

1-1-2006

Secondary Electron Production and Transport Mechanisms By Measurement of Angle-Energy Resolved Cross Sections of Secondary and Backscattered Electron Emission from Gold

Jason T. Kite

Recommended Citation

Kite, Jason T., "Secondary Electron Production and Transport Mechanisms By Measurement of Angle-Energy Resolved Cross Sections of Secondary and Backscattered Electron Emission from Gold" (2006). *All Graduate Theses and Dissertations*. Paper 2089.
<http://digitalcommons.usu.edu/etd/2089>

This Dissertation is brought to you for free and open access by the Graduate Studies, School of at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Theses and Dissertations by an authorized administrator of DigitalCommons@USU. For more information, please contact becky.thoms@usu.edu.



Secondary Electron Production and Transport Mechanisms

By Measurement of Angle-Energy Resolved Cross Sections of Secondary and
Backscattered Electron Emission from Gold

Jason T. Kite

A dissertation submitted in partial fulfillment of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

In

Physics

Dr. J. R. Dennison
Major professor

Dr. D. Mark Riffe
Committee member

Dr. John W. Raitt
Committee member

Dr. Charles Swenson
Committee member

Dr. Jan J. Sojka
Committee member

Dr. Byron R. Burnham
Vice Provost and Dean of
Graduate Studies

Utah State University

Logan, Utah

2006

Copyright © Jason T. Kite 2006

All Rights Reserved

Secondary Electron Production and Transport Mechanisms
By Measurement of Angle- Energy- Resolved Cross Sections of Secondary and Backscattered Electron
Emission from Gold

A dissertation submitted in partial fulfillment of the requirements for the degree

By

Jason T. Kite, Doctor of Philosophy

Utah State University

2006

Major Professor: Dr. J.R. Dennison

Department: Physics

Abstract: This work provides information about interactions that produce emitted electrons from polycrystalline Au. Emission energy- angle- dependent electron spectra from a polycrystalline Au surface have been measured at several incident electron beam energies. The range of incident energies (\sim 100 eV to 2500 eV) extends from below the first crossover energy, through E_{\max} , to above the second crossover energy. The conventional distinction between secondary electrons (SE) (<50 eV) and backscattered electrons (BSE) (>50 eV) is found to be crude for the investigation of electron yields using these energy-angle- resolved measurements. A more realistic boundary occurs at the local minima of the emission spectra; this feature is studied as a function of incident energy and emission angle. In addition, deviations observed in the angular resolved emission spectra from isotropic behavior suggests that residual signatures exist in the emission spectra resulting from the anisotropic SE production mechanisms. Based on the disparity between our observations and recent modeling of the emission spectra, the most recent theory and simulation studies may overestimate the occurrence of randomizing collisions of scattered secondary electrons in the model of the transport mechanism. Finally, description of extensive modification to instrumental and analysis methods are described, and their effectiveness is evaluated.

ACKNOWLEDGMENT

I would like to acknowledge Dr. J.R. Dennison for his advising and overseeing this work. He has influenced me to write (and rewrite) in a style, which is more like I am. I would like to acknowledge Dr. Mark Riffe for “bailing me out” so that this work could continue. Dr. W. John Raitt, Dr. Jan J. Sojka, Dr. Charles Swenson, Dr. James Wheeler, Dr. Charles Torre, Dr. David Peak, Dr. Edwards, Dr. Dwane Doty, and Dr. Ranganathan have been an encouragement and have kept me going in the proper direction. I express gratitude to Dr. John Wilson for believing my potential. I express gratitude towards Dr. Y. Gupta for reflecting scattering sentiment to change my direction towards the physics of reality.

I would like to acknowledge the Surface Science research group (Jodie Gillespi, Dr. Albert (Yen Wen) Chang, Dr. Rob Davies, Carl Ellsworth, Robert Franckowiak, Parker Judd, Spenser Nelson, Dr. Neal Nickels, Dr. Ali Sabbah, Ryan Hoffmann, John Abbott, Jerilyn Brunson, Joshua Hodges, A. Hunt, R. Spaulding, and especially Dr. Clint Thomson) for all of their work in the Materials Physics Group including modifications and upkeep to vacuum chambers. Quick acknowledgement is paid to Bill Fletcher for circuit design and materials, which cannot be reimbursed.

I would like to acknowledge Marilyn Griggs, Shawna Johnson, Melanie Oldroyd, Karalee Ransom, and Deborah Reece who have maintained order in the Physics Department.

I would like to acknowledge the NASA Space Environments and Effects Program for funding this work and the NASA Rocky Mountain Space Grant Consortium for my fellowship.

I also thank the people Larry and Sylvia Slate, Lt. Col. Johnny and Audrey Hays, Bill and Mary Ann Kincaid, Ken and June Nickelson, Mark and Shelley Kellis, Rich and Sandy Dawson (especially Matt Dawson), Virgil and Miriam, Mike and Trelyss Henley, Jon and Char Lugger, Ron Batchelder, Harvey Cooper, and Sandra Malik for giving much room and board when funds were dire. Other memorable people have helped me with my psyche, Dr. Clarence Hibbs and Tauna Balahi, while completing this physics study.

