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Summary

In this thesis we present the results of an experimental study of electronic transport in certain unique mesoscopic systems. In its main lines, the work can be subdivided into two parts. The first part (by far the largest one) is concerned with the investigation of electronic transport phenomena in hybrid normal/superconductor systems where transport in the normal conductor is ballistic and phase coherent. The aim of this part of the work is twofold. First, phase coherent ballistic transport in hybrid normal/superconductor systems has never been investigated experimentally before and it is interesting to look for new phenomena that are characteristic of this transport regime, as compared, for instance, with the diffusive transport regime. Second, owing to the ballistic nature of transport, one expects the concepts required in the description of the experiments to be "simple" and as close to fundamental theoretical idealizations as possible. This simplicity permits to study relevant theoretical issues experimentally and, at the same time, makes it easy to conceive new experimental systems, capable of providing both useful fundamental information and possible novel applications.

The second part of the work reports an experimental study of the properties of Aharonov-Bohm effect conductance oscillations measured in the presence of a strong uniform spin orbit interaction. The possibility of investigating this interesting problem experimentally had not been foreseen at the beginning of the research project and it originates from the combination of three factors. These are a fairly broad knowledge of mesoscopic physics and of its open problems, the development of submicron processing technology of InAs/AlSb heterostructures, and the availability of such a heterostructure, in which the magnitude of spin-orbit interaction turned out to be comparable to the largest ever observed: the first two of these three factors provide a link between the first and the second parts of the thesis.

A good starting point to summarize in some details the specific contents of this thesis is by emphasizing the role of the progress in submicron fabrication technology which has made most of the work possible. One of the few experimental systems presently available in which it is possible to perform the experiments described in this thesis is a 2 dimensional electron gas present in an InAs/Al(Ga)Sb

heterostructure. If one wants the transport in such a system to be fully phase coherent and ballistic, it is mandatory to realize submicron electronic circuits. The technology to process InAs and AlSb on this small dimension scale was not available at the time when the work here discussed was started, and the development of that technology is one of the relevant results discussed in this thesis (Chapter 3). Extensive electrical characterization of very small samples (down to a size of approximately 100 nm) fabricated with this technology demonstrates that the technology itself preserves the characteristics of the material and that it does not introduce substantial damage.

The first experimental systems realized with the newly developed processing technology are 2 dimensional ballistic cavities, connected to two superconducting electrodes (via highly transparent interfaces) on one side and to one or two ballistic point contacts on the opposite side (Chapter 4). The use of point contacts makes it possible to perform spatially resolved injection of electrons and detection of Andreev reflected holes. In addition, the tunability of the phase of the order parameter in the two superconducting electrodes allows us to observe directly quantum effects due to the interference of Andreev reflected holes. In practice the effects of spatially resolved electron (hole) injection (detection) and of quantum interference effects manifest themselves when measuring the differential resistance of the point contact as a function of magnetic field and energy of the injected electrons.

The experimental results show that the so called classical retroreflection of holes associated with Andreev reflection is absent in our system, due to disorder present at the 2DEG/superconductor interface. Nevertheless, Andreev reflected holes have a larger probability to return to the point of injection of the electrons, as compared to what is expected from a classical point of view (i.e. if one assumes that electrons and holes behave as classical particles), as a consequence of phase conjugation of the electron-hole wave which produces a large constructive quantum interference.

One of the important outcomes of these experiments is to show how the study of the conductance oscillations induced by the tunable superconducting phase difference provides useful information on the quantum dynamics of electron and holes. The validity of this statement is not limited to the specific geometry envisaged in the experiments just mentioned: in general one can use the study of the resistance oscillations as an experimental tool in the investigation of a number of phenomena. This tool has played a key role in another experiment discussed in this thesis, namely the study of Andreev bound states formed between two superconductors which confine the electron-hole motion at energy smaller than the superconducting energy gap.

