Interplay between Negative Photoconductivity and Enhanced Andreev Reflection in InGaAs-based S-Sm-S Junctions when Exposed to Infrared Light

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Abstract. We investigated the transport properties of an S-Sm-S junction with a two-dimensional electron gas (2DEG) in an In0.52Al0.48As/In0.7Ga0.3As heterostructure when exposed to light from infrared laser diodes. When the sample was illuminated with λ = 1.3 µm, we observed a reduction in the junction resistance as well as an enhancement of Andreev reflection. In contrast, we observed negative photoconductivity owing to a reduction in the number of electrons in the 2DEG when it was exposed to 1.3 µm light, by employing both Shubnikov-de Haas and Hall-effect measurements. These experimental results indicate that the improvement in the superconducting properties does not originate from the photo-induced carriers in the 2DEG but from the increase in the Andreev reflection probability at the S/Sm interface caused by lowering the interface barrier.

1. Introduction
It is very attractive to investigate the optical effect on the superconducting properties in superconductor-semiconductor-superconductor (S-Sm-S) junctions. This is because new quantum phenomena can be expected from the interplay between Cooper pairs with spin-singlet and spin-aligned carriers, which are generated in semiconductors when electrons are excited by circularly polarized light. In the first measurements related to the optical effect in an S-Sm-S junction undertaken in the 60’s, Giaever showed that a Josephson current appears in an S-Sm-S junction that has CdS as a photosensitive semiconductor as a result of light exposure [1]. Thirty years later, Schäpers et al. demonstrated that light exposure can be used to adjust the Josephson current in an S-Sm-S junction with a two-dimensional electron gas (2DEG) in an In0.52Al0.48As/In0.7Ga0.3As/InP heterostructure [2]. They mentioned that light exposure can increase the carrier concentration of a semiconductor channel and thus improve the superconducting properties in S-Sm-S junctions.

In this paper, we report on the transport properties of an S-Sm-S junction with a 2DEG in an In0.52Al0.48As/In0.7Ga0.3As heterostructure when exposed to light from infrared laser diodes. In
First, we investigated the influence of light exposure on the 2DEG in the InAlAs heterostructure. Figure 1 is a schematic diagram of an S-Sm-S junction with an InGaAs channel layer. The critical temperature, $T_C$, of the Nb electrodes was about 7.5 K. The coupling length $L$ between the two Nb electrodes was designed to be 0.6 $\mu$m. The InGaAs channel width $W$ was designed to be 10 $\mu$m. For the light exposure, we used infrared laser diodes with continuous waves that operated at room temperature. The laser light was guided through an optical fiber close to the surface of a sample at a low temperature. Light at $\lambda = 1.3$ $\mu$m has an emission energy of 0.954 eV, which is lower than the absorption bandgap of the InAlAs barrier layer. Therefore, photon absorption mainly occurs in the InGaAs channel layer.

Figure 1. Schematic diagram of an S-Sm-S junction with an In$_{0.52}$Al$_{0.48}$As/In$_{0.7}$Ga$_{0.3}$As heterostructure.

In the dark, the total sheet carrier density $n_{2\text{DEG}}$ became constant. As Figure 1 is a schematic diagram of an S-Sm-S junction with an InAlAs barrier layer. Therefore, photon absorption mainly occurs in the InGaAs channel layer. The critical temperature, $T_C$, of the Nb electrodes was about 7.5 K. The coupling length $L$ between the two Nb electrodes was designed to be 0.6 $\mu$m. The InGaAs channel width $W$ was designed to be 10 $\mu$m. For the light exposure, we used infrared laser diodes with continuous waves that operated at room temperature. The laser light was guided through an optical fiber close to the surface of a sample at a low temperature. Light at $\lambda = 1.3$ $\mu$m has an emission energy of 0.954 eV, which is lower than the absorption bandgap of the InAlAs barrier layer. Therefore, photon absorption mainly occurs in the InGaAs channel layer.

First, we investigated the influence of light exposure on the 2DEG in the In$_{0.52}$Al$_{0.48}$As/In$_{0.7}$Ga$_{0.3}$As heterostructure. Figure 2 shows the time dependence of $R_{2\text{DEG}}$ and $n_{2\text{DEG}}$ before and during illumination with 1.3 $\mu$m light. In the dark, the total sheet carrier density $n_{2\text{DEG}}$ became constant. As Figure 1 is a schematic diagram of an S-Sm-S junction with an InAlAs barrier layer. Therefore, photon absorption mainly occurs in the InGaAs channel layer. The critical temperature, $T_C$, of the Nb electrodes was about 7.5 K. The coupling length $L$ between the two Nb electrodes was designed to be 0.6 $\mu$m. The InGaAs channel width $W$ was designed to be 10 $\mu$m. For the light exposure, we used infrared laser diodes with continuous waves that operated at room temperature. The laser light was guided through an optical fiber close to the surface of a sample at a low temperature. Light at $\lambda = 1.3$ $\mu$m has an emission energy of 0.954 eV, which is lower than the absorption bandgap of the InAlAs barrier layer. Therefore, photon absorption mainly occurs in the InGaAs channel layer.

