SUPERCONDUCTING CONTACTS TO A TWO-DIMENSIONAL ELECTRON GAS IN GaAs/AlGaAs-HETEROSTRUCTURES

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Abstract — Recently we succeeded in making superconducting contacts of μm -scale to the two-dimensional electron gas in GaAs/AlGaAs-heterostructures, in combination with gate structures. The contacts produced by this method are highly transmissive down to very low temperatures. We present the first preliminary results of the resistance measurements at $T=80\text{ mK}$. These give clear evidence for the occurrence of Andreev reflection. Moreover a strong influence of the gate voltage on the $dV/dI - V$ -curves has been observed, which proves the essential role of the semiconductor.

I. INTRODUCTION

Since the idea of a Josephson field-effect transistor or superconducting transistor was described by T.D. Clark et al. [1], the interest for this device has been growing. It is based on the proximity coupling of two superconducting electrodes [2], connected by a semiconductor. The supercurrent which can flow through the device can be modulated by varying the electron density with a gate voltage.

The devices realized until now [3,4,5,6,7,8] are all operating in the dirty limit, where the electron transport is diffusive. Very different and new effects are expected in the clean limit, where the electron transport is phase coherent. Only recently the availability of very high mobility two-dimensional semiconductors and the state of microfabrication techniques make it possible to achieve this limit. This has resulted in a renewed interest in this subject, both theoretically and experimentally.

In this paper we will first discuss some aspects of the theory for this new class of superconducting devices. In the third section the fabrication of the samples is discussed, followed by the results of the first measurements in section IV.

II. THEORY

A superconducting weak link consists of a conducting material (metal or semiconductor), denoted by N, between two superconducting regions S. If there is a good electrical contact at the SN-interfaces, Cooper-pairs can "diffuse"

into the N-region, which results in a finite order parameter. This means that a supercurrent can flow through a semiconductor, if the distance L between the superconducting regions is small enough, i.e. of the order of the normal coherence length

$$\xi_N = \sqrt{\frac{\hbar D}{2\pi k_B T}}, \quad (1)$$

where D is the electron diffusion constant and k_B the Boltzmann constant. This formula is valid in the dirty limit $l_e < L$ (l_e is the elastic mean free path).

Recently it has been predicted that the critical supercurrent is quantized in the ballistic regime [9,10]. It would be interesting to test this with a quantum point contact between two ballistically connected superconducting electrodes.

An other process which can occur in SNS-systems is Andreev-reflection [11,12]. An electron in the N-region with an excitation energy E smaller than the superconducting gap Δ cannot enter the superconductor, because no excitation states are available. The electron will be reflected as a hole with excitation energy $-E$ in exactly the opposite direction with respect to the incoming electron, while a Cooper-pair is created in the superconductor. Since the incoming electron (hole) and the reflected hole (electron) contribute both to a current in the same direction, Andreev-reflection gives rise to an excess current and reduces the interface resistance [13]. In SNS-junctions multiple Andreev-reflection can take place, if L is sufficiently small. This will result in changes in the differential resistance at voltages corresponding to submultiples of the gap ($2\Delta/n$ with n integer).

The probability of Andreev-reflection is determined strongly by the transmission of the NS-interface. In particular at interfaces with semiconductors the Schottky-barrier can introduce normal reflection and reduce this probability significantly.

Especially in the clean limit Andreev-reflection is a very powerful concept for describing multiprobe SNS-systems, because it is easily incorporated in a generalized Landauer-Büttiker formalism [14,15]. New effects are expected in this ballistic regime, because of the phase coherence of the electrons. For example, because an electron which was reflected at one NS-interface can undergo the

Figure 1: Layout of the centre of the sample; the dashed lines are the boundaries of the etched mesa, the black areas are gold layers, the two rectangles are the Sn/Ti-contacts

reversed reflection process at the other NS-interface, a periodic motion can arise. This will result in quantization of the energy levels of the excitations and will lead to a Josephson current [16,17].

