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journal or publication title	Physical Review. B
volume	49
number	5
page range	3659-3662
year	1994
URL	http://hdl.handle.net/10097/52862

doi: 10.1103/PhysRevB.49.3659

RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 49, NUMBER 5 1 FEBRUARY 1994-I

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(Received 11 October 1993; revised manuscript received 15 November 1993)

The differential resistance in an InAs-inserted-channel $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure-coupled superconducting junction is enhanced within the Nb superconducting gap energy by applying a magnetic field. However, the enhancement saturates under a magnetic field of several mT. This behavior suggests the reduction of Andreev-reflection (AR) probabilities by the magnetic field. The AR probabilities are calculated as a function of the pair-potential penetration length into the InAs channel. The enhanced AR probabilities decrease with decreasing pair-potential penetration length. The magnetic field reduces the penetration of the pair potential in the channel and therefore reduces the AR probability. This reduction of AR probability causes an enhancement of dV/dI.

In recent years, much attention has been devoted to the superconductor-semiconductor-superconductor (S-Sm-S) system. It has been suggested that Andreev reflection (AR) plays an important role in transport in the normal state as well as the superconducting state.[1] The dc Josephson current is given by the AR probability and is carried by the discrete excitation bound state in the Sm region.[2] The differential resistance (dV/dI-V) of the normal state shows subharmonic energy-gap structure (SGS) due to multiple AR.[3] Most of the experimental results on the finite voltage state transport had been explained in terms of the Blonder Tinkham, and Klapwijk (BKT) theory.[4] Recently, the anomalous conductances in S-Sm (Ref. 5) or S-Sm-S (Ref. 6) systems have been observed, which cannot be explained by the existing BTK theory. This has led to the interpretation that the interference due to elastic scattering enhances the AR probabilities and conductance.[7]

The S-Sm-S system with an InAs-inserted $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure[8] is interesting because the two-dimensional electron gas (2DEG) InAs channel has a long mean free path and the S-Sm-S shows clean-limit transport properties.[9] Therefore, the enhanced AR probabilities due to the interference effect *in the channel* are negligible. This paper reports on an anomalous magnetic-field dependence of the dV/dI-V characteristics in the S-Sm-S junction with an InAs-inserted-channel $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure. The dV/dI within the Nb superconducting gap energy is enhanced by applying the magnetic field. The weak magnetic field modifies the phase of incident electron and Andreev-reflected hole, but does not reduce the AR probabilities. If we assume the pair potential in the InAs channel is induced by the superconducting proximity effect, the experimental results can be qualitatively explained.

The structure of the junction is schematically illustrated in Fig. 1. The magnetic field H is applied perpendicular to the junction plane. A 2DEG channel is formed in the 4-nm undoped InAs layer inserted into the undoped $In_{0.53}Ga_{0.47}As$ layer. Two superconducting Nb electrodes, 100-nm thick, were defined by a lift-off process using electron beam lithography. Chemical etching was used to remove the undoped $In_{0.52}Al_{0.48}As$ Schottky layer and undoped $In_{0.5}Ga_{0.47}As$ layer. The carrier is supplied from the doped $In_{0.52}Al_{0.48}As$ layer to the channel. High-electron mobility is maintained by this modulation doped structure.

The two electrodes were made by electron beam deposition after rf sputter cleaning in an evaporation chamber to eliminate the surface oxide layer. The length L between Nb electrodes is about 0.8 μm. The electrode width W is 35 μm. The junction area was defined by mesa etching to reduce the leakage current. The carrier concentration N_s and mobility μ were measured to be 2.1×10^{12} cm^{-2} and 87 200 cm^2/Vs, respectively, from the Shubnikov-de Haas oscillation (SdH) period and sheet resistance. The effective mass m^* was obtained to be 0.045 from the temperature dependence of the SdH amplitude. The 2DEG InAs channel is in the one-sub-band conduction state since the oscillation had one-frequency component. The mean free path is given by $l=2.1$ μm, which is longer than the junction length L. This fact ensures that the scattering events occur mainly at the S-Sm interface. The coherence length ξn is given by $\xi n=\hbar v_F/2\pi k_B T$ and is 0.26 μm at 4.2 K. The mean free path l is much longer than the coherence length. Therefore, this S-Sm-S is in the clean limit region. Note that superconducting Nb electrodes are probably in the dirty limit.

