1. Introduction

In 1911 the Dutch physicist Heike Kammerlingh Onnes discovered that mercury looses its electrical resistance when cooled down below a characteristic transition temperature T_c [1]. This phenomenon is called superconductivity. In the superconducting state currents up to a certain amount, called the critical current I_c, can be driven through the superconductor (S) without any dissipation of energy, i. e., without a voltage drop across the sample. For this striking discovery Onnes was awarded the Nobel prize in 1913. It took 46 years after his pioneering work before in 1957 a microscopic theory was developed that is valid for conventional low-temperature superconductors like mercury and niobium (Nb). It is known as BCS theory, named after its authors Bardeen, Cooper, and Schrieffer [2]. In the BCS theory the formation of so-called Cooper pairs with charge $2e$ is postulated. A Cooper pair consists of two electrons with opposite momentum and spin that are bound by an attractive electron-electron interaction which originates from the crystal lattice and even overcomes the Coulomb repulsion. Cooper pairs constitute the superconducting ground state for a huge number of interacting electrons. The crucial result of the BCS theory is that they are described by one macroscopic wave function $\Psi = |\Psi| \cdot e^{i\varphi}$. Here, φ denotes the phase and $|\Psi| \sim \sqrt{N}$ is the amplitude that is proportional to the square root of the Cooper pair density N. The motion of the Cooper pairs is scatterless. This is possible because the ground state is separated from the single-particle states by an energy gap Δ whose value is characteristic for each superconductor. The energy gap opens monotonously and symmetrically to the chemical potential for decreasing temperatures below T_c and eventually saturates for $T \to 0$. To destroy a Cooper pair one has to excite carriers from the superconducting ground state, thus creating so-called quasiparticles. This requires an energy of at least $2\Delta(T)$. Within the BCS model the switching of a superconductor into the resistive state when exceeding I_c can be understood: Above I_c the momentum and thus, the energy of the Cooper pairs is larger than $2\Delta(T)$ which results in the destruction of the Cooper pairs and concurrently in the breakdown of the superconducting state.

If two superconducting electrodes are separated by a few nm thick insulating barrier (I) a supercurrent still can flow from one electrode to the other due to Cooper pair tunneling. This effect was predicted in 1962 by Brian Josephson and eventually named after him as dc Josephson effect [3]. Superconductors coupled by an insulating barrier support a current according to the first Josephson equation (e. g. $I = I_\mathrm{c} \cdot \sin\phi$) which connects the supercurrent through the SIS junction with the phase difference $\phi = \varphi_1 - \varphi_2$ of the two superconductors. Such a contact is called Josephson junction. The maximum supercurrent I_c flows when the phase difference ϕ reaches $\pi/2$. ϕ can be tuned by the bias-current or an external magnetic field [4]. The dc Josephson effect was found experimentally one year later in 1963 by Anderson *et al.* [5]. If the current in the junction exceeds I_c another remarkable property becomes evident which is formulated in the second Josephson equation: $\omega_\mathrm{J} = \mathrm{d}\phi(t)/\mathrm{d}t = 2eV(t)/\hbar$. The meaning of this fundamental equation is that in the resistive state a radio-frequency (rf) voltage drops across the junction that is accompanied by the emission of electromagnetic waves with a well defined frequency of 483.6 GHz per mV. This effect is called the ac Josephson effect and has been found experimentally in 1963 by Sidney Shapiro [6]. In 1975 Brian Josephson received the Nobel price for his seminal works on the dc and ac Josephson effects that have paved the way for a large variety of interesting applications.

As for the dc Josephson effect, in magnetometers consisting of dc superconducting quantum interference devices (SQUID) the high sensitivity and low signal to noise ratio are exploited to detect very small magnetic fields, e. g., such as produced by the currents that flow in the human brain [7]. Nb-based gradiometer systems are used for geomagnetic and archeologic measurements [8]. In the highly topical field of quantum computing Josephson junctions may become a central part of quantum bits [9] where also Josephson field-effect transistors can be used as switches [10].

The most familiar application using the ac Josephson effect is the volt-standard for the definition of the unit "Volt" [11]. Moreover, superconductors are employed for the fabrication of high quality mixers for astronomical observations [12], optical-microwave converters and detectors for sub-THz waves [13], or high frequency-filters for cell-phone stations [14, 15].

