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Size dependence of the vortex states in mesoscopic superconductors

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Abstract

We investigated the sample size dependence of the types of vortex states, i.e., multivortex states or giant vortex states, in mesoscopic superconducting squares by using the temperature dependence of vortex expulsion fields. The giant vortex states are stable in small samples and at high magnetic fields. The experimental results are compared with theoretical simulations based on the nonlinear Ginzburg–Landau theory.

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Keywords: Mesoscopic superconductivity; Vortex states; Phase transitions

1. Introduction

In the mixed states of mesoscopic type-II superconductors that have sizes comparable to the superconducting coherence length, ξ, and/or the magnetic penetration depth, not only the vortex–vortex interaction but also the vortex-sample boundary interaction determine the vortex configuration, leading to corruption of the Abrikosov triangular lattice common for bulk superconductors. The resulting new vortex states are divided into two categories: (i) multivortex states (MVSs) with a unique spatial arrangement of singly quantized vortices, and (ii) multiply quantized or giant vortex states (GVSs) [1–4]. Note that in a GVS the Cooper-pair density 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 into the disk center due to the repulsive interaction with the sample boundary. Therefore, it is stabilized in a small disk (radius $R \approx \xi$), or even in larger disks under high magnetic fields where a strong shielding current along the boundary exerts a repulsive force to vortices. This sample size dependence of the vortex states is one of the basic properties of mesoscopic superconductors that have been theoretically predicted [1,5] but have not been verified experimentally yet.

Experimentally, we succeeded in the direct distinction between MVSs and GVSs in a mesoscopic disk by taking into account the geometrical symmetry of the supercurrent distribution [6]. We used the multiple-small-tunnel-junction (MSTJ) method, in which several small tunnel junctions are attached to a mesoscopic superconductor to detect small changes in the local density of states caused by supercurrents [7,8]. Subsequently, we found a less direct method for the distinction in a mesoscopic disk by using the temperature dependence of the vortex expulsion fields [9]; When the disk is in a MVS, the expulsion field is almost independent of temperature, while when the disk is in a GVS, it increases with temperature.

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In the present paper, we employ the latter method to experimentally verify the theoretical prediction on the sample size dependence of the vortex states.

2. Experiment and results

The vortex penetration/expulsion fields are detected using a small tunnel junction attached to the superconductor. Fig. 1 shows a scanning electron micrograph of a sample. Normal-metal (Cu) leads are connected to a superconducting Al square through highly resistive small superconductor–insulator–normal metal tunnel junctions. Squares with five different sides $W = 0.40$, 0.50, 0.71, 0.87, 1.0 μm were fabricated. As the coherence length ξ was 0.15–0.19 μm, these side dimensions correspond to $(2.1–2.7)\xi$, $(2.6–3.3)\xi$, $(3.7–4.7)\xi$, $(4.6–5.8)\xi$, and $(5.3–6.7)\xi$, respectively. The thickness of the Al squares and Cu leads are 33 nm and 65 nm, respectively. The superconducting transition temperature is 1.3–1.4 K. In the measurement, we fixed the current flowing through one of the junctions to 100 pA, and measured the voltage between the Cu lead and the drain as a function of the applied perpendicular magnetic field, which was swept at a typical rate of 5 mT/min.

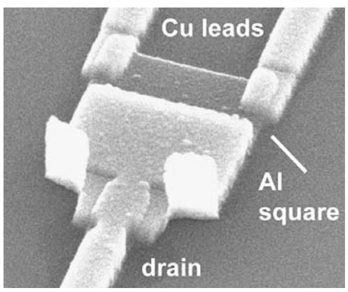

Fig. 1. Scanning electron micrograph of a sample with side $W = 1.0$ μm, fabricated using *e*-beam lithography followed by double-angle evaporation of Al and Cu.