CONTENTS

<u>ABSTRACT</u>	iii
<u>ACKNOWLEDGMENT</u>	iv
<u>LIST OF TABLES</u>	viii
<u>LIST OF FIGURES</u>	ix
<u>ABBREVIATIONS, SYMBOLS, AND NOTATION</u>	xiii

CHAPTER

1. <u>INTRODUCTION</u>	1
1.1. Prognosis	1
1.2. Inspiration.....	3
1.3. Applications.....	5
1.4. Objective.....	5
1.5. Synopsis.....	9
2. <u>SECONDARY ELECTRON EMISSION</u>	10
2.1. Historical Perspective	10
2.2. Semi-Empirical Theory	11
2.3. Quantum Mechanical Theory	14
2.4. Nearly Free Electron Metals.....	20
2.5. Backscattering	22
2.6. Previous Observations and Investigations of Gold	23
3. <u>INSTRUMENTATION</u>	31
3.1. Equipment Overview	31
3.1.(a) UHV Chamber	31
3.1.(b) Electron Gun.....	32
3.1.(c) Chamber Apparatus	32
3.1.(d) Experimental Electronics Schematics.....	38

3.2. Evaluation of Modifications to the AER apparatus	44
3.2.(a) Angular Motion	45
3.2.(b) Counting Statistics	48
3.2.(c) Electron Beam Voltage Supply.....	50
3.2.(d) Electron Beam Current Stability and Monitoring.....	53
3.2.(e) Voltage Biasing of Rotatable Detector	55
3.2.(f) Ambient Field Distortions	65
3.2.(g) Secondary Electron Production within the Chamber Apparatus.....	76
3.2.(h) Secondary Electron Production within the Rotatable Detector.....	76
3.2.(i) Data Analysis Algorithm	80
3.2.(j) Analysis Anomalies	88
3.3. Measured Quantities	92
3.3.(a) Notation	92
3.3.(b) Definition.....	93
3.4. Data Acquisition Procedure	100
3.4.(a) Previous Data Acquisition Procedure	100
3.4.(b) Beam Current Scales with Controller Voltage.....	100
3.4.(c) Determination of Quantities of Data.....	104
3.5. Measurement Techniques	110
3.5.(a) δ_{AER} Determination	110
3.5.(b) δ_{AR} Determination.....	111
3.5.(c) δ_{ER} Determination	112
3.5.(d) Determination of the Total SE Yield	113
4. <u>SAMPLE</u>	114
4.1. Choice of Sample Material	114
4.2. Sample Information	116

4.2.(a) Trace Analysis	116
4.2.(b) Morphology	116
4.2.(c) Surface Condition.....	120
4.3. Surface Preparation.....	122
4.3.(a) Chemical Cleaning.....	126
4.3.(b) Electron Bombardment.....	127
4.3.(c) Sputtering	127
4.3.(c)1 Surface Roughening.....	127
4.3.(c)2 Argon Embedding.....	128
4.3.(c)3 Equal and Opposite Changes in SE and BSE Yields.....	129
4.3.(d) Annealing.....	129
4.3.(d)1 No Chemical Reactions or Changes in Crystalline Structure	129
4.3.(d)2 Diffusion of Bulk Contaminants.....	131
4.3.(d)3 Desorption of Physisorbed Surface Contaminants.....	132
4.4. Previous Measurement Comparison.....	132
4.5. Systematic Error Using the Tertiary Samples.....	134
4.5.(a) Estimating the Gamma Factor	135
4.5.(b) δ and η as Functions of Beam Energy	137
4.5.(c) Comparison to Theory	139
4.6. Conclusion.....	140
5. <u>ANGLE- BEAM ENERGY- RESOLVED ENERGY SPECTRAL MEASUREMENTS</u>	142
5.1. Elastic Peak Features	147
5.1.(a) Elastic Peak Energy	151
5.1.(b) Elastic Peak Intensity	155
5.1.(c) Shape Characteristics (FWHM).....	159
5.1.(d) Elastic Yield	161

5.2. Plasmon Peak Features	166
5.2.(a) Plasmon Peak Energy	166
5.2.(b) Plasmon Peak Intensity	171
5.2.(c) High Energy Plasmon Peak Comparison	174
5.2.(d) Plasmon Yield Calculation	174
5.2.(e) Comparison of High Energy Yields.....	179
5.3 BSE Peak	181
5.3.(a) BSE Peak Features.....	183
5.3.(a)1 BSE Peak Energy.....	185
5.3.(a)2 BSE Peak Intensity	188
5.3.(b) High Energy BSE Peak Comparison	191
5.3.(c) BSE Yield	193
5.3.(c)1 Customary Boundary	193
5.3.(c)2 E_{\min} Boundary	198
5.3.(c)3 Ratio of Elastic Yield to BSE Yield	202
5.3.(c)4 Ratio of BSE Yield to Total Yield.....	204
5.3.(c)5 Angle Integrated Comparisons	206
5.3.(b) Angle Resolved BSE Yield Distributions.....	193
5.4 SE Peak	208
5.4.(a) SE Peak Features	208
5.4.(a)1 SE Peak Energy	210
5.4.(a)2 SE Peak Intensity	213
5.4.(a)3 Normalized SE Peak (FWHM).....	218
5.4.(b) SE Yield	220
5.4.(b)1 Customary Boundary	220
5.4.(b)2 E_{\min} Boundary	224
5.4.(b)3 Ratio of SE Yield to Total Yield	22

5.4.(b)4	Finer Resolution SE Yields	231
5.4.(b)5	Angle Integrated Comparisons	234
5.4.(c)	Angle Resolved SE Yield Distributions	236
5.4.(d)	Auger Peaks.....	238
5.5	Transitions.....	244
5.5.(a)	BSE and SE Peak Delineation (E_{\min} Features).....	244
5.5.(a)1	E_{\min} Energy Position	248
5.5.(a)1a	E_{\min} Dependence on E_b	256
5.5.(a)1b	E_{\min} Dependence on Emission Angle	261
5.5.(a)2	$dN(E_{\min})/dE$ Yield Intensity.....	255
5.5.(b)	Elastic-Plasmon Minimum Transition.....	260
5.5.(b)1	Elastic-Plasmon Energy.....	260
5.5.(b)2	Elastic-Plasmon Intensity	263
5.5.(c)	Elastic-BSE Minimum Transition	266
5.5.(c)1	Elastic-BSE Energy	266
5.5.(c)2	Elastic-BSE Intensity.....	269
5.6	Incident Beam Energy Resolved Total Yield	272
5.7	Angle Resolved Total Yield Distributions	277
5.8	Angle Integrated Total Yields	279
5.9	Undercounted SE's, Overcounted BSE's	281
5.10	Conclusion.....	284
6.	<u>DISCUSSION AND CONCLUSION</u>	287
6.1.	Summary of Results	290
6.1.(a)	Evaluation of the Performance of the Instrument and Method.....	291
6.1.(b)	Summary of Results	291
	6.1.(b)1 Overview of Measured Results.....	291

