

Andreev reflection and enhanced subgap conductance in NbN/Au/InGaAs-InP junctions

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We report on the fabrication of highly transparent superconductor/normal metal/two-dimensional electron gas junctions formed by a superconducting NbN electrode, a thin (10 nm) Au interlayer, and a two-dimensional electron gas in an InGaAs/InP heterostructure. High junction transparency has been achieved by exploiting developed process of Au/NbN evaporation and rapid annealing at 400 °C. This allowed us to observe a decrease in the differential resistance with pronounced double-dip structure within the superconducting energy gap in superconductor/two-dimensional electron gas (2DEG) proximity systems. The effect of a magnetic field perpendicular to the plane of the 2DEG on the differential resistance of the interface was studied. It has been found that the reduced subgap resistance remains in high magnetic fields. Zero-field data are analyzed within the previously established quasiclassical model for the proximity effect. © 2004 American Institute of Physics. [DOI: 10.1063/1.1783612]

I. INTRODUCTION

The study of hybrid systems consisting of superconductors (S) in contact with a two-dimensional electron gas (2DEG) has attracted considerable interest in recent years. Various new effects arising due to the Andreev reflection at the S/2DEG interface were studied in such systems, both theoretically and experimentally.^{1–12} By taking phase-coherent Andreev reflection into account, the oscillations in the conductance of a S/2DEG junction in magnetic field have been predicted which are based on an Aharonov-Bohm-type interference effect.^{2–5} The current transport across the S/2DEG interface in the quantum Hall effect regime was investigated by Hoppe, Zülicke, and Schön.^{6,7} They could show that bound states are formed at the S/2DEG interface which are the coherent superposition of electron and hole edge excitations.⁶ Very recently, the magneto-tunneling spectrum and the thermal conductance have been studied in a superconductor/quasi-one-dimensional semiconductor structure.⁸ The transport across a superconductor/semiconductor interface in the Hall geometry was discussed in Refs. 2 and 9. In Ref. 9, it is predicted that the Hall voltage is significantly suppressed near the interface compared to its normal metal value.

Experimental observation of these phenomena is a chal-

lenging problem because in most cases the high probability of Andreev reflection at the interface is essential. Since Andreev reflection is a two-particle process,¹³ it is strongly affected by the transmissivity at the S/2DEG interface. Therefore, a serious effort has to be made to achieve a high junction transparency in order to access the novel transport regimes of interest. Recently, Takayanagi *et al.*¹² reported the preparation of good ohmic contacts between NbN/AuGeNi electrodes and a 2DEG in an AlGaAs/GaAs heterostructure.

In this work, we report on the fabrication of highly transparent superconductor/2DEG junctions formed by superconducting NbN electrodes and a 2DEG in an InGaAs/InP heterostructure. High junction transparency has been achieved by the use of a thin (10 nm) Au interlayer between NbN and the heterostructure. This achievement allowed us to observe a decrease in the differential resistance with pronounced double-dip structure within the superconducting energy gap and to measure the dependence of this structure on the magnetic field. Previously, experiments on transparent S/2DEG junctions (in diffusive limit) revealed a peculiar non-monotonic voltage dependence of the differential resistance with a maximum at zero bias, referred to as “reentrant” resistance.^{14–18} In diffusive S/2DEG contacts with Schottky barriers, a large and narrow peak in the differential conductance of the junctions around zero bias voltage was observed.^{19–21} The latter effect, known as “reflectionless tunneling,” has been studied theoretically in Refs. 22–35. Below

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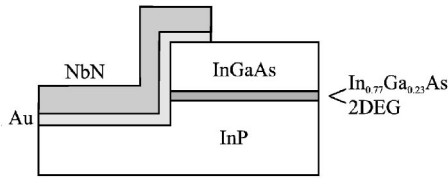


FIG. 1. Schematic of the sample layout. The two-dimensional electron gas is located in the strained In_{0.77}Ga_{0.23}As layer. The semiconductor mesa is defined by reactive ion etching. The Au/NbN electrodes make contact at the sidewalls of the mesa.

we will argue that the double-dip structure in the differential resistance detected in our measurements is related to the transport in SN-2DEG contacts in a ballistic regime.¹ Experimental data for zero magnetic field will be analyzed in our work within the quasiclassical model for the proximity effect developed in Refs. 1 and 36.

