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NON-INVASIVE MEASUREMENTS OF MESOSCOPIC SUPERCONDUCTORS BY SUPERCONDUCTING SINGLE ELECTRON TRANSISTORS

HIDEKI SATO, SHINGO KATSUMOTO and YASUHIRO IYE
Institute for Solid State Physics, University of Tokyo, 7-22-1 Roppongi, Tokyo 106, Japan

Abstract—We have applied single-electron transistors (SETs) for the measurement of the energy gap of a quasiparticle as a function of magnetic field in mesoscopic superconductors. Through the measurements, it turned out that the randomness results in the pinning force of vortices, though the configuration of the order parameter is dominated by the edge nucleation of the superconductivity. The pinning of vortex in the Coulomb island enabled us to explore the energy spectra of metastable states with a fixed number of fluxoids. © 1998 Elsevier Science Ltd. All rights reserved

1. INTRODUCTION

Quantized magnetic fluxes in type-II superconductors, called vortices, are a kind of elementary excitation in macroscopic wavefunction and can be treated as bosons which interact with each other with a logarithmic potential[1]. The vortices are conjugate excitation with the excess (deficient) Cooper pairs in an isolated superconductor though the duality between them is not perfect. A superconducting state is then labeled by the number of vortices and Cooper pairs in the clean limit. One of the most important issues in mesoscopic superconductors is, thus, the properties of vortices confined in small spaces.

For the study of the structure of individual vortices, microscopic pick-up methods such as scanning tunneling microscopy or electron holography are advantageous[2–4]. However these methods usually require expensive equipment, a long set-up time and are not always very sensitive, e.g. to the variation of the energy gap. On the other hand, the transport measurement through the mesoscopic systems is easy to perform and usually very sensitive though the attached electrodes may modify the superconductivity of the system.

In this article, we introduce a method to measure the energy gap of mesoscopic superconductors by using superconducting single-electron transistors (SSETs). This method is highly sensitive and non-invasive to the superconductivity because the system is isolated by the Coulomb blockade. In the present study, the disorder caused some pinning force of the vortices, though the averaged properties of the superconducting states are dominated by the edge nucleation of the superconductivity. Using the pinning force, we measured the gap spectra of the metastable fluxoid states.

2. EXPERIMENT

The principle of the measurement is very simple as follows. In a double Josephson junction system, such as an SSET, the threshold source-drain voltage $V_{\rm th}$ for the quasiparticle current is $V_{\rm th} = (3E_{\rm C} + 2\Delta_{\rm i} + 2\Delta_{\rm e})/e$, where $E_{\rm C}$ is the single-electron charging energy, $\Delta_{\rm i}$ is the superconducting energy gap in the island and $\Delta_{\rm e}$ is that in the electrodes. Therefore, if we can determine $V_{\rm th}$ correctly and assume $E_{\rm C}$ is independent of the magnetic field, we can directly obtain the variation of $\Delta_{\rm i} + \Delta_{\rm e}$ as a function of the field. As discussed in Ref.[5], $\Delta_{\rm e}$ only weakly depends on the magnetic field when the width of the electrodes is comparable to or lower than the coherence length. Roughly speaking the current–voltage (I–V) characteristics are approximated as $I = 0$ for $|V| < V_{\rm th}$ and $I = (V - V_{\rm th})/R_{\rm n}$ for $|V| > V_{\rm th}$, where $R_{\rm n}$ is twice the normal resistance of the junction[6]. Under the current biased condition, $V_{\rm th}$ is obtained by just measuring the source-drain voltage. Similarly under the voltage bias, the same information is obtained from the source-drain current. In this case, the variation in the energy gap is expressed as $2(\partial V/\partial I) \times e\delta I$.

In this method the sample is thus built in the SSET, i.e. the Coulomb island. In order to investigate the size effect on the superconductivity, we prepared various types of Coulomb islands. These samples were fabricated by electron beam lithography and oblique angle deposition of Al. The inset to Fig. 1 shows a schematic view of a sample, which consists of a comparatively large ($1.2 \times 1\ \mu{\rm m}^2$) Coulomb island, source and drain electrodes. These parts are connected with two small ($0.1 \times 0.1\ \mu{\rm m}^2$) Josephson junctions. The coherence length at 1.2 K is determined from a transport measurement to be about 50 nm and is much shorter than the penetration depth. Hence the

Al films are no longer good type-I superconductors but the properties are close to those of type-II.