By substituting the insulating barrier I with a normal-conducting (N) material and thus forming a SNS junction, the physics changes significantly. Large supercurrents can be observed in SNS junctions of lengths where Cooper pair tunneling can be ruled out completely. Also, the sinusoidal current-phase-relation (CPR) formulated in the first Josephson equation changes to a saw-tooth like CPR for SNS junctions with highly transparent interfaces. Still, these junctions obey the second Josephson equation. The occurrence of supercurrents in SNS junctions can be explained with the concept of Andreev reflection (AR). The AR is a phase-coherent process in which an electron (hole) in the normal conductor with energy $|\varepsilon| < \Delta$ is reflected as a hole (electron) at the SN interface while creating (annihilating) a Cooper pair in the superconductor. Since AR processes are possible at both SN interfaces of a SNS junction the flow of a supercurrent can be understood in terms of multiple AR processes as Cooper pairs that are destroyed on one side and created on the other side of the contact. These current-carrying states only exist for certain energies that are determined by a specific quantization condition [16]. They are called Andreev bound states or Andreev levels. The magnitude and direction of the supercurrents carried by the single Andreev levels depend on the phase difference between the two S layers and the shape of the levels. The shape again is connected with the SN interface quality and the length L of the junction. In particular, the magnitude of the supercurrent increases with the interface quality and decreasing L. To observe supercurrents in SNS junctions their length L has to be smaller than the coherence length ξ_N of the normal-conductor which depends on the Fermi velocity and mobility of the electrons in the N layer. In the ballistic (L smaller than the elastic mean free path l_e) and clean limit ($\xi_\mathrm{N} < l_e$) the electron motion in the N layer is scatterless and the supercurrent is fully determined by the occupation of few Andreev bound states. In this regime their direct observation is possible since only a very small number of levels is located within the energy gap and can be made visible by a resonant tunneling experiment.

To fabricate ballistic samples in the clean limit the use of pure metals is not suitable because junctions with normal metals are mostly in the diffusive regime due to the small elastic mean free path l_e. If, instead, the two-dimensional electron system (2DES) of a semiconductor is used as N layer the preparation of ballistic junctions in the clean limit is possible with electrode separations between 0.1 and 1 μm depending on the semiconductor (see material systems in chapter 2).

In this thesis hybrid devices consisting of Nb and indium arsenide (InAs) with a 2DES are investigated. The advantage of InAs is the absence of a Schottky barrier in contact to metals which allows for the fabrication of highly transparent SN interfaces. Unique transport phenomena occurring only in ballistic SNS junctions are investigated and presented here for Nb/InAs(2DES)/Nb SNS junctions. The 2DES is provided in the native inversion layer on p-type bulk InAs or in the InAs channel of a modulation-doped InAs heterostructure grown on GaAs. The dc and ac Josephson effects are studied in both types of junction. Since the charge $2e$ is transported through the SN interface for every AR process the conductance of such a SNS junction is considerably enhanced for voltages $V < 2\Delta/e$. The additional current produced by multiple AR processes is called excess current and is one of the most prominent differences between SNS and SIS tunnel junctions. In particular, the interplay of the ac Josephson effect with the occurrence of large excess currents leads to considerable effects: The slope of the direct current-voltage (I–V) characteristic is much less steep than that in tunnel junctions. Concurrently, the Shapiro steps are more pronounced and their widths are enhanced noticeably.
By using a 2DES the normal state resistance can be tuned by changing the carrier density via the field effect. Moreover, in so-called superconducting quantum point contacts the combination of a quantum point contact, in which the number of conducting channels can be tuned, with the superconducting properties of Nb is possible. Then, the quantization of the critical current is expected.

This thesis is organized as follows. In chapter 2 an overview of the used materials is given. Because the Nb sputter technique is crucial for this work it is briefly described followed by the different preparation techniques that are applied for the fabrication of the samples. Chapter 3 summarizes and compares transport measurements that have been performed on ballistic SNS Josephson junctions on different semiconducting systems. In chapter 4 the microwave properties of these junctions are described. The spectroscopy of Andreev bound states in heterostructure-based SNS Josephson junctions is presented in chapter 5. The conclusions can be found in chapter 6. Important parameters of the preparation processes are quoted in the Appendix.

2. Materials and Sample Preparation

Abstract

A short overview of the used materials is given and the magnetron sputter deposition process of the low-temperature superconductor niobium is briefly described. Depending on the basic material system different preparation techniques have to be applied for the fabrication of hybrid devices.

2.1. Introduction

In this thesis hybrid devices consisting of semiconductors and superconductors are investigated. They all have been fabricated in the clean room facilities of the "Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung" in Hamburg. The Josephson junctions consist of two superconducting (S) niobium (Nb) electrodes that are weakly coupled by a quasi two-dimensional electron system (2DES) which provides our normal conductor (N). Two different systems that contain a 2DES are used, namely p-type bulk InAs single crystals and modulation-doped InAs-inserted-channel heterostructures grown on GaAs using molecular-beam epitaxy (MBE). On p-type InAs the 2DES covers the whole crystal surface whereas in the heterostructures it is buried 50 nm underneath the surface. Both materials have their specific advantages: the location of the 2DES on p-type InAs allows for the fabrication of highly transparent SN interfaces. In InAs heterostructures only a few nm thick InAs layer is available to make side contact to the superconductor. However, very high mobilities in the heterostructures lead to electronic mean free paths ($\approx 2.5\,\mu$m) and coherence lengths[1] that are larger by more than an order of magnitude compared to bulk InAs. This means that ballistic SNS junctions can be prepared comfortably up to electrode separations in the range of 1 μm. Moreover, only in InAs heterostructures the fabrication of quantum point contacts (QPC) and superconducting quantum point contacts (SQPC) can be realized because only here it is possible to create different electronically separated areas on one sample. Due to the different structures of the two normal-conducting materials specific fabrication techniques have to be applied.