6.1.(b)2	Summary of Parameter Resolved Results (E_b , Angle).....	292
6.1.(b)3	Angular Cross Section Results	293
6.2	Recommendations for Further Research	294
6.2.(a)	Recommended Instrument Modifications.....	291
6.2.(b)	Recommended Theoretical Modeling.....	296
6.2.(c)	Recommendations for Experimental Research.....	302
6.3	Concluding Remarks	305
References		306
Appendix A: Varian Electron Gun Source	.....	312
Appendix B: Stepper Motor Controller	.....	326
Appendix C: LabVIEW Programs	.....	331
Appendix D: Angle-Resolved Diagnostic Measurements	.....	360
Appendix E: Angle- Energy-Resolved Data Summary	.....	369
Curriculum Vitae.....		487

LIST OF TABLES

	Page
Table 2-1 Summary of Experimental AR studies on NFE metals	25
Table 3-1 Doniach and Sunjic Fitting Parameters	61
Table 3-2 Smooth Numbers utilized with the Savitsky-Golay type 2 Smoothing Algorithm.....	90
Table 3-3 Spectral and Integrated Yield Labels.....	99
Table 4.1 δ , η , and σ as a function of surface on sample “D”	125
Table 4.2 Using the tertiary samples provides a realistic estimate for the upper and lower error	135
Table 4.3 Summarization of empirically and numerically derived correction factors	135
Table 5.1 Elastic Peak Energy	153
Table 5.2 Elastic Peak Intensity.....	157
Table 5.3 The Elastic Peak Yield at 0.1 eV resolution	164
Table 5.4 Plasmon Peak Energy	167
Table 5.5 Plasmon Peak Intensity.....	172
Table 5.6 The Plasmon Peak Yield.....	177
Table 5.7 BSE Peak Energy.....	186
Table 5.8 BSE Peak Intensity Rutherford fit coefficients.....	187
Table 5.9 BSE Peak Intensity	189
Table 5.10 BSE Peak Yield (50 eV to E_b eV) Rutherford fit coefficients	193
Table 5.11 The BSE Yield (50 - E_b)	196
Table 5.12 BSE Peak Yield (E_{\min} eV to E_b eV) Rutherford fit coefficients.....	197
Table 5.13 The BSE Yield (E_{\min} - E_b).....	200
Table 5.14 The SE Peak Energy	213
Table 5.15 The SE Peak Intensity.....	218
Table 5.16 The SE Peak Yield (0 – 50 eV).....	224
Table 5.17 The SE Peak Yield (0 eV to E_{\min} eV)	229

Table 5.18 Local Minimum Energy Location (eV) Between the SE and BSE Peaks.....	255
Table 5.19 Fit coefficients for E_{\min}	257
Table 5.20 Yield Intensity at Local Minimum Energy Location Between the SE and BSE Peaks	262
Table 5.21 Elastic-Plasmon Boundary Minimum Transition Energy	267
Table 5.22 Elastic-Plasmon Boundary Minimum Transition Intensity.....	270
Table 5.23 Elastic-BSE Boundary Minimum Transition Energy	273
Table 5.24 Elastic-BSE Boundary Minimum Transition Intensity	277
Table 5.25 The Incident Beam Energy Resolved Total Yield	280
Table 5.26 The Yield for 50 eV - E_{\min} eV	289
Table A-1 Modifications to the Varian Electron Gun Controller	326
Table A-2 Zener Diode Resistance Measurements.....	330
Table C-1 LabVIEW Programs	343
Table E-1 Angle- Energy- Resolved Data Summary for Incident Beam Energies of 100 eV, 500 eV, 600 eV, 700 eV, 900 eV, 1200 eV, 2000 eV, and 2500 eV	386

LIST OF FIGURES

	Page
Figure 1-1 General Diagram for Electron Bombardment and Emission	2
Figure 1-2 AR Spectrum of Polycrystalline Gold	4
Figure 1-3 SE Yield of Polycrystalline Gold.....	7
Figure 2-1 Cross Sections for Production Mechanisms	11
Figure 2-2 Conclusion of Electron Emission	13
Figure 2-3 SE Cross Sections for Au	16
Figure 2-4 Selected ER Cross Sections	17
Figure 2-5 Normalized ER Angular Distributions of Surface D6	18
Figure 3-1 The Chamber Apparatus.....	22
Figure 3-2 The Rotatable Detector.....	24
Figure 3-3 The Non-Symmetric RD Angle Configuration.....	25
Figure 3-4 Relationship of Detector Position and Emission Angle.....	26
Figure 3-5 Experimental Electronic Schematic.....	28
Figure 3-6 Resistance Diagram for the Primary and Tertiary Detectors	30
Figure 3-7 Resistance Diagram for the RD	31
Figure 3-8 Symmetric RD Angle Configuration	35
Figure 3-9 MonitorPressure LabVIEW VI Program	37
Figure 3-10 Double Elastic Peak.....	39
Figure 3-11 Consistent Double Elastic Peak	40
Figure 3-12 Beam Current vs RD Energy Bias	43
Figure 3-13 Davies RD Bias Scheme	44
Figure 3-14 Tandem Supply RD Bias Scheme.....	45
Figure 3-15 Elastic Peak for 1500 eV Incident Beam Energy at 17° Counter-Clockwise Emission....	47
Figure 3-16 Elastic Peak for 1500 eV Beam Energy with Clockwise Emission	48

