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Observation of giant thermal noise due to multiple Andreev reflection in a ballistic SNS junction with an InGaAs-based heterostructure

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Abstract. We report on the fabrication of a ballistic SNS junction with a two-dimensional electron gas (2DEG) in an InGaAs-based heterostructure. We have observed the Josephson current as well as the subharmonic energy-gap structures caused by the MAR. Moreover, we experimentally estimated the thermal noise by comparing measured *IV* characteristics with those obtained with an extension of the Ambegaokar and Halperin theory. As a consequence, we have observed giant thermal noise that is much larger than that expected with normal reservoirs. The experimentally obtained "giant" thermal noise can be qualitatively explained by the Martín-Rodero theory that considers both the ballistic transport of the 2DEG and the thermal fluctuation in the coherent multiple Andreev reflection regime.

Keywords: Thermal noise, Multiple Andreev reflection, SNS junction
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INTRODUCTION

In a mesoscopic superconductor-normal metal-superconductor (SNS) structure, multiple Andreev reflection (MAR) constructs discrete bound states. At a finite temperature the upper level can be thermally populated giving rise to a reverse in the sign of the supercurrent. This switching between positive and negative current caused by thermal fluctuation leads to a huge increase in the thermal noise. In this paper, we report on the fabrication of a ballistic SNS junction with a two-dimensional electron gas (2DEG) in an InGaAs-based heterostructure [1]. This ballistic SNS junction shows clear evidence of enhanced thermal noise. Thermal noise has been experimentally estimated from a fit of current-voltage (*IV*) characteristics, according to an extension of the Ambegaokar and Halperin theory [2, 3]. The experimentally obtained temperature dependence of thermal noise can be qualitatively explained by a theoretical description that considers both the ballistic transport of the 2DEG and the thermal fluctuation in the coherent MAR regime.

EXPERIMENTS AND DISCUSSION

Figure 1(a) shows the schematic structure of the SNS junction formed by 2DEG in an InGaAs-based heterostructure. The InGaAs-based heterostructure was grown by

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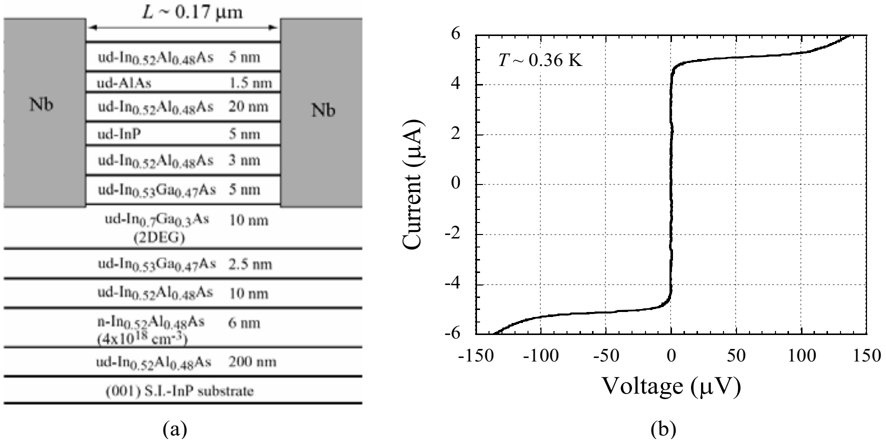
metal-organic chemical vapor deposition (MOCVD) on a semi-insulating (100) InP substrate. The sheet carrier density n_S and mobility μ of the 2DEG at ~ 0.35 K were found to be 2.07 x 10^{12} cm^{-2} and 129,000 cm^2/Vs by Shubnikov-de Haas measurements. These values correspond to a mean free path l of 3.05 μm. The Nb electrodes were coupled by the 2DEG in a 10 nm thick $In_{0.7}Ga_{0.3}As$ channel layer in Fig. 1(a). The critical temperature T_C of the Nb electrodes was about 8.5 K. The coupling length L between the two Nb electrodes was about 0.17 μm. The InGaAs channel width W was about 8.5 μm.