Fig. 2 shows the junction voltage of the sample with side $W = 1.0$ μm as a function of the applied magnetic field for different temperatures between 0.15 and 1.05 K. The voltage jumps, indicated by the filled circles, correspond to transitions between vortex states with a vorticity change of ±1, which cause an abrupt change in the supercurrent distribution. In increasing magnetic fields (Fig. 2(a)), the penetration fields always decrease with increasing temperature. On the other hand, in decreasing magnetic fields (Fig. 2(b)), the temperature dependence of the expulsion fields shows two regimes: For some vortex states with small vorticity L, the expulsion field is almost independent of temperature or slightly decreases, while for the other states with larger L, the expulsion field increases with tempera-

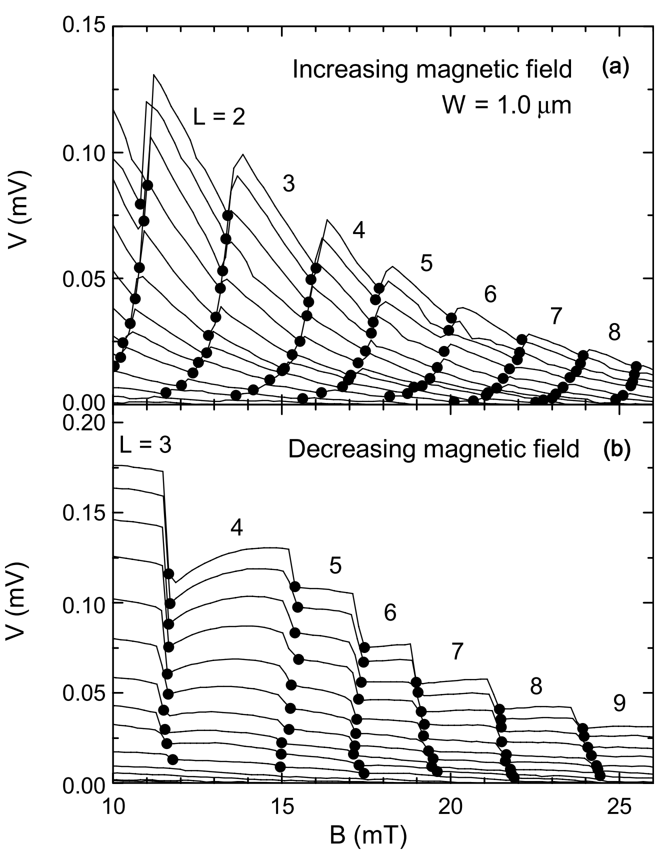

Fig. 2. The measured voltage as a function of (a) increasing and (b) decreasing magnetic field for a square with side $W = 1.0$ μm at different temperatures, $T = 0.15$ (highest curve), 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.65, 0.75, 0.85, 0.95 and 1.05 K (lowest curve). The filled circles indicate the transition fields.

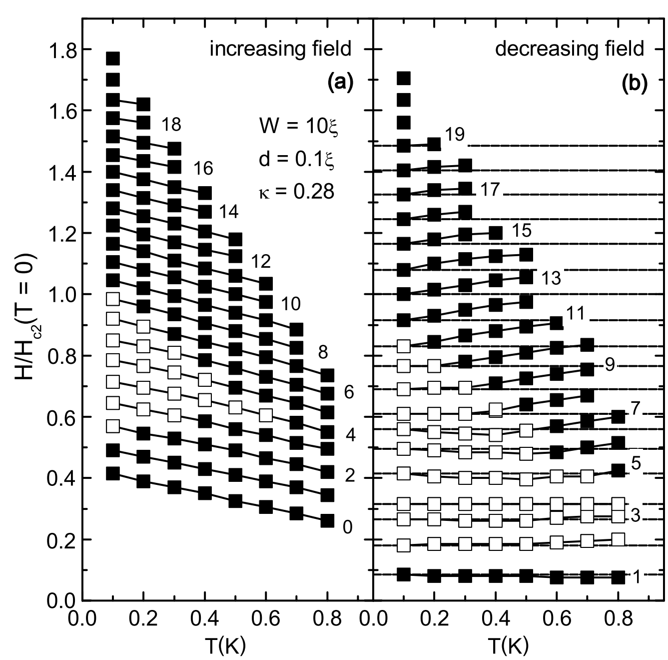

Fig. 3. (a) Theoretical penetration fields and (b) theoretical expulsion fields of vortices as a function of temperature for a disk with side $W = 10\xi$, thickness $d = 0.1\xi$, and the Ginzburg–Landau parameter $\kappa = 0.28$. The numbers indicate the vorticity before the transitions. The closed symbols correspond to a GVS and the open symbols to a MVS before the transition. The horizontal dashed lines correspond to the values of the expulsion fields at the lowest temperature (0.1 K) and are guides to the eye.