Transport Properties of Hybrid Nanostructures

Summary of thesis

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1 Introduction

Mesoscopic devices have become the system of choice for studying transport properties over the last decades of the 20th century. Advances in nanotechnology and interest of chaos research both had a great impact on mesoscopic physics. Phase-coherence over the whole system had brought numerous new effects along, like Universal Quantum Fluctuations, Weak Localisation or Aharonov–Bohm interference. Most of these effects have been explained with methods based on the Random Matrix Theory (RMT) or short-wavelength semi-classical descriptions.

During the 90's advances in nanotechnology have made feasible the fabrication of hybrid systems, in wihich mesoscopic size ballistic semiconductors and bulk superconductors are attached. In these systems an electron (or hole) can be phase-coherently retroreflected as a hole (or electron) at the normal–superconductor interface. This process is known as Andreev reflection and was predicted by Andreev in 1964. Since then the influence of Andreev reflection on the transport in nanostructures has been widely discussed. The BTK theory (after *Blonder, Tinkham and Klapwijk*, 1982) has suggested a significant below-gap-conductance, which has been proven by the experiments. Furthermore the qunatum mechanical methods and semi-classical treatments, often used in mesoscopic physics, had to be extended to the presence of superconducting regions.

In the mid-nineties the Phase Length Spectrum (PLS), defined as the power spectrum of reflection or transmission amplitudes, of normal (non-superconducting) billiard systems were studied by several authors. There were peaks found in the PLS at certain lengths, which have been identified as the length of the classical orbits. In general the quantum mechanical result and the semi-classical treatment were in agreement. Some authors also mentioned so-called ghost orbits, which only occur in the quantum mechanical calculation. These orbits can be semi-classically understood only if diffractive points are included. In this thesis I show the first analysis of the PLS in a normal–superconductor hybrid system. To have a non-trivial PLS the system must have a diffractive point i.e. a point-like scatterer.

The energy spectra of Andreev billiards were also investigated by several authors. *Beenakker et al.* studied the density of states (DOS) around Fermi energy in Andreev billiards in 1996. The DOS can be calculated in Bohr–Sommerfeld approximation for an N–S hybrid system. In this approximation a fully classical quantity emerges, the return probability function (RPF), which tells the probability of a particle returning to the entry after travelling a distance of s. The RPF can be calculated by geometrical tools or simulations in general. Moreover, using RMT a mini-gap was predicted in the DOS if the underlying normal billiard was chaotic while the DOS was a linear function of the energy in case of an integrable normal billiard.

1988 launches the success of spintronics (spin-based electronics) by the discovery of the Giant Magneto Resistance (GMR). Exchange splitting, describing spin-polarisation in ferromagnet, and superconducting gap are two competitive energy scales. Hence hybrid systems fabricated of ferromagnet and superconductor show new effects, like suppression of GMR because of superconducting contacts or extreme strong proximity. In 2001 *Falci et al.* have investigated a system of two fully polarised ferromagnetic wires with opposite polarisations in contact with a spin-singlet superconductor and found that a potential-induced current in one of the wires induces a non-local current of equal magnitude and sign in the other wire. The main process in this system was the tunnelling of Cooper pairs, and therefore had an exponentially decaying magnitude with the distance between the wires.

2 Thesis points

The most important results from the thesis are collected in the following points:

1. I have investigated the PLS in a normal–superconductor hybrid system for the first time. I found peaks at negative lengths in the PLS in case of a system including diffractive scatterers. It was shown that the position of the peaks were at the length of the classical orbits starting and ending at the entry.

2. I have calculated the secular equation of Andreev billiards, made up of a normal system connected to a bulk superconductor via an infinitesimally short neck. The secular equation was expressed in terms of the scattering matrix of the normal system. If scattering into closed channels is negligible, the secular equation can be rewritten as a real equation, which was preferred in numerical calculation.

3. I have re-derived the Bohr–Sommerfeld approximation of the number of states and the density of states (DOS) in separable Andreev billiards by taking into account the energy dependent phase shift due to the Andreev reflection. I have also given a formula to for the classical return

probability in terms of the eigenphases derived from the quantisation condition. I have also calculated the leading order of the Weyl formula in separable Andreev billiards, such as box- and disk hybrid billiards.

4. I have calculated the numerically exact energy levels of box and disk billiard systems without assuming Andreev approximation. In the DOS singularities were found at equal distances. I have understood these singularities to be related to a singular length in the classical return probability. In disk billiard I have showed that there is an additional contribution to the Andreev States (AS), stemming from the Whispering Gallery States (WGS). The WGS give a finite value in the DOS even at the Fermi energy.

5. I calculated the conductance of a system, where two fully polarised ferromagnetic wires with opposite polarisations make contact with a diffusive spacer and a spin-singlet superconductor, by solving the BdG equation with a recursive Green function technique. I have found that a potential induced current in one of the wires induces a so-called non-local current in the other wire with equal sign. The important process here is the Andreev transmission. The dependence of Andreev transmission on geometrical parameters can be explained by a simple resistor model. I have also found that a square shaped spacer maximises the Andreev transmission.

3 Publications

1. G. Vattay, J. Cserti, G. Szálka and J. Koltai:
   „Periodikus mezoszkopikus struktúrák vezetési tulajdonságai"
   Proceedings of the Hungarian Academy of Sciences (1999).

2. J. Cserti, G. Vattay, J. Koltai, F. Taddei and C. J. Lambert:
   "Negative Length Orbits in Normal-Superconductor Billiard Systems"
   Phys. Rev. Lett. **85**, 3704 (2000).

3. J. Cserti, A. Kormányos, Z. Kaufmann, J. Koltai and C. J. Lambert:
   "Proximity-induced sub-gaps in Andreev billiards"
   Phys. Rev. Lett. **89**, 057001 (2002).

4. J. Cserti, A. Bodor, J. Koltai and G. Vattay:
   "Excitation spectra for Andreev billiards of box and disk geometries"
   Phys. Rev. B **66**, 064528 (2002).

5. C. J. Lambert, J. Koltai and J. Cserti:
   "Non-local current correlations in ferromagnet/superconductor nanojunction"
   in *"Towards the Controllable Quantum States, Mesoscopic Superconductivity and Spintronics"* (eds.: H. Takayanagi and J. Nitta),
   World Scientific, New Jersey, pp. 119-124 (2003).
   (Proceedings of the International Symposium on Mesoscopic Superconductivity and Spintronics (MS+S2002).)

6. J. Koltai, J. Cserti and C. J. Lambert:
   "Andreev bound states for superconducting-ferromagnetic box"
   Phys. Rev. B **69** 092506 (2004).