4) \cdot \text{PnIVVIElecFit(2)});

\text{RefTIVVIn}=\text{TScale} \cdot (\text{PpIVVITherFit(3)}/2+(I \cdot 2/4) \cdot \text{PpIVVITherFit(1)}) ./ (\text{PnIVVIElecFit(4)}+(I \cdot 2/4) \cdot \text{PnIVVIElecFit(2)}) \cdot \text{Srel};

\text{KsubIVVIn}=((\text{Srel} \cdot (\text{PnIVVIContFit(3)}/2+(I \cdot 2/4) \cdot \text{PpIVVIContFit(1)}) ./ (\text{PnIVVIElecFit(4)}+(I \cdot 2/4) \cdot \text{PnIVVIElecFit(2)}) \cdot (\text{TScale} ./ \text{RefEIVVIn})-1) \cdot \text{KnmIVVIn};
%
KnmlIVVIn=TS\_scale.*L./PnChanRestFit(2);
RefEIVVIn=S\_rel.*TS\_scale.*PnIVVIElecFit(1)./PnIVVIElecFit(2);
RefTIVVIn=TS\_scale.*PnIVVITherFit(1)./PnIVVIElecFit(2).*S\_rel;
KsubIVVIn=((S\_rel.*PnIVVIContFit(1)./PnIVVIElecFit(2)).*(TS\_scale./RefEIVVIn)-1).*KnmlIVVIn;%
PJEIVVIn=I^2*RefEIVVIn;
PJTIVVIn=I^2*RefTIVVIn;
PPiEIVVIn=I^2*S\_rel.*TS\_scale;

DeltaT2tIVVIn=PJTIVVIn.*KnmlIVVIn./(KsubIVVIn.*(KsubIVVIn+2*KnmlIVVIn));
DeltaT1tIVVIn=(PJTIVVIn./KsubIVVIn)-DeltaT2tIVVIn;
DeltaTttIVVIn=DeltaT1tIVVIn-DeltaT2tIVVIn;

SDSEIVVIn=(PnsubAP2IVVITherFit(1).*I^2)./(DeltaTttIVVIn*.001*RmisIVV);%

II-\text{VV Negative Saturation}
KnmlIVVn=cell2mat({TS\_scale( : ).*L./PpChanRestFit( : ,2)});
RefEIVVn=cell2mat({S\_rel( : ).*TS\_scale( : ) .*IIVVPnElecFit( : ,1)./IIVVPnElecFit( : ,2)})

181
RefTIIVVn=cell2mat ({ TScale (: ) .* IIVVPnTherFit (: , 1 ) ./
                   IIVVPnElecFit (: , 2 ) .* Srel (: ) });
KsubIIIVn=cell2mat ({ ( ( Srel (: ) .* IIVVPnContFit (: , 1 ) ./
                          IIVVPnElecFit (: , 2 ) ) .* ( TScale (: ) ./ RefEIIVVn (: ) ) -1 ) .* KnmIIIVn (: ) });

PJEIIIVVn=I^2*RefEIIVVn;
PJTIIVVn=I^2*RefTIIVVn;
PPiEIIIVVn=I^2*Srel (: ) .* TScale (: );

DeltaT2tIIIVVn=PJTIIVVn.* KnmIIIVVn ./ ( KsubIIIVn.* ( KsubIIIVn+2*KnmIIIVVn ) );
DeltaT1tIIIVVn=(PJTIIVVn ./ KsubIIIVVn)-DeltaT2tIIIVVn;
DeltaTttIIIVVn=DeltaT1tIIIVVn-DeltaT2tIIIVVn;

SDSEIIIVVn=(IIVVPnSubAP2TherFit (: , 3 )*I^2)./( DeltaTttIIIVVn (: ) *.001*RmisIIIVV )

%IV–VI Positive Saturation
KnmlIVVIp=cell2mat ({ TScale (: ) .* L./ PpChanRestFit (: , 2 ) });
RefEIVVIp=cell2mat ({ Srel (: ) .* TScale (: ) .* 
                         IIVVIPpElecFit (: , 1 ) ./ IIVVIPpElecFit (: , 2 ) });
RefTIVVIp=cell2mat ({ TScale (: ) .* IIVVIPpTherFit (: , 1 ) ./ 
                         IIVVIPpElecFit (: , 2 ) .* Srel (: ) });
KsubIVVIp=cell2mat\{((Srel(:))\cdot IVVIPpContFit(:,1) ./ IVVIPpElecFit(:,2))\cdot (TScale(:) ./ RefEIVVIp(:)-1)\cdot KnmIVVIp(:)\};

PJEIVVIp=I^2\cdot RefEIVVIp;  
PJTIVVIp=I^2\cdot RefTIVVIp;  
PPiEIVVIp=I^2\cdot Srel(:) \cdot TScale(:); 

DeltaT2tIVVIp=PJTIVVIp\cdot KnmIVVIp ./ (KsubIVVIp\cdot (KsubIVVIp+2\cdot KnmIVVIp)) ;  
DeltaT1tIVVIp=(PJTIVVIp ./ KsubIVVIp)-DeltaT2tIVVIp;  
DeltaTttIVVIp=DeltaT1tIVVIp-DeltaT2tIVVIp;  

SDSEIVVIp1=(IVVIPpSubAP1TherFit(:,1)\cdot I^2) ./ (DeltaTttIVVIp(:)\cdot .01\cdot RmisIVVI) 
SDSEIVVIp2=((IVVIPpTherFit(:,1)-IVVIAP2TherFit(:,1))\cdot I^2) ./ (DeltaTttIVVIp(:)\cdot .01\cdot RmisIVVI);  

E.2.11 NLSVRegressionDifConFixed

Differential Conductance regression

A big limitation of the other data taking version is the poor way I handled the error analysis. Here the error is more properly calculated from the R vs I
data, rather than the integrated V vs I data. This is explained in my thesis, Appendix B.1

```matlab
f = fit (PpIIVVElec(:,1), PpIIVVElec(:,3), 'poly1');
cf = confint (f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/4), (abs(cf(1,2) - cf(2,2))/2)];
PpIIVVElecFit = [coeffvalues(f) 0 cdf];
```

```matlab
f = fit (PpIIVVTHER(:,1), PpIIVVTHER(:,3), 'poly1');
cf = confint (f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/4), (abs(cf(1,2) - cf(2,2))/2)];
PpIIVVTHERFit = [coeffvalues(f) 0 cdf];
```

```matlab
f = fit (PpIIVVCont(:,1), PpIIVVCont(:,3), 'poly1');
cf = confint (f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/4), (abs(cf(1,2) - cf(2,2))/2)];
PpIIVVContFit = [coeffvalues(f) 0 cdf];
```

```matlab
f = fit (PpIVVIELEC(:,1), PpIVVIELEC(:,3), 'poly1');
cf = confint (f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/4), (abs(cf(1,2) - cf(2,2))/2)];
PpIVVIELECFit = [coeffvalues(f) 0 cdf];
```

```matlab
f = fit (PpIVVITHER(:,1), PpIVVITHER(:,3), 'poly1');
```

\begin{verbatim}
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PpIVVITherFit=[coeffvalues(f) 0 cdf];

f=fit(PpIVVICont(:,1),PpIVVICont(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PpIVVIContFit=[coeffvalues(f) 0 cdf];

f=fit(PpChanRest(:,1),PpChanRest(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PpChanRestFit=[coeffvalues(f) 0 cdf];

%Pn
f=fit(PpIIVVElec(:,1),PnIIVVElec(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PnIIVVElecFit=[coeffvalues(f) 0 cdf];

f=fit(PpIIVVTher(:,1),PnIIVVTher(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PnIIVVTherFit=[coeffvalues(f) 0 cdf];
\end{verbatim}
f=fit(PpIVVCont(:,1),PnIVVCont(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PnIVVContFit=[coeffvalues(f) 0 cdf];

f=fit(PpIVVIElec(:,1),PnIVVIElec(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PnIVVIElecFit=[coeffvalues(f) 0 cdf];

f=fit(PpIVVICont(:,1),PnIVVICont(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PnIVVIContFit=[coeffvalues(f) 0 cdf];

f=fit(PpChanRest(:,1),PnChanRest(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PnChanRestFit=[coeffvalues(f) 0 cdf];
%AP1

f=fit (AP1IVVElec(:,1),AP1IVVElec(:,3),'poly1');
cf=confint (f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
AP1IVVElecFit=[coeffvalues(f) 0 cdf];

f=fit (AP1IVVTher(:,1),AP1IVVTher(:,3),'poly1');
cf=confint (f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
AP1IVVTherFit=[coeffvalues(f) 0 cdf];

f=fit (AP1IVVIElec(:,1),AP1IVVIElec(:,3),'poly1');
cf=confint (f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
AP1IVVIElecFit=[coeffvalues(f) 0 cdf];

f=fit (AP1IVVITher(:,1),AP1IVVITher(:,3),'poly1');
cf=confint (f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
AP1IVVITherFit=[coeffvalues(f) 0 cdf];