The magnetic field dependence of dV/dI-V characteristics at 4.2 K are shown in Fig. 2(a). The dV/dI is normalized by the normal resistance Rn of 6.3 Ω at 5 meV higher than 2Δ. The calculated resistance of the channel Rsm is 0.76Ω from the experimentally obtained N_S and μ. The Rsm is much smaller than the measured

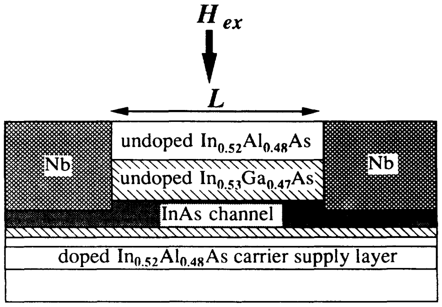

FIG. 1. Cross-sectional view of the junction.

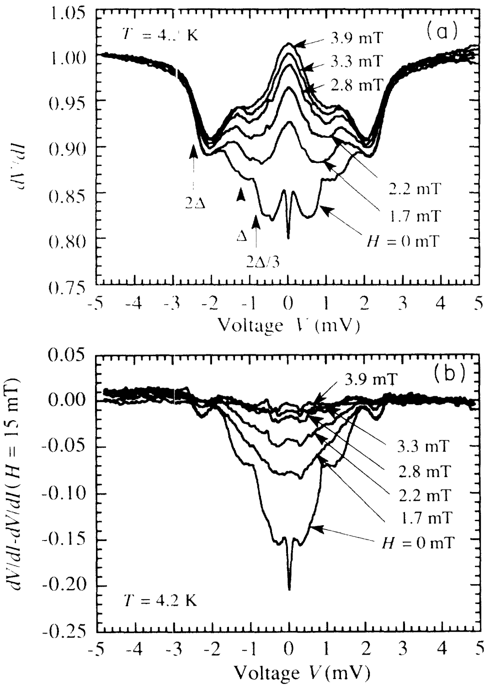

FIG. 2. (a) Differential resistance as a function of voltage (dV/dI-V characteristics) under a magnetic field. (b) Subtracted dV/dI-V characteristics by the saturated data at $H_{\mathrm{ex}}=15$ mT. R_n is the normalized resistance at 5 MeV. dV/dI is normalized by R_n.

normal resistance. Therefore, Rn reflects the S-Sm interface and the voltage drop occurs at the interface.

Gradual decreases in dV/dI-V with dip structures were observed below 3 meV. This decrease in dV/dI corresponds to the excess current on the I-V characteristics. The structure appears near voltages equal to $2\Delta/ne$, with $n=1,2,3$ where Δ is the Nb superconducting energy gap. This is subharmonic energy-gap structure (SGS) due to the multiple Andreev reflection. The arrows denote the well-known multiple Andreev reflections at submultiples of the superconducting energy gap. The sharp dip at zero voltage disappears under a very low magnetic field $H_{\mathrm{ex}}<1$ mT. By applying magnetic field H_{ex}, the dV/dI below 2Δ is gradually enhanced up to several mT, but the normal resistance at 5 meV does not change. The enhancement in dV/dI is almost saturated below several mT.

Figure 2(b) shows the subtracted dV/dI-V characteristics by the saturated data at $H_{\mathrm{ex}}=15$ mT. The subtraction is performed to more clearly show the magnetic-field effect. The difference from the saturated data increases with decreasing bias voltage. This means that the enhancement of dV/dI by the magnetic field is dominant at low energy. The subtracted data for $H_{\mathrm{ex}}=0$ remains SGS at $2\Delta/ne$ with $n=1,2,3$ but only the structure at $n=1$ remains for a magnetic field higher than $H_{\mathrm{ex}}=1.7$ mT. With increasing H_{ex}, the structure at 2Δ also smears. This means that SGS is smeared by applying H_{ex}.

The anomalous magnetic-field dependence of conductance in the Nb-$\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ S-Sm system has been reported by Kastalsky *et al.*[5] The enhanced conductance appears near zero bias below 0.5 meV and is smeared by applying a magnetic field of several tens of mT or by increasing the temperature to more than 2 K. In our experiment on the S-Sm-S system, low resistance (enhanced conductance) appeared at higher voltage just below 2Δ and at higher temperature of 4.2 K than in Kastalsky's results. Our results are different, although, they may be related to Kastalsky's results. They attributed the enhanced conductance to the proximity-induced pair current. Our S-Sm-S junction, which has a supercurrent, shows a very sharp dip near the zero voltage. The observed sharp dip near zero voltage in Fig. 2(a) is thought to be the precursor of the supercurrent of the junction.