Figure 1(b) shows the *IV* characteristics of the SNS junction at 0.36 K. A "superficial" critical current I_C^* of about 5 μA can be estimated from the current value at the corners of the *IV* characteristics ("real" critical current is discussed below). When a magnetic field is applied, the I_C^* follows a Fraunhofer pattern. Moreover, we obtained resistance minima within $|V| \leq 2\Delta_S/e$ as well as dip structures near $|V| = 2\Delta_S/ne$, with n = 1 to 3 or 4. Here, we assumed the Nb superconducting energy gap Δ_S to be 1.2 meV, which is somewhat lower than the typical value of ~ 1.5 meV. A normal resistance R_N of ~33 Ω is obtained in the voltage region above $2\Delta_S$. These dip structures are the subharmonic energy-gap structures caused by the MAR. These results provide clear evidence that our SNS junction formed by 2DEG in an InGaAs-based heterostructure offers ballistic transport in the 2DEG and sufficient transparency between Nb and the 2DEG.

Next, we estimated the thermal fluctuation of our ballistic SNS junction. We can quantitatively evaluate the effect of thermal fluctuation on the SNS junction from a fit of the *IV* characteristics, by using an extension of the Ambegaokar and Halperin theory including the additional term for phase-dependent dissipative current, namely the $\cos\phi$ term, proposed by Falco *et al.* [3]. Figure 2(a) shows the *IV* characteristics of the SNS junction measured at several temperatures. The dashed lines are the results of a parameter fit of the data to the theory in the low-voltage region below ~10 μV. Here, the dimensionless parameter $\gamma \equiv \hbar I_C/ek_BT_{noise}$ is defined as a fitting parameter, where



(a) (b)

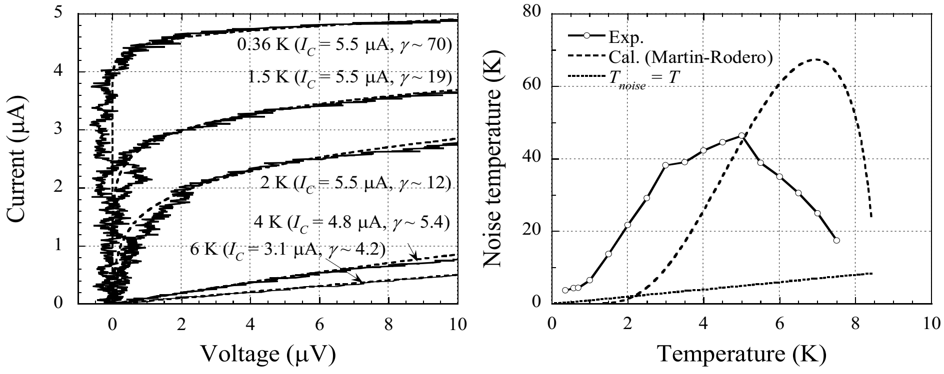
FIGURE 1. (a) Schematic structure of an SNS junction formed by 2DEG in an InGaAs-based heterostructure. (b) *IV* characteristics of the SNS junction at 0.36 K.

I_C is the “real” critical current and T_{noise} is the “effective” noise temperature. By using both an I_C of 5.5 μA and a γ of 70 at the lowest temperature of 0.36 K, we can obtain the best fit between the measured and calculated *IV* characteristics. In the low temperature region, we can easily determine I_C since it almost the same as I_C^*. However, in the high temperature region, it is hard to determine I_C due to the thermal noise. Therefore, the temperature dependence of I_C has been evaluated theoretically by fitting the I_C of 5.5 μA at 0.36 K to the calculated value. Since our SNS junction can be considered to be ballistic ($L << l$) and short [$L << \xi_0$, ξ_0: coherence length ($=\hbar v_F/\pi\Delta_S$), v_F: Fermi velocity in the normal region], the temperature dependence of I_C was calculated from the following expression for a ballistic and short SNS junction [4, 5]:

$$I(\phi,T)=\frac{e\Delta_S{}^2(T)}{2\hbar}\sin\phi\sum_{n=1}^{M}\frac{T_n}{E_n(\phi,T)}\tanh\left(\frac{E_n(\phi,T)}{2k_BT}\right) \qquad (1a)$$