%AP2

f=fit (AP2IVVElec(:,1),AP2IVVElec(:,3),'poly1');
cf=confint (f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
AP2IVVElecFit=[coeffvalues(f) 0 cdf];

f=fit(AP2IVVTher(:,1),AP2IVVTher(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
AP2IVVTherFit=[coeffvalues(f) 0 cdf];

f=fit(AP2IVVIElec(:,1),AP2IVVIElec(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
AP2IVVIElecFit=[coeffvalues(f) 0 cdf];

f=fit(AP2IVVITher(:,1),AP2IVVITher(:,3),'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
AP2IVVITherFit=[coeffvalues(f) 0 cdf];

% P−AP Stuff
% II−VV
% Pp−PV
f=fit(PpIIVVElec(:,1),(PpIIVVElec(:,3)−AP2IVVVElec(:,3))
    , 'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)-cf(2,1))/4),(abs(cf(1,2)-cf(2,2))/2)];
PpsubAP2IVVVElecFit=[coeffvalues(f) 0 cdf];
%Pn–AP1
f=fit(PnIIVVElec(:,1),(PnIIVVElec(:,3)–AP1IIVVElec(:,3))
    , 'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)–cf(2,1))/4),(abs(cf(1,2)–cf(2,2))/2)];
PnsubAP1IIVVElecFit=[coeffvalues(f) 0 cdf];

%IV–VI

%Pp–AP1
f=fit(PpIVVIElec(:,1),(PpIVVIElec(:,3)–AP1IVVIElec(:,3))
    , 'poly1');
cf=confint(f,.64);
cdf=[(abs(cf(1,1)–cf(2,1))/4),(abs(cf(1,2)–cf(2,2))/2)];
PnsubAP1IIVVTherFit=[coeffvalues(f) 0 cdf];
cdf = [(abs(cf(1,1) - cf(2,1))/4), (abs(cf(1,2) - cf(2,2))/2)];
PpsubAP1IVVIElecFit = [coefvalues(f) 0 cdf];

f = fit(PpIVVITher(:,1), (PpIVVITher(:,3) - AP1IVVITher(:,3)) , 'poly1');
cf = confint(f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/4), (abs(cf(1,2) - cf(2,2))/2)];
PpsubAP1IVVITherFit = [coefvalues(f) 0 cdf];

%Pn–AP2
f = fit(PnIVVIElec(:,1), (PnIVVIElec(:,3) - AP2IVVIElec(:,3)) , 'poly1');
cf = confint(f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/4), (abs(cf(1,2) - cf(2,2))/2)];
PnsubAP2IVVIElecFit = [coefvalues(f) 0 cdf];

f = fit(PnIVVITher(:,1), (PnIVVITher(:,3) - AP2IVVITher(:,3)) , 'poly1');
cf = confint(f, .64);
cdf = [(abs(cf(1,1) - cf(2,1))/4), (abs(cf(1,2) - cf(2,2))/2)];
PnsubAP2IVVITherFit = [coefvalues(f) 0 cdf];

%Pp–Pn
%IVV
f = fit (PpIIVVElec(:, 1), (PpIIVVElec(:, 3) - PnIIVVElec(:, 3)), 'poly1');
cf = confint (f, .64);
cdf = [(abs(cf(1, 1) - cf(2, 1))/4), (abs(cf(1, 2) - cf(2, 2))/2)];
PpsubPnIIVVElecFit = [coeffvalues(f) 0 cdf];

f = fit (PpIIVVTher(:, 1), (PpIIVVTher(:, 3) - PnIIVVTher(:, 3)), 'poly1');
cf = confint (f, .64);
cdf = [(abs(cf(1, 1) - cf(2, 1))/4), (abs(cf(1, 2) - cf(2, 2))/2)];
PpsubPnIIVVTherFit = [coeffvalues(f) 0 cdf];

% IVVI
f = fit (PpIVVIElec(:, 1), (PpIVVIElec(:, 3) - PnIVVIElec(:, 3)), 'poly1');
cf = confint (f, .64);
cdf = [(abs(cf(1, 1) - cf(2, 1))/4), (abs(cf(1, 2) - cf(2, 2))/2)];
PpsubPnIVVIElecFit = [coeffvalues(f) 0 cdf];

f = fit (PpIVVITher(:, 1), (PpIVVITher(:, 3) - PnIVVITher(:, 3)), 'poly1');
cf = confint (f, .64);
cdf = [(abs(cf(1, 1) - cf(2, 1))/4), (abs(cf(1, 2) - cf(2, 2))/2)];
PpsubPnIVVITherFit = [coeffvalues(f) 0 cdf];
%FileWrite

Output=

'PpIVVElec', PpIVVElecFit(3), PpIVVElecFit(2),
PpIVVElecFit(1)/2, PpIVVElecFit(5), PpIVVElecFit(4);

'PpIVVTher', PpIVVTherFit(3), PpIVVTherFit(2),
PpIVVTherFit(1)/2, PpIVVTherFit(5), PpIVVTherFit(4);

'PpIVVCont', PpIVVContFit(3), PpIVVContFit(2),
PpIVVContFit(1)/2, PpIVVContFit(5), PpIVVContFit(4);

'PpIVVIElec', PpIVVIElecFit(3), PpIVVIElecFit(2),
PpIVVIElecFit(1)/2, PpIVVIElecFit(5), PpIVVIElecFit(4);

'PpIVVITher', PpIVVITherFit(3), PpIVVITherFit(2),
PpIVVITherFit(1)/2, PpIVVITherFit(5), PpIVVITherFit(4);

'PpIVVICont', PpIVVIContFit(3), PpIVVIContFit(2),
PpIVVIContFit(1)/2, PpIVVIContFit(5), PpIVVIContFit(4);

'PpChanRest', PpChanRestFit(3), PpChanRestFit(2),
PpChanRestFit(1)/2, PpChanRestFit(5), PpChanRestFit(4);
'PnIIIVVElec', PnIIIVVElecFit (3), PnIIIVVElecFit (2),
   PnIIIVVElecFit (1) /2, PnIIIVVElecFit (5), PnIIIVVElecFit (4);

'PnIIIVVTher', PnIIIVVTherFit (3), PnIIIVVTherFit (2),
   PnIIIVVTherFit (1) /2, PnIIIVVTherFit (5), PnIIIVVTherFit (4);

'PnIIIVVCont', PnIIIVVContFit (3), PnIIIVVContFit (2),
   PnIIIVVContFit (1) /2, PnIIIVVContFit (5), PnIIIVVContFit (4);

'PnIVVIElec', PnIVVIElecFit (3), PnIVVIElecFit (2),
   PnIVVIElecFit (1) /2, PnIVVIElecFit (5), PnIVVIElecFit (4);

'PnIVVITher', PnIVVITherFit (3), PnIVVITherFit (2),
   PnIVVITherFit (1) /2, PnIVVITherFit (5), PnIVVITherFit (4);

'PnIVVICont', PnIVVIContFit (3), PnIVVIContFit (2),
   PnIVVIContFit (1) /2, PnIVVIContFit (5), PnIVVIContFit (4);

'PnChanRest', PnChanRestFit (3), PnChanRestFit (2),
   PnChanRestFit (1) /2, PnChanRestFit (5), PnChanRestFit (4);

'AP1IIIVVElec', AP1IIIVVElecFit (3), AP1IIIVVElecFit (2),
   AP1IIIVVElecFit (1) /2, AP1IIIVVElecFit (5),
   AP1IIIVVElecFit (4);
'PpsubAP2IIVVTher', PpsubAP2IIVVTherFit (3),
PpsubAP2IIVVTherFit (2), PpsubAP2IIVVTherFit (1)/2,
PpsubAP2IIVVTherFit (5), PpsubAP2IIVVTherFit (4);