Van Wees *et al.*[7] have theorized that the quantum interference due to the elastic scattering near the interface enhances the AR probabilities and therefore enhances the conductance. In our junction, the mean free path is longer than the junction length, and therefore the scattering event occurs almost at the S-Sm interface. The quantum interference due to *the elastic scattering in the channel* is unaffected in our system.

In the S-Sm-S system using InAs-AlSb quantum well structures,[6] Nguyen *et al.* observed a single conductance peak and a conductance dip at voltages an order of magnitude larger than the superconducting gap voltage. They explain the behavior in terms of the AR, modified by multiple normal reflections between the Nb electrodes and the bottom barrier of the quantum well. We observed a clear SGS and did not observe a dip at those higher voltages. This means that AR occurs mainly at the interface and the ordinary multiple AR between two superconducting electrodes is important in our system. Our sample geometry has a small difference from Nguyen's one. The edges of Nb electrodes are thought to be under the top of the InAs channel because of the chemical etching and the rf sputter cleaning just before Nb deposition. The AR, modified by multiple normal reflections between the Nb electrode and the bottom barrier is a possible explanation for the enhanced AR. However, we focus on the InAs channel between the Nb electrodes to explain the enhanced AR.

According to the BTK theory,[4] the barrier strength Z has a strong influence on I-V characteristics. The increase of Z at the interface leads to the enhancement of dV/dI because the AR probabilities are reduced. For low Z, BTK predicts a reduction of dV/dI and I-V characteristics show excess current because the AR probabilities are enhanced. For increasing Z the excess current turns into a current deficit and dV/dI gradually increases below 2Δ. Crossover from the excess current to the current deficit has been observed in the Nb-$\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$-Nb system[10] by decreasing the interfacial dopant concentration. In this experiment, the normal resistance Rn which is proportional to $(1+2Z^2)$ did not change with increasing H_{ex}. This means the barrier strength Z is not affected by the magnetic field, and should be constant.

Van Son, Van Kempen, and Wyder[11] extended the BTK theory to study the effect of a gradual variation of the pair potential near the superconducting-normal metal (S-N) interface. According to the calculation, AR probabilities $A(E)$ within the gap voltage are enhanced by the pair potential in the normal metal. This is because the influence of the barrier at the S-Sm interface is weakened by the pair potential for low quasiparticle energy. The wave function of the quasiparticle is exponentially damped in the pair potential of the normal metal and the value at the barrier is small. The increase in the dV/dI enhancement with decreasing bias voltage suggests the pair potential in the InAs channel because the penetration of the pair potential becomes longer.

The penetration of the pair potential is reduced due to the pair-breaking effect of the magnetic field.[12] The coherence length in the magnetic field is decreased by a factor of $(1+2\alpha/\pi k_B T)^{-1/2}$, where α is the pair-breaking parameter and is given by $\alpha = DeH$. Here, D is the diffusion constant. The applied magnetic field is enhanced by the shielding effect of superconducting Nb electrodes. The enhanced mean field H_{eff} is given by $H_{\text{eff}} = (2W/L)^{2/3} H_{\text{ex}}$, where H_{ex} is the externally applied field.[13] For example, the magnetic field $H_{\text{ex}} = 4$ mT which gives $H_{\text{eff}} = 79$ mT reduces the coherence length to approximately 9%. In the actual situation, however, the magnetic field is inhomogeneous and very strong at the S-Sm interface. The *enhanced Andreev reflection probabilities* are expected to be reduced by the magnetic field if we assume the pair potential in the InAs channel.

