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博士論文（要約）

Transport characteristics of superconductor - InAs dot / nanowire junctions
(超伝導-InAs ドット/ナノワイヤー接合の伝導特性)

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Unique transport properties of the junctions of superconductor and other materials - normal metals, semiconductors, and insulators – have been attracting interests of many researchers for decades. Andreev reflection (AR), which takes place at these junctions, is a process where an electron injected to a superconductor is accompanied by a hole reflected in the direction of the incoming electron. This transport process is supported by particular density of states of electrons in a superconductor, where electrons form spin-singlet Cooper pairs and condense near the Fermi surface. If two such superconductors are placed in proximity with a thin layer of another material (i.e. insulator or semiconductor) in between, forming a so-called Josephson junction, coherent and repetitive ARs will lead to the formation of Andreev bound states (ABSs). Singlet-paired electrons flow through the ABSs to generate non-dissipative Josephson current. On the other hand, crossed Andreev reflection (CAR) is an AR process, where the reflected hole will flow into a different path/lead from that of the incoming electron.

Thanks to the recent advances in the semiconductor nano-device fabrication, various kinds of nano-scale junctions of superconductor and other materials, particularly semiconductors have been developed to investigate more deeply or newly on the above mentioned transport processes. Among such devices, particularly interesting and also relevant to this study are Cooper-pair splitters. In Cooper-pair splitters a superconductor is contacted to two normal-metal leads via two parallel quantum dots (QDs), whose charging energies suppress a process where paired electrons enter the same dot without splitting (local-pair tunneling: LPT), and eventually enhance the efficiency of CAR process. The Cooper-pair splitters are regarded as a promising candidate for a source of non-local entangled electrons, which are the essential ingredient for solid-state quantum information processing.

Studies on Cooper-pair splitters have been performed widely. In this scheme, Cooper-pair split (CPS) process is ensured by the observation of positive correlation between differential conductances of two QDs which is absent under a magnetic field higher than the critical field (B_c) of the superconducting lead. With this positive correlation, splitting efficiency $2G_{\mathrm{CPS}}/G_{\mathrm{total}}$, where G_{CPS} is the conductance of the CPS process and G_{total} is the total conductance, ranging from a few % to near 100% has been obtained in previous studies. Even after these preceding reports, however, the spin correlation of split electrons or what determines the splitting efficiency remains unclear.

This thesis is composed of four experiments. The first experiment is conducted to tackle the first question: spin correlation of CPS electrons flowing through two QDs. The other three experiments are aimed to give a better insight into the determining factors of the splitting efficiency.

In the first experiment, we fabricated and measured a device called double QD Josephson junction. In contrast to the conventional Cooper-pair splitters, this device consists of two superconducting Al leads with a nanogap in between, and parallel coupled two QDs (closely spaced two InAs self-assembled QDs) placed in the nanogap and contacted by the two Al leads. Sidegates are fabricated in proximity to the junction in order to tune each QD individually. We measured supercurrent through such junctions while changing each gate voltage and driving each QD on or off resonance. We observed enhanced supercurrent when both QDs are on resonance, where by “enhanced” we mean that the supercurrent observed was significantly higher than the sum of supercurrents when one of the two dots is on resonance with the other dot off resonance. We attribute this enhancement of supercurrent to existence of CPS process which contributes to non-dissipative supercurrent. This result not only confirms the CPS process, but ensures that split Cooper-pairs maintain their spin coherence while the two electrons are in different dots, meaning that non-local spin entanglement is maintained during the split tunneling process.

Following the first experiment, we moved on to the investigation of splitting efficiency. According to theoretical reports, splitting efficiency of CPS devices is formulated as follows;

$$\frac{I_{CPS}}{I_{LPT}} = \frac{2\varepsilon^2}{\Gamma^2}\left[\frac{\sin(k_F \delta r)}{k_F \delta r}\right]^2 \exp\left(-\frac{2\delta r}{\pi\xi}\right) \qquad \cdots(1)$$

$$\frac{1}{\varepsilon} = \frac{1}{\pi\Delta} + \frac{1}{U}, \qquad \cdots(2)$$

where I_{CPS} and I_{LPT} are current of each process, δr is the distance between the QDs, ξ is the coherence length of the superconductor, Δ is the superconducting gap energy, and U is the charging energy of the QDs, respectively.

Replacing Al with Nb for the superconducting lead material can enhance the splitting efficiency, because Nb has a larger Δ~1.5meV in bulk (for Al: Δ~ 0.15meV), which will make the efficiency more than 10 times larger, given the charging energy U~2meV. Use of Nb also affects the exponential term due to its shorter coherence length ξ~ 30nm (for Al: ξ~ 1μm). However, assuming δr ~ 10nm, this term only makes a small difference of ~ 20-30%, suggesting that if one manages to make the inter-dot distance short enough, the exponential term becomes of less significance.

In order to experimentally evaluate the discussion above, we performed experiments with Nb-based QDJJs. It is well known that Nb based nano-structures are generally difficult to fabricate compared to those of Al, because Nb is more easily oxidized. We improved our fabrication process in several respects, which include the use of low-damage SEM and NbTiN alloy as a superconductor. With the use of low-damage SEM we can locate InAs self-assembled dots on a GaAs substrate without charging up the dots, which often damages them severely, much faster and more efficiently than with AFM. The reason for NbTiN yielding better contacts to QDs than Nb is yet to be discussed, but supposedly has to do with the quality and size of interface with QDs.

