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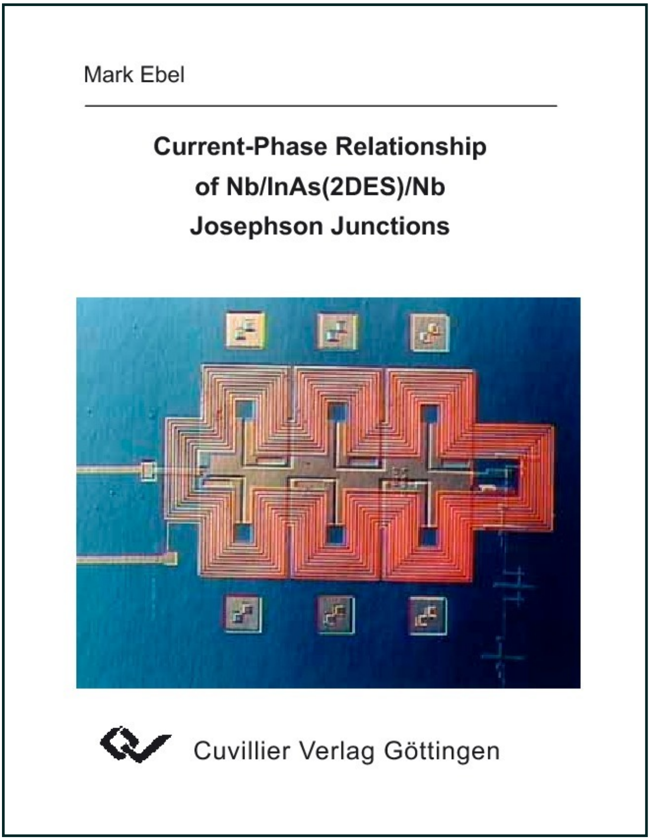
Current-Phase Relationship of Nb/InAs(2DES9/Nb Josephson Junctions



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1. Introduction

Superconductivity, i.e. the complete disappearance of electrical resistance in various solids when cooled below a characteristic temperature T_C, was discovered by the Dutch physicist Kamerlingh Onnes (1911), who was awarded the Nobel prize in physics in 1913. A microscopic explanation became available with the BCS theory developed by Bardeen, Cooper, and Schrieffer (1957), earning them the Nobel prize in physics in 1972. Cooper discovered that electrons in superconductors are grouped in Cooper pairs, and that all of the Cooper pairs within a superconductor are correlated by a single macroscopic wave function. As a certain minimal amount of energy is needed to break up a Cooper pair, there is a gap Δ in the distribution of energy levels available to the electrons. Δ is temperature-dependent and vanishes at T_C.

Some of the most fascinating aspects of superconductivity are shown by Josephson junctions. Josephson (1962) predicted that a supercurrent could flow even between superconductors separated by a short area of non-superconducting material. He was shortly validated experimentally by Anderson and Rowell (1963) and was awarded the Nobel prize in physics in 1973. This Josephson current exhibits curious properties, for which many applications have been found since. The devices showing the effect are known as Josephson junctions. While Josephson initially focussed on tunneling junctions, where the superconductors are separated by an insulator, Josephson junctions exist for all small areas of weakened superconductivity between bulk superconductors, e.g. a constriction or a normal conducting layer. The family of Josephson junctions with finite normal conductivity is known as weak links, in contrast to tunneling junctions. Andreev (1964) proposed a microscopic model to explain the superconductivity in superconductor/normal conductor/superconductor (SNS) junctions, illustrated in Fig. 1.1, by a special Andreev reflection of quasiparticles[1] at the interfaces, in which Cooper pairs can cross the barrier in a coherent process. Competing with Andreev reflection are the familiar processes of normal reflection and quasiparticle transmission into the superconductor. The respective probabilities depend on energy and the interface properties and can be calculated using the Blonder, Tinkham, and Klapwijk (1982) (BTK) model. This model was extended into the OTBK model of Octavio, Tinkham, Blonder, and Klapwijk (1983) to deal with the complex phenomena in a SNS junction. However, as incoherent ballistic models, their range of applicability is restricted, as the quasi-classical assumptions are not satisfied in most junctions. Therefore these models, which are relatively easy to understand, are useful to explain the basic effects, but for

[1] When a Cooper pair breaks apart, the unpaired electrons are called quasiparticles.