$$I_C(T)=\max I(\phi,T)\ \text{at each}\ T. \qquad (1b)$$

Here, the energy level of the Andreev bound state $E_n(\phi,T)$ is given by $E_n(\phi,T) = \Delta_S(T)[1 - T_n\sin(\phi/2)]^{1/2}$, where T_n is the transmission probability in the normal region and $\Delta_S(T)$ is the superconducting energy gap. For our SNS junction, we assume that $\Delta_S(0)$ is 1.2 meV and that the temperature dependence Δ_S is in accordance with the BCS theory. M is the number of transmission modes, which is given by $2W/\lambda_F$, [λ_F: Fermi wavelength of 2DEG]. For simplicity, we approximate that all transmission modes are equivalent. The T_n of ~ 0.4 is given from $T_n = R_{sh}/R_N$, [R_{sh}: Sharvin resistance of 2DEG, $R_{sh} = (h/2e^2)(\lambda_F/2W)$]. As shown in Fig. 2(a), we determined the



(a) (b)

FIGURE 2. (a) The *IV* characteristics of the SNS junction measured at several temperatures. The solid and lines are experimental and calculated data for the low-voltage region below ~10 μV. (b) The temperature dependence of the noise temperature of the SNS junction. The open circles with the solid line indicate the experimentally obtained noise temperature from the comparison with an extension of the Ambegaokar and Halperin theory. The dashed line represents the calculated temperature dependence of the noise temperature according to the Martín-Rodero theory. The dotted line represents the environment temperature *T*.

fitting parameter γ using the evaluated I_C. As a consequence, we can evaluate the temperature dependence of T_{noise} from the evaluated I_C and γ. Figure 2(b) shows the temperature dependence of T_{noise} of the SNS junction. We found that T_{noise} is larger than the environment temperature T, represented by the dotted line in Fig. 2(b) as well as an exponential increase with increasing temperature in the sufficiently low temperature regime where the decrease in Δ_S can be disregarded. The theory of thermal noise in SQPC can explain these results as follows [6]. Martín-Rodero *et al.* have theoretically studied the frequency-dependent current fluctuations in SQPC within the dc transport regime. The zero-frequency thermal noise in SQPC is given by

$$P_{SQPC}(\phi,T)=\frac{2e^2}{h}\frac{\pi}{\eta}\frac{\Delta_S{}^4(T)T_n{}^2\sin^2\phi}{E_n{}^2(\phi,T)}f\left(E_n(\phi,T)\right)\left[1-f\left(E_n(\phi,T)\right)\right]. \qquad (2)$$

Here, $f(E)$ is the Fermi distribution function. η is the small energy relaxation rate that takes into account the damping of quasiparticle states due to inelastic processes inside electrodes. A typical estimation of η for a traditional superconductor is $\eta/\Delta_S \sim 10^{-2}$ [6]. Thermal noise power P_{SQPC} is directly related to both the noise temperature and the conductance by the fluctuation dissipation theorem [7], $P_{SQPC} = 4k_BT_{noise}G$. We use the estimated T_n of ~0.4 as well as $G = (2e^2/h)\times T_n$. The calculated temperature dependence of T_{noise} is shown by the dashed line in Fig. 2(b). The calculated curve shows the exponential increase with increases in temperature, which agrees qualitatively with the measured temperature dependence of T_{noise}. The experimentally obtained enhanced thermal noise can be qualitatively explained by the Martín-Rodero theory

CONCLUSIONS

We have investigated the superconducting properties of a ballistic SNS junction with a 2DEG in an InGaAs-based heterostructure. We have observed the Josephson current as well as the subharmonic energy-gap structures caused by the MAR. Moreover, we experimentally estimated the thermal noise by comparing measured *IV* characteristics with those obtained with an extension of the Ambegaokar and Halperin theory. As a consequence, we have observed enhanced thermal noise. This enhanced thermal noise can be explained by a theory that considers both the ballistic transport of the 2DEG and the thermal fluctuation in the coherent MAR regime.

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