'PpsubAP1IVVIElec', PpsubAP1IVVIElecFit (3),
PpsubAP1IVVIElecFit (2), PpsubAP1IVVIElecFit (1)/2,
PpsubAP1IVVIElecFit (5), PpsubAP1IVVIElecFit (4);

'PpsubAP1IVVITher', PpsubAP1IVVITherFit (3),
PpsubAP1IVVITherFit (2), PpsubAP1IVVITherFit (1)/2,
PpsubAP1IVVITherFit (5), PpsubAP1IVVITherFit (4);

'PnsubAP1IIVVElec', PnsubAP1IIVVElecFit (3),
PnsubAP1IIVVElecFit (2), PnsubAP1IIVVElecFit (1)/2,
PnsubAP1IIVVElecFit (5), PnsubAP1IIVVElecFit (4);

'PnsubAP1IIVVTher', PnsubAP1IIVVTherFit (3),
PnsubAP1IIVVTherFit (2), PnsubAP1IIVVTherFit (1)/2,
PnsubAP1IIVVTherFit (5), PnsubAP1IIVVTherFit (4);

'PnsubAP2IVVIElec', PnsubAP2IVVIElecFit (3),
PnsubAP2IVVIElecFit (2), PnsubAP2IVVIElecFit (1)/2,
PnsubAP2IVVIElecFit (5), PnsubAP2IVVIElecFit (4);

'PnsubAP2IVVITher', PnsubAP2IVVITherFit (3),
PnsubAP2IVVITherFit (2), PnsubAP2IVVITherFit (1)/2,
PnsubAP2IVVITherFit (5), PnsubAP2IVVITherFit (4);

'PpsubPnIIVVElec', PpsubPnIIVVElecFit (3),
PpsubPnIIVVElecFit (2), PpsubPnIIVVElecFit (1)/2,
PpsubPnIIVVElecFit (5), PpsubPnIIVVElecFit (4);
'PpsubPnIVVTher', PpsubPnIVVTherFit(3),
    PpsubPnIVVTherFit(2), PpsubPnIVVTherFit(1)/2,
    PpsubPnIVVTherFit(5), PpsubPnIVVTherFit(4);
'PpsubPnIVVIElec', PpsubPnIVVIElecFit(3),
    PpsubPnIVVIElecFit(2), PpsubPnIVVIElecFit(1)/2,
    PpsubPnIVVIElecFit(5), PpsubPnIVVIElecFit(4);
'PpsubPnIVVITher', PpsubPnIVVITherFit(3),
    PpsubPnIVVITherFit(2), PpsubPnIVVITherFit(1)/2,
    PpsubPnIVVITherFit(5), PpsubPnIVVITherFit(4);
}
OutputTable=cell2table(Output, 'VariableNames',{
    'Test', 'YCept', 'R1', 'R2', 'R1STD', 'R2STD'});
Filename1=strcat(DeviceName, T, ' DifCon.txt');
Filename2=strcat(DeviceName, T, ' DifCon.csv');
writetable(OutputTable, Filename1);
writetable(OutputTable, Filename2)
%

E.2.12 NLSVDeviceSummation

Device Summation Description

This code is meant to organize all of the fit parameters for the V vs I curves for 6 temperatures. This allows us to observe P-AP and Pp-Pn in electrical and thermal injection for both orientations and compare that to the
thermal background resistance as they all change with temperature. This file loads 6 saved regression files, one for each temperature, that are saved from RegressionJustSave. This loads data from the 6 temperature regression files into a massive 6x5x34 array. Each total variable below is compiled from each of these points. I'm sure some things can be improved. Plot was commented out and implemented separately individually later.

DeviceName='Run6a500nm';
Holder='DifCon';

NLSVTotal78K=importdata( strcat(DeviceName,' 78K', Holder ,'.txt'),',',1);
NLSVTotal100K=importdata( strcat(DeviceName,'100K', Holder ,'.txt'),',',1);
NLSVTotal150K=importdata( strcat(DeviceName,'150K', Holder ,'.txt'),',',1);
NLSVTotal200K=importdata( strcat(DeviceName,'200K', Holder ,'.txt'),',',1);
NLSVTotal250K=importdata( strcat(DeviceName,'250K', Holder ,'.txt'),',',1);
NLSVTotal300K=importdata( strcat(DeviceName,'300K', Holder ,'.txt'),',',1);

%mkdir( strcat( 'SummationPlots / ') )
%%IVVI AP2
IVVIAP2TherTot=cell2mat ({ 78, NLSVTot78K.data(22,2),
NLSVTot78K.data(22,3), NLSVTot78K.data(22,4),
NLSVTot78K.data(22,5);
100, NLSVTot100K.data(22,2), NLSVTot100K.data(22,3),
NLSVTot100K.data(22,4), NLSVTot100K.data(22,5);
150, NLSVTot150K.data(22,2), NLSVTot150K.data(22,3),
NLSVTot150K.data(22,4), NLSVTot150K.data(22,5);
200, NLSVTot200K.data(22,2), NLSVTot200K.data(22,3),
NLSVTot200K.data(22,4), NLSVTot200K.data(22,5);
250, NLSVTot250K.data(22,2), NLSVTot250K.data(22,3),
NLSVTot250K.data(22,4), NLSVTot250K.data(22,5);
300, NLSVTot300K.data(22,2), NLSVTot300K.data(22,3),
NLSVTot300K.data(22,4), NLSVTot300K.data(22,5)});

%%IVVI AP1
IVVIAP1TherTot=cell2mat ({ 78, NLSVTot78K.data(18,2),
NLSVTot78K.data(18,3), NLSVTot78K.data(18,4),
NLSVTot78K.data(18,5);
100, NLSVTot100K.data(18,2), NLSVTot100K.data(18,3),
NLSVTot100K.data(18,4), NLSVTot100K.data(18,5);
150, NLSVTot150K.data(18,2), NLSVTot150K.data(18,3),
NLSVTot150K.data(18,4), NLSVTot150K.data(18,5);
200, NLSVTot200K.data(18,2), NLSVTot200K.data(18,3),
NLSVTot200K.data(18,4), NLSVTot200K.data(18,5);
250, NLSVTot250K.data(18,2), NLSVTot250K.data(18,3),
NLSVTot250K.data(18,4), NLSVTot250K.data(18,5);
300, NLSVTot300K.data(18,2), NLSVTot300K.data(18,3),
NLSVTot300K.data(18,4), NLSVTot300K.data(18,5)});
250, NLSVTotal250K.data(18,2), NLSVTotal250K.data(18,3),
NLSVTotal250K.data(18,4), NLSVTotal250K.data(18,5);
300, NLSVTotal300K.data(18,2), NLSVTotal300K.data(18,3),
NLSVTotal300K.data(18,4), NLSVTotal300K.data(18,5));

%%IVV Pp Elec Tot Compile and Plot
IVVPpElecTot=cell2mat({78, NLSVTotal78K.data(1,2),
NLSVTotal78K.data(1,3), NLSVTotal78K.data(1,4),
NLSVTotal78K.data(1,5);
100, NLSVTotal100K.data(1,2), NLSVTotal100K.data(1,3),
NLSVTotal100K.data(1,4), NLSVTotal100K.data(1,5);
150, NLSVTotal150K.data(1,2), NLSVTotal150K.data(1,3),
NLSVTotal150K.data(1,4), NLSVTotal150K.data(1,5);
200, NLSVTotal200K.data(1,2), NLSVTotal200K.data(1,3),
NLSVTotal200K.data(1,4), NLSVTotal200K.data(1,5);
250, NLSVTotal250K.data(1,2), NLSVTotal250K.data(1,3),
NLSVTotal250K.data(1,4), NLSVTotal250K.data(1,5);
300, NLSVTotal300K.data(1,2), NLSVTotal300K.data(1,3),
NLSVTotal300K.data(1,4), NLSVTotal300K.data(1,5)});
%
figure
[hAx,h1,h2]=plotyy(IVVPpElecTot(:,1),((1E6)*
IVVPpElecTot(:,2)),IVVPpElecTot(:,1),((1E3)*
IVVPpElecTot(:,3)));
set(hAx,'fontsize',18)
title(strcat(DeviceName, 'IIIVp Electrical Injection A1 and A2 vs T'))
xlabel('T (K) ')
set(h1,'Marker','.', 'MarkerSize',18)
set(h2,'Marker','.', 'MarkerSize',18)
ylabel(hAx(1), 'A1 (microOhm) ')
ylabel(hAx(2), 'A2 (nV/mA^2) ')
legend('A1', 'A2')
saveas(gcf, strcat('SummationPlots/',DeviceName,' Pp II-VV Elec vs T.png'))

