Contents

1 Introduction **1**

1.1 The History of Kondo Effect: Dilute Magnetic Alloys 1

1.2 Kondo Effect in Tunnel Junctions 3

1.3 Why We Study Kondo Effect through the $Al/AlO_x/Sc$ Tunnel Junctions? 5

2 Theory **6**

2.1 Electron Tunneling Spectroscopy 6

2.1.1 Tunneling between Two Free-Electron Metals 8

2.1.2 Density of States Effect and Assisted Tunneling 17

2.2 Kondo Effect in Bulk Samples 26

2.2.1 Weak Coupling Regime 26

2.2.2 Strong Coupling Regime 27

2.3 Kondo Effect in Tunnel Junctions 29

2.3.1 Weak Coupling Regime 29

2.3.2 Strong Coupling Regime 39

3 Experiment **42**

3.1 Samples Fabrication 42

3.1.1 Al Films Deposition 42

3.1.2 The Growth of the AlO_x 43

3.1.3 Sc Films Deposition 46

3.1.4 Initial Test of the Junctions 46

3.2 Measurement Circuits 46

3.2.1 The Principles of the Lock-in Amplifier 46

3.2.2 The "Send I Measure V" Circuit 51

3.2.3 The "Send V Measure I" Circuit 52

3.3 The ^{3}He Cryostat 54

3.3.1 A Brief Description 54

3.3.2 The Cool Down Process 54

4 Results and Discussion **58**

4.1 The Quality, Height, and Thickness of the Barrier 58

4.1.1 The Quality of the Barrier 58

4.1.2 The Height and Thickness of the Barrier 64

4.2 Differential Conductance in Al/AlO_x/Sc Tunnel Junctions 65

4.2.1 $G(0,T)$ vs. T 65

4.2.2 $G(V,T)$ vs. V 67

4.3 The DOS Effects in the Al and Sc Leads 72

4.3.1 The DOS Effect in the Al Lead 72

4.3.2 The DOS Effect in the Sc Lead 77

4.4 Subtracting the Background from the Measured dI/dV Data 80

4.5 Weak Coupling Regime 86
4.5.1 $G_{even,data}(V,T)$ 86
4.5.2 $G_{even,data}(0,T)$ 99
4.5.3 $G_{odd,data}(V,T)$ 101
4.6 Strong Coupling Regime 103
4.7 The Effect of Applying a Magnetic Field 116
4.8 Summary 119

5 Conclusions **122**

A The Proof of $G_{even}^{weak}(V)$ Is an Even Function **125**
A.1 $Q(\omega)$ Is an Even Function 125
A.2 $G_{even}^{weak}(V)$ Is an Even Function 126

B Simpson's Rule and Composite Simpson's Rule **127**

List of Tables

4.1 The fitted values of T_K and α in several Al/AlO_x/Sc tunnel junctions. 113

List of Figures

2.1 (a) A M-I-M tunnel junction. (b) The band diagram of the M-I-M tunnel junction. 7

