Detecting superconducting states in nanoscale superconductors using multiple-small-tunnel-junction method

Akinobu Kanda1,2, Sinya Hatsumi1, Ryo Furugen1, Youiti Ootuka1
1 Institute of Physics and TIMS, University of Tsukuba, Tsukuba 305-8571, Japan
2 Japan Science and Technology Agency, CREST, Kawaguchi 332-0012, Japan
E-mail: kanda@lt.px.tsukuba.ac.jp

Abstract. The multiple-small-tunnel-junction method to detect superconducting states in a mesoscopic superconductor is described. The sensitive detection of changes in local supercurrents allows one to confirm the novel superconducting states as well as to determine the vortex positions in superconductors with antidots.

1. Introduction
In the mixed state of bulk type II superconductors, vortices form triangular lattices (the Abrikosov lattices) due to the repulsive forces between them. Because the energy associated with an interface between a normal core and surrounding superconducting parts is negative, each vortex encloses the minimum magnetic flux (flux quantum: $\Phi_0 = h/2e \approx 2 \times 10^{-15}$ Wb) and the phase of the order parameter changes by $2\pi$ around the core. On the other hand, in nanoscale mesoscopic superconductors with sizes comparable to the superconducting coherence length $\xi$, the vortex configuration is affected not only by the vortex-vortex interaction but also by the boundary of the superconductor, leading to corruption of the Abrikosov triangular lattice and the formation of fundamentally new vortex states which is quite sensitive to the size and shape of the superconductor. For example, multiple vortices can merge into one (giant vortex state, GVS) in a disk.[1, 2, 3, 4] Note that the Cooper-pair density near the central core of the GVS does not have multiple small dips, but is fully axially symmetric with respect to the disk center. This GVS appears because the vortices are pushed toward the disk center due to the repulsive interaction with the sample boundary. Therefore, it is stabilized in a small disk (radius $\approx \xi$), or even in larger disks under high magnetic fields where a stronger shielding current along the boundary exerts a repulsive force to vortices. In the latter case, a transition from GVS to multiple singly-quantized vortices (multivortex states, MVS) occurs in decreasing magnetic field.

Experimentally, a variety of techniques have been developed for the observation of the theoretically predicted novel vortex states in mesoscopic superconductors. The most preferable one is the direct visualization of the vortices. Such techniques include scanning SQUID microscopy, scanning tunnel microscopy, and Bitter decoration technique. However, the smallest SQUID loop available now has a diameter of several microns, which limits severely the spatial resolution. This size is not sufficient even for the Al samples having relatively large coherence
length ($\xi \approx 0.2\mu m$). The STM observation requires mesoscopic samples with atomically flat surfaces, which are difficult to prepare at present.[5] The Bitter decoration technique, in which deposited small ferromagnetic particles on a superconductor are observed by scanning electron microscope, has a better resolution, but it is impossible to observe a successive motion of vortices. There are alternative indirect methods: cusps in the superconducting phase boundary $T_c(H)$ obtained in resistance measurements have been attributed to transitions between different vortex states, corresponding to the Little-Parks effect in superconducting cylinders. The transition fields are in good agreement with theoretical predictions.[6] Ballistic Hall magnetometry for an isolated sample that is placed on a $\mu$m-scale Hall bar shows multiple magnetization curves as a function of applied magnetic field, each of which corresponds to different vortex states.[7] It is noted that these indirect methods do not give us any information on the vortex positions, so that a numerical study (minimization of the free energy) is essential to identify the vortex states (even to determine whether the state is a GVS or an MVS) in these experiments.

Recently we have developed the multiple-small-tunnel-junction (MSTJ) method, which is based on the classical technique for estimating the superconducting energy gap from the current-voltage ($I-V$) characteristics of a superconductor-insulator-normal metal (SIN) tunnel junction.[2] Our method gives us partial information on the spatial distribution of the supercurrent in the sample, so that by taking into account the symmetry of the sample geometry, one can guess the vortex configuration. In the MSTJ method, several normal-metal leads are connected to a mesoscopic superconductor with an insulating layer as interface, forming highly resistive SIN tunnel junctions with tunnel resistance $R \gg R_Q = h/4e^2 \approx 6.4k\Omega$. The $I-V$ characteristics of a SIN tunnel junction at low temperatures have a gap structure around the origin, reflecting the superconducting density of states. The threshold voltage for the current onset, $V_g$, equals the superconducting energy gap divided by $e$ at low temperatures. Therefore, when the current through the tunnel junction is fixed to a small value (typically at 0.1 - 1 nA in our measurement), the resulting voltage is sensitive to a change in the energy gap. Moreover, if the junction size is smaller than the superconducting coherence length, the voltage reflects the local energy gap below the junction, and by employing multiple small tunnel junctions, one can obtain information on the supercurrent distribution and consequently on the vortex structure.

2. Superconducting states in rings

As an illustrative example, Fig. 1 shows the results for a small superconducting ring under a perpendicular magnetic field. The Al ring is 0.20 $\mu$m in radius, 70 nm in linewidth, and 20 nm in thickness. Two Cu leads are attached to it with an interface layer of AlO$_x$. A constant current of 100 pA flows form one lead to the other (see Fig. 1(a)). The ring is considered to be one-dimensional with a uniform supercurrent density because the linewidth is smaller than the coherence length $\xi = 150 - 190$ nm. Note that the superconducting proximity effect is expected to be negligible due to the high tunnel resistance. In Fig. 1(b), the voltage in increasing (decreasing) magnetic field is indicated by the filled (open) circles, which displays complicated structures. The voltage variations result from two origins: (1) smearing of the energy gap due to pair-breaking by the magnetic field, and (2) a decrease of the energy gap because of the supercurrent. The former leads to a monotonic decrease in voltage as the strength of the magnetic field increases, so both the upward parabolas and the jumps in voltage come from the latter. Each parabola reflects the change in supercurrent satisfying the fluxoid quantization condition of the ring. That is, near the maximum of each parabola, the applied magnetic flux in the ring is $n\Phi_0$ ($n$: integer, fluxoid quantum number), and no supercurrent flows. Also, the voltage jumps correspond to transitions between adjacent fluxoid quantum states: $n \rightarrow n \pm 1$. These results demonstrate that the voltage of small SIN tunnel junctions is sensitive to the change in local supercurrent flowing in a mesoscopic superconductor.