%%dIIIV Vp Ther Tot Compile and Plot
IIIVVpPpTherTot=cell2mat({78,NLSVTotal78K.data(2,2),
    NLSVTotal78K.data(2,3),NLSVTotal78K.data(2,4),
    NLSVTotal78K.data(2,5);
100,NLSVTotal100K.data(2,2),NLSVTotal100K.data(2,3),
    NLSVTotal100K.data(2,4),NLSVTotal100K.data(2,5);
150,NLSVTotal150K.data(2,2),NLSVTotal150K.data(2,3),
    NLSVTotal150K.data(2,4),NLSVTotal150K.data(2,5);
200,NLSVTotal200K.data(2,2),NLSVTotal200K.data(2,3),
    NLSVTotal200K.data(2,4),NLSVTotal200K.data(2,5);
250,NLSVTotal250K.data(2,2),NLSVTotal250K.data(2,3),
    NLSVTotal250K.data(2,4),NLSVTotal250K.data(2,5);
300,NLSVTotal300K.data(2,2),NLSVTotal300K.data(2,3),
NLSVTotal300K.data(2,4),NLSVTotal300K.data(2,5));

figure
[hAx,h1,h2]=plotyy(IIVVPpTherTot(:,1),((1E6)*
IIVVPpTherTot(:,2)),IIVVPpTherTot(:,1),((1E3)*
IIVVPpTherTot(:,3)));
set(hAx,'fontsize',18)
title(strcat(DeviceName,'IIVVp Thermal Injection B1 and
B2 vs T'))
xlabel('T (K)')
set(h1,'Marker','.','MarkerSize',18)
set(h2,'Marker','.','MarkerSize',18)
ylabel(hAx(1),'B1 (microOhm)')
ylabel(hAx(2),'B2 (nV/mA^2)')
legend('B1','B2')
saveas(gcf,strcat('SummationPlots/','DeviceName','Pp II−
VV Ther vs T.png'))

%IIVV Pp Cont Tot Compile and Plot
IIVVPpContTot=cell2mat({78,NLSVTotal78K.data(3,2),
NLSVTotal78K.data(3,3),NLSVTotal78K.data(3,4),
NLSVTotal78K.data(3,5);
100, NLSVTotal100K.data(3,2), NLSVTotal100K.data(3,3),
    NLSVTotal100K.data(3,4), NLSVTotal100K.data(3,5);
150, NLSVTotal150K.data(3,2), NLSVTotal150K.data(3,3),
    NLSVTotal150K.data(3,4), NLSVTotal150K.data(3,5);
200, NLSVTotal200K.data(3,2), NLSVTotal200K.data(3,3),
    NLSVTotal200K.data(3,4), NLSVTotal200K.data(3,5);
250, NLSVTotal250K.data(3,2), NLSVTotal250K.data(3,3),
    NLSVTotal250K.data(3,4), NLSVTotal250K.data(3,5);
300, NLSVTotal300K.data(3,2), NLSVTotal300K.data(3,3),
    NLSVTotal300K.data(3,4), NLSVTotal300K.data(3,5));

figure
%
[hAx, h1, h2] = plotyy(IIVVPpContTot(:,1), ((1E6) * 
    IIVVPpContTot(:,2)), IIVVPpContTot(:,1), ((1E3) * 
    IIVVPpContTot(:,3)));
set(hAx, 'fontsize', 18)
title(strcat(DeviceName, ' IIVVp Contact C1 and C2 vs T'))
xlabel('T (K)')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'C1 (microOhm)')
ylabel(hAx(2), 'C2 (nV/mA^2)')
legend('C1', 'C2')
saveas(gcf, strcat('SummationPlots/', DeviceName, ' Pp II – VV Cont vs T.png'))
%

%%IVV Pn Elec Tot Compile and Plot
IIVVPnElecTot=cell2mat({
    78, NLSVTotal78K.data(8,2), NLSVTotal78K.data(8,3), NLSVTotal78K.data(8,4),
    NLSVTotal78K.data(8,5);
    100, NLSVTotal100K.data(8,2), NLSVTotal100K.data(8,3), NLSVTotal100K.data(8,4),
    NLSVTotal100K.data(8,5);
    150, NLSVTotal150K.data(8,2), NLSVTotal150K.data(8,3), NLSVTotal150K.data(8,4),
    NLSVTotal150K.data(8,5);
    200, NLSVTotal200K.data(8,2), NLSVTotal200K.data(8,3), NLSVTotal200K.data(8,4),
    NLSVTotal200K.data(8,5);
    250, NLSVTotal250K.data(8,2), NLSVTotal250K.data(8,3), NLSVTotal250K.data(8,4),
    NLSVTotal250K.data(8,5);
    300, NLSVTotal300K.data(8,2), NLSVTotal300K.data(8,3), NLSVTotal300K.data(8,4),
    NLSVTotal300K.data(8,5)});

figure
%

{[hAx,h1,h2]=plotyy(IIVVPnElecTot(:,1),((1E6)*
    IIVVPnElecTot(:,2)),IIVVPnElecTot(:,1),((1E3)*
    IIVVPnElecTot(:,3)));
set(hAx,'fontsize',18)
title(strcat(DeviceName, 'IIVVn Electrical Injection A1 and A2 vs T'))
xlabel('T (K)')
set(h1,'Marker','.', 'MarkerSize',18)
set(h2,'Marker','.', 'MarkerSize',18)
ylabel(hAx(1),'A1 (microOhm)')
ylabel(hAx(2),'A2 (nV/mA^2)')
legend('A1', 'A2')
saveas(gcf, strcat('SummationPlots/',DeviceName,' Pn II-VV Elec vs T.png'))
}

%%IVV Pn Ther Tot Compile and Plot
IIVVPnTherTot=cell2mat({78,NLSVTotal78K.data(9,2),
                    NLSVTotal78K.data(9,3),NLSVTotal78K.data(9,4),
                    NLSVTotal78K.data(9,5);
100,NLSVTotal100K.data(9,2),NLSVTotal100K.data(9,3),
                    NLSVTotal100K.data(9,4),NLSVTotal100K.data(9,5);
150,NLSVTotal150K.data(9,2),NLSVTotal150K.data(9,3),
                    NLSVTotal150K.data(9,4),NLSVTotal150K.data(9,5);
200,NLSVTotal200K.data(9,2),NLSVTotal200K.data(9,3),
                    NLSVTotal200K.data(9,4),NLSVTotal200K.data(9,5);
250,NLSVTotal250K.data(9,2),NLSVTotal250K.data(9,3),
                    NLSVTotal250K.data(9,4),NLSVTotal250K.data(9,5);
300, NLSVTotal300K.data(9,2), NLSVTotal300K.data(9,3),
NLSVTotal300K.data(9,4), NLSVTotal300K.data(9,5));

figure

[hAx, h1, h2] = plotyy(IIVVPnTherTot(:,1),((1E6)*
IIVVPnTherTot(:,2)), IIVVPnTherTot(:,1),((1E3)*
IIVVPnTherTot(:,3)));

set(hAx, 'fontsize', 18)
title(strcat(DeviceName, ' IIVVn Thermal Injection B1 and
B2 vs T'))
xlabel('T (K)')

set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'B1 (microOhm)')
ylabel(hAx(2), 'B2 (nV/mA^2)')

legend('B1', 'B2')
saveas(gcf, strcat('SummationPlots/', DeviceName, ' Pn II−
VV Ther vs T.png'))

}

%%IIVV Pn Cont Tot Compile and Plot

IIVVPnContTot=cell2mat({78, NLSVTotal78K.data(10,2),
NLSVTotal78K.data(10,3), NLSVTotal78K.data(10,4),
NLSVTotal78K.data(10,5);
100, NLSVTotal100K.data(10,2), NLSVTotal100K.data(10,3),
NLSVTotal100K.data(10,4), NLSVTotal100K.data(10,5);
150, NLSVTotal150K.data(10,2), NLSVTotal150K.data(10,3),
NLSVTotal150K.data(10,4), NLSVTotal150K.data(10,5);
200, NLSVTotal200K.data(10,2), NLSVTotal200K.data(10,3),
NLSVTotal200K.data(10,4), NLSVTotal200K.data(10,5);
250, NLSVTotal250K.data(10,2), NLSVTotal250K.data(10,3),
NLSVTotal250K.data(10,4), NLSVTotal250K.data(10,5);
300, NLSVTotal300K.data(10,2), NLSVTotal300K.data(10,3),
NLSVTotal300K.data(10,4), NLSVTotal300K.data(10,5));

figure

{[hAx, h1, h2] = plotyy(IIVVPnContTot(:,1),((1E6)*
IIVVPnContTot(:,2)), IIVVPnContTot(:,1),((1E3)*
IIVVPnContTot(:,3)));
set(hAx, 'fontsize', 18)
title(strcat(DeviceName, ' IIVVn Contact C1 and C2 vs T'))
xlabel('T (K)')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'C1 (microOhm)')
ylabel(hAx(2), 'C2 (nV/mA^2)')
legend('C1', 'C2')
saveas(gcf, strcat('SummationPlots/',DeviceName,' Pn II−VV Cont vs T.png'))
%