Our experimental study of Andreev bound states exploits an analogy with resonant tunnelling through two tunnel barriers connected in series (the analogy is discussed in Chapter 5). It is possible to study resonant tunnelling by substituting the tunnel barriers with "superconducting barriers" which allow either Andreev reflection or tunnelling through the superconducting gap. Electron transmission resonances through the "superconducting double barrier" thus created occur at specific values of the electron energy. In analogy with the well known case of conventional resonant tunnelling, where the resonances reflect the existence of quasi bound states between the two tunnel barriers, these resonances are a manifestation of the existence of Andreev "quasi" bound states in which the electron hole motion is confined by the superconducting gap. Also in analogy with a conventional resonant tunnelling system, the electronic processes responsible for the existence of Andreev states (and of the corresponding resonances) are multiple Andreev reflections occurring at the two superconducting barriers. It is important to realize that these are the same processes responsible for the resistance oscillations that one observes when measuring the resistance of a superconducting double barrier as a function of the superconducting phase difference. Therefore, studying the energy dependence of these resistance oscillations in a superconducting double barrier provides a way to investigate the properties of Andreev bound states.

In practice, the experimental implementation of a superconducting double barrier consists of a ballistic channel etched in a 2 dimensional electron gas with two superconducting electrodes connected in series (Chapter 6). Because of technical reasons, one of the superconducting "barriers" is realized by connecting a superconductor only to a region at the sides of the channel (and not across the entire channel, as it would be ideally preferrable), so that the electron hole motion is not truly confined in the region between the two superconductors. Such a side superconducting contact can be considered as a very transparent superconducting barrier, with a rather large electron transmission probability, therefore capable of providing only a weak confinement. As a consequence of this weak confinement, one expects (on the basis of the study of the idealized model discussed in Chapter 5 and in analogy with the case of conventional resonant tunnelling) the Andreev states to be very broadened. Consequently one does not expect to observe sharp lorentzian resonances in the Andreev and normal reflection probabilities as a function of the electron energy. The resonances are smeared into an oscillatory energy dependence, which can be described by the lowest order processes of the infinite series of multiple Andreev reflections responsible for the formation of fully developed Andreev bound states.

We have measured the phase dependent part of the differential resistance of the "superconducting double barrier" samples, as a function of the bias voltage, which gives us direct information on how the (phase modulated part of the) Andreev reflection probability depends on energy. Indeed, consistently with the previous discussion, we have observed that the phase modulated part of the Andreev reflection probability oscillates as a function of energy. The period of the oscillation corresponds to the value estimated from the known system parameters (sample dimensions, magnitude of the electron Fermi vector and Fermi energy). A semiclassical model based on the physical picture outlined above makes it possible to interpret satisfactorily the main features of the experimental data in some detail.

Perhaps the most notable property of Andreev bound states, which makes their investigation relevant, is the relation with the supercurrent flowing in superconducting junctions. Each bound state gives a contribution to this supercurrent and the total supercurrent can be expressed theoretically as the sum of the contributions due to all the bound states between the superconducting electrodes of the junction. The contribution of a single bound state to the supercurrent is proportional to the bound state occupation probability. Therefore, if one is able to control the occupation probability of bound states in a superconducting junction, one can modify the supercurrent. This possibility is attractive in two respects. On the one hand, by studying the supercurrent flow as a function of the bound states occupation probability one can obtain information on the properties of the bound states themselves. On the other hand, the ability of affecting the supercurrent flow is useful of its own, since it can have potentially relevant consequences for superconducting electronics applications. Theoretical ideas related to this kind of effects and possibilities have been discussed in the past, but no experimental work has ever been done.

We have realized a new kind of superconducting junction in which the electronic population in the region between the superconducting electrodes can be electrically controlled. For technical reasons this new superconducting junctions (described in Chapter 7) have been realized by using a diffusive normal metal in between two superconducting electrodes, but the same kind of junctions would work (and would be definitely interesting to study) if a ballistic 2DEG would be used. The results obtained demonstrate the controllability of the supercurrent, and give a fairly clear and consistent picture of the phenomenon. The work done on this kind of superconducting junctions has been limited by the available time and the possibilities for future experiments seem to provide a variety of interesting research directions.