2.2 The integration range of Eq. (2.15). 11

2.3 The asymmetric barrier. 15

2.4 (a) Transfer-Hamiltonian model. (b) $G(V)$ as $T \to 0$. 18

2.5 The plots of of $R_{Hamann}(T/T_K)$ and $R_{NRG}(T/T_K)$. 30

2.6 A schematic representation of a tunnel junction which contains a magnetic impurity in its barrier. 31

3.1 A schematic representation of the glow discharge. 45

3.2 The functional block diagram of the SR830 lock-in Amplifier. 50

3.3 The "send I measure V" circuits. 51

3.4 The "send V measure I" circuits. 52

3.5 The schematic representation of the IVC of the ^{3}He fridge. 55

4.1 The bias polarity in the tunnel junctions under measurement. 59

4.2 The superconducting gap of the Al film. 61

4.3 The zero-bias conductance $G(0,T)$ as a function of temperature. . . . 63

4.4 The $G(V,T)$ spectra of two Al/AlO$_x$/Al junctions. 66

4.5 $G(0,T)$ as a function of temperature for $T \lesssim 50$ K. 68
4.6 $G(V,T)$ as a function of V at several temperatures of a Al/AlO_x/Sc tunnel junction. 69
4.7 $G(V,T)$ as a function of V for several temperatures of another Al/AlO_x/Sc tunnel junction 70
4.8 $\rho(T)$ vs. T for an Al film whose $\rho(300\ \text{K}) \approx 15.6\ \mu\Omega$ cm. 73
4.9 The $G(V,T)$ spectra of an Al (15 $\mu\Omega$ cm)/AlO_x/Al (15 $\mu\Omega$ cm) tunnel junction. 74
4.10 $\rho(T)$ vs. T for an Al film whose $\rho(300\ \text{K}) \approx 66\ \mu\Omega$ cm 76
4.11 The $G(V,T)$ spectra of an Al (15 $\mu\Omega$ cm)/AlO_x/Al (66 $\mu\Omega$ cm) tunnel junction. 78
4.12 $\rho(T)$ vs. T for a Sc film whose $\rho(300\ \text{K}) \approx 107\ \mu\Omega$ cm. 79
4.13 $G(V,T)$ as a function of V at several temperatures of the 20061002_Al/AlO_x/Sc tunnel junction. 82
4.14 $G_{remainder} (\equiv G_{original} - G_{background})$ of the 20061002_Al/AlO_x/Sc tunnel junction. 83
4.15 $G_{even,data}(V,T)$ as a function of V at several temperatures. 84
4.16 $G_{odd,data}(V,T)$ as a function of V at several temperatures. 85
4.17 $G_{even,data}(V,T)$ vs. $h(V,T)$ plots at several temperatures. 88
4.18 The linear fitting of $G_{even,data}(V,T)$ vs. $h(V,T)$ plots at $T = 32, 24, 16$ K. 89
4.19 The fitting of $G_{even,data}(V,T)$ in terms of $G_{even}^{weak}(V,T)$ at $T = 32$ K. . . 90
4.20 The fitting of $G_{even,data}(V,T)$ in terms of $G_{even}^{weak}(V,T)$ at $T = 24$ K. . . 91
4.21 The fitting of $G_{even,data}(V,T)$ in terms of $G_{even}^{weak}(V,T)$ at $T = 16$ K. . . 92

4.22 The fitting of $G_{even,data}(V,T)$ in terms of $G^{weak}_{even}(V,T)$ at $T = 12$ K. . . 93
4.23 The fitting of $G_{even,data}(V,T)$ in terms of $G^{weak}_{even}(V,T)$ at $T = 8$ K. . . 94
4.24 The fitting of $G_{even,data}(V,T)$ in terms of $G^{weak}_{even}(V,T)$ at $T = 5.5$ K. . 95
4.25 The fitting of $G_{even,data}(V,T)$ in terms of $G^{weak}_{even}(V,T)$ at $T = 2.5$ K. . 96
4.26 The fitting of $G_{even,data}(V,T)$ in terms of $G^{weak}_{even}(V,T)$ at $T = 32$, 24, and 16 K. 97
4.27 The fitting of $G_{even,data}(V,T)$ in terms of $G^{weak}_{even}(V,T)$ at $T = 12$, 8, 5.5, and 2.5 K. 98
4.28 The fitting of $G_{even,data}(0,T)$ in terms of $G^{weak}_{even}(0,T)$. 100
4.29 The fitting of $G_{odd,data}(V,T)$ in terms of $G^{weak}_{odd}(V,T)$ at $T = 32$ K. . . 104
4.30 The fitting of $G_{odd,data}(V,T)$ in terms of $G^{weak}_{odd}(V,T)$ at $T = 24$ K. . . 105
4.31 The fitting of $G_{odd,data}(V,T)$ in terms of $G^{weak}_{odd}(V,T)$ at $T = 16$ K. . . 106
4.32 The fitting of $G_{odd,data}(V,T)$ in terms of $G^{weak}_{odd}(V,T)$ at $T = 12$ K. . . 107
4.33 The fitting of $G_{odd,data}(V,T)$ in terms of $G^{weak}_{odd}(V,T)$ at $T = 8$ K. . . . 108
4.34 The fitting of $G_{odd,data}(V,T)$ in terms of $G^{weak}_{odd}(V,T)$ at $T = 5.5$ K. . . 109
4.35 The fitting of $G_{odd,data}(V,T)$ in terms of $G^{weak}_{odd}(V,T)$ at $T = 2.5$ K. . . 110
4.36 The fitting of $G_{odd,data}(V,T)$ in terms of $G^{weak}_{odd}(V,T)$ at $T = 32$, 24, and 16 K. 111
4.37 The fitting of $G_{odd,data}(V,T)$ in terms of $G^{weak}_{odd}(V,T)$ at $T = 12$, 8, 5.5, and 2.5 K. 112
4.38 The fitting of $G_{even,data}(0,T)$ in terms of $G_{NRG}(0,T)$ for several $Al/AlO_x/Sc$ tunnel junctions. 114
4.39 The fitting of $G_{even,data}(V,T)$ in terms of $G^{strong}_{even}(V,T)$ at $T = 2.5$ K. . 116
4.40 The $G_{even,data}(V,T)$ at $T = 2.5$ K for $H = 0$ and $H = 4$ T. 117

4.41 The $G_{even,data}(V,T)$ at $T = 2.5$ K for $H = 0$ and $H = 4$ T, which is enlarged from Fig. 4.40. 118

B.1 The composite Simpson's rule. 128