Figure 3-17 Elastic Peak for 1500 eV Beam Energy with Counter-Clockwise Emission	49
Figure 3-18 SE Spectra at 1500 eV Beam Energy for Clockwise Emission	54
Figure 3-19 SE Spectra at 1500 eV Beam Energy for Counter-Clockwise Emission	55
Figure 3-20 SE Yield at 17° for 1500 eV Incident Beam Energy	56
Figure 3-21 SE Yield at 24° for 1500 eV Incident Beam Energy	57
Figure 3-22 SE Yield at 38° for 1500 eV Incident Beam Energy	58
Figure 3-23 SE Yield at 46° for 1500 eV Incident Beam Energy	59
Figure 3-24 SE Yield at 53° for 1500 eV Incident Beam Energy	60
Figure 3-25 Compiled Difference SE Spectra for 1500 eV Incident Beam Energy	61
Figure 3-26 Compiled Percent Difference SE Spectra for 1500 eV Incident Beam Energy	62
Figure 3-27 RD Produced SE's	64
Figure 3-28 Ratio of RD produced SE's to Sample produced SE's	65
Figure 3-29 Reproducibility of RD produces SE's	66
Figure 3-30 Comparison of Elastic Pre—Differentiated Data Using 0.1 and 1 eV Resolutions	68
Figure 3-31 Comparison of Error Bars for Bias Voltage Using the 0.1 and 1 eV Resolutions	69
Figure 3-32 Comparison Overlay of PreDiff StDev and Spectral Error Bar for Elastic 0.1 and 1 eV Resolutions	72
Figure 3-33 Comparison of Error Bars for Elastic PreDiff 0.1 and 1 eV Resolutions	73
Figure 3-34 Experimental Geometry	77
Figure 3-35 Beam Current vs. Controller Voltage (2002)	81
Figure 3-36 Beam Current vs. Controller Voltage (2001)	82
Figure 3-37 Slope and Intercept of the Beam Current	84
Figure 3-38 Sample Current Data with Varying Sampling Statistics	86
Figure 3-39 Sampling Statistics for the Sample Current	87
Figure 3-40 Beam Current Controller Voltage	89
Figure 3-41 Sampling Statistics for the Beam Current ($V_{controller}$)	90
Figure 4-1 Optical micrograph images of the sample gold material	98

Figure 4-2 Scanning tunneling microscope (STM) image of the sample material	99
Figure 4-3 Auger Electron Spectra (AES) of polycrystalline Au.....	101
Figure 4-4 Au sample “D” mounted between four Faraday cups on rhodium-coated blank.....	103
Figure 4-5 Total Yield, σ , SE Yield, δ , and BSE Yield, η , as functions of surface and location for sample D, respectively [Davies, 1999].....	105
Figure 4-6 δ , η , and σ as functions of incident electron energy: comparison of (a) surface A0i and (b) surface D9 measurements with previous experiment and empirical SEE models.....	116
Figure 5-1 Total Spectra at $E_b = 900$ eV and emission angle of 14° Counter—Clockwise.....	123
Figure 5-2 Pre—differentiated data using the 1 eV resolution (red) and using 10 eV, 1 eV, and 0.1 eV resolutions (green) at $E_b = 900$ V and emission angle of 14° Counter—Clockwise.....	125
Figure 5-3 Raw data (green and red) and integrated derivative (black and blue) at $E_b = 900$ eV and emission angle of 14° Counter—Clockwise	128
Figure 5-4 Fine energy resolution for 900 eV incident beam energy using the 0.1 eV and 1 eV resolutions.	129
Figure 5-5 Angular Resolved Elastic Peak Position measured at 0.1 eV Resolution.....	131
Figure 5-6 Beam Energy Resolved Elastic Peak Position at 0.1 eV resolution.....	132
Figure 5-7 Elastic Peak Intensity versus Incident Beam Energy measured using the 0.1 eV resolution for selected emission angles.	135
Figure 5-8 Elastic Peak Intensity versus emission angle measured using the 0.1 eV resolution for selected incident beam energies.....	136
Figure 5-9 Beam Energy Resolved Elastic Peak Energy Spectra at 14° Counter-Clockwise emission for selected beam energies.....	139
Figure 5-10 Elastic Peak Yield versus angle for several Incident Beam Energies measured using 1 eV (circles) and 0.1 eV (squares) resolution.....	141
Figure 5-11 Elastic Peak versus angle for Several Incident Beam Energies measured at 1 eV and 0.1 eV resolution	142
Figure 5-12 Elastic Peak Cross Sections for several emission angles at 0.1 eV resolution spectra. ..	143
Figure 5-13 Smoothing Anomalies For 2 nd order Savitzky—Golay 900 eV Incident beam energies and 14° Counter-Clockwise emission.	146
Figure 5-14 Plasmon Peak Energy given in terms of its displacement from the incident beam energy.149	
Figure 5-15 Yield Intensity at the location of the First surface Plasmon Peak.....	152