Figure 3(a) shows the schematic model of this system where the pair potential penetrates into the InAs channel. We assume that the pair-potential Δn in the Sm region is linearly decreased from the S-Sm interface. The Andreev reflection probabilities $A(E)$, the normal reflection probabilities $B(E)$, and transmission probabilities $T(E)$ are calculated as a function of the penetration of the pair potential by integrating the Bogoliubov equation based on the Van Son's method. The $A(E)$ and $B(E)$ are represented by $A(E) = |a_e|^2$ and $B(E) = |b_e|^2$, respectively. Here the coefficients a_e and b_e are the amplitudes of the Andreev-reflected wave and the ordinary reflected wave, respectively, for an incident electron wave with amplitude 1. These coefficients are given by

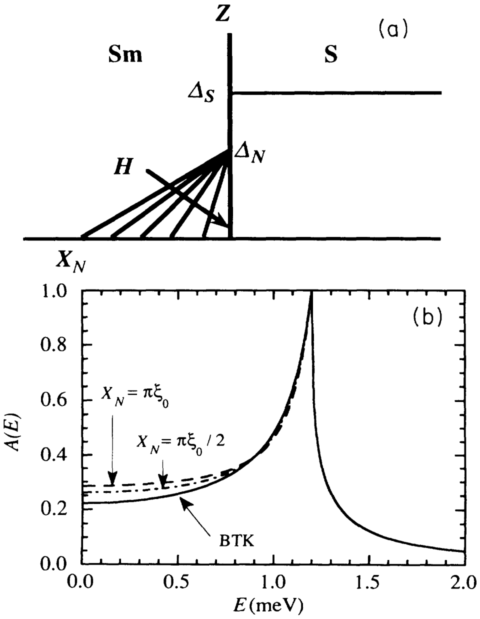

FIG. 3. (a) Schematic model of this system where the pair potential penetrates into the InAs channel. (b) Calculated Andreev reflection probabilities as a function of pair-potential penetration length Xn. As Xn decreases, the probabilities decrease.

$$a_e = \frac{uv}{(1+Z^2)u^2 - Z^2v^2} e^{-2i\kappa_N x_N} ,$$
$$b_e = \frac{iZ(1-iZ)(v^2-u^2)}{(1+Z^2)u^2 - Z^2v^2} e^{-2i\kappa_N x_N} , \tag{1}$$

where u and v are the complex values at $x = Xn$ where the pair potential reaches zero from the S-Sm interface. Below the superconducting gap energy, this relation $A(B)+B(E)=1$ is satisfied while $A(E)+B(E)+T(E)=1$ for $E > \Delta s$. These u and v are governed by the following Bogoliubov de Gennes equation where higher-order terms are neglected.

$$\frac{\partial u}{\partial x} = i(\pi\xi_0\Delta_s)^{-1}[Eu - \Delta(x)v] ,$$
$$\frac{\partial v}{\partial x} = -i(\pi\xi_0\Delta_s)^{-1}[Ev - \Delta(x)u] . \tag{2}$$

Here, E is the energy from the Fermi energy and $\Delta(x)$ is the spatially varying pair potential. It is assumed that the pair-potential Δs in the superconductor is constant and 1.2 meV.

Here, we set the pair potential at the interface $\Delta n = 0.8$ meV and $Z = 0.75$ and assumed $Xn = 1$, 0.7, 0.5, 0.3, 0.1. The penetration depth Xn is normalized by $\pi\xi_0$ where ξ_0 is the BCS coherence length and is given by $\hbar v_F/\pi\Delta s$. Figure 3(b) shows the calculated AR probabilities for $Xn = \pi\xi_0$, $\pi\xi_0/2$, and 0. When the penetration depth Xn is 0, $A(E)$, $B(E)$, and $T(E)$ become the same as the BTK results. Here $\pi\xi_0$ corresponds to $1.9\xi n(4.2\text{ K})$, and gives AR probability of 0.29 at the Fermi energy, which is larger than the usual BTK result of 0.21 with $Z = 0.75$. As the penetration depth Xn decreases, $A(E)$ reduces and $B(E)$ is enhanced within the gap energy.

The theoretical model to explain dV/dI of the S-Sm-S system was proposed by Flensberg, Bindslev Hansen, and Octavio.[14] This model does not assume elastic or inelastic scattering in the normal region and only elastic scattering at the interface is taken into account. The current through the junction is given by two nonequilibrium distribution functions which depend on the direction of their motion:

$$I = (eRn)^{-1} \int dE [f_{\rightarrow}(E) - f_{\leftarrow}(E)] . \tag{3}$$

Here, Rn is the normal state resistance defined at a higher voltage than the superconducting energy gap. The nonequilibrium distribution function depends on the barrier strength through $A(E)$, $B(E)$, and $T(E)$. Using the appropriate boundary conditions at the interface and symmetry arguments, the distribution function is given by[14]

$$f_{\rightarrow}(E) = A(E) f_{\rightarrow}(E-eV) + B(E)[1 - f_{\rightarrow}(-E-eV)] + T(E) f_0(E) \tag{4}$$

Using the above calculated $A(E)$, $B(E)$, and $T(E)$ based on the Van Son's method, dV/dI are obtained in Fig. 4. As the penetration depth Xn decreases, the dV/dI within the gap voltage is enhanced since $A(E)$ is reduced and $B(E)$ is enhanced.