%%IVVI Pp Elec Tot Compile and Plot
IVVIPpElecTot=cell2mat({78,NLSVTotal78K.data(4,2),
    NLSVTotal78K.data(4,3),NLSVTotal78K.data(4,4),
    NLSVTotal78K.data(4,5);
100,NLSVTotal100K.data(4,2),NLSVTotal100K.data(4,3),
    NLSVTotal100K.data(4,4),NLSVTotal100K.data(4,5);
150,NLSVTotal150K.data(4,2),NLSVTotal150K.data(4,3),
    NLSVTotal150K.data(4,4),NLSVTotal150K.data(4,5);
200,NLSVTotal200K.data(4,2),NLSVTotal200K.data(4,3),
    NLSVTotal200K.data(4,4),NLSVTotal200K.data(4,5);
250,NLSVTotal250K.data(4,2),NLSVTotal250K.data(4,3),
    NLSVTotal250K.data(4,4),NLSVTotal250K.data(4,5);
300,NLSVTotal300K.data(4,2),NLSVTotal300K.data(4,3),
    NLSVTotal300K.data(4,4),NLSVTotal300K.data(4,5)});
%

%figure
[hAx,h1,h2]=plotyy(IVVIPpElecTot(:,1),((1E6)*
    IVVIPpElecTot(:,2)),IVVIPpElecTot(:,1),((1E3)*
    IVVIPpElecTot(:,3)));
set(hAx,'fontsize',18)
title(strcat(DeviceName, ' IV–VIP Electrical Injection A1 and A2 vs T'))
xlabel('T (K) ')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'A1 (microOhm) ')
ylabel(hAx(2), 'A2 (nV/mA^2) ')
legend('A1', 'A2')
saveas(gcf, strcat('SummationPlots/',DeviceName, ' Pp IV–VI Elec vs T.png'))
%

%%IVVI Pp Ther Tot Compile and Plot
IVVIPpTherTot=cell2mat({
78,NLSVTotal78K.data(5,2),
NLSVTotal78K.data(5,3),NLSVTotal78K.data(5,4),
NLSVTotal78K.data(5,5);
100,NLSVTotal100K.data(5,2),NLSVTotal100K.data(5,3),
NLSVTotal100K.data(5,4),NLSVTotal100K.data(5,5);
150,NLSVTotal150K.data(5,2),NLSVTotal150K.data(5,3),
NLSVTotal150K.data(5,4),NLSVTotal150K.data(5,5);
200,NLSVTotal200K.data(5,2),NLSVTotal200K.data(5,3),
NLSVTotal200K.data(5,4),NLSVTotal200K.data(5,5);
250,NLSVTotal250K.data(5,2),NLSVTotal250K.data(5,3),
NLSVTotal250K.data(5,4),NLSVTotal250K.data(5,5);
300, NLSVTotal300K.data(5,2), NLSVTotal300K.data(5,3),
    NLSVTotal300K.data(5,4), NLSVTotal300K.data(5,5));
%
figure
[hAx, h1, h2] = plotyy(IVVIPpTherTot(:,1),((1E6)*IVVIPpTherTot(:,2)), IVVIPpTherTot(:,1),((1E3)*IVVIPpTherTot(:,3)));
set(hAx, 'fontsize', 18)
title(strcat(DeviceName, ' IV-VIP Thermal Injection B1 and B2 vs T'))
xlabel('T (K)')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'B1 (microOhm)')
ylabel(hAx(2), 'B2 (nV/mA^2)')
legend('B1', 'B2')
saveas(gcf, strcat('SummationPlots/', DeviceName, '_Pp IV-VI Ther vs T.png'))
%

% IVVI Pp Cont Tot Compile and Plot
IVVIPpContTot = cell2mat({78, NLSVTotal78K.data(6,2),
    NLSVTotal78K.data(6,3), NLSVTotal78K.data(6,4),
    NLSVTotal78K.data(6,5);
100, NLSVTotal100K.data(6,2), NLSVTotal100K.data(6,3),
NLSVTotal100K.data(6,4), NLSVTotal100K.data(6,5);
150, NLSVTotal150K.data(6,2), NLSVTotal150K.data(6,3),
NLSVTotal150K.data(6,4), NLSVTotal150K.data(6,5);
200, NLSVTotal200K.data(6,2), NLSVTotal200K.data(6,3),
NLSVTotal200K.data(6,4), NLSVTotal200K.data(6,5);
250, NLSVTotal250K.data(6,2), NLSVTotal250K.data(6,3),
NLSVTotal250K.data(6,4), NLSVTotal250K.data(6,5);
300, NLSVTotal300K.data(6,2), NLSVTotal300K.data(6,3),
NLSVTotal300K.data(6,4), NLSVTotal300K.data(6,5));
%
%figure
[hAx, h1, h2] = plotyy(IVVIPpContTot(:,1), ((1E6)*
IVVIPpContTot(:,2)), IVVIPpContTot(:,1), ((1E3)*
IVVIPpContTot(:,3)));
set(hAx, 'fontsize', 18)
title(strcat(DeviceName, ' IV-VIp Contact C1 and C2 vs T'))
xlabel('T (K)')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'C1 (microOhm)')
ylabel(hAx(2), 'C2 (nV/mA^2)')
legend('C1', 'C2')

210
saveas(gcf, strcat('SummationPlots/', DeviceName, ' Pp IV–VI Cont vs T.png'))

%%IVVI Pn Elec Tot Compile and Plot

IVVIPnElecTot=cell2mat(
    {78, NLSVTotal78K.data(11,2), NLSVTotal78K.data(11,3), NLSVTotal78K.data(11,4), NLSVTotal78K.data(11,5);
    100, NLSVTotal100K.data(11,2), NLSVTotal100K.data(11,3), NLSVTotal100K.data(11,4), NLSVTotal100K.data(11,5);
    150, NLSVTotal150K.data(11,2), NLSVTotal150K.data(11,3), NLSVTotal150K.data(11,4), NLSVTotal150K.data(11,5);
    200, NLSVTotal200K.data(11,2), NLSVTotal200K.data(11,3), NLSVTotal200K.data(11,4), NLSVTotal200K.data(11,5);
    250, NLSVTotal250K.data(11,2), NLSVTotal250K.data(11,3), NLSVTotal250K.data(11,4), NLSVTotal250K.data(11,5);
    300, NLSVTotal300K.data(11,2), NLSVTotal300K.data(11,3), NLSVTotal300K.data(11,4), NLSVTotal300K.data(11,5)});

%{
%figure

[hAx, h1, h2]=plotyy(IVVIPnElecTot(:,1),((1E6)*IVVIPnElecTot(:,2)),IVVIPnElecTot(:,1),((1E3)*IVVIPnElecTot(:,3)));

set(hAx,'fontsize',18)
title( strcat(DeviceName, 'IV−VI Electrical Injection A1 and A2 vs T'))
xlabel('T (K)')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'A1 (microOhm)')
ylabel(hAx(2), 'A2 (nV/mA^2)')
legend('A1', 'A2')
saveas(gcf, strcat('SummationPlots/', DeviceName, 'Pn IV−VI Elec vs T.png'))