Figure 5-16 Ratio of Intensity of the First Plasmon Peak to the Elastic Peak.....	155
Figure 5-17 Elastic—Plasmon boundary minimum Energy at 0.1 eV resolution	157
Figure 5-18 Elastic—Plasmon boundary minimum Intensity at 0.1 eV resolution.....	160
Figure 5-19 Plasmon Peak Yield versus emission angle for several incident beam energies.....	163
Figure 5-20 Ratio of the Plasmon Peak Yield to the Elastic Peak Yield versus the incident beam energy for various emission angles	166
Figure 5-21 Normalized AR Energy Spectra at 14° Counter-Clockwise emission for selected beam energies.....	168
Figure 5-22 Normalized $E_b R$ Energy For 900 eV Emission Angle for selected emission angles.	169
Figure 5-23 The Local Minimum Energy Position in terms of the percentage of E_b plotted against emission angle for several E_b	173
Figure 5-24 The Average Ratio of E_{min} to E_b versus E_b	175
Figure 5-25 Yield intensity, $dN_{min}(E_{min})/dE$, at the local minimum yield, E_{min} , located between the SE and BSE peaks	178
Figure 5-26 Isotropic Fitting Parameter $B * \pi$ vs Incident Beam Energy using $dN(E_{min})/dE = B * \pi * \cos(\alpha)$	181
Figure 5-27 AR spectra for $E_b = 2500$ eV and for emission angles of 17° Clockwise to 76° Counter—Clockwise.....	183
Figure 5-28 Auger spectra for $E_b = 2500$ eV given at emission angles of 17° Clockwise to 76° Counter—Clockwise.....	184
Figure 5-29 Total Yield distributions given in units of inverse steradians for selected incident beam energies.....	186
Figure 5-30 Total Yield versus Incident Beam energy given in units of inverse steradians for the twelve selected angles.	187
Figure 5-31 E_b Total Yield versus Incident Beam energy and emission angle.....	189
Figure 5-32 AR Total yield distribution for $E_b = 100$ eV, 500 eV, 600 eV, 700 eV, 900 eV, and 1500 eV measured in the non-symmetric angle configuration.	191
Figure 5-33 Total Yield integrated over angle (isotropically).	193
Figure 5-34 BSE and Elastic Peaks for 900 eV Incident Beam Energy.	195
Figure 5-35 Normalized BSE AR Energy Spectra measured with 1 eV resolution at 14° Counter-Clockwise emission for selected beam energies.	198
Figure 5-36 BSE Peak position of the Fine 1 eV resolution.....	200

Figure 5-37 BSE Peak intensity at the peak energy position using the 1 eV resolution.....	203
Figure 5-38 BSE Peak to Elastic Peak Intensity Ratio for selected beam energies using the 1 eV resolution.	206
Figure 5-39 Elastic—BSE boundary minimum Position at Fine 1 eV resolution.	208
Figure 5-40 Elastic—BSE boundary minimum intensity of the Fine 1 eV resolution	211
Figure 5-41 Back Scattered Electron angular distributions for selected beam energies in the 50- E_b eV range.....	214
Figure 5-42 Back Scattered Electron angular distributions for selected beam energies in the 50- E_b eV range.....	215
Figure 5-43 Back Scattered Electron angular distributions for selected beam energies in the E_{min} - E_b eV range.....	218
Figure 5-44 Back Scattered Electron angular distributions for selected beam energies in the E_{min} - E_b eV range.....	219
Figure 5-45 Ratio of Elastic Yield to BSE Yield ($E_{min} - E_b$).....	222
Figure 5-46 The ratio of BSE Yield, calculated using E_{min} , to the Total Yield.	224
Figure 5-47 BSE Yield integrated over angle (isotropically) and calculated with boundaries of E_{min} eV – E_b eV and 50 eV – E_b eV	226
Figure 5-48 SE peak at 900 eV incident beam energy for selected emission angles.....	228
Figure 5-49 SE peak position using the 1 eV and 0.1 eV resolutions.	230
Figure 5-50 The SE peak intensity using the 1 eV (circles) and 0.1 eV (squares) resolutions.....	233
Figure 5-51 The SE peak intensity on a logarithmic scale using the 1 eV (circles) and 0.1 eV (squares) resolutions.....	234
Figure 5-52 The SE peak intensity on a logarithmic vertical scale using the 1 eV and 0.1 eV resolutions.	235
Figure 5-53 Normalized SE peak at 2500 eV incident beam energy using the 0.1 eV resolution for selected emission angles.	238
Figure 5-54 Secondary Electron angular distributions for selected beam energies in the 0 - 50 eV range using the 10 eV resolution.....	240
Figure 5-55 Secondary Electron angular distributions for selected beam energies in the 0 - 50 eV range.	241
Figure 5-56 Secondary Electron angular distributions for selected beam energies in the 0 - E_{min} eV range.	245
Figure 5-57 Secondary Electron angular distributions for selected beam energies in the 0 - E_{min} eV range.	246

Figure 5-58 SE Yield 0 eV – E _{min}	248
Figure 5-59 The ratio of the SE Yield, calculated using E _{min} , to the Total Yield.....	250
Figure 5-60 Secondary Electron angular distributions for selected beam energies in the 0 - 50 eV range using the 1 eV resolution.	252
Figure 5-61 SE yield in Fine Resolution. The boundaries of Integration are the SEmaxPosition and 20 eV.	253
Figure 5-62 SE Yield integrated over angle (isotropically) and calculated with boundaries of 0 eV – E _{min} and 0 eV – 50 eV. SE yield measured using 0 eV – 50 eV taken within the Fatman chamber is shown for comparison.	255
Figure 5-63 The SE yield cross section resolved at fine emission angle.....	257
Figure 5-64 Yield 50 eV – E _{min}	259
Figure 6-1 Schematic depicting double-sphere design for measurement of angle-resolved SE spectra. [Davies, 1999, p. 173]	272
Figure A-1 Varian Electron Gun (Side View).....	286
Figure A-2 Varian Electron Gun (45° view)	287
Figure A-3 Varian electron gun stabilizing current feedback circuit board (front)	291
Figure A-4 Varian electron gun stabilizing current feedback circuit board (back)	292
Figure A-5 Varian Electron Gun Current Stabilizing Controller Schematic	294
Figure A-6 Precision Resistor Complement.....	296
Figure A-7 1000V Beam Profiles For Two Different Extractor Settings.....	298
Figure A-8 2000V Beam Profiles For Two Different Extractor Settings.....	299
Figure B-1 The RD gear rests on a bearing (side view) and is driven by the small gear, which is attached to the cable. The small gear shaft is pressed to fit into a small plate, which is fixed to the bottom plate.....	301
Figure B-2 Feedthrough ports for the Signal, Heater, and Thermocouple (on top) and the RD cable.	302
Figure B-3 The Stepper Motor with wiring diagram on left and the Stepper Motor Controller Schematic on right. The numbers 1 through 6 connect.	304
Figure C-1 StepperMotor LabVIEW Program	308
Figure C-2 Motor1 LabVIEW Program	309
Figure C-3 Angular Movement LabVIEW Wiring Diagram.....	310