This method is simple but has several advantages. First, the variation in Δ, which is obtained only indirectly by other methods, is detectable. Secondly, Δ of single samples can be measured. Thirdly, since the tunneling current is directly measured, the sensitivity is much higher than indirect measurements such as the detection of the magnetization. Fourthly, the isolation of the sample is better than that in conductance measurement. Note that the current for the measurement is usually much smaller than the shielding current and is negligible. A problem in this method may be that the *I–V* characteristics are significantly rounded just below the critical temperature T_C. In the present experiment, T_C rose to 1.9 K due to some disorder in the films[7] and we adopt 1.2 K for the experiments. At this temperature, we did not have, in practice, the problem of rounded *I–V* characteristics.

3. RESULTS AND DISCUSSION

Figure 1 shows the source-drain current as a function of the applied magnetic flux per sample area (Φ) normalized with the flux quantum $\Phi_0 \equiv h/2e$. Many jumps appear in the magneto-current resulting in oscillatory behavior. As discussed in Refs.[5,8], these jumps are due to one by one entrance of quantized fluxoid. Hence the fluxoid number is fixed between two adjacent jumps. As noticed before, we can thus label the superconducting states in the Coulomb island by the number of fluxoids in the most naive approximation.

The applied external magnetic flux increases the free energy of the superconducting states by the "kinetic energy" of Cooper pairs, which is roughly proportional to $(\Phi - n\Phi_0)^2$, with n as the number of fluxoids[1]. This exactly corresponds to the electrostatic energy $(Q - n_C(2e))^2/2C_\Sigma$, where Q is the charge induced on the Coulomb island by the gate voltage, n_C the number of Cooper-pairs and C_Σ the total capacitance of the device. The electrostatic effect leads to the Coulomb oscillation of source-drain current, in which the Cooper-pair current flows only when the degeneracy between a state and neighboring states in n_C occurs. We may infer from the duality between fluxoid and Cooper-pair that we can use the device as a "single-vortex transistor"[9], in which the fluxes flow only when the degeneracy between the two adjacent states occurs.

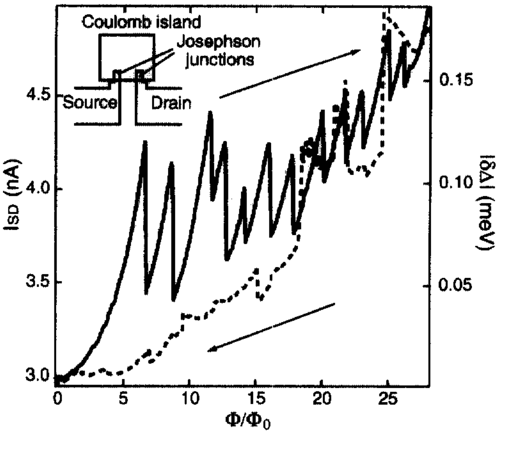

Fig. 1. Source-drain current as a function of applied magnetic flux for the sample with 1.2 × 1.0 μm^2 Coulomb island. The bias voltage is 0.98 mV. The arrows indicate the direction of the field sweep. The variation of the energy gap is estimated by the relation described in the text. Inset: a schematic view of the sample.

