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Physica B 249–251 (1998) 453–457

PHYSICA B

Fluxoid states in mesoscopic superconductors

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Abstract

We measured the superconducting energy gap as a function of the external magnetic field for various samples of mesoscopic sizes, using single-electron transistors. The energy gap spectra of 'fluxoid states', in which the numbers of fluxoid are fixed, were obtained and found to have both sample-specific and common characteristics. The former is due to the geometry of the defects while the latter originates from the edge superconductivity. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Mesoscopic superconductor; Fluxoid quantization; Magnetofingerprint; Single-electron transistor

1. Introduction

Superconductors provide a useful stage for experimenting on quantum states in macroscopic scales. Recent development of nano-fabrication has enabled us to experimentally investigate the behavior of the order parameter $\psi = |\psi|e^{i\varphi}$ in artificially created mesoscopic structures. There are numerous studies addressing the classical and quantum mechanical behavior of the phase φ in Josephson junctions. In particular, a phenomenon of macroscopic quantum tunneling (MQT) in the φ-space is intensively explored [1,2]. By comparison, studies on mesoscopic effects on the other degree of freedom, i.e. the amplitude $|\psi|$ or equivalently the energy gap Δ, are less abundant.

Recently, experiments along this line have been reported, in which the response of ψ in mesoscopic superconductors to an external magnetic field has been probed by magnetization [3,4] or transport [5] measurement. These experiments and related theoretical efforts [6,7] have elucidated a general aspect of mesoscopic superconductivity. One of the characteristic features in mesoscopic physics lies in that the outcome of measurement reveals a non-ensemble-averaged property of a particular sample. In the present work, we explore such sample-specific behavior of mesoscopic superconductors.

As a sensitive probe for a mesoscopic superconductor, we utilized a superconducting single-electron transistor (SSET) consisting of a superconducting Coulomb island Josephson coupled to a source and a drain electrode. The change in the energy gap of the superconducting Coulomb island was monitored by the source-drain current I_{SD} as a function of the external magnetic

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PII: S0921-4526(98)00162-8

field. This allowed us to keep track of transitions between the quantum states that could be labeled with the number of fluxoids (hence called 'fluxoid states' in this article).

2. Experiment

We fabricated SSETs with Coulomb islands of various sizes by electron beam lithography and oblique angle deposition of 15 nm thick Al. Fig. 1 is a scanning electron micrograph of one of the samples. The dimensions of the Coulomb island are $1.25 \times 1\ \mu m^2$ and the junction area is $0.1 \times 0.1\ \mu m^2$.

Measurements were done by cooling the samples down to 1.2 K by pumping on ^{4}He. Though the superconducting critical temperature T_C for bulk Al is 1.1 K, T_C of Al thin films usually rises up to about 2 K due to disorder [8]. In the present case, T_C was 1.9 K. The coherence length was estimated from a separately conducted measurement as $\xi \sim 50$ nm. The bias voltage was applied by an analog source and the cryostat was placed in a shielded room, in which no digital circuit was operated. A magnetic field perpendicular to the sample plane was applied by a superconducting solenoid.

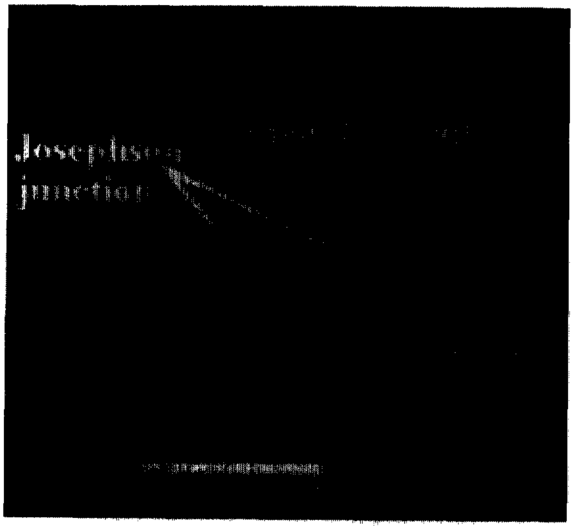

Fig. 1. A scanning electron micrograph of a sample. The area of the junctions is $0.1 \times 0.1\ \mu m^2$.