II. EXPERIMENT

Our experiments have been performed with strained InGaAs/InP heterostructures fabricated by metal organic vapor phase epitaxy (MOVPE) on a semi-insulating InP substrate. The InGaAs/InP heterostructures consist of a 400 nm thick InP buffer, a 10 nm thick (Si)-InP dopant layer ($N_d = 4.2 \times 10^{17} \text{ cm}^{-3}$), a 20 nm thick InP spacer, a 10 nm thick In_{0.77}Ga_{0.23}As layer containing the 2DEG, and a 150 nm thick In_{0.53}Ga_{0.47}As cap. The use of InGaAs/InP heterostructures with a strained In_{0.77}Ga_{0.23}As layer allows one to achieve a high mobility in the 2DEG owing to a low effective electron mass of $m^* = 0.036 m_e$ and a reduced contribution of alloy scattering. Shubnikov-de Haas and Hall effect measurements of our 2DEG structures revealed a carrier concentration of $7 \times 10^{11} \text{ cm}^{-2}$ and a mobility of about $250\,000 \text{ cm}^2/\text{V s}$ at 0.3 K. From these values a Fermi energy E_f of 37 meV and a transport mean free path of $3.6 \mu\text{m}$ were estimated.

A schematic of the sample layout is shown in Fig. 1. The semiconductor mesa was defined by electron beam lithography and reactive ion etching (RIE) using CH₄/H₂ gas mixture. We prepared two different types of electrodes to the two-dimensional electron gas in an InGaAs/InP heterostructure. The electrodes of the first type were 100 nm thick NbN layers deposited by dc magnetron sputtering. The NbN electrodes are contacted at the mesa sidewalls to the 2DEG. Directly prior to the deposition of NbN, the semiconductor surface was cleaned by an Ar plasma, in order to remove residual atoms at the surface. At the final processing step, the geometry of the NbN electrodes were defined using a lift-off technique. The electrodes of the second type were prepared by a modified two-step process. First, after the cleaning of the surface of the etched InGaAs/InP heterostructure by Ar-plasma, a thin (10 nm) Au interlayer was deposited *in situ* by dc magnetron sputtering followed by the deposition of the NbN electrode. Subsequently, we employed a rapid ($\approx 10 \text{ sec}$) annealing step. The temperature of annealing was 400 °C.

For the electrical characterization a three-terminal measurement scheme has been employed where a small ac current is superimposed to a dc bias current. The differential

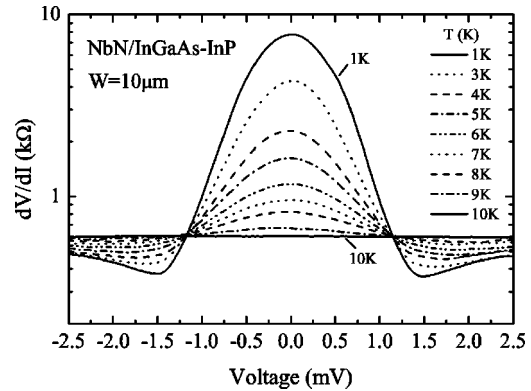


FIG. 2. Differential resistance vs bias voltage for a NbN/2DEG interface at different temperatures.

resistance is obtained by detecting the ac voltage by a lock-in amplifier. The ac excitation current was 10 nA. The measurements were performed at temperatures down to 0.3 K in a He-3 cryostat equipped with a superconducting solenoid with a magnetic field up to 10 T.

III. EXPERIMENTAL RESULTS

In Fig. 2, the differential resistance dV/dI as a function of the bias voltage measured at different temperatures is shown for a $10 \mu\text{m}$ wide NbN/2DEG interface. It is seen that at low temperatures, a pronounced resistance peak occurs at zero bias voltage, indicating a strong barrier at the NbN/2DEG interface. Measurements show that the height of the resistance peak does not depend on temperature in the low temperature range $T < 1.5 \text{ K}$. If the dc bias voltage approaches a value of 1.5 mV, a minimum in the differential resistance is observed. The position of this resistance minimum coincides with the superconducting energy gap determined from the critical temperature of superconductor T_c . At voltages $V_{dc} > 4 \text{ meV}$ a constant differential resistance is found. With increasing the temperature the resistance peak at zero bias as well as the minima at about $\pm 1.5 \text{ mV}$ become weaker and disappear completely at temperatures above $T_c \approx 10 \text{ K}$. The interface resistances of the NbN/InGaAs-InP interfaces are relatively high due to a high-barrier at the interface. In order to improve the contact characteristics, we modified the method of preparation of the S/2DEG interfaces of the structures as was discussed in the previous section. By using a thin gold interlayer, we succeeded to obtain a considerably smaller interface resistance.