%%IVVI Pn Ther Tot Compile and Plot
IVVIPnPnTherTot=cell2mat({78, NLSVTotal78K.data(12,2),
                         NLSVTotal78K.data(12,3), NLSVTotal78K.data(12,4),
                         NLSVTotal78K.data(12,5);
100, NLSVTotal100K.data(12,2), NLSVTotal100K.data(12,3),
                         NLSVTotal100K.data(12,4), NLSVTotal100K.data(12,5);
150, NLSVTotal150K.data(12,2), NLSVTotal150K.data(12,3),
                         NLSVTotal150K.data(12,4), NLSVTotal150K.data(12,5);
200, NLSVTotal200K.data(12,2), NLSVTotal200K.data(12,3),
                         NLSVTotal200K.data(12,4), NLSVTotal200K.data(12,5);
250, NLSVTotal250K.data(12,2), NLSVTotal250K.data(12,3),
                         NLSVTotal250K.data(12,4), NLSVTotal250K.data(12,5);
300, NLSVTotal300K.data(12,2), NLSVTotal300K.data(12,3),
    NLSVTotal300K.data(12,4), NLSVTotal300K.data(12,5));
%
% figure
[hAx, h1, h2]= plotyy (IVVIPnTherTot(:,1),((1E6)*IVVIPnTherTot(:,2)), IVVIPnTherTot(:,1),((1E3)*IVVIPnTherTot(:,3)));
set(hAx, 'fontsize', 18)
title(strcat(DeviceName, ' IV−VI Thermal Inj ection B1 and B2 vs T'))
xlabel('T (K)')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'B1 (microOhm) ')
ylabel(hAx(2), 'B2 (nV/mA^2) ')
legend('B1', 'B2')
saveas(gcf, strcat('SummationPlots/', DeviceName, ' Pn IV−VI Ther vs T.png'))
%

%% IV VI Pn Cont Tot Compile and Plot
IVVIPnContTot=cell2mat({78, NLSVTotal78K.data(13,2),
    NLSVTotal78K.data(13,3), NLSVTotal78K.data(13,4), NLSVTotal78K.data(13,5)});
100, NLSVTotal100K.data(13,2), NLSVTotal100K.data(13,3),
    NLSVTotal100K.data(13,4), NLSVTotal100K.data(13,5);
150, NLSVTotal150K.data(13,2), NLSVTotal150K.data(13,3),
    NLSVTotal150K.data(13,4), NLSVTotal150K.data(13,5);
200, NLSVTotal200K.data(13,2), NLSVTotal200K.data(13,3),
    NLSVTotal200K.data(13,4), NLSVTotal200K.data(13,5);
250, NLSVTotal250K.data(13,2), NLSVTotal250K.data(13,3),
    NLSVTotal250K.data(13,4), NLSVTotal250K.data(13,5);
300, NLSVTotal300K.data(13,2), NLSVTotal300K.data(13,3),
    NLSVTotal300K.data(13,4), NLSVTotal300K.data(13,5));
%
%figure
[hAx, h1, h2] = plotyy(IVVIPnPnContTot(:,1), IVVIPnPnContTot(:,2),
    IVVIPnPnContTot(:,1), ((1E3)*IVVIPnPnContTot(:,3)));
set(hAx, 'fontsize', 18)
title(strcat(DeviceName, ' IV−VI In Contact C1 and C2 vs T'))
xlabel('T (K)')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'C1 (microOhm)')
ylabel(hAx(2), 'C2 (nV/mA^2)')
legend('C1', 'C2')
saveas(gcf, strcat('SummationPlots/', DeviceName, '_Pn IV−VI Cont vs T.png'))

214
Channel Resistance

PpChanRestTot = cell2mat ([
    78, NLSVTotal78K.data(7, 2),
    NLSVTotal78K.data(7, 3), NLSVTotal78K.data(7, 4),
    100, NLSVTotal100K.data(7, 2), NLSVTotal100K.data(7, 3),
    NLSVTotal100K.data(7, 4), NLSVTotal100K.data(7, 5),
    150, NLSVTotal150K.data(7, 2), NLSVTotal150K.data(7, 3),
    NLSVTotal150K.data(7, 4), NLSVTotal150K.data(7, 5),
    200, NLSVTotal200K.data(7, 2), NLSVTotal200K.data(7, 3),
    NLSVTotal200K.data(7, 4), NLSVTotal200K.data(7, 5),
    250, NLSVTotal250K.data(7, 2), NLSVTotal250K.data(7, 3),
    NLSVTotal250K.data(7, 4), NLSVTotal250K.data(7, 5),
    300, NLSVTotal300K.data(7, 2), NLSVTotal300K.data(7, 3),
    NLSVTotal300K.data(7, 4), NLSVTotal300K.data(7, 5)])

%{
figure
[hAx, h1, h2] = plotyy (PpChanRestTot(:, 1), ((1E6)*
    PpChanRestTot(:, 2)), PpChanRestTot(:, 1), ((1E3)*
PpChanRestTot(:, 3)));
set (hAx, 'fontsize', 18)
title ('Channel Resist R1 and R2 vs T')
xlabel ('T (K)')

215
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'R1 (microOhm) ')
ylabel(hAx(2), 'R2 (nV/mA^2) ')
legend( 'R1', 'R2')
saveas(gcf, strcat('SummationPlots/', DeviceName, 'Pp Channel vs T.png'))
%

%%IIVV PpsubAP1Elec
IIVVPpSubAP2ElecTot=cell2mat({78, NLSVTotal78K.data(23,2),
NLSVTotal78K.data(23,3), NLSVTotal78K.data(23,4),
NLSVTotal78K.data(23,5);
100, NLSVTotal100K.data(23,2), NLSVTotal100K.data(23,3),
NLSVTotal100K.data(23,4), NLSVTotal100K.data(23,5);
150, NLSVTotal150K.data(23,2), NLSVTotal150K.data(23,3),
NLSVTotal150K.data(23,4), NLSVTotal150K.data(23,5);
200, NLSVTotal200K.data(23,2), NLSVTotal200K.data(23,3),
NLSVTotal200K.data(23,4), NLSVTotal200K.data(23,5);
250, NLSVTotal250K.data(23,2), NLSVTotal250K.data(23,3),
NLSVTotal250K.data(23,4), NLSVTotal250K.data(23,5);
300, NLSVTotal300K.data(23,2), NLSVTotal300K.data(23,3),
NLSVTotal300K.data(23,4), NLSVTotal300K.data(23,5)})
%
%figure

216
[hAx,h1,h2]=plotyy(IIVVPpSubAP2ElecTot(:,1),((1E6)*
    IIVVPpSubAP2ElecTot(:,2)),IIVVPpSubAP2ElecTot(:,1)
 ,((1E3)*IIVVPpSubAP2ElecTot(:,3))); set(hAx,'fontsize',18)
title(strcat(DeviceName,' IIVV Electrical Injection Pp–
AP1 R1 and R2 vs T'))
xlabel('T (K)')
set(h1,'Marker','.','MarkerSize',18)
set(h2,'Marker','.','MarkerSize',18)
ylabel(hAx(1),'R1 (microOhm)')
ylabel(hAx(2),'R2 (nV/mA^2)')
legend('R1','R2')
saveas(gcf,strcat('SummationPlots/','DeviceName',' Pp–AP1
II–VV Elec vs T.png'))
%

%%IIVV PpsubAP1Ther
IIVVPpSubAP2TherTot=cell2mat({78,NLSVTotal78K.data(24,2)
 ,NLSVTotal78K.data(24,3),NLSVTotal78K.data(24,4),
 NLSVTotal78K.data(24,5);
100,NLSVTotal100K.data(24,2),NLSVTotal100K.data(24,3),
 NLSVTotal100K.data(24,4),NLSVTotal100K.data(24,5);
150,NLSVTotal150K.data(24,2),NLSVTotal150K.data(24,3),
 NLSVTotal150K.data(24,4),NLSVTotal150K.data(24,5);
200, NLSVTotal200K.data(24,2), NLSVTotal200K.data(24,3),
NLSVTotal200K.data(24,4), NLSVTotal200K.data(24,5);
250, NLSVTotal250K.data(24,2), NLSVTotal250K.data(24,3),
NLSVTotal250K.data(24,4), NLSVTotal250K.data(24,5);
300, NLSVTotal300K.data(24,2), NLSVTotal300K.data(24,3),
NLSVTotal300K.data(24,4), NLSVTotal300K.data(24,5));
%
{figure
[hAx, h1, h2] = plotyy(IIVVPpSubAP2TherTot(:,1),((1E6)*
IIVVPpSubAP2TherTot(:,2)), IIVVPpSubAP2TherTot(:,1)
,((1E3)*IIVVPpSubAP2TherTot(:,3)));
set(hAx, 'fontsize', 18)
title(strcat(DeviceName, 'IIVV Thermal Injection Pp–AP1
R1 and R2 vs T'))
xlabel('T (K)')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'R1 (microOhm)')
ylabel(hAx(2), 'R2 (nV/mA^2)')
legend('R1', 'R2')
saveas(gcf, strcat('SummationPlots/’, DeviceName, ‘ Pp–AP1
II–VV Ther vs T.png'))
%