In an SSET, a quasi-particle current starts to flow when the source-drain voltage V_{SD} exceeds $V_{th} = (2\Delta_i + 2\Delta_e + 3E_C)/e$, where Δ_i is the energy gap in the Coulomb island, Δ_e is that in the electrodes and E_C is the single-electron charging energy [9]. If we assume E_C is independent of the magnetic field H, the variation in $2(\Delta_i + \Delta_e)$ can be detected through I_{SD}. In most measurements V_{SD} was fixed just above V_{th}, in which condition the change in Δ was most sensitively manifested in I_{SD}. The traces of $I_{SD}(H)$ reflects penetration of fluxoids into the superconducting Coulomb island. The width of the electrodes was made comparable to the coherence length ξ, so as not to allow the trapping of fluxoids. Therefore, Δ_e was smooth-varying with H, and hence rapid changes in $I_{SD}(H)$ to be discussed below was attributed to that of Δ_i.

3. Results and discussion

3.1. Energy gap for each fluxoid state

Fig. 2 shows the $I_{SD}(\Phi)$, where Φ is the magnetic flux per the area of the superconducting Coulomb island, for the sample shown in Fig. 1. After a number of experiments we found these $I_{SD}(\Phi)$ patterns were sample-specific and highly reproducible (they do not change by heat cycling to room temperature) [10]. As seen in Fig. 2, the pattern has many jumps of current, which correspond to the abrupt changes in the energy gap upon entrance or departure of a fluxoid. Because the average period of jumps is nearly one flux quantum, the system mostly jumps between fluxoid states which differs in the number of fluxoids by one. Another prominent feature is the large hysteresis, which means that the system does not necessarily trace the ground state but can be trapped to the metastable states. By tracking the hysteretic behavior, we can determine the energy gap in each of the metastable states, as shown in Fig. 3.

3.2. Irregularity of the $i_{sd}(\phi)$ pattern

A remarkable point in Fig. 3 is that the oscillation is not quite regular though it is caused by the

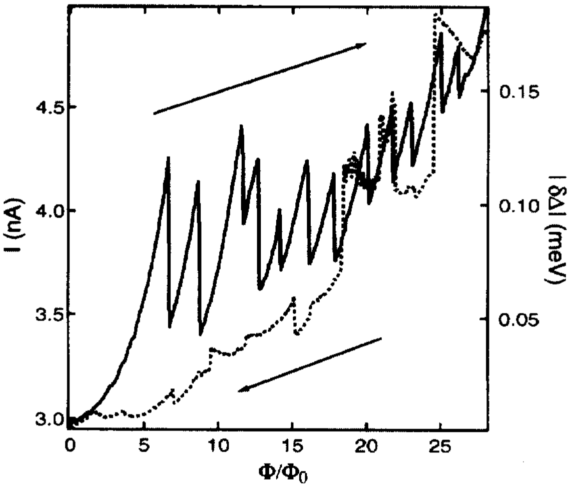

Fig. 2. Source-drain current of the sample shown in Fig. 1 as a function of magnetic flux per the area of the Coulomb island in units of the flux quantum Φ_0. The arrows indicate the direction of the field sweep. The corresponding energy gap is also shown ($|\delta\Delta| = |\delta I| \times (\mathrm{d}V/\mathrm{d}I)/2$).

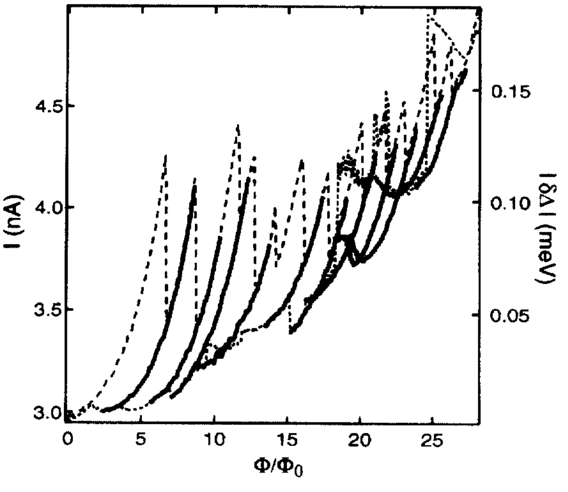

Fig. 3. The energy gap spectra for the sample shown in Fig. 1 are shown by solid curves. The broken curve and the dotted curve are the same data as in Fig. 2.