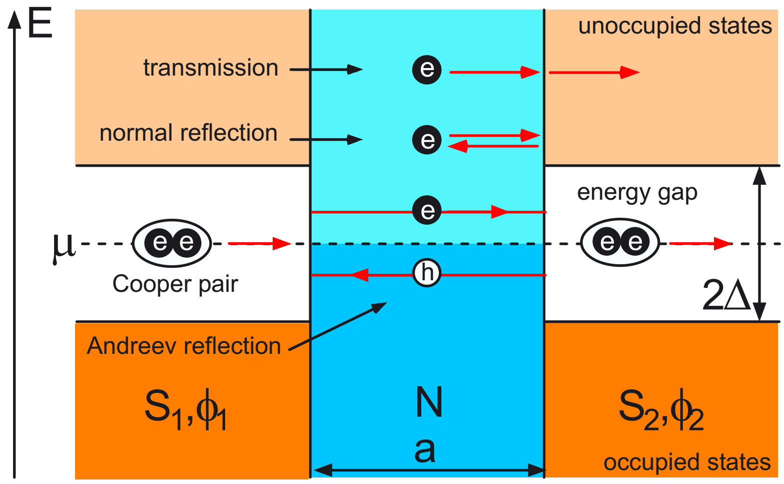

Figure 1.1: An electron e approaching the NS interface cannot enter the superconductor S if its energy E is less than the energy gap Δ, because there are no available single-particle states. However, together with a matching electron from the Fermi sea, carrying opposite momentum and energy relative to the chemical potential μ, a Cooper pair can be formed in a process called Andreev reflection. A hole h remains, which traces the path of the incident electron and is reflected at the other SN interface as an electron, absorbing a Cooper pair in the process. Thus, a round trip provides a coherent mechanism for transporting Cooper pairs from one electrode to the other, forming an Andreev bound state. Interference of wave functions allows only certain numbers and positions of bound states, depending on the phase difference across the junction $\varphi = \Phi_1 - \Phi_2$ and the junction length. Also pictured are the alternative processes of transmission, if the electron energy is sufficient to reach an unoccupied state; and normal reflection, which occurs at imperfect interfaces.

the quantitative evaluation advanced mesoscopic scattering-matrix models should be used (see Bratus et al., 1995; Samuelsson et al., 2003, and references therein).

This work reports on highly transparent weak links, i.e. such with a high probability of Andreev reflection, in the Nb/InAs(2DES)/Nb system. These devices offer many exciting possibilities for basic research and applications. One example is a tunable superconductor/normal conductor/superconductor (SNS) Josephson junction, where the properties of the coupling two-dimensional electron system (2DES) can be influenced via a gate electrode. This device is known as Josephson field-effect transistor (JoFET), and was developed by Takayanagi and Kawakami (1985). It is also possible to construct a transistor by influencing the 2DES via current injection (Richter et al., 2002). The exact conduction mechanisms in these devices are still not fully understood. Although there are several theoretical models for certain aspects of junction behavior, none of them explains all aspects and is acknowledged universally.

For theoretical modeling of a Josephson junction, the dependency of the supercurrent I_S flowing through it on the phase difference φ across the junction is fundamental. $I_S(\varphi)$ is known as current-phase relationship (CPR). Josephson (1962) predicted a sinusoidal CPR $I_S(\varphi) = I_C \sin\varphi$ for tunnel junctions. SNS junctions with highly transparent interfaces are predicted to show significant deviations from a simple sinusoidal CPR at low temperatures. Direct experimental access to it could lead to further insights into the complex conduction mechanisms in these devices. Conversely, with a knowledge of the mechanism, evaluation of the CPR can yield information on the junction characteristics. Additionally, precise knowledge of the CPR is important for using these junctions as sensors or components in superconducting electronics. Standard methods in circuit design like the RCSJ[2] model (Stewart, 1968) implicitly assume a sinusoidal CPR, so these will either have to be modified or restricted in their range of validity for junctions with non-standard CPRs.