Figure C-4 DaqBoard LabVIEW Program.....	314
Figure C-5 EARspectraDAQ2000 LabVIEW Program	315
Figure C-6 DAQBoard2000 Monitoring LabVIEW Wiring Diagram	316
Figure C-7 EARspectraDAQ2001 LabVIEW Program	317
Figure C-8 EARspectraDAQTert LabVIEW Program.....	318
Figure C-9 MonitorPressure LabVIEW Program.....	319
Figure C-10 Keithly237 Initialization LabVIEW Wiring Diagram.....	320
Figure C-11 SEpeakfine LabVIEW Program.....	323
Figure C-12 BSEpeakfine LabVIEW Program	324
Figure C-13 SEpeak LabVIEW Program	325
Figure C-14 BSEpeak1V LabVIEW Program.....	326
Figure C-15 MidEnergy1V LabVIEW Program	327
Figure C-16 MidEnergy10V LabVIEW Program	328
Figure C-17 DetermineZeroAngle LabVIEW Program	330
Figure C-18 ARGChart LabVIEW Program	332
Figure C-19 ARGAcycle LabVIEW Program.....	333
Figure D-1 Energy Resolve Angular Distribution.....	336
Figure D-2 Ratio of the Tertiary to Sample Currents	337
Figure D-3 Ratio of the RD to the Tertiary Currents.....	338
Figure D-4 Angle Resolved Distributions for Several Beam Energies	341
Figure D-5 Angular Resolved SE Yields	342
Figure E-1 Comparison of Chamber Pressure, Rotatable Detector Current and electron gun controller voltage, Vcontroller. The duration of each rap to the LittleBoy was ~0.1 s. The gun controller voltage was not affected during these raps.....	345
Figure E-2 Nout/Nin * <S/Ib>200 at Eb = 100V with all six ranges concatenated given in units of inverse steradians.....	351
Figure E-3 Nout/Nin * <S/Ib>220 at Eb = 500V with all five ranges concatenated given in units of inverse steradians.....	352

Figure E-4 Nout/Nin * $\langle S/I_b \rangle$ 220 at Eb = 600V with all three ranges concatenated given in units of inverse steradians	353
Figure E-5 Nout/Nin * $\langle S/I_b \rangle$ 220 at Eb = 700V with all five ranges concatenated given in units of inverse steradians.....	354
Figure E-6 Nout/Nin * $\langle S/I_b \rangle$ 220 at Eb = 900V with all seven ranges concatenated given in units of inverse steradians	355
Figure E-7 Nout/Nin * $\langle S/I_b \rangle$ 220 at Eb = 1200V with all eight ranges concatenated given in units of inverse steradians.....	356
Figure E-8 Nout/Nin * $\langle S/I_b \rangle$ 220 at Eb = 2000V with all thirteen ranges concatenated given in units of inverse steradians	357
Figure E-9 Nout/Nin * $\langle S/I_b \rangle$ 220 at Eb = 2500V with all eighteen ranges concatenated given in units of inverse steradians	358
Figure E-10 AR spectra for Eb = 100V resolved at 1 Volt for emission angles of 14° Counter-Clockwise to 76° Counter-Clockwise.....	361
Figure E-11 AR spectra for Eb = 500V and for emission angles of 14 degrees counterclockwise to 76 degrees counterclockwise. No Smooth	362
Figure E-12 AR spectra for Eb = 600V and for emission angles of 14 degrees counterclockwise to 76 degrees counterclockwise.....	363
Figure E-13 AR spectra for Eb = 700V and for emission angles of 14 degrees counterclockwise to 76 degrees counterclockwise.....	364
Figure E-14 AR spectra for Eb = 900V and for emission angles of 17 degrees clockwise to 76 degrees counterclockwise.....	365
Figure E-15 AR spectra for Eb = 1200V and for emission angles of 17 degrees clockwise to 76 degrees counterclockwise.....	366
Figure E-16 AR spectra for Eb = 2000V and for emission angles of 17 degrees clockwise to 76 degrees counterclockwise.....	367
Figure E-17 AR spectra for Eb = 2500V and for emission angles of 17 degrees clockwise to 76 degrees counterclockwise.....	368
Figure E-18 Normalized AR Energy Spectra at 17° Clockwise emission for selected beam energies.	370
Figure E-19 Normalized AR Energy Spectra at 14° Clockwise emission for selected beam energies.	371
Figure E-20 Normalized AR Energy Spectra at 14° Counter-Clockwise emission for selected beam energies.	372
Figure E-21 Normalized AR Energy Spectra at 17° Counter-Clockwise emission for selected beam energies.	373