Figure 3 shows the differential resistance of a $5 \mu\text{m}$ wide NbN/Au/2DEG interface as a function of the voltage drop at different temperatures. It is seen that a decrease in the differential resistance is observed within the range of voltages $\pm 1 \text{ mV}$ at temperatures below 6 K. This result is a characteristic of the transport across a junction with high probability of Andreev reflection, resulting in excess current at low bias.^{1,36} At zero dc bias voltage, the differential resistance exhibits a minimum. At 0.5 K, the zero-bias resistance dip reaches a value of about 15% of the normal state resistance R_N . At low temperatures ($< 2 \text{ K}$), in the voltage dependence of the differential resistance, we observed two shoulders, both symmetric in voltage. As the temperature is

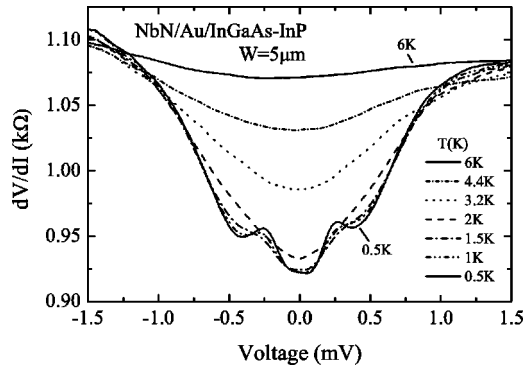


FIG. 3. Differential resistance as a function of the bias voltage for a NbN/Au/2DEG interface. The measurements are performed at several temperatures in the 0.5–6 K range.

increased, the double-dip structure in the differential resistance progressively disappears. At temperatures higher than 2 K, the feature at small voltages is suppressed and only a broad resistance dip within the range of 1 mV remains. Finally, at temperatures about 6 K almost constant differential resistance is measured. At this temperature the sample is effectively normal conductive, since the temperature is close to T_c .

Figure 4 demonstrates the effect of a magnetic field perpendicular to the plane of the 2DEG on the differential resistance of the NbN/Au/2DEG interface. The differential resistance is plotted versus dc bias current I_{dc} and is normalized to the resistance value R_i measured at 1.5 μ A. The measurements were performed at 0.5 K. It is seen that with increasing magnetic field B the reduction of the resistance at zero bias as related to its value at $I_{dc}=1.5 \mu$ A becomes smaller. The double-dip structure occurs on the scale of about several 100 mT and is still clearly seen at $B=0.9$ T. At high fields, the features are no longer well resolved, however a reduced zero-bias resistance remains even at magnetic fields of about 3 T. Note that in our samples, the onset of the Shubnikov-de Haas oscillations in the 2DEG is observed at a magnetic field of about 0.25 T. Therefore, our experiments indicate that the subgap conductance enhancement due to Andreev reflection is preserved in the regime of high-quantizing magnetic fields.

IV. DISCUSSION AND COMPARISON WITH THEORY

Detailed interpretation of the I-V curves in magnetic field requires separate study and will be reported elsewhere.

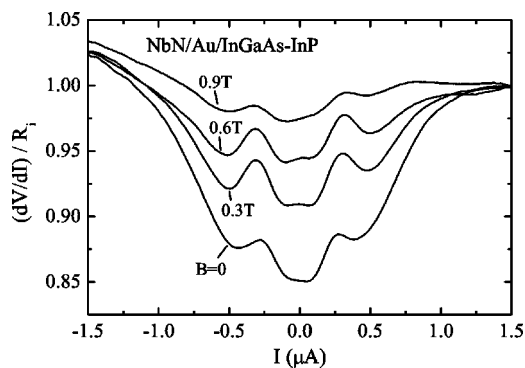


FIG. 4. Normalized differential resistance vs bias current of NbN/Au/2DEG interface for several magnetic fields. $T=0.5$ K.

Here we shall discuss the experimental data in zero field, in order to demonstrate that the regime of highly-transparent S/2DEG interfaces was achieved in our junctions.

First we analyze the experimental data using the well established Blonder, Tinkham, and Klapwijk (BTK) model for the current transport.³⁷ Although the BTK model does not include effects of disorder and an intermediate nonsuperconducting layer at the interface,¹ it is widely applied to both ballistic and diffusive systems, in order to obtain an estimate of the junction transmissivity. In the BTK model, a potential barrier at the interface is approximated by a δ -function potential. A transmission coefficient T_N in the normal state is given by $T_N=1/(1+Z^2)$ where Z is the dimensionless parameter characterizing the potential barrier strength.³⁷ Following Ref. 38, from the drop of the differential resistance at zero bias compared to the large bias case (experimental curve at $T=0.5$ K, Fig. 3), a barrier strength $Z=0.5$ for the NbN/Au/InGaAs-InP junction is obtained. The normal-state transmission coefficient T_N calculated from Z -value is 0.8, which is considerably higher than the value of $T_N=0.2$ obtained for NbN/InGaAs-InP junctions.