We first measured single QD Josephson junctions, and characterized their basic parameters. Obtained parameters are largely improved from those of Al devices, including Δ~ 0.7meV B_c > 1T, which in the case of Al were ~0.15meV and ~ 0.1T respectively. Next, with the same material, we fabricated DQDJJs, and performed measurements similar to the Al-DQDJJ experiment. We took I-V curves while changing two sidegate voltages to tune each QD individually such that each QD is on or off resonance. Here, we were unable to define clear switching current as opposed to the case of Al devices prepared in the first experiment. We attribute this to thermal phase dissipation or poor quality of the contacts between QDs and leads. However, by comparing the value of bias current at which voltage starts to increase rapidly – we call it threshold current I_{th} -, we observed the enhancement of I_{th} when both QDs are on resonance, qualitatively reproducing the result of Al-DQDJJ experiment.

The third and fourth experiments are of double-InAs nanowire systems. Use of double nanowire (DNW) systems can help to solve the problem of poor contacts discussed above because in such systems areal overlap between the superconducting lead and the InAs surface is much larger than that of self-assembled-QD devices. The different device geometry as well as the large contact area in the NW systems can also provide deeper insight into the microscopic mechanism of the CPS processes. After many works on CPS devices, a question still remains; does CAR take place exactly at the boundary of superconductor and QDs? or does it happen via the superconductivity-proximitized region in the semiconductor? This fundamental question is also related to the splitting efficiency, because the middle squared term in Eq. (1) can be different by a factor of 10^4, between the above described two cases because the λ_F value is less than 1 nm for superconducting metal but ~ 100 nm for semiconductor, indicating the superconductivity-proximitized region made in the semiconductor gives a higher CPS efficiency.

In order to selectively place DNW onto previously-fabricated array of finger bottom gates, we established the following process. We first pick up hundreds of nanowires (NWs) from the growth substrate with a cotton bud, and transfer them to the second substrate, on which two layers of EBL (electron beam lithography) resists are deposited beforehand. Next we peel off only the top layer with nanowires on, and flip and contact it to the device substrate. During this second transfer, we observe the film and device substrate with an optical microscope, and carefully align them with a home-made micro manipulator. At this step, DNW has a slightly brighter color in the microscope image than single NWs, so it is possible to selectively transfer DNWs onto the gate arrays.

We performed the third measurement using such DNWs. Here our goal is to establish the fabrication process and evaluate the basic characteristics and gate performances of DNW junctions, so we deposited a normal metal (Ti/Au) onto DNWs. The gapsize is as small as ~100nm, which leads to the natural formation of QDs on both NWs (NW-QDs). We measured the differential conductance of the junction while tuning each QD with two different finger bottom gates which are parallel to the NWs, and obtained a charge stability diagram (CSD). Resonance peaks with two different slopes in the CSD ensure the formation of parallel double quantum dot on DNW. In some gate regions we observed honey-comb like crossings of such peaks, suggesting the capacitive coupling between two QDs.

Finally, in the fourth experiment, we fabricated a DNW device with a superconducting source contact, to both NWs and a separate normal drain contact to each NW to study CPS for separate two NWs. We measured a differential conductance of each NW, while tuning the electrostatic potentials of the two NWs with sidegates as performed in the third experiment. The conductance obtained simultaneously for both NWs shows a series of Coulomb peaks (or CSD), due to the formation of gate-induced NW-QDs in each NW as expected from the third experiment. We observed a positive correlation of the differential conductances at and near crossings of resonance peaks in the CDSs. With this correlation CPS process in the DNW junction is confirmed. The maximum CPS efficiency obtained here is ~13%.

Aside from the above mentioned positive correlation, we observed two characteristic features in the CSDs. The first is the resonance peaks with low amplitude but large width, which appear at 0 T but not at ~250mT (> B_c). These "secondary" peaks observed for one of the two NW-QDs show a positive correlation as well when the other NW-QD is on resonance. Note the gate capacitance evaluated from the CSDs is slightly larger for the secondary peaks than for the main peaks. The existence of these secondary peaks can be attributed to two different tunneling processes. In the first tunneling process, Cooper-pairs tunnel into the gated NW-QD through the edge of the superconductor, experiencing a large tunnel barrier at the interface. In the second tunneling process, in contrast, Cooper-pairs first make their way into the superconductivity-proximitized region in the coupled two NWs below the superconducting contact, and then separately tunnel into the two NW-QDs. The junction barrier for such a tunneling process is assumed to be lower than that of the first process, and therefore makes the tunnel coupling for this process larger. Considering the charging energy and single-particle level spacing obtained in these NW-QDs, it is reasonable to assume that the first excited states of the NW-QDs are only accessed by the second tunneling process, due to its stronger tunnel coupling, giving rise to the emergence of the "secondary" peaks. This argument agrees well with the observation that these peaks disappear with the increasing field, and that they have different gate capacitance from the main peaks because one can assume that the spatial positions of the tunnel barriers for the two processes are different.

The second notable feature is the positive correlation observed between the main resonance peaks for one of the two NW-QDs when the other NW-QD is on resonance. This is also explained by the second tunneling process mentioned above owing to the large tunnel coupling for the CPS process.

In conclusion for the last experiment, we confirmed the CPS process in DNW systems, and observed features suggest that the two CAR process - one at the boundary of contact and QDs, and the other through the superconductivity-proximitized region – coexist, which provides an insight into microscopic mechanisms of CAR process.