%%IIVV PnsubAP2Elec

218
IIVVPnPnSubAP1ElecTot=cell2mat({78,NLSVTot78K.data(27,2),NLSVTot78K.data(27,3),NLSVTot78K.data(27,4),NLSVTot78K.data(27,5);100,NLSVTot100K.data(27,2),NLSVTot100K.data(27,3),NLSVTot100K.data(27,4),NLSVTot100K.data(27,5);150,NLSVTot150K.data(27,2),NLSVTot150K.data(27,3),NLSVTot150K.data(27,4),NLSVTot150K.data(27,5);200,NLSVTot200K.data(27,2),NLSVTot200K.data(27,3),NLSVTot200K.data(27,4),NLSVTot200K.data(27,5);250,NLSVTot250K.data(27,2),NLSVTot250K.data(27,3),NLSVTot250K.data(27,4),NLSVTot250K.data(27,5);300,NLSVTot300K.data(27,2),NLSVTot300K.data(27,3),NLSVTot300K.data(27,4),NLSVTot300K.data(27,5)})

%%
%figure
[hAx,h1,h2]=plotyy(IIVVPnPnSubAP1ElecTot(:,1),((1E6)*IIVVPnPnSubAP1ElecTot(:,2)),IIVVPnPnSubAP1ElecTot(:,1),((1E3)*IIVVPnPnSubAP1ElecTot(:,3)));set(hAx,'fontsize',18)
title(strcat(DeviceName,'IIVV Electrical Injection Pn–AP2 R1 and R2 vs T'))
xlabel('T (K)')
set(h1,'Marker','.','MarkerSize',18)
set(h2,'Marker','.','MarkerSize',18)
ylabel(hAx(1),'R1 (microOhm)')
ylabel(hAx(2), 'R2 (nV/mA^2) ')
legend('R1', 'R2')
saveas(gcf, strcat('SummationPlots/', DeviceName, ' Pn-AP2 II-VV Elec vs T.png'))

%%IVV PnsubAP2Ther
IIIVVPnSubAP1TherTot=cell2mat({78, NLSVTotal78K.data(28,2), NLSVTotal78K.data(28,3), NLSVTotal78K.data(28,4), NLSVTotal78K.data(28,5);
100, NLSVTotal100K.data(28,2), NLSVTotal100K.data(28,3), NLSVTotal100K.data(28,4), NLSVTotal100K.data(28,5);
150, NLSVTotal150K.data(28,2), NLSVTotal150K.data(28,3), NLSVTotal150K.data(28,4), NLSVTotal150K.data(28,5);
200, NLSVTotal200K.data(28,2), NLSVTotal200K.data(28,3), NLSVTotal200K.data(28,4), NLSVTotal200K.data(28,5);
250, NLSVTotal250K.data(28,2), NLSVTotal250K.data(28,3), NLSVTotal250K.data(28,4), NLSVTotal250K.data(28,5);
300, NLSVTotal300K.data(28,2), NLSVTotal300K.data(28,3), NLSVTotal300K.data(28,4), NLSVTotal300K.data(28,5)});

%%figure
[hAx, h1, h2]=plotyy(IIIVVPnSubAP1TherTot(:,1), ((1E6)*IIIVVPnSubAP1TherTot(:,2)), IIIVVPnSubAP1TherTot(:,1), ((1E3)*IIIVVPnSubAP1TherTot(:,3)));
set(hAx,'fontsize',18)
title(strcat(DeviceName,' IIVV Thermal Injection Pn–AP2 R1 and R2 vs T'))
xlabel('T (K)')
set(h1,'Marker','.','MarkerSize',18)
set(h2,'Marker','.','MarkerSize',18)
ylabel(hAx(1),'R1 (microOhm)')
ylabel(hAx(2),'R2 (nV/mA^2)')
legend('R1','R2')
saveas(gcf,strcat('SummationPlots/','DeviceName',' Pn–AP2 II–VV Ther vs T.png'))

%%IVVI PpsubAP2Elec
IVVIPpSubAP1ElecTot=cell2mat({78,NLSVTotal78K.data(25,2)
 ,NLSVTotal78K.data(25,3),NLSVTotal78K.data(25,4)
,NLSVTotal78K.data(25,5)
,100,NLSVTotal100K.data(25,2),NLSVTotal100K.data(25,3)
,NLSVTotal100K.data(25,4),NLSVTotal100K.data(25,5)
,150,NLSVTotal150K.data(25,2),NLSVTotal150K.data(25,3)
,NLSVTotal150K.data(25,4),NLSVTotal150K.data(25,5)
,200,NLSVTotal200K.data(25,2),NLSVTotal200K.data(25,3)
,NLSVTotal200K.data(25,4),NLSVTotal200K.data(25,5)
,250,NLSVTotal250K.data(25,2),NLSVTotal250K.data(25,3)
,NLSVTotal250K.data(25,4),NLSVTotal250K.data(25,5)

221
300,NLSVTotal300K.data(25,2),NLSVTotal300K.data(25,3),
    NLSVTotal300K.data(25,4),NLSVTotal300K.data(25,5));

figure
[hAx,h1,h2]=plotyy(IVVIPpSubAP1ElecTot(:,1),((1E6)*
    IVVIPpSubAP1ElecTot(:,2)),IVVIPpSubAP1ElecTot(:,1)
    ,((1E3)*IVVIPpSubAP1ElecTot(:,3)));
set(hAx,'fontsize',18)
title(strcat(DeviceName,' IVVI Electrical Injection Pp−
    AP2 R1 and R2 vs T'))
xlabel('T (K) ')
set(h1,'Marker','.','MarkerSize',18)
set(h2,'Marker','.','MarkerSize',18)
ylabel(hAx(1),'R1 (microOhm) ')
ylabel(hAx(2),'R2 (nV/mA^2) ')
legend('R1','R2')
saveas(gcf,strcat('SummationPlots/','DeviceName',' Pp−AP2
    IV−VI Elec vs T.png'))

figure
IVVIPpSubAP1TherTot=cell2mat({78,NLSVTotal78K.data(26,2)
    ,NLSVTotal78K.data(26,3),NLSVTotal78K.data(26,4),
    NLSVTotal78K.data(26,5);
```matlab
100, NLSVTotal100K.data(26,2), NLSVTotal100K.data(26,3),
NLSVTotal100K.data(26,4), NLSVTotal100K.data(26,5);
150, NLSVTotal150K.data(26,2), NLSVTotal150K.data(26,3),
NLSVTotal150K.data(26,4), NLSVTotal150K.data(26,5);
200, NLSVTotal200K.data(26,2), NLSVTotal200K.data(26,3),
NLSVTotal200K.data(26,4), NLSVTotal200K.data(26,5);
250, NLSVTotal250K.data(26,2), NLSVTotal250K.data(26,3),
NLSVTotal250K.data(26,4), NLSVTotal250K.data(26,5);
300, NLSVTotal300K.data(26,2), NLSVTotal300K.data(26,3),
NLSVTotal300K.data(26,4), NLSVTotal300K.data(26,5));
%
%figure
[hAx, h1, h2] = plotyy(IVVIPpSubAP1TherTot(:, 1), ((1E6) * 
IVVIPpSubAP1TherTot(:, 2)), IVVIPpSubAP1TherTot(:, 1) ,
, ((1E3) * IVVIPpSubAP1TherTot(:, 3)));
set(hAx, 'fontsize', 18)
title(strcat(DeviceName, ' IVVI Thermal Injection Pp–AP2
R1 and R2 vs T'))
xlabel('T (K) ')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'R1 (microOhm) ')
ylabel(hAx(2), 'R2 (nV/mA^2) ')
legend('R1', 'R2')
```
saveas(gcf, strcat('SummationPlots/', DeviceName, 'Pp-AP2
 IV-VI Ther vs T.png'))
%