This chapter is organized as follows. In Sec. 2.2 the properties of the superconductor Nb and the sputter process are briefly described. Sections 2.3 and 2.4 give an overview of the two material systems p-type bulk InAs and InAs heterostructure together with the corresponding preparation techniques[2].

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[1] The coherence length is the relevant length scale of the superconducting coupling in SNS contacts. To observe supercurrents in a SNS junction its length must be smaller than the coherence length of the semiconductor.

[2] Detailed process parameters can be found in the Appendix.

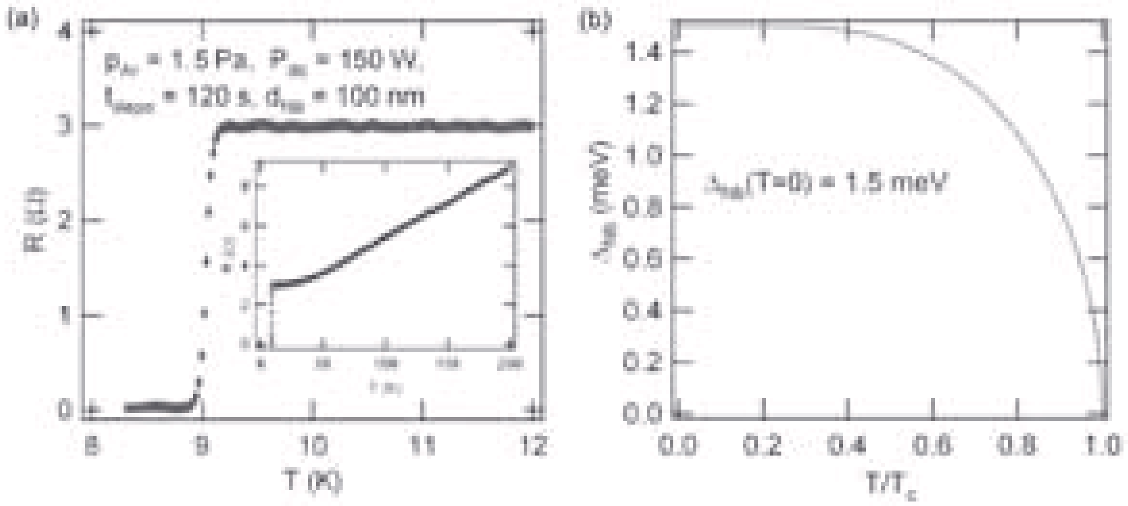

Fig. 2.1.: **(a)** Temperature dependence of the resistance of a Nb film. The process pressure was $p_{\mathrm{Ar}} = 1.5$ Pa, the dc power 150 W. A deposition time of $t = 120$ s leads to a film thickness of $d_{\mathrm{Nb}} = 100$ nm. The inset shows the whole recorded temperature range. **(b)** Temperature dependence of the superconducting energy gap according to the BCS theory.

2.2. Niobium

Niobium is a type II superconductor. It is the element with the highest critical temperature of $T_{\mathrm{c}} = 9.2$ K for polycristalline films. In the sputter deposited 100 nm thin Nb films critical temperatures up to $T_{\mathrm{c}} = 9$ K are achieved as shown in Fig. 2.1(a). The temperature dependence of the superconducting energy gap as predicted in the BCS theory [2] is depicted in Fig. 2.1(b). For $T = 0$ the gap value is $\Delta_{\mathrm{Nb}} = 1.5$ meV. Subharmonic gap structures (SGS) or excess currents (see Sec. 3.2) are expected to have a BCS-like temperature dependence as shown in Fig. 2.1(b).

2.2.1. Sputter Deposition

The deposition of Nb on the semiconductor samples is realized by magnetron sputtering in an ultra-high vacuum (UHV) vessel. The sample is put into a transfer chamber that allows for a convenient process time of about 3 hours because only the transfer chamber and not the whole vessel has to be vented and again evacuated prior to the process. After transferring the sample into the vessel it is flooded with Ar (≈ 1.5 Pa) and a three-step sputter process begins. At first, the Nb target is cleaned by dc magnetron sputtering. Concurrently, impurities from the atmosphere like oxygen and nitrogen are gettered. A special shutter system prevents the sample from being polluted during the cleaning step. At second, the sample surface is cleaned by rf sputtering (dc bias ≈ 180 V). This step can also be used as etching process. Finally, the shutter is opened and a 100 nm thick Nb film is deposited by dc magnetron sputtering. For details of the sputter process see, for instance, [17, 18].