The dips in the subharmonic energy-gap voltages in the experimental results are small compared with the calculated curves. The voltage across the sample, which has a coplanar structure, varies over the interface. This smears the structures.[15,16] However, the calculated results qualitatively explain the experimentally obtained enhancement of dV/dI by assuming the pair potential in the Sm region.

The smearing of SGS by the magnetic field is not explained by this model because the inelastic scattering effect is not taken into account. It is known that the multiple AR process is broken by the quasiparticle energy relaxation. The fact that SGS is observed up to $n=3$ suggests the particle traverses about three times through the junction without energy relaxation. The effective length between sequential AR is shorter than the junction length if the pair potential penetrates into the channel. The magnetic field increases the effective length because the penetration of the pair potential is reduced. This increase in the effective length accelerates the energy relaxation of the particles and smears the SGS. The smearing of SGS by increasing the InAs-channel resistance has been observed in the same Nb-InAs-Nb junction.[17] The resistance increase leads to the enhancement of the inelastic scattering rate and therefore smears SGS.

Recently, several experiments have suggested the existence of the pair potential in the semiconductor of S-Sm or S-Sm-S systems. An energy gap in an $In_{0.53}Ga_{0.47}As$ layer has been observed by proximity effect tunneling spectroscopy in Nb on an $In_{0.43}Ga_{0.47}As$-InP-$In_{0.53}Ga_{0.47}As$ heterostructure.[18] Local tunneling spectroscopy using low-temperature scanning tunnel microscope suggests the existence of the pair potential in a Nb-InAs-Nb system.[19] Double gap edge at Nb-Si interface has been observed by point contact spectroscopy.[20] To verify the pair potential in the Sm region, further experimental as well as theoretical studies would be required. However, our experimental result that the dV/dI-V characteristics are enhanced by the magnetic field suggests the pair potential.

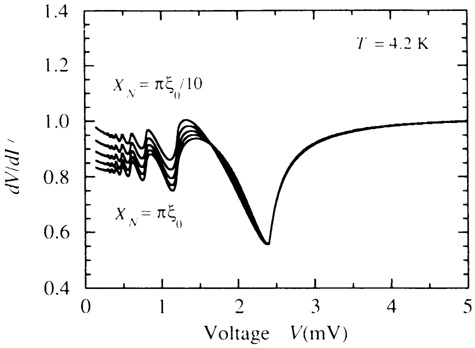

FIG. 4. Calculated dV/dI-V characteristics as a function of pair-potential penetration length Xn. As Xn decreases, dV/dI within the gap voltage is enhanced. R_n is the normal resistance at 5 MeV. dV/dI is normalized by R_n.

In conclusion, we have investigated magnetic-field dependence of differential resistance in a *clean* S-Sm-S junction using a 2DEG in an InAs-inserted-channel $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure. The dV/dI within the Nb superconducting energy gap is enhanced by the weak magnetic field. This behavior suggests the pair potential in the InAs channel. The applied magnetic field reduces the penetration of the pair potential. We calculated the AR probability under the condition that the pair potential is induced in the channel. The AR probability within the superconducting gap energy is reduced by decreasing the penetration of the pair potential. This reduction of the AR probability leads to the enhancement of dV/dI.

We thank Y. Ishii and T. Kobayashi for their collaboration in this work and K. Arai for his valuable discussion on transport in the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure. We also thank T. Kawashima for the electron beam lithography and H. Nakano for valuable discussions. We are also indebted to H. Hiratsuka and T. Kimura for their encouragement.

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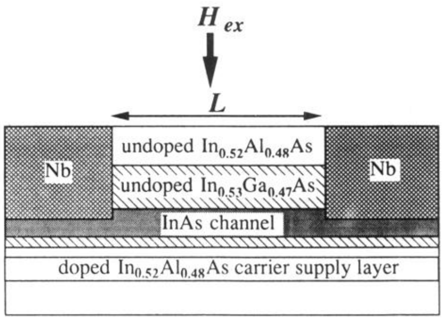

FIG. 1. Cross-sectional view of the junction.