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Figure 3. The differential resistance of the S-Sm-S junction as a function of bias voltage $dV/dI - V$ at 1.8 K before and during illumination with 1.3 $\mu$m light. The arrows indicate subharmonic energy-gap structures corresponding approximately to integer fractions of $2\Delta_{Nb}/e$. Approximately 20% less than its initial value. This result indicates that exposure to $\lambda = 1.3$ $\mu$m light leads to negative photoconductivity (PC) [3]. As a result of negative PC, $R_{2DEG}$ increases with light exposure.

Next, to investigate the interplay between negative PC and superconducting properties, we measured the transport properties of an S-Sm-S junction with a 2DEG in an In$_{0.52}$Al$_{0.48}$As/In$_{0.7}$Ga$_{0.3}$As heterostructure when exposed to 1.3 $\mu$m light. Figure 3 shows the differential resistance of the S-Sm-S junction as a function of bias voltage $dV/dI - V$ at 1.8 K before and during illumination. In both cases, we observed the zero-bias resistance anomaly caused by the phase-coherent Andreev reflection [4] as well as dip structures near $|V| = 2\Delta_{Nb}/ne$, with $n = 1$ and 2. Here, we assumed the Nb superconducting energy gap $\Delta_{Nb}$ to be 1.1 meV, which is somewhat lower than the typical value of $\sim 1.5$ meV. These dip structures are subharmonic energy-gap structures caused by the multiple Andreev reflection [5]. When the sample was illuminated, the $dV/dI$ decreased in the overall bias voltage, although $R_{2DEG}$ increased with negative PC. To emphasize the difference between the two, we normalized the $dV/dI - V$ characteristics by the $dV/dI$ value near $V = 4$ mV, as shown in Fig. 4. We obtained a reduction in the normalized $dV/dI$ with light exposure only within $|V| = 2\Delta_{Nb}/e$. These results provide clear evidence that light exposure both reduces the junction resistance and enhances the Andreev reflection probability.

Next, we quantitatively evaluated the barrier strength $Z$ at the S/Sm interface with respect to the Andreev reflection probability from a fit of the normalized $dV/dI - V$ characteristics obtained by using the model proposed by Bakker [6]. Bakker modeled elastic scattering based on the Octavio-Tinkham-Blonder-Klapwijk (OTBK) model [5] by assuming that all scattering is confined to one barrier with a transmission probability $P_e$ for electrons in the center of the normal area. This is the only difference from the original OTBK model. In Fig. 4, we compare the normalized $dV/dI - V$ characteristics calculated from the Bakker model with experimental
data. By using both a $Z$ of 0.85 and a $P_e$ of 0.2, we obtained the best fit between the calculated and measured $dV/dI - V$ characteristics during illumination, while both a $Z$ of 1 and a $P_e$ of 0.25 yield reasonable agreement between them before illumination. The reduction in the $Z$ parameter indicates that light exposure reduces the barrier strength at the S/Sm interface.

Finally, we discuss the origin of the improvement in the superconducting properties as a result of light exposure. We have to consider the effect of light exposure not only in the 2DEG but also in the contact region near the S/Sm interface. Many deep impurity levels are generated in the S/Sm contact region by process damage, compared with the 2DEG channel. Therefore, these deep impurity levels trap electrons and then the Fermi level near the S-Sm interface is pinned. The absorption of a photon leads to the detrapping of the electrons trapped in the deep impurity levels near the S/Sm interface and then a reduction in the interface barrier height caused by the depinning of the Fermi level. As a consequence, reducing the barrier height overcomes the negative PC that occurs in the 2DEG and then leads to a reduction in the junction resistance as well as an enhancement of the Andreev reflection probability.

3. Conclusions
We have investigated the transport properties of an S-Sm-S junction with a 2DEG in an In$_{0.52}$Al$_{0.48}$As/In$_{0.7}$Ga$_{0.3}$As heterostructure when exposed to light from infrared laser diodes. When the sample was illuminated with $\lambda = 1.3 \, \mu m$ light, we observed a reduction in the junction resistance as well as an enhancement of Andreev reflection by comparing measured $dV/dI - V$ characteristics with those obtained with an extension of the OTBK model. In contrast, we observed negative PC owing to a reduction in the number of electrons in the 2DEG when exposed to 1.3 $\mu m$ light, by employing both Shubnikov-de Haas and Hall-effect measurements. These experimental results indicate that the improvement in the superconducting properties does not originate from the photo-induced carriers in the 2DEG but from the increase in the Andreev reflection probability at the S/Sm interface caused by lowering the interface barrier.

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