Golubov *et al.*^{1,36} extended the BTK model by taking into account the presence of a nonsuperconducting N layer at the interface. The structure therefore may be represented as an SN-2DEG junction. The S and N layers are assumed to be in the dirty limit, while the 2DEG channel is in the clean limit.¹ The N-2DEG interface is simulated in the model by the BTK Z -factor.

The equilibrium state of the S and N layers is described by the angle-averaged Green's functions G and F , which are obtained from the Usadel equations.¹⁸ By formally introducing a complex angle $\theta(\epsilon, x)$ with $G(\epsilon, x)=\cos \theta(\epsilon, x)$ and $F=\sin \theta(\epsilon, x)$, the Usadel equations are written as:¹

$$\xi_{S,N}^2 \theta''_{S,N}(x) + i\epsilon \sin \theta_{S,N}(x) + \widetilde{\Delta}_{S,N} \cos \theta_{S,N}(x) = 0, \quad (1)$$

where $\epsilon=E/\pi k_B T_c$ and $\widetilde{\Delta}_{S,N}=\Delta_{S,N}/\pi k_B T_c$ are the normalized energy and pair potential, and T_c is the critical temperature of the superconductor. The coherence lengths $\xi_{S,N}$ are given by $\xi_{S,N}=(\hbar D_{S,N}/2\pi k_B T_c)^{1/2}$ where D_S and D_N are the diffusion coefficients in the superconductor and normal layers, respectively.

The pair potential $\widetilde{\Delta}_S$ in the superconductor is determined by the self-consistency equation

$$\widetilde{\Delta}_S(x) \ln \frac{T}{T_c} + 2 \frac{T}{T_c} \sum_{\omega_n > 0} \left[\frac{\widetilde{\Delta}_S(x)}{\omega_n} - \sin \theta_S(i\omega_n, x) \right] = 0, \quad (2)$$

where $\omega_n=(2n+1)T/T_c$ are the normalized Matsubara frequencies. In the normal conductor, the pair potential Δ_N is assumed to be zero. The quasiparticle density of states (DOS) in terms of the proximity angle θ is obtained from $N(E)=N_0 \text{Re}(\cos \theta)$, where N_0 is the Fermi level DOS in the normal state.

In order to calculate the current across a junction, the solution of the Eqs. (1) and (2) for the proximity effect in the dirty SN sandwich, including the influence of a clean 2DEG, has to be found. Equations (1) and (2) must be supplemented

with the two sets of boundary conditions: at the SN interface and at the 2DEG-N interface. For the SN interface the boundary conditions are given by

$$\gamma_{B_1} \xi_N \theta'_N = \sin(\theta_S - \theta_N), \quad (3)$$

$$\gamma_1 \xi_N \theta'_N = \xi_S \theta'_S, \quad (4)$$

where $\gamma_1 = \rho_S \xi_S / \rho_N \xi_N$ is a parameter characterizing the strength of the proximity effect between S and N layers and $\gamma_{B_1} = R_B / \rho_N \xi_N$ describes the effect of the SN interface transparency, R_B is the SN interface resistance, ρ_S and ρ_N are the normal state resistivities. In the bulk of the superconductor, θ_S is given by $\theta_S = \arctan(i\Delta_0/E)$ where Δ_0 is the bulk value of the pair potential. For the N-2DEG interface, which separates the disordered N layer (of thickness d_N) and the clean 2DEG, the material-dependent parameters for the boundary conditions, similar to Eqs. (3) and (4), are found from the estimates:¹ $\gamma_2 \approx (3k_{2DEG}/k_N^2 l_N) \xi_N / \xi_{2DEG}$ and $\gamma_{B_2} = Z^2$, where k_{2DEG} and k_N are the Fermi wave vectors in the 2DEG and in the N layer, l_N is the mean free path in the N layer, and Z is the barrier strength in the BTK model. The estimations show that for our NbN/Au/2DEG junctions one may set $\gamma_2 = 0$.