Figure E-22 Normalized AR Energy Spectra at 24o Counter-Clockwise emission for selected beam energies	374
Figure E-23 Normalized AR Energy Spectra at 30o Counter-Clockwise emission for selected beam energies	375
Figure E-24 Normalized AR Energy Spectra at 38o Counter-Clockwise emission for selected beam energies	376
Figure E-25 Normalized AR Energy Spectra at 46o Counter-Clockwise emission for selected beam energies	377
Figure E-26 Normalized AR Energy Spectra at 53o Counter-Clockwise emission for selected beam energies	378
Figure E-27 Normalized AR Energy Spectra at 60o Counter-Clockwise emission for selected beam energies	379
Figure E-28 Normalized AR Energy Spectra at 70o Counter-Clockwise emission for selected beam energies	380
Figure E-29 Normalized AR Energy Spectra at 76o Counter-Clockwise emission for selected beam energies	381
Figure E-30 Fine energy resolution for 100 Volt incident beam energy	383
Figure E-31 Fine energy resolution for 500 Volt incident beam energy	384
Figure E-32 Fine energy resolution for 900 Volt incident beam energy	385
Figure E-33 Fine energy resolution for the 1200 Volt incident beam energy	386
Figure E-34 Fine energy resolution for the 2000 Volt incident beam energy	387
Figure E-35 Fine energy resolution for the 2500 Volt incident beam energy	388
Figure E-36 Elastic AR Energy Spectra at 17o Clockwise emission for selected beam energies	390
Figure E-37 Elastic AR Energy Spectra at 14o Clockwise emission for selected beam energies	391
Figure E-38 Elastic AR Energy Spectra at 14o Counter-Clockwise emission for selected beam energies	392
Figure E-39 Elastic AR Energy Spectra at 17o Counter-Clockwise emission for selected beam energies	393
Figure E-40 Elastic AR Energy Spectra at 24o Counter-Clockwise emission for selected beam energies	394
Figure E-41 Elastic AR Energy Spectra at 30o Counter-Clockwise emission for selected beam energies	395
Figure E-42 Elastic AR Energy Spectra at 38o Counter-Clockwise emission for selected beam energies	396
Figure E-43 Elastic AR Energy Spectra at 46o Counter-Clockwise emission for selected beam energies	397

Figure E-44 Elastic AR Energy Spectra at 53° Counter-Clockwise emission for selected beam energies.....	398
Figure E-45 Elastic AR Energy Spectra at 60° Counter-Clockwise emission for selected beam energies.....	399
Figure E-46 Elastic AR Energy Spectra at 70° Counter-Clockwise emission for selected beam energies.....	400
Figure E-47 Elastic AR Energy Spectra at 76° Counter-Clockwise emission for selected beam energies.....	401
Figure E-48 BSE and Elastic Peaks measured with the 1 Volt resolution for 500 Volt Incident Beam Energy.....	403
Figure E-49 BSE and Elastic Peaks measured with the 1 Volt resolution for 600 Volt Incident Beam Energy.....	404
Figure E-50 BSE and Elastic Peaks measured with the 1 Volt resolution for 700 Volt Incident Beam Energy.....	405
Figure E-51 BSE and Elastic Peaks measured with the 1 Volt resolution for 900 Volt Incident Beam Energy.....	406
Figure E-52 BSE and Elastic Peaks measured with the 1 Volt resolution for 1200 Volt Incident Beam Energy.....	407
Figure E-53 BSE and Elastic Peaks measured with the 1 Volt resolution for 2000 Volt Incident Beam Energy.....	408
Figure E-54 BSE and Elastic Peaks measured with the 1 Volt resolution for 2500 Volt Incident Beam Energy.....	409
Figure E-55 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 17° Clockwise emission and selected beam energies.....	411
Figure E-56 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 14° Clockwise emission and selected beam energies.....	412
Figure E-57 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 14° Counter-Clockwise emission and selected beam energies.....	413
Figure E-58 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 17° Counter-Clockwise emission and selected beam energies.....	414
Figure E-59 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 24° Counter-Clockwise emission and selected beam energies.....	415
Figure E-60 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 30° Counter-Clockwise emission and selected beam energies.....	416
Figure E-61 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 38° Counter-Clockwise emission and selected beam energies.....	417
Figure E-62 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 46° Counter-Clockwise emission and selected beam energies.....	418

Figure E-63 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 53o Counter-Clockwise emission and selected beam energies.....	419
Figure E-64 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 60o Counter-Clockwise emission and selected beam energies.....	420
Figure E-65 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 70o Counter-Clockwise emission and selected beam energies.....	421
Figure E-66 Angular Resolved BSE and Elastic Peaks measured using the 1 Volt resolution at 76o Counter-Clockwise emission and selected beam energies.....	422
Figure E-67 SE peak resolved in 1 volt at 500 Volt incident beam energy for selected emission angles.	424
Figure E-68 SE peak resolved in 1 volt at 900 Volt incident beam energy for selected emission angles.	425
Figure E-69 SE peak resolved in 1 volt at 1200 Volt incident beam energy for selected emission angles.	426
Figure E-70 SE peak resolved in 1 volt at 2000 Volt incident beam energy for selected emission angles.	427
Figure E-71 SE peak resolved in 1 volt at 2500 Volt incident beam energy for selected emission angles.	428
Figure E-72 SE peak resolved in 1 volt at 17 degree Clockwise emission for selected incident beam energies.....	430
Figure E-73 SE peak resolved in 1 volt at 14 degree Clockwise emission for selected incident beam energies.....	431
Figure E-74 SE peak resolved in 1 volt at 14 degree Counter-Clockwise emission for selected incident beam energies.....	432
Figure E-75 SE peak resolved in 1 volt at 17 degree Counter-Clockwise emission for selected incident beam energies.....	433
Figure E-76 SE peak resolved in 1 volt at 24 degree Counter-Clockwise emission for selected incident beam energies.....	434
Figure E-77 SE peak resolved in 1 volt at 30 degree Counter-Clockwise emission for selected incident beam energies.....	435
Figure E-78 SE peak resolved in 1 volt at 38 degree Counter-Clockwise emission for selected incident beam energies.....	436
Figure E-79 SE peak resolved in 1 volt at 46 degree Counter-Clockwise emission for selected incident beam energies.....	437
Figure E-80 SE peak resolved in 1 volt at 53 degree Counter-Clockwise emission for selected incident beam energies.....	438
Figure E-81 SE peak resolved in 1 volt at 60 degree Counter-Clockwise emission for selected incident beam energies.....	439

