Differential resistance oscillations with microwave irradiation in a superconductor-semiconductor junction

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Abstract. Transport properties of a superconductor-semiconductor junction are measured. Differential resistance as a function of bias voltage of the junction showed oscillation with a microwave irradiation of specific frequencies (1.715 GHz), which indicate the modulation of Andreev reflection probability by microwave irradiation.

1. Introduction

Recent development of superconducting electronics/photonics demands more investigation of the low-energy transport properties in a superconductor-semiconductor interface. A new method of generating an entangled single photon pair was proposed and discussed [1]. Either electron Cooper pairs or hole Cooper pairs are injected into a semiconductor quantum dot, and they are expected to recombine simultaneously into photon pairs in the quantum dot. One of the key issues of this method is high probability amplitude of Cooper pair in the quantum dot or high Andreev reflection probability at the superconductor-quantum dot interface.

In order to enhance Cooper pair injection into semiconductor, we prepare a sample with superlattice structures in the neighborhood of superconductor-semiconductor interface, which is found to show oscillatory differential resistance as a function of bias voltage upon microwave irradiation. We speculate that this oscillation of differential resistance is due to the modulation of Andreev reflection probability related to superlattice phonons, which has not been reported so far.
2. Experimental Setup

Figure 1 shows the schematic cross sectional view of the S/Sm/Superlattice/n-GaAs/Superlattice/Sm/S junction, where S denotes a superconducting niobium (Nb) electrode and Sm denotes 5-nm-thick GaAsNSe semiconductor layer [2]. Superlattice structure consists of two GaAs(2 nm)/GaAsNSe(2 nm) layers and three GaAs(1 nm)/GaAsNSe(1 nm) layers. Sm/Superlattice structure was introduced in order to enhance Cooper pair injection from S to n-GaAs which has a Shottky barrier against metals. The length of junction $L$ is ~300 nm.

For the measurement below 1 K, $^3$He-cryostat was used. Microwave is transmitted by a semi rigid coaxial cable and irradiated by means of a handmade $\lambda/2$-antenna. Due to the impedance mismatch, most of the microwave is reflected back at the end of the coaxial cable. We can, however, estimate irradiated microwave power as ~-20 dB using a spectrum analyzer. Differential resistance was measured using a low-noise amplifier and two lock-in amplifiers.

3. Results and Discussion

Figure 2(a) shows the differential resistance of junction as a function of applied bias voltage ($dV/dI-V$ characteristics). For temperatures less than 1 K, the $dV/dI$ at zero bias voltage ($V = 0$) is slightly reduced (~0.3 %) compared with $dV/dI$ value at a higher bias voltage ($V \sim 3$ mV) which corresponds to the superconducting Nb energy gap. This is considered to be due to the enhancement of Andreev reflection probability. However, the percentage of reduction is still limited. (It is well known that the differential resistance at zero bias voltage is reduced 50 % in junctions with no Shottky barriers [3].)

Upon 1.715-GHz microwave irradiation, $dV/dI$ oscillates with applied bias voltage as shown in Fig. 2(b). It is also noteworthy that the oscillation of $dV/dI$ can cause more significant reduction of $dV/dI$ at
zero bias voltage. We found that $dV/dI$ oscillates only for voltages lower than $\sim 3$ mV. This critical voltage of $\sim 3$ mV coincides with the superconducting gap of niobium (Nb) electrodes, which indicates that the oscillation of $dV/dI$ is related with the superconductivity such as Andreev reflection and superconducting proximity effect.

Another important feature of the oscillation is that it is found for specific microwave frequency and power. Figures 3 and 4 show the $dV/dI$-$V$ characteristics for different frequencies and powers of irradiated microwave, respectively. The $dV/dI$-$V$ characteristics oscillates only for microwave at frequency $\sim 1.715$ GHz (in the range of 20 MHz) and at power $\sim 0.4$ dBm (in the range of 1.2 dBm). Such resonance-like response is considered to be related to the superlattice structure on the junction. Indeed, we do not find the $dV/dI$ oscillation in a junction without superlattice structure.

Both in Figs. 3 and 4, we give several guides to the eye which indicate the first and second peaks of $dV/dI$ in positive/negative voltage side. While the peak period ($\sim 0.3$ mV) in either positive or negative voltage range is almost independent of irradiated microwave frequency and power, the central interval between peaks in positive and negative voltage range increases with increasing microwave frequency and with decreasing microwave power.

The $dV/dI$ oscillation reflects the low-energy transport properties at superconductor-semiconductor interfaces which necessarily include the modulation of Andreev reflection probability. We speculate that the Andreev reflection is affected by low-energy phonons in superlattice structure which are excited by irradiated microwave. Energy of optical phonon in superlattice structure is roughly estimated as $\hbar \omega_{\text{phonon}} \sim 2 \pi \hbar v_{\text{phonon}} / A$ where $A$ is the period of superlattice structure and $v_{\text{phonon}}$ is the group velocity of optical phonon. In our superlattice structure, $A$ is $\sim 3$ nm. For long wave limit, energy dispersion of optical phonon is so small that we can assume $v_{\text{phonon}}$ is $\sim v_0/100$ where the sound velocity of bulk GaAs $v_0$ is $\sim 3 \times 10^4$ cm/s [4]. Substituting these values, estimated energy of optical phonon corresponds to microwave frequency of 1.6 GHz. Although this estimation may be optimistic, it is sufficiently possible to excite optical phonon in superlattice by microwave irradiation.

![Graph](image-url)

Fig. 3 $dV/dI$-$V$ characteristics for different irradiated microwave frequencies.

Microwave power is fixed to 0 dBm. The broken lines are guides to the eye.
4. Conclusion

In conclusion, transport properties of a superconductor-semiconductor junction are measured, and differential resistance as a function of bias voltage is found to oscillate with a microwave irradiation of specific frequencies (1.715 GHz) and powers (-0.4 dBm). The bias voltage range where \( \frac{dV}{dI} \) oscillates corresponds to the superconducting gap of niobium electrodes. The origin of oscillation is speculated to be the modulation of Andreev reflection probability by low-energy phonons in superlattice structure which are excited by irradiated microwave.

Fig. 4 \( \frac{dV}{dI} \)-V characteristics for different irradiated microwave powers.

Microwave frequency is fixed to 1.715 GHz. The broken lines are guides to the eye.

References

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