The complete self-consistent problem requires numerical simulations. The self-consistent solution is then used to determine the Andreev and normal reflection coefficients at the 2DEG-N interface and the current across a junction,^{1,36}

$$A = \frac{|\sin \theta_N(\epsilon, 0)|^2}{|1 + 2Z^2 + \cos \theta_N(\epsilon, 0)|^2}, \quad (5)$$

$$B = \frac{4Z^2(1 + Z^2)}{|1 + 2Z^2 + \cos \theta_N(\epsilon, 0)|^2}, \quad (6)$$

$$I = \frac{e^2 k_N W}{\pi^2 \hbar} \int_{-\infty}^{+\infty} [f_0(\epsilon + eV) - f_0(\epsilon)] (1 + A - B) d\epsilon, \quad (7)$$

where f_0 is the Fermi distribution function, V is the voltage drop in the junction, and W is the contact width. In Eqs. (5) and (6), the function $\theta_N(\epsilon, 0)$ is taken in the N region near the N-2DEG interface.

An essential feature of the model^{1,36} is the existence of a gap in the density of states $\text{Re}(\cos \theta)$ of the N layer which is in proximity to a superconductor. This leads to the characteristic two-gap structures in the energy dependence of Andreev and normal reflection coefficients and thus in the voltage dependence of the resistance.³⁹ Figure 5 shows the corresponding calculated $dV/dI - V_{dc}$ curves for NbN/Au/2DEG junctions. The parameters for the calculated curves were chosen within a realistic range given by the characteristic material constants.⁴⁰⁻⁴⁵ As can be seen from Figs. 3 and 5, the calculated and measured curves show a rather good qualitative agreement. However, we could not find a good quantitative fit to the experimental curves. The main discrepancies are in the detailed shape and in the amplitude of variations of the differential resistance. A weaker dip in the experimental curve than calculated within the model¹ can possibly be explained by smearing due to the inhomogeneity of the junction (i.e., variation of the interface quality over the width of the junction).

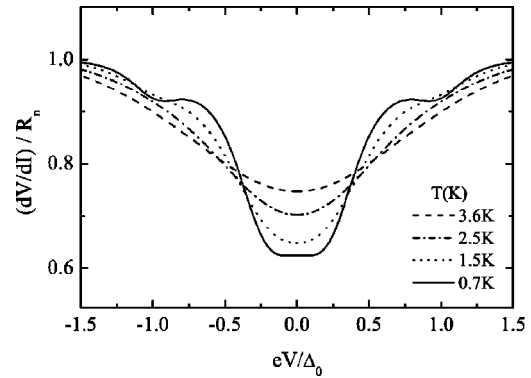


FIG. 5. Calculated normalized differential resistance as a function of the bias voltage according to the model.¹ Parameters of the model¹ are: $\gamma_1 d_N / \xi_N = 0.25$; $Z = 0.35$; and $\gamma_{B_1} d_N / \xi_N = 5$.

We have also considered the model of diffusive contact when a disordered 2DEG channel exists between the clean 2DEG and SN electrode and a potential drop is distributed between the SN-2DEG interface and the disordered region in the 2DEG. Properties of disordered contacts have been first studied theoretically by Artemenko, Volkov, and Zaitsev⁴⁶ and later in Refs. 15–18 and 22–35. The transport measurements on the S/N structures in the diffusive limit have been carried out in Refs. 19–21 and have revealed a conductance peak around zero bias voltage, which arises due to an interplay between Andreev scattering and disorder-induced scattering in the normal electrode. The fitting parameters we obtained within the model of diffusive contact (in particular, large thickness of the disordered 2DEG channel $d_{N'} \approx 28 \xi_{N'}$) appeared to be unrealistic. Therefore, it is less likely that the diffusive model can be applied in our case when the 2DEG is in the extreme clean limit. We believe that the observation of the two-gap like structure in the differential resistance is related to the transport between the NS bilayer and clean 2DEG through the clean constriction (the situation which was considered in Ref. 1 and 36).

In conclusion, we fabricated highly transparent superconductor/normal metal/two-dimensional electron gas junctions formed by a superconducting NbN electrode, a thin (10 nm) Au interlayer, and a 2DEG in an InGaAs/InP heterostructure. High junction transparency has been achieved by exploiting a developed process of Au/NbN evaporation and rapid annealing at 400 °C. A decrease in the differential resistance with pronounced double dip structure was observed within the superconducting energy gap in junctions investigated and its magnetic field dependence was measured. It has been found that the reduced subgap resistance remains in high magnetic fields. Experimental data in zero field are analyzed within a model based on the quasiclassical Green-function approach. The present results suggest that our preparation method is not only advantageous for the fabrication of highly transparent S/2DEG interfaces but it might also have important implications for S/2DEG/S Josephson junction based devices.

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