Figure E-82 SE peak resolved in 1 volt at 70 degree Counter-Clockwise emission for selected incident beam energies.....	440
Figure E-83 SE peak resolved in 1 volt at 76 degree Counter-Clockwise emission for selected incident beam energies.....	441
Figure E-84 SE peak resolved at 0.1 volt for 100 Volt incident beam energy given in selected emission angles	443
Figure E-85 SE peak resolved at 0.1 volt for 500 Volt incident beam energy given in selected emission angles.	444
Figure E-86 SE peak resolved at 0.1 volt for 900 Volt incident beam energy given in selected emission angles. D3501	445
Figure E-87 SE peak resolved at 0.1 volt for 2500 Volt incident beam energy given in selected emission angles.	446
Figure E-88 SE peak resolved in 0.1 volt at 17 degree Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	448
Figure E-89 SE peak resolved in 0.1 volt at 14 degree Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	449
Figure E-90 SE peak resolved in 0.1 volt at 14 degree Counter-Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	450
Figure E-91 SE peak resolved in 0.1 volt at 17 degree Counter-Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	451
Figure E-92 SE peak resolved in 0.1 volt at 24 degree Counter-Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	452
Figure E-93 SE peak resolved in 0.1 volt at 30 degree Counter-Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	453
Figure E-94 SE peak resolved in 0.1 volt at 38 degree Counter-Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	454
Figure E-95 SE peak resolved in 0.1 volt at 46 degree Counter-Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	455
Figure E-96 SE peak resolved in 0.1 volt at 53 degree Counter-Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	456
Figure E-97 SE peak resolved in 0.1 volt at 60 degree Counter-Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	457
Figure E-98 SE peak resolved in 0.1 volt at 70 degree Counter-Clockwise emission for 500, 900, and 2500 Volt incident beam energies.....	458

Figure E-99 SE peak resolved in 0.1 volt at 76 degree Counter-Clockwise emission for selected incident beam energies..... 459

ABBREVIATIONS, SYMBOLS, AND NOTATION

AR	angle-resolved
AI	angle-integrated
BSE	backscattered electron
CA	chamber apparatus
DAQ	data acquisition
EDX	energy-dispersive x-ray
ER	energy-resolved
ESA	electron-stimulated adsorption
ESD	electron-stimulated desorption
HV	high voltage
IP	inelastic peak
LET	low-energy tail
PE	primary electron
QM	quantum mechanical
RD	rotatable detector
RGA	residual gas analyzer
SE	secondary electron
SEE	secondary electron emission
SEM	scanning electron microscope
UHV	ultra-high vacuum
\bar{E}	ambient electric field
\bar{B}	ambient magnetic field
α	emission angle
E_B	incident electron beam energy
Φ_{RD}	sample bias
$d\Omega$	solid angle subtended by the RD

$n(x, E_0)$	average number of SE's produced per incident PE in a layer of thickness dx at a depth x below the surface
$f(x)$	probability for an SE to migrate to the surface from a depth x and escape
$\frac{-dE}{dx}$	average PE energy loss per unit path length (stopping power)
δ_{max}	maximum SE yield for a given material
E_{max}	incident energy at which δ_{max} occurs
φ_{RD}	detector position
E_e	emitted energy
δ	total SE yield
δ_{AER}	angle-energy-resolved SE yield
δ_{AR}	angle-resolved SE yield
δ_{ER}	energy-resolved SE yield
$\delta(\alpha')$	AR SE yield
$\delta(\alpha)$	SE angular distribution function
$\delta(E_e)$	energy-resolved SE yield
$\delta(E_e)$	SE energy distribution function
$\delta(\alpha', E'_e)$	angle-energy-resolved SE yield
$\delta(\alpha', E'_e)$	AR SE energy distribution function
$\delta(\alpha, E'_e)$	energy-resolved SE angular distribution function
$\delta(\alpha, E_e)$	SE angle and energy distribution function
η	total BSE yield
$\eta(\alpha')$	AR BSE yield
$\eta(\alpha)$	BSE angular distribution function
$\eta(E_e)$	energy-resolved BSE yield
$\eta(E_e)$	BSE energy distribution function

$\eta(\alpha', E'_e)$	angle-energy-resolved BSE yield
$\eta(\alpha', E_e)$	AR BSE energy distribution function
$\eta(\alpha, E'_e)$	energy-resolved BSE angular distribution function
$\eta(\alpha, E_e)$	BSE angle and energy distribution function
σ	total emitted electron yield ($\delta+\eta$)
$\sigma(\alpha')$	AR total emitted yield
$\sigma(\alpha)$	emitted-electron angular distribution function
$\sigma(E'_e)$	energy-resolved emitted-electron yield
$\sigma(E_e)$	emitted-electron energy distribution function
$\sigma(\alpha', E'_e)$	angle-energy-resolved emitted-electron yield
$\sigma(\alpha', E_e)$	AR emitted-electron energy distribution function
$\sigma(\alpha, E'_e)$	energy-resolved emitted-electron angular distribution function
$\sigma(\alpha, E_e)$	emitted-electron angle and energy distribution function