Paramagnetic supercurrent in a mesoscopic superconducting disk

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Abstract

We report an experimental evidence for the paramagnetic supercurrent flowing along the periphery of a mesoscopic superconducting disk in decreasing perpendicular magnetic fields. The sample is an Al superconducting disk with a thin drain lead. Several Cu leads are connected to different parts of the ring periphery through highly resistive tunnel junctions. From voltage drop across a tunnel junction, we study the change in the local superconducting energy gap as a function of perpendicular magnetic field. We find that the energy gap at the ring periphery decreases with decreasing the magnetic field, showing that the circulating supercurrent is in the direction supporting the external magnetic field (*paramagnetic*). The condition for the observation is the same as that for the paramagnetic Meissner effect [A. K. Geim *et al.*, Nature **390**, 259 (1997)], implying that the origin of the paramagnetic Meissner effect is the paramagnetic supercurrent.

Key words: mesoscopic superconductor ; paramagnetic Meissner effect ; supercurrent

1. Introduction

Recently, paramagnetic Meissner effect has been observed in many kinds of superconductors, including both high-T_c and conventional materials. For mesoscopic Al superconducting disks with a diameter of several μm, Geim *et al.* [1] observed positive magnetization in decreasing perpendicular magnetic field by using their original technique, ballistic Hall magnetometry. To explain the phenomenon, several theories have been proposed so far such as (1) flux compression combined with flux penetration at the disk boundary [1,2], (2) detector effects [3], (3) reversal of supercurrent direction [4]. However the origin has not been revealed experimentally.

Here, we have experimentally determined the direction in which supercurrent flows along the periphery of mesoscopic superconducting disks by electron tunneling.

2. Experiment and results

Figure 1 shows a schematic drawing of a sample. Four normal-metal (Cu) leads are connected to the periphery of a superconducting Al disk (0.75 μm in radius and 33 nm in thickness) through highly resistive small tunnel junctions with an area of about 0.01 μm^2. The junction resistance ranges from 16 kΩ to 65 kΩ, which is high enough that the proximity effect is expected to be negligible. The disk is directly connected to an Al drain lead (width: 0.1 μm) so that a current from each Cu lead empties into the drain. This structure was fabricated by using electron beam lithography and the double-angle deposition technique. To prevent inhomogeneous oxidation of the disk surface in the air, the disk is covered with Ge layer, which becomes insulating at low temperatures. All of the evaporation processes were performed in a single vacuum with the base pressure of 2×10^{-8} Pa. The dc electrical transport measurement was performed in a dilution refrigerator down to 0.03 K. A magnetic field perpendicular to the disk was applied.

Figure 2 shows the magnetic field dependence of volt-

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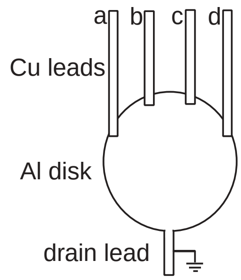

Fig. 1. Schematic drawing of the sample.

age across each tunnel junction fed with a small current $I = 0.1$ nA. Voltages for four junctions were measured simultaneously. On increasing magnetic fields (Fig. 2(a)), behavior is almost the same for four junctions: a moderate voltage decrease followed by a jump is repeated. This kind of complex variation of voltage is attributed to the change in the local superconducting energy gap due to the field-induced supercurrent. As shown by J. Bardeen in 1962 [5], the dependence of the superconducting energy gap on the supercurrent is given by:

$$\frac{\delta\Delta}{\Delta} = -\frac{2}{27}\left(\frac{J_S}{J_C}\right)^2. \qquad (1)$$

Here, J_S is the supercurrent density with the critical value of J_C. From eq. (1), when $\partial\Delta/\partial B > 0$, there are two possibilities for the signs of J_S and $\partial J_S/\partial B$: ($J_S > 0$, $\partial J_S/\partial B < 0$) and ($J_S < 0$, $\partial J_S/\partial B > 0$). However, the latter is not physical because it represents the paramagnetic response of the superconductor. (i.e., diamagnetic current decreases as magnetic field increases.) The former corresponds to the diamagnetic response to the field change, but the supercurrent is flowing in the direction supporting the applied magnetic field (*paramagnetic* supercurrent). In the same way, the case $\partial\Delta/\partial B < 0$ corresponds to $J_S < 0$ and $\partial J_S/\partial B < 0$, so that a diamagnetic supercurrent is flowing. In Fig. 2(a), the slope of the moderate voltage changes is negative, showing that a diamagnetic supercurrent is flowing along the disk boundary. We note that voltage jump corresponds to sharp change of the supercurrent, presumably due to a transition between different vortex states, n → n+1. Data show that the supercurrent flowing underneath junctions decreases by the transitions. This is the same as one expected in bulk superconductors and is attributed to the Bean-Livingston surface barrier [6,7].

On decreasing magnetic field, on the other hand, the slopes in a vortex state for all four points are positive in the magnetic field range in Fig. 2, showing that paramagnetic supercurrent is flowing along the disk boundary. The slopes for junctions at symmetric positions (“a” and “d” (“b” and “c”)) are almost the same, indicating the uniform current flow along the disk periphery. We have measured four samples and the paramagnetic supercurrent is seen only in decreasing magnetic field. This condition is the same as that for paramagnetic Meissner effect, strongly indicating that the origin of the paramagnetic Meissner effect is the paramagnetic supercurrent, consistent with ref.[4].

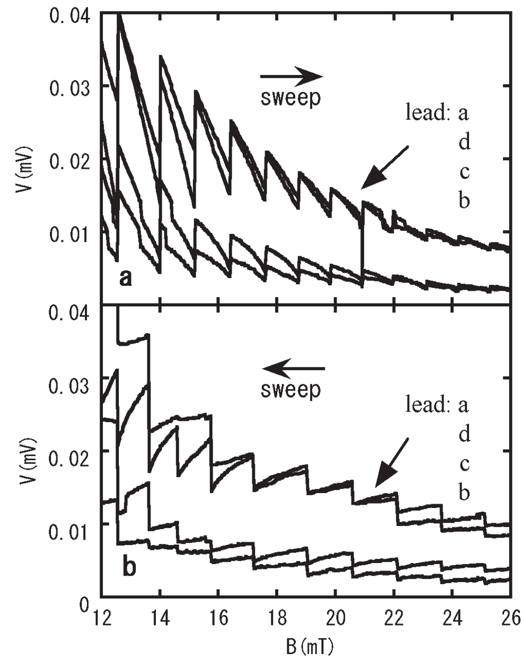

Fig. 2. Magnetic field dependence of voltage for (a) increasing and (b) decreasing magnetic fields at 0.03 K. Current is fixed at 0.1 nA in each junction.

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