Before proceeding to discuss the second part of the work done on this thesis (electronic interference in presence of spin-orbit interaction) we would like to put the results discussed so far in the proper perspective. In particular we would like to emphasize that the study of ballistic transport in a 2DEG connected to superconductors presented here should not considered as a complete and fully understood piece of work. Those presented in this thesis are the first experiments on the subject, and we have confined ourselves to the analysis of some of the most apparent features of our experimental results. More investigations are required before our understanding of the influence of superconductors on phase coherent ballistic transport can reach a level comparable to that presently achieved in the study of diffusive phase coherent conductors connected to superconductors. This is true from both the experimental and the theoretical point of views.

We now move on to summarize the second and final part of the work discussed in this thesis, namely the study of the Aharonov-Bohm effect in the presence of strong spin-orbit interaction. Within the realm of mesoscopic physics a typical way to study the Aharonov-Bohm effect is by measuring the conductance oscillations of a ring shaped conductor (small enough for electron transport to occur in the phase coherent regime) as a function of a magnetic field producing a magnetic flux piercing the hole of the ring. The period of these oscillations (for a single ring) corresponds to a flux of h/e through the ring. Normally, the electron spin does not play an important role in the Aharonov-Bohm effect: conductance oscillations with the same frequency would also be observed if the electrons were spinless.

However, if the ring is fabricated using a material in which spin-orbit interaction is strong, the properties of the Aharonov-Bohm conductance oscillations can be affected by the behaviour of the electron spin. In particular, in the presence of spin-orbit interaction, the electron spin is free to rotate while the electrons circulate in the ring. During this rotation the spin part of the electron wave function acquires a Berry's (or Aharonov-Anandan) geometric phase which couples to the electron dynamics in a way that is very similar to the way in which the Aharonov-Bohm flux does. This geometricc phase, which has opposite sign for electron states having spin pointing in opposite directions, manifests itself when one measures the conductance of a ring as a function of an applied perpendicular magnetic field. The perpendicular field generates a magnetic flux piercing the ring causing the Aharonov-Bohm conductance oscillations. Besides, because of Zeeman interaction, the perpendicular field tends to align the electron spin parallel to itself, thus suppressing the spin rotation and, consequently, the magnitude of the geometric phase. The decrease of the Berry phase with increasing perpendicular field results in an experimentally observable splitting of the frequency of the Aharonov-Bohm conductance oscillations.

The experimental detection of this splitting is the aim of the work discussed in this thesis. The difficulty of the experiment is related to the fact that the magnitude of the splitting is expected to be rather small. Specifically, the experimentally measured Aharonov-Bohm conductance oscillations do not have a sharply defined value of frequency. Instead the possible frequency values have a continuous distribution whose width is determined by the geometrical width of the arms of the ring used in the experiment. Given the dimensions of the samples presently realizable, this width is larger than the expected splitting associated with the effect of the geometric phase. In practice this implies that if one studies the Fourier spectrum of the Aharonov-Bohm oscillations one cannot expect to observe two well separated peaks (corresponding to the two split frequencies), but only a small feature present on the top of a single, broad, peak. In the Fourier spectrum obtained from a single measurement of an Aharonov-Bohm ring this features is in general hidden by sample specific effects.

In order to achieve the sensitivity necessary to observe such a small splitting we have succeeded in suppressing the sample specific fluctuations superimposed on the Fourier spectrum of the Aharonov-Bohm conductance oscillations. The central idea is to measure the "ensemble-averaged" Fourier spectrum, a quantity that had not received much attention in previous investigations of the Aharanov-Bohm conductance oscillations. The experimental study of this quantity makes it possible to reveal the presence of a splitting in the peak of the (ensemble-averaged) Fourier spectrum, whose magnitude is compatible with the one that should be produced by the presence of a geometric phase.