Now we consider the superconducting state at $\Phi = \Phi_0/2$. In a relatively large ring as shown
Figure 1. (a) A SEM picture of a superconducting ring with two small SIN tunnel junctions. (b) Change in the voltage between two leads under a constant current of 100 pA in increasing (filled circles) and decreasing (open circles) magnetic field.

in Fig. 1(a), the $n = 0$ ($n = 1$) state appears in increasing (decreasing) magnetic field. When the ring diameter is comparable to the coherence length $\xi$, it is known that the global coherence of the superconductivity is destroyed, leading to the Little-parks oscillation of the superconducting transition temperature. This is a consequence of the fluxoid quantization in the ring. Note that there is an alternative way to satisfy the fluxoid quantization: By breaking the superconductivity across the whole width and having a phase difference of $\pm \pi$ across this part, one can satisfy the fluxoid quantization condition without any supercurrent flowing along the ring. This so-called one-dimensional vortex state has been confirmed experimentally by using the MSTJ method.[8]

3. Vortex configurations in a square with artificial pinning centers

The MSTJ method can also be used to know whether a vortex is situated at predetermined points. Figure 2(a) shows a superconducting square with $2 \times 2$ antidots A1 - A4 and drains D1 - D4. Here, two SIN tunnel junctions J1 and J2 detect the vortices pinned at antidots A1 and A3, respectively, e.g., when a vortex is pinned at A1, a part of the shielding supercurrent flowing along the boundary is canceled out by the current flowing around the vortex, so that the voltage of junction J1 becomes larger than the value without vortex. In particular, when the number of vortices trapped at an antidot changes, the junction voltage close to the antidot displays a large jump. Figure 2(b,c) shows the magnetic field dependence of voltage at junctions J1 (solid curve) and J2 (dotted curve) in increasing and decreasing magnetic field, respectively. The arrows indicate the positions of voltage jumps, corresponding to vortex penetration (expulsion) in Fig. 2(b) (Fig. 2(c)). The numbers indicate the number of vortices (or, vorticity) in the square. In increasing magnetic field (Fig. 2(b)), the $4k$-th vortex ($k$: integer) always enters into antidot A1 and the $4k + 2$-th vortex into A3, because the corresponding voltage jumps are larger than adjacent jumps. In the same way, for decreasing magnetic field (Fig. 2(c)), the $4k + 1$-th vortex always exits from A1 and the $4k + 3$-th vortex exits from A3.

This kind of detection of the vortex position indicates the possibility that the MSTJ method can be used as the read-out of the single-flux-quanta circuits.
Figure 2. (a) A schematic view of a superconducting square with $2 \times 2$ antidots A1 - A4 and drains D1 - D4. Here, two SIN tunnel junctions J1 and J2 (gray regions) are connected to points close to the antidots A1 and A3, respectively. In the measurement, a constant current flows from each junction to drains and the junction voltages are measured simultaneously. (b,c) Magnetic field dependence of voltage at junctions J1 (solid curve) and J2 (dotted curve) in increasing (b) and decreasing (c) magnetic field. The arrows indicate the positions of voltage jumps, corresponding to vortex penetration (expulsion) in increasing (decreasing) magnetic field. The numbers indicate the number of vortices (or, vorticity) in the square.

4. Conclusion
The multiple-small-tunnel-junction method for the detection of superconducting states in a mesoscopic superconductor is described. In a ring, the fluxoid quantum number is accurately determined, and in superconductors with antidots, the positions of vortices can be detected.

Acknowledgments
This work was supported by the Grant-in-Aid for Scientific Research (B) (17340101), CTC-NES Program of JSPS and the Sumitomo Foundation. AK greatly acknowledges R. Geurts, M. V. Milosevic, and F. M. Peeters for discussions.

References
[1] Schweigert V A, Peeters F M and Deo P S, 1998 Phys. Rev. Lett. 81 2783
[2] Kanda A, Baelus B J, Peeters F M, Kadowaki K and Ootuka Y 2004 Phys. Rev. Lett. 93 257002
[3] Baelus B J, Kanda A, Peeters F M, Ootuka Y and Kadowaki K 2005 Phys. Rev. B71 140502 (R).
[4] Baelus B J, Kanda A, Shimizu N, Tadano K, Ootuka Y, Kadowaki K and Peeters F M 2006 Phys. Rev. B 73 024514.
[5] Karapetrov G, Fedor J, Iavarone M, Rosenmann D and Kwok W K 2005 Phys. Rev. Lett 95 167002
[6] Bruyndoncx V, Rodrigo J G, Puig T, Van Look L and Moshchalkov V V 1999 Phys Rev B 60 4285
[7] Geim A K, Dubonos S V, Lok J G S, Grigorieva I V, Maan J C, Theil Hansen L and Lindelof P E 1997 Appl. Phys. Lett.71 2379
[8] Kanda A, Baelus B J, Vodolazov D Y, Berger J, Furugen R, Ootuka Y and Peeters F M 2007 Phys. Rev. B 76 094519