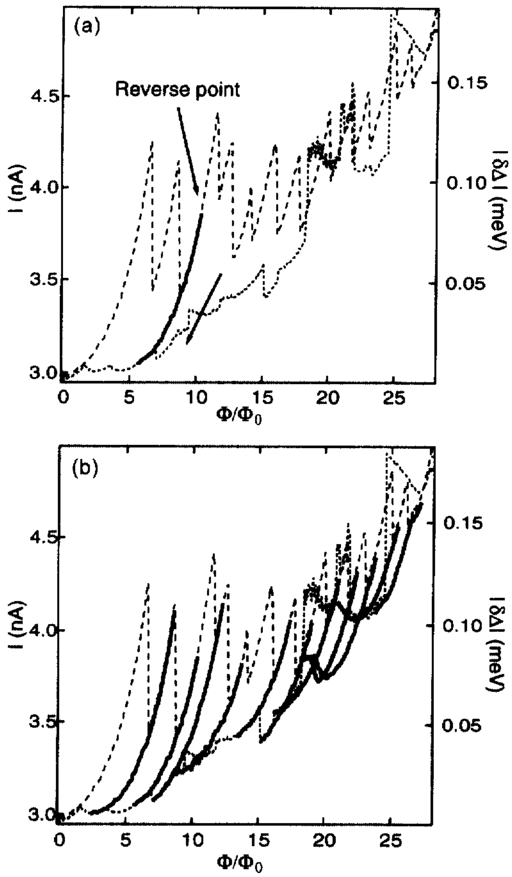

Fig. 2. (a) An example of the procedure to extract the energy spectrum of a fluxoid state. The broken and dotted curves show the same data as in Fig. 1. "Reverse point" means the point at which the sweep direction is reversed. (b) Energy diagram obtained through the procedures similar to that in (a) for many fluxoid branches.

However it is apparent that this cannot be realized in the present system from the prominent hysteresis effect shown in Fig. 1. The hysteretic behavior is manifested in the fluxoids being trapped at some defects and the observed "fluxoid states" being not in equilibrium but metastable. Instead, we can trace the energy gap of the metastable states as a function of applied magnetic flux as shown in Fig. 2(a). The procedure is simply that we stopped the field sweeping on a branch and reversed the sweep direction. Because of the pinning force, the system kept the number of fluxoids until it resumed to a branch in the returning curve and had a jump. The resultant energy gap spectra are shown in Fig. 2(b). The energy gap is proportional to the free energy difference between the normal state and the superconducting one and the functional form of the gap spectra and that of the free energy should be the same. As inferred above, the Φ-dependence of the gap is roughly quadratic.

We would like to go into more detailed analysis and extract some general properties of mesoscopic superconductors. Figure 3 shows a log–log plot of the averaged period of magnetic field for current jumps vs the sample area. The broken line represents the flux quantum per sample area. The apparent correlation along the line manifests that the fluxoid states are not completely randomized by disorder but affected by the edge nucleation of superconductivity[10], which was claimed to be proven in magnetization measurements[11,12] and transport measurements[13]. A jump corresponds to the transition from one metastable state to another and may be strongly affected by disorder. According to the edge nucleation model, the effect of disorder should be weak on the gap at the bottom of parabolas because there is no shielding current in principle. If the randomness is so strong that the random matrix theory is applicable, the distribution of the bottom current is still not random Poissonian but the Wigner distribution, which has a long tail[14].

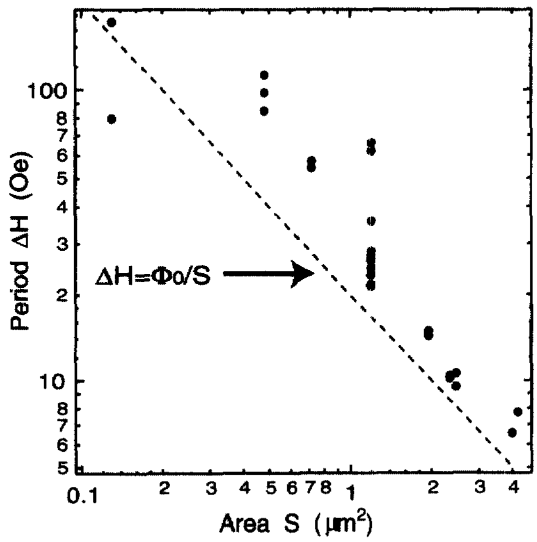

Fig. 3. Average period of the source-drain current jump for many samples as a function of the area of the Coulomb islands. The broken line shows the relationship $\Delta H = \Phi_0/S$ where S is the area of the Coulomb islands.

