Contents

Preface *XI*

Abbreviations and Symbols *XV*

Color Plates *XXI*

Part One Theoretical Aspects of Superconductivity in 1D Nanowires *1*

1 Superconductivity: Basics and Formulation *3*
1.1 Introduction *3*
1.2 BCS Theory *4*
1.3 Bogoliubov–de Gennes Equations – Quasiparticle Excitations *8*
1.4 Ginzburg–Landau Theory *10*
1.4.1 Time-Dependent Ginzburg–Landau Theory *12*
1.5 Gorkov Green's Functions, Eilenberger–Larkin–Ovchinnikov Equations, and the Usadel Equation *12*
1.6 Path Integral Formulation *19*
References *27*

2 1D Superconductivity: Basic Notions *31*
2.1 Introduction *31*
2.2 Shape Resonances – Oscillations in Superconductivity Properties *33*
2.2.1 Early Treatments of Shape Resonances in 2D Films *35*
2.2.2 Bogoliubov–de Gennes Equations, Finite Temperature, and Parabolic-Band Approximation for Realistic Materials *40*
2.2.3 Numerical Solutions and Thin Film Shape Resonances *42*
2.2.4 1D Nanowires – Shape Resonances and Size Oscillations *45*
2.3 Superconductivity in Carbon Nanotubes – Single-Walled Bundles and Individual Multiwalled Nanotubes *48*
2.4 Phase Slips *50*
2.4.1 Finite Voltage in a Superconducting Wire and Phase Slip *51*
2.4.2 Phase Slip in a Josephson Junction *52*
2.4.3 Langer–Ambegaokar Free Energy Minima in the Ginzburg–Landau Approximation *55*
2.4.4 Transition Rate and Free Energy Barrier *59*

2.4.5 Free Energy Barrier for a Phase Slip in the Ginzburg–Landau Theory *60*
2.4.6 Physical Scenario of a Thermally-Activated Phase Slip *64*
2.4.7 McCumber–Halperin Estimate of the Attempt Frequency *66*
References *71*

3 Quantum Phase Slips and Quantum Phase Transitions *75*
3.1 Introduction *75*
3.2 Zaikin–Golubev Theory *79*
3.2.1 Derivation of the Low Energy Effective Action *80*
3.2.2 Core Contribution to the QPS Action *88*
3.2.3 Hydrodynamic Contribution to the Phase-Slip Action *91*
3.2.4 Quantum Phase-Slip Rate *92*
3.2.5 Quantum Phase-Slip Interaction and Quantum-Phase Transitions *95*
3.2.6 Wire Resistance and Nonlinear Voltage–Current Relations *97*
3.3 Short-Wire Superconductor–Insulator Transition: Büchler, Geshkenbein and Blatter Theory *100*
3.4 Refael, Demler, Oreg, Fisher Theory – 1D Josephson Junction Chains and Nanowires *105*
3.4.1 Discrete Model of 1D Josephson Junction Chains *107*
3.4.2 Resistance of the Josephson Junctions and the Nanowire *114*
3.4.3 Mean Field Theory of the Short-Wire SIT *116*
3.5 Khlebnikov–Pryadko Theory – Momentum Conservation *121*
3.5.1 Gross–Pitaevskii Model and Quantum Phase Slips *123*
3.5.2 Disorder Averaging, Quantum Phase Transition and Scaling for the Resistance and Current–Voltage Relations *126*
3.5.3 Short Wires – Linear QPS Interaction and Exponential QPS Rate *130*
3.6 Quantum Criticality and Pair-Breaking – Universal Conductance and Thermal Transport in Short Wires *136*
References *143*

4 Duality *149*
4.1 Introduction *149*
4.2 Mooij–Nazarov Theory of Duality – QPS Junctions *152*
4.2.1 QPS Junction Voltage-Charge Relationship and Shapiro Current Steps *156*
4.2.2 QPS Qubits *157*
4.3 Khlebnikov Theory of Interacting Phase Slips in Short Wires: Quark Confinement Physics *159*
References *165*

5 Proximity Related Phenomena *167*
5.1 Introduction *167*
5.2 Transport Properties of Normal-Superconducting Nanowire-Normal (N-SCNW-N) Junctions *169*
5.2.1 Nonequilibrium Usadel Equations *169*
5.2.2 Parameterization of the Usadel Equations *174*

5.2.3 Numerical Results *175*
5.3 Superconductor–Semiconductor Nanowire–Superconductor Junctions *179*
5.4 Majorana Fermion in S-SmNW-S Systems with Strong Spin–Orbit Interaction in the Semiconductor *184*
References *188*

Part Two Review of Experiments on 1D Superconductivity *193*

6 Experimental Technique for Nanowire Fabrication *195*
6.1 Experimental Technique for the Fabrication of Ultra Narrow Nanowires *195*
6.2 Introduction to the Techniques *196*
6.2.1 Lithography *197*
6.2.2 Metal Deposition *198*
6.2.3 Etching *199*
6.2.4 Putting It All Together *199*
6.3 Step-Edge Lithographic Technique *201*
6.4 Molecular Templating *202*
6.5 Semiconducting Stencils *205*
6.6 Natelson and Willet *205*
6.7 SNAP Technique *206*
6.8 Chang and Altomare *208*
6.9 Template Synthesis *209*
6.10 Other Methods *211*
6.10.1 Ion Beam Polishing *211*
6.10.2 Angled Evaporation *213*
6.10.3 Resist Development *213*
6.11 Future Developments *214*
References *216*

7 Experimental Review of Experiments on 1D Superconducting Nanowires *219*
7.1 Introduction *219*
7.2 Filtering *220*
7.3 Phase Slips *221*
7.4 Overview of the Experimental Results *223*
7.4.1 Giordano's Experiments *225*
7.4.2 Recent Experiments on QPS *226*
7.4.3 QPS Probed via Switching Current Measurements *239*
7.5 Other Effects in 1D Superconducting Nanowires *248*
7.5.1 S-Shaped Current–Voltage Characteristic *248*
7.6 Antiproximity Effect *250*
7.6.1 Stabilization of Superconductivity by a Magnetic Field *253*
7.6.2 Shape Resonance Effects *255*
References *257*

8 Coherent Quantum Phase Slips *263*
8.1 Introduction *263*
8.2 A Single-Charge Transistor Based on the Charge-Phase Duality of a Superconducting Nanowire Circuit *263*
8.3 Quantum Phase-Slip Phenomenon in Ultranarrow Superconducting Nanorings *266*
8.4 Coherent Quantum Phase Slip *267*
8.5 Conclusion *272*
References *273*

9 1D Superconductivity in a Related System *275*
9.1 Introduction *275*
9.2 Carbon Nanotubes *275*
9.2.1 Proximity Effects in SWNT *276*
9.2.2 Intrinsic Superconductivity in SWNT *278*
9.2.3 Superconductivity in Ropes Mediated by the Environment *281*
9.3 Majorana Experiments *286*
9.3.1 Majorana Experiment in Semiconducting Nanowires *286*
9.3.2 Majorana Experiment in Hybrid Superconductor-Topological Insulator Devices *290*
9.4 Superconducting Nanowires as Single-Photon Detectors *292*
References *297*

10 Concluding Remarks *301*

Index *303*