%%IVVI PnsubAP2Elec

IVVIPnPnSubAP2ElecTot=cell2mat({78 ,NLSVTotal78K .data(29,2)
 ,NLSVTotal78K .data(29,3),NLSVTotal78K .data(29,4),
 NLSVTotal78K .data(29,5);
100 ,NLSVTotal100K .data(29,2),NLSVTotal100K .data(29,3),
 NLSVTotal100K .data(29,4),NLSVTotal100K .data(29,5);
150 ,NLSVTotal150K .data(29,2),NLSVTotal150K .data(29,3),
 NLSVTotal150K .data(29,4),NLSVTotal150K .data(29,5);
200 ,NLSVTotal200K .data(29,2),NLSVTotal200K .data(29,3),
 NLSVTotal200K .data(29,4),NLSVTotal200K .data(29,5);
150 ,NLSVTotal250K .data(29,2),NLSVTotal250K .data(29,3),
 NLSVTotal250K .data(29,4),NLSVTotal250K .data(29,5);
300 ,NLSVTotal300K .data(29,2),NLSVTotal300K .data(29,3),
 NLSVTotal300K .data(29,4),NLSVTotal300K .data(29,5)});
%

%figure

[hAx,h1,h2]=plotyy(IVVIPnPnSubAP2ElecTot(:,1),((1E6)*
 IVVIPnPnSubAP2ElecTot(:,2)),IVVIPnPnSubAP2ElecTot(:,1)
 ,((1E3)*IVVIPnPnSubAP2ElecTot(:,3)));
set(hAx,'fontsize',18)
```matlab
% Function to plot IV-VI curves for different temperatures

% Plot title
title(strcat(DeviceName, ' IV-VI Electrical Injection Pn-AP1 R1 and R2 vs T'))

% Set labels
xlabel('T (K)')
set(h1,'Marker','.','MarkerSize',18)
set(h2,'Marker','.','MarkerSize',18)
ylabel(hAx(1),'R1 (microOhm)')
ylabel(hAx(2),'R2 (nV/mA^2)')
legend('R1','R2')
saveas(gcf,strcat('SummationPlots/','DeviceName',' Pn-AP1 IV-VI Elec vs T.png'))

%%% IVVI PnsubAP2Ther

IVVIPnSubAP2TherTot=cell2mat({78,NLSVTot78K.data(30,2)
  ,NLSVTot78K.data(30,3),NLSVTot78K.data(30,4)
  ,NLSVTot78K.data(30,5)
  ,100,NLSVTot100K.data(30,2),NLSVTot100K.data(30,3)
  ,NLSVTot100K.data(30,4),NLSVTot100K.data(30,5)
  ,150,NLSVTot150K.data(30,2),NLSVTot150K.data(30,3)
  ,NLSVTot150K.data(30,4),NLSVTot150K.data(30,5)
  ,200,NLSVTot200K.data(30,2),NLSVTot200K.data(30,3)
  ,NLSVTot200K.data(30,4),NLSVTot200K.data(30,5)
  ,250,NLSVTot250K.data(30,2),NLSVTot250K.data(30,3)
  ,NLSVTot250K.data(30,4),NLSVTot250K.data(30,5)
});
```
300, NLSVTotal300K.data(30,2), NLSVTotal300K.data(30,3),
NLSVTotal300K.data(30,4), NLSVTotal300K.data(30,5));
%

figure
[hAx, h1, h2] = plotyy(IVVIPnSubAP2TherTot(:, 1), ((1E6) *
IVVIPnSubAP2TherTot(:, 2)), IVVIPnSubAP2TherTot(:, 1)
, ((1E3) * IVVIPnSubAP2TherTot(:, 3)));
set(hAx, 'fontsize', 18)
title(strcat(DeviceName, ' IVVI Thermal Injection Pn–AP1
R1 and R2 vs T'))
xlabel('T (K)')
set(h1, 'Marker', '.', 'MarkerSize', 18)
set(h2, 'Marker', '.', 'MarkerSize', 18)
ylabel(hAx(1), 'R1 (microOhm)')
ylabel(hAx(2), 'R2 (nV/mA^2')
legend('R1', 'R2')
saveas(gcf, strcat('SummationPlots/', DeviceName, ' Pn–AP1
IV–VI Ther vs T.png'))
%

%% IVV_PpSubPnElec
IVVPPpSubPnElecTot = cell2mat({78, NLSVTotal78K.data(31,2),
NLSVTotal78K.data(31,3), NLSVTotal78K.data(31,4),
NLSVTotal78K.data(31,5);,
100, NLSVTotal100K.data(31,2), NLSVTotal100K.data(31,3),
    NLSVTotal100K.data(31,4), NLSVTotal100K.data(31,5);
150, NLSVTotal150K.data(31,2), NLSVTotal150K.data(31,3),
    NLSVTotal150K.data(31,4), NLSVTotal150K.data(31,5);
200, NLSVTotal200K.data(31,2), NLSVTotal200K.data(31,3),
    NLSVTotal200K.data(31,4), NLSVTotal200K.data(31,5);
250, NLSVTotal250K.data(31,2), NLSVTotal250K.data(31,3),
    NLSVTotal250K.data(31,4), NLSVTotal250K.data(31,5);
300, NLSVTotal300K.data(31,2), NLSVTotal300K.data(31,3),
    NLSVTotal300K.data(31,4), NLSVTotal300K.data(31,5));

% IIVV PpsubPnTher
IIVVPpSubPnTherTot = cell2mat({78, NLSVTotal78K.data(32,2),
    NLSVTotal78K.data(32,3), NLSVTotal78K.data(32,4),
    NLSVTotal78K.data(32,5);
100, NLSVTotal100K.data(32,2), NLSVTotal100K.data(32,3),
    NLSVTotal100K.data(32,4), NLSVTotal100K.data(32,5);
150, NLSVTotal150K.data(32,2), NLSVTotal150K.data(32,3),
    NLSVTotal150K.data(32,4), NLSVTotal150K.data(32,5);
200, NLSVTotal200K.data(32,2), NLSVTotal200K.data(32,3),
    NLSVTotal200K.data(32,4), NLSVTotal200K.data(32,5);
250, NLSVTotal250K.data(32,2), NLSVTotal250K.data(32,3),
    NLSVTotal250K.data(32,4), NLSVTotal250K.data(32,5);
300, NLSVTotal300K.data(32,2), NLSVTotal300K.data(32,3),
    NLSVTotal300K.data(32,4), NLSVTotal300K.data(32,5)});

% IVVI PpsubPnElec
227
IVVIPpSubPnElecTot=cell2mat ({78,NLSVTotal78K.data(33,2),
NLSVTotal78K.data(33,3),NLSVTotal78K.data(33,4),
NLSVTotal78K.data(33,5);}
100,NLSVTotal100K.data(33,2),NLSVTotal100K.data(33,3),
NLSVTotal100K.data(33,4),NLSVTotal100K.data(33,5);}
150,NLSVTotal150K.data(33,2),NLSVTotal150K.data(33,3),
NLSVTotal150K.data(33,4),NLSVTotal150K.data(33,5);)
200,NLSVTotal200K.data(33,2),NLSVTotal200K.data(33,3),
NLSVTotal200K.data(33,4),NLSVTotal200K.data(33,5);)
250,NLSVTotal250K.data(33,2),NLSVTotal250K.data(33,3),
NLSVTotal250K.data(33,4),NLSVTotal250K.data(33,5);)
300,NLSVTotal300K.data(33,2),NLSVTotal300K.data(33,3),
NLSVTotal300K.data(33,4),NLSVTotal300K.data(33,5})

%%IVVI_PpsubPnElec

IVVIPpSubPnTherTot=cell2mat ({78,NLSVTotal78K.data(34,2),
NLSVTotal78K.data(34,3),NLSVTotal78K.data(34,4),
NLSVTotal78K.data(34,5);}
100,NLSVTotal100K.data(34,2),NLSVTotal100K.data(34,3),
NLSVTotal100K.data(34,4),NLSVTotal100K.data(34,5);}
150,NLSVTotal150K.data(34,2),NLSVTotal150K.data(34,3),
NLSVTotal150K.data(34,4),NLSVTotal150K.data(34,5);)
200,NLSVTotal200K.data(34,2),NLSVTotal200K.data(34,3),
NLSVTotal200K.data(34,4),NLSVTotal200K.data(34,5);)
250,NLSVTotal250K.data(34,2),NLSVTotal250K.data(34,3),
NLSVTotal250K.data(34,4),NLSVTotal250K.data(34,5);)
300,NLSVTotal300K.data(34,2),NLSVTotal300K.data(34,3),
NLSVTotal300K.data(34,4),NLSVTotal300K.data(34,5})
300, NLSVTotal300K.data(34,2), NLSVTotal300K.data(34,3),
NLSVTotal300K.data(34,4), NLSVTotal300K.data(34,5)) ;