III. SAMPLE FABRICATION

To study the transport in the clean, ballistic regime the condition $l_e > L$ should be fulfilled. Moreover L should be large enough to put split-gate structures between the superconducting contacts. That means $l_e > \xi_N \gtrsim 10^{-6} \text{m}$. Because of the large mobility μ_e of the two-dimensional electron gas (2DEG), combined with the excellent gating properties GaAs/AlGaAs-heterostructures are preferred. Moreover the Fermi-wavelength is rather large, which facilitates the study of quantum effects ($\lambda_F \approx 50 \text{ nm}$). The material we used for the first tests had the following properties: $\mu_e = 42 \text{ m}^2/\text{Vs}$ and electron density $n_e = 3.1 \cdot 10^{15} \text{ m}^{-2}$, resulting in $l_e = 4 \text{ }\mu\text{m}$ and $\xi_N = 2.7 \text{ }\mu\text{m}$ at $T = 80 \text{ mK}$. The material was grown by Molecular Beam Epitaxy and consists of a GaAs-substrate with a $4 \text{ }\mu\text{m}$ undoped GaAs-layer, a 20 nm undoped $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ -spacer, a 40 nm n -doped $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ -layer and an 18 nm undoped GaAs-capping layer.

Fabricating a clean, superconducting, ohmic contact to the 2DEG, situated 80 nm below the surface, is a major problem. Dry etching, to bring the metallic contact closer to the 2DEG by removing the toplayer, will damage the material over considerable distances ($\gtrsim 100 \text{ nm}$) near the etched surfaces. That is why we have chosen a diffusion process. Details of the fabrication will be published elsewhere, so here we only give a short outline.

The layout of the sample is shown in figure 1. Because of the required resolution we used electron beam lithography. To align all the processing steps (one etching and up to three metallization steps) we had to use especially prepared gold markers. The alignment was done by automatic

Figure 2: The differential resistance as function of the voltage at different temperatures ($V_g = 0 \text{ V}$)

marker search. The achieved relative alignment turned out to be better than $\approx 30 \text{ nm}$.

The most important process steps are preparing gold markers, mesa-etching for device isolation, Sn/Ti-metallization and diffusion for the actual contacts and Au-metallization. In this first sample there are gates at the sides of the S-contacts to confine the area where the (super-)current can flow. The distance between the contacts was defined lithographically as $L = 1000 \text{ nm}$, the contact width is $10 \text{ }\mu\text{m}$. Four separated larger contacts were added, to enable tests (e.g. quantum Hall-measurement to test two-dimensionality). The measurements were performed in a dilution refrigerator at $T \approx 80 \text{ mK}$. The resistances were measured by a current-biased ac lock-in technique as well by dc methods.

IV. RESULTS

The results of the differential resistance measurements at different temperatures are presented in figure 2. Because of bonding problems the measurements on this sample were done in a three-terminal configuration. The estimated series resistance is $100\text{--}150 \text{ }\Omega$. A low resistance region exists around zero-voltage, flanked by two peaks. It has been checked by measuring the two contacts separately using the larger contacts, that this is not only a feature of a single contact. At first glance these measurements could be explained by the flow of a supercurrent in the system, taking into account a constant series resistance. However the series resistance turned out to be influenced by applying a gate voltage. Nevertheless the shape is typical for Andreev-reflection in NS-structures. The voltage where the jump in resistance occurs should correspond with 2Δ . In the Blonder-Tinkham-Klapwijk-model [13] the resistance below the jump should be half the resistance above it (in the clean case). This yields a series resistance of $139 \text{ }\Omega$. The corresponding gap is $9 \text{ }\mu\text{eV}$ at $T = 80 \text{ mK}$, which is possible for Ti. Moreover the typical shape of the curve has disappeared completely at 0.5 K .

This is in agreement with the critical temperature of Ti ($T_c \approx 0.4$ K). No evidence for multiple Andreev-reflection was found; perhaps the mobility of the 2DEG was not high enough to measure this.

At large negative gate-voltages V_g the resistance dip disappears completely. This remarkable effect is not very well understood yet, but it proves that the semiconductor plays an essential role in the origin of the peak structure.

V. CONCLUSIONS

The process of Sn/Ti-diffusion provides low-resistance (highly transmissive) contacts to the 2DEG in GaAs/AlGaAs-heterostructures. At temperatures down to 80 mK the resistance stays very low. The temperature and gate-voltage dependence of the dV/dI - V -curves show that Andreev-reflection must take place in the sample. The measurements suggest that Ti is the relevant superconductor and not Sn. The fact that the bottom of the low resistance region is very flat and does not show a peak near $V = 0$ V means that the transmission of the NS-interface is very close to 1. Therefore these superconducting contacts seem to be very suitable to study SNS-junctions in the clean limit.

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