quantized fluxoids. The spectra of these fluxoid states are determined by two factors: (i) the functional form of the energy gap ($\delta\Delta(\Phi)$) for each branch; (ii) the energy gap at the critical fields where the system jumps to the neighboring states ($|\delta\Delta|_{\max}$ or $|\delta\Delta|_{\min}$). The irregular pattern of $I_{\mathrm{SD}}(\Phi)$ is thus due to the irregularity in $\delta\Delta(\Phi)$ and/or $|\delta\Delta|_{\max,\min}$.

As seen in Fig. 3, the functional form of $\delta\Delta(\Phi)$ for each fluxoid state is similar to each other and can be approximated by a parabolic form, which is due to the kinetic energy of the supercurrent. However, the coefficients of the quadratic terms and the positions of the parabolas are not perfectly regular. If the system is a disc with perfect axial symmetry, i.e., the fluxoids that penetrate the sample will always sit at the center of the disc, then, the oscillation pattern should be regularly ordered as expected from the simple solution of the Ginzburg–Landau (GL) equation [6,7]. The irregularity found in the present experiment indicates that the fluxoid states are strongly affected by the lack of symmetry. In other words, the oscillation pattern reflects the disorder in the sample that governs the fluxoid configuration. In this sense the phenomenon is reminiscent of the universal conductance fluctuation (UCF) [11] in disordered conductors and therefore may be called 'magneto-fingerprints' of a mesoscopic superconductor [10].

Note that the measured energy gap is the local one around the two junctions. The spatial range of the energy gap detection is on the order of ξ, which is somewhat shorter than the size of the island. Therefore, we are observing only a part of the whole 'order parameter hologram' in the mesoscopic superconductor.

An interesting test of the above inference is to introduce an artificial 'defect' into the sample. This is realized by preparing a sample with a ring-shaped Coulomb island shown in Fig. 4a. In this structure, the fluxoids tend to be trapped in the central hole so as to minimize the total energy. In this case, the experiment is very similar to that by Little and Parks [12]. Fig. 4b shows the result. Now, the array of the 'parabolas' is much more regularly ordered than the previous case. This makes a strong case that the oscillation pattern of $I_{\mathrm{SD}}(\Phi)$ is a sensitive probe of the fluxoid configuration.

3.3. *Surface (edge) superconductivity*

In the previous section, the similarity between the oscillation pattern in $I_{\mathrm{SD}}(\Phi)$ and the UCF was