The continuing interest in superconductivity is exemplified in the awarding of the 2003 Nobel prize in physics to Ginzburg and Abrikosov for pioneering contributions to the theory of superconductors. Superconductors are slowly finding economic applications besides their use in research. The main advantages of devices made from superconductors are low power dissipation, high-speed operation, and high sensitivity. Because of their high costs of operation, they are initially introduced in areas where quality takes precedence over price, e.g. for medical, scientific or military applications. Current uses for superconducting materials include magnets, medical devices, power distribution equipment, magnetically levitated trains, motors, generators, transformers, computer parts, and the devices known as superconducting quantum interference devices (SQUID), which provide the most sensitive way of measuring magnetic fields, voltages, or currents. One exciting possible application of superconductivity is the field of quantum computing, where much research activity has been focussed in recent years. This rapidly developing field promises breakthroughs in computing power and could solve mathematical problems not accessible with conventional digital electronics. Although a commercially useful quantum computer is not expected in the next decades and is by no means certain at all, the interest of the international business press is exemplified by an article of the Economist (2001). The basic component of quantum computing is the quantum bit or qubit, a quantum mechanical system with two basic states. Many physical realizations of qubits have been proposed and built. Because of the inherent coherence of the macroscopic wave function in superconductors, they represent obvious candidates for solid state qubits. Research has focussed on two candidates, the flux and the charge qubit (see Makhlin et al. (2001) for a review). Although most projects up to now have used tunnel junctions, there is no fundamental reason against SNS weak links. The use of tunable junctions, e.g. JoFETs, in building qubits would allow fine-tuning of the devices after fabrication, thus eliminating the inevitable variance of device characteristics, which is feared to impede quantum computation in solid state devices (Keyes, 2002). Additionally, the application of JoFETs as switches for qubits has been proposed by Storcz and Wilhelm (2003).

[2] The resistively and capacitively shunted junction model offers an equivalent circuit to calculate Josephson device characteristics.

This work is organized as follows: Chapter 2 gives details on the design and fabrication of the Josephson junctions used in this project. Transport measurements of these devices, employed to determine their electrical properties, are presented in Chap. 3. The current-phase relationship is investigated in Chap. 4, before concluding in Chap. 5. Appendix A describes the Niobium sputter deposition system, the most important tool for the fabrication of the samples. The publications derived from this work are listed in Appendix B, detailed preparation parameters and a list of abbreviations are given in the Appendices C and D, respectively.

2. Design and Preparation of Nb/InAs(2DES)/Nb Josephson Junctions

The basic component of superconducting electronics is the Josephson junction. In our samples, two superconducting electrodes S are weakly coupled by a normal conducting layer N, defining a superconductor/normal conductor/superconductor (SNS) Josephson junction. The normal conducting layer is a two-dimensional electron system (2DES). Because of its direct (i.e. non-tunnel) conductivity, this type of junction is known as weak link as opposed to the much more common tunneling SIS junctions with insulating barriers I. We use two distinct junction designs on two substrates for a total of three junction types. Although they share some common properties, there are several important distinctions. At first, the different junction types and their working principles are introduced. Afterwards, their fabrication is described in detail.

2.1. Junction Types

Niobium (Nb) is the sole superconductor used in this project. As pure polycrystalline bulk metal, Nb becomes superconducting at $T_C = 9.25\,\mathrm{K}$ (Gmelin, 1969). This is the highest value of all elements. Nb is an attractive material for our purposes because of its relatively straightforward preparation and handling as thin film. By using Nb instead of alloys or ceramic high T_C superconductors, we do not have to worry unduly about stoichiometry, crystal orientation or effects of unconventional superconductivity.

Figure 2.1(a) shows an overlap junction as developed by Chrestin and Merkt (1997). Two Nb electrodes on a substrate of p-type InAs single crystals are separated by an insulating oxide layer of some 10 nm thickness. Bulk p-type InAs is chosen for the naturally forming 2DES on its surface and its lack of a Schottky barrier (Mead and Spitzer, 1964), which facilitates contact to metals. The overlap layout is similar to a tunneling junction, but the thickness of the oxide barrier prevents significant tunneling, so all current flows through the 2DES. In the vicinity of the superconductors, the electronic properties of the 2DES in the inversion layer at the surface of the InAs are influenced by the proximity effect, resulting in an area of induced superconductivity (de Gennes, 1964; Chrestin et al., 1997). The main advantage of this design is the short channel length a of $10-40\,\mathrm{nm}$, which can be controlled with nanometer precision. At a typical