Contents

Contents i

Introduction vii

I Theory 1

1 Basic properties of Josephson junctions 3
1.1 Superconductivity . . . 3
1.2 The Josephson Relations . . . 4
1.2.1 Types of Josephson junctions . . . 6
1.3 Tunneling of Cooper pairs and quasiparticles . . . 6
1.3.1 Resistively and Capacitively Shunted Junction model . . . 8
1.3.2 Temperature dependence of j_c in SIS and SNS junctions . . . 10
1.3.3 Washboard potential . . . 10
1.4 Josephson junction in magnetic field . . . 11
1.4.1 Sine-Gordon-model . . . 13
1.5 Excitation in long Josephson junctions . . . 15
1.5.1 Zero Field steps (ZFS) . . . 16
1.5.2 Fiske steps . . . 17
1.6 Shapiro steps . . . 17

2 JJs with ferromagnetic barrier 18
2.1 The π state . . . 18
2.1.1 Proximity effect in F-layer . . . 19
2.1.2 Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state . . . 19
2.2 Microscopic origin of π shift . . . 20
2.2.1 Itinerant magnets . . . 20
2.2.2 Andreev bound states in SNS and SFS junctions . . . 22
2.3 Theory of π junctions . . . 24
2.3.1 Josephson effect in the SFS/SIFS sandwich . . . 25
2.3.2 Spontaneous supercurrent in π coupled loop . . . 27
2.3.3 Critical temperature T_c of SF multilayers . . . 28
2.4 Experiments with SFS/SIFS Josephson junctions . . . 29
2.5 Advantages of π coupled SIFS junctions . . . 31
2.6 Higher harmonics: $\sin 2\phi$ component . . . 32

3 Fractional vortices in 0–π JJs **33**
3.1 Sine-Gordon equation including 0–π phase boundaries . . . 33
3.2 Integer and semi-integer fluxons . . . 34
3.3 Short and long 0–π JJs . . . 35
3.3.1 Energy of symmetric and asymmetric 0–π JJs . . . 35
3.3.2 Spontaneous flux in short 0–π JJs . . . 36
3.3.3 0–π JJ in magnetic field . . . 37
3.4 Bias current and semi-integer fluxons . . . 38
3.4.1 Semi-integer Zero Field steps . . . 39
3.5 Realization of 0–π junctions . . . 40
3.5.1 $YBa_2Cu_3O_7 - Nb$ ramp zigzags . . . 41
3.5.2 Artificial 0–κ junctions . . . 41
3.5.3 SFS/SIFS Josephson junctions . . . 42
3.6 Current status of 0–π SFS/SIFS junctions . . . 43

II Experimental results **47**

4 Sample preparation **49**
4.1 Sputter deposition . . . 49
4.2 Multilayer deposition . . . 50
4.3 Oxidation process of tunnel barrier . . . 52
4.4 Anodic oxidation process . . . 53
4.5 Patterning . . . 54
4.5.1 Idle region and capacitance . . . 55
4.6 SIFS junctions with step in the F-layer . . . 57
4.6.1 Patterning of step in the F-layer . . . 58
4.6.2 Structural analysis of the step . . . 59

5 Ferromagnetic NiCu alloys **61**
5.1 Theory of NiCu alloys . . . 61
5.1.1 Very thin NiCu films . . . 62
5.2 Characterization of $Ni_{60}Cu_{40}$ . . . 62
5.2.1 Stoichiometry . . . 62
5.2.2 Electric properties . . . 63
5.2.3 Magnetic properties . . . 64
5.2.4 Calculation of remanent magnetization in NiCu films . . . 66

6 0 and π coupled Josephson junctions **68**
6.1 SIS junctions . . . 69
6.1.1 Anodization spectroscopy . . . 69
6.2 SIS junctions formed at various oxidation exposures . . . 70
6.2.1 Proximity effect on aluminium . . . 72
6.2.2 Stewart-McCumber parameter β_c . . . 73
6.2.3 Temperature dependence of IVC . . . 73
6.2.4 Magnetic field diffraction pattern . . . 74
6.3 SIFS junctions with $Ni_{60}Cu_{40}$ alloy . . . 75

6.3.1 SIFS and SINFS junctions . . . 76
6.4 IVC of JJs with thin F-layer . . . 81
6.4.1 Temperature dependence of IVC . . . 84
6.5 F-layer thickness dependence of SINFS junctions . . . 85
6.5.1 Critical current . . . 85
6.5.2 Stewart-McCumber parameter β_c . . . 87
6.5.3 Transparency parameters . . . 87
6.6 $I_c(H)$ of JJs with ferromagnetic interlayer . . . 88
6.6.1 $I_c(H)$ as function of T and d_F . . . 89
6.7 Fiske steps in SIFS JJs . . . 90
6.8 Temperature dependence of 0 and π SINFS junctions . . . 92
6.8.1 Temperature dependence of I_c and β_c . . . 93
6.8.2 Temperature induced 0 to π transition . . . 94
6.9 Upper limit of j_c for π coupled JJs . . . 96

7 0, π and 0–π SIFS JJs 98
7.1 JJ with step in the F-layer . . . 99
7.1.1 Fabrication of step in the F-layer . . . 99
7.1.2 Quality of the etched junctions . . . 100
7.2 0–π SIFS JJs . . . 101
7.2.1 0, π and 0–π Josephson junctions . . . 102
7.3 Physics of 0–π JJs . . . 104
7.3.1 Ground state diagram . . . 104
7.3.2 $I_c(H)$ dependences . . . 107
7.3.3 Remanent magnetization in short 0–π JJ . . . 108
7.3.4 Discussion of experimental $I_c^{0\text{-}\pi}(H)$ . . . 109
7.3.5 Increase of minimum in $I_c^{0\text{-}\pi}(H)$ . . . 110
7.4 Zero Field steps in 0–π and 0, π JJs . . . 111

III Appendix 113

A LTSEM measurements on SIFS junctions 115
A.1 LTSEM on SIFS junctions . . . 116
A.2 SIFS JJ with very thin F-layer in magnetic field . . . 118
A.3 Elliptical and circular SINFS JJs . . . 118
A.3.1 Elliptical junction . . . 120
A.3.2 Circular junction . . . 122

B Quantum states of π junction 124
B.1 π JJ in low temperature limit . . . 124
B.1.1 Current ramp experiments . . . 125
B.2 Escape temperature measurements . . . 126
B.3 Microwave spectroscopy . . . 126
B.3.1 Spectroscopic determination of ω_{p0}, I_{c0} and C . . . 127

C List of symbols 130

Summary and outlook **133**

Bibliography **137**