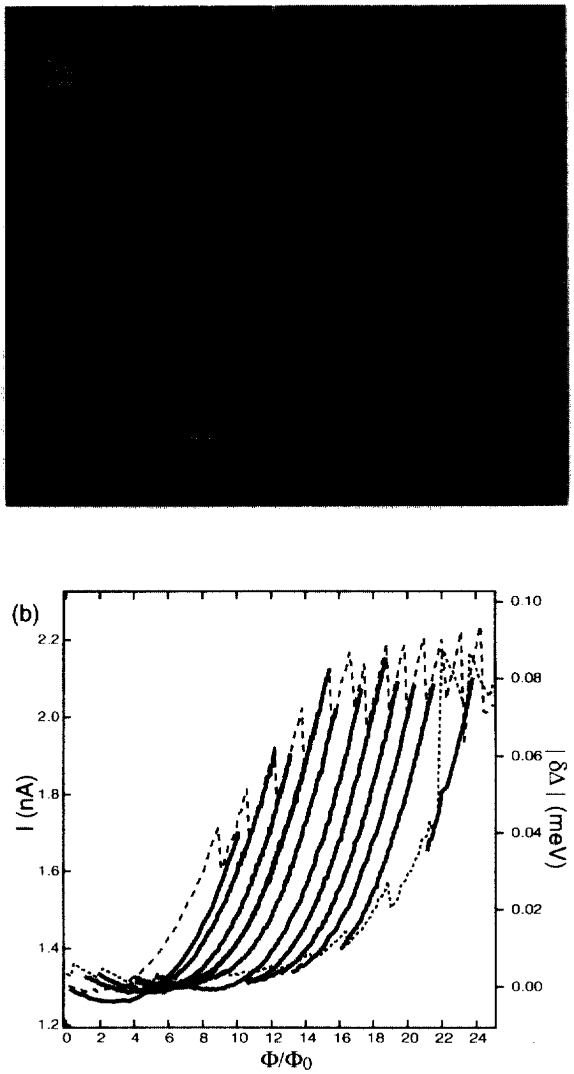

Fig. 4. (a) A scanning electron micrograph of a sample with a ring-shaped Coulomb island. (b) The energy gap spectra for the sample shown in (a). The broken curve is the up sweep and the dotted curve is the down sweep.

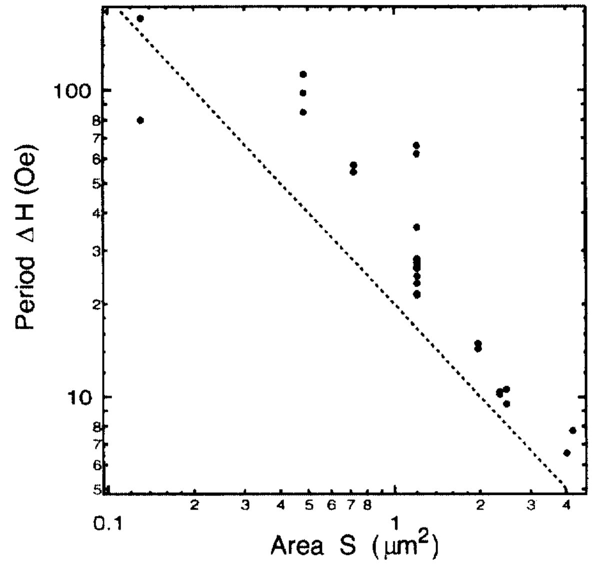

Fig. 5. Average period of the energy gap jump in the external magnetic field for many samples against the area of the Coulomb islands. The broken line indicates single flux quantum per area of the island ($\Delta H = \Phi_0/S$).

emphasized. There is, however, an important difference, which arises from nucleation of superconductivity in the vicinity of the boundary, i.e. surface superconductivity (or edge superconductivity for the present geometry) [13]. This leads to a tendency for the supercurrent to flow around the peripheral part of the island. Even a bulk island, therefore, tends to look like a ring. This is corroborated by the fact that the 'parabolas' for the bulk island in Fig. 3 are to a certain extent equally spaced, just like those for the ring island in Fig. 4b.

Moreover, this spacing is found to scale with the area of the island. This is seen in Fig. 5, which shows the average period of oscillations in the I_{SD} patterns for different dimensions. The slope of the broken line corresponds to a single flux quantum per area of the island. The agreement between the data points and the broken line strongly suggests the validity of the above picture of edge superconductivity. Thus, the superconducting magnetofinerprint is more strongly affected by the edge geometry than the defects distributed in the interior of the island. The crucial role of the edge superconductivity emphasized in the analysis of the magnetization of a mesoscopic superconducting disc [6]. The present result implies that the same is also true in a dirty mesoscopic superconductor of general shape.

4. Conclusion

We have measured magnetic-field variation of the energy gap of disordered mesoscopic superconductor by use of an SSET. The hysteresis in the oscillation of $I_{SD}(\Phi)$ has enabled us to study the gap spectrum of each fluxoid state in detail. The oscillation patterns show irregularity which carries information on sample-specific defect arrangement. On the other hand, the quasi-regular oscillation clearly indicates the surface nucleation of the superconductivity.

Acknowledgements

This work was partly supported by a Grant-in-Aid for Scientific Research on the Priority Area, 'Single Electron Devices and Their High Density Integration', from the Ministry of Education, Science, Sports and Culture of Japan.

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