On the other hand the positions of parabolas along the field axis should fairly reflect the amplitude distribution of the order parameter. Figure 4 shows the current at the bottoms of the parabolas (filled symbols) and at the jumps of spectra (open symbols) as a function of the positions along the field axis. For reference we plot the data for the ring-shaped sample, in which the effect of disorder is significantly suppressed. The filled symbols are quite in order even for the simply connected sample. These strongly suggest that the edge nucleation dominates the distribution of the shielding current though we have not analyzed them quantitatively.

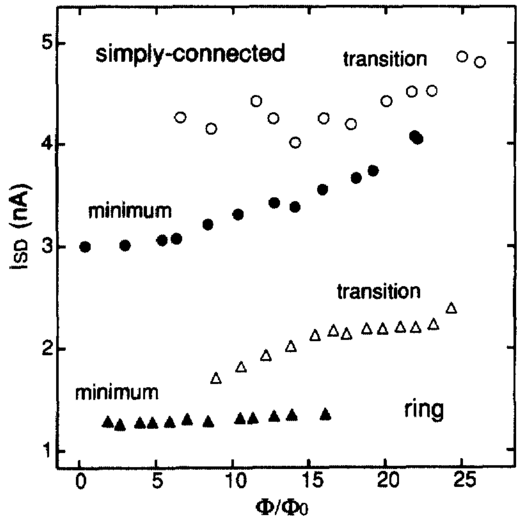

Fig. 4. Filled symbols: the minimum points of the parabolas which are fitted to the energy gap spectra. Open symbols: the jump points of the spectra. Circles are the results for the simply connected sample. Triangles are those for the sample with a ring-shaped Coulomb island.

Combining the above result with the fact that the coherence length cannot be ignored, i.e. the vortex core has a finite area, we should correct our previous primitive picture as follows. A vortex is not pinned to a specific defect but only the distribution of the shielding current is distorted by the disorder, which leads to some "pinning" force and randomness in the current oscillation pattern.

In Fig. 5 we show a possible application, in which we have two Coulomb islands connected with the center Josephson junction. This consists of a kind of "superconducting molecule" and if the Josephson coupling energy is large enough, some molecular coupling effect, e.g. effect of level-anticrossing, can be seen. In this case, however, the coupling is weak and the two Coulomb islands are almost independent. However, the current jump should be affected by small fluctuation of the shielding current and there may be some coherence. Also the "Josephson vortex" state, which only penetrates into one of the layers in a layered structure, has higher energy than that which penetrates through the structure and because the area of the center Josephson junction is not negligible, this may also cause some coherency. In the resultant oscillations,

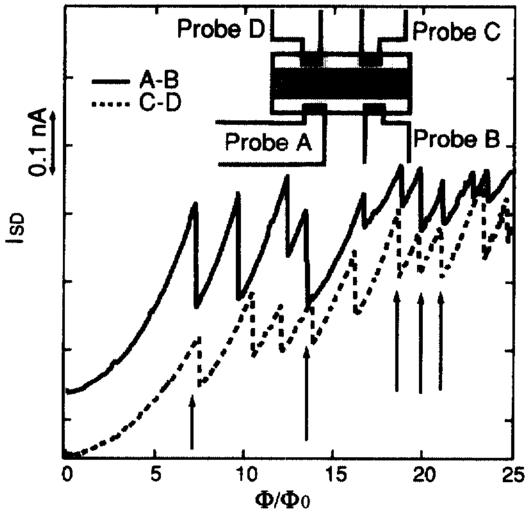

Fig. 5. The effect of the Josephson junction which connects two Coulomb islands. The solid line shows the result with probes A–B and the dashed line shows that with C–D. The arrows indicate the coincidences in the current jumps. Inset: a schematic view of a sample. The shaded areas indicate Josephson junctions.

we see several coincidences in the current jumps indicated by the arrows, which may be due to such processes. For confirmation, more experiments are needed.

In conclusion, we measured the magneto-current of SSETs, which directly reflects the energy gap of the Coulomb islands. The hysteresis in the pattern enabled us to trace the energy spectra of all the "fluxoid states". It turned out that the randomness results in the pinning force of vortices though the configuration of the order parameter is dominated by the edge nucleation of the superconductivity.

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