Study of vortex state in mesoscopic superconductors by Hall magnetometry

H Sano, A Endo, S Katsumoto and Y Iye

Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha Kashiwa, Chiba 277-8581 Japan

E-mail: h-sano@issp.u-tokyo.ac.jp

Abstract. The vortex states in mesoscopic superconductors with the size comparable to the coherence length differ from those in macroscopic superconductors. The change in the vortex configuration is reflected in the profile of stray magnetic field emanating from the superconductor, which can be detected by a local field probe. In the present study, a mesoscopic Hall cross structure fabricated from GaAs/AlGaAs two-dimensional electron gas (2DEG) was used as the local field probe. The mesoscopic superconductor sample (an Al square with a hole at each corner) was placed on top of the 2DEG Hall probe, which had several arms around the Al square. Because these arms were smaller than the square, we could detect the change of the local field distribution from the change of Hall resistance obtained from different sets of current/voltage probes. The changes furnish relevant information on the vortex configuration.

1. Introduction

When vortices are introduced into a bulk superconductor, they form an Abrikosov triangular lattice. In the case of a mesoscopic superconductor with the size comparable to its coherence length ξ and magnetic penetration depth λ, different vortex configurations may arise from the subtle interplay of vortex-vortex interaction and vortex-boundary interaction[1, 2]. For a superconducting disk, for instance, two vortex states are expected. One is the ordinary multi-vortex state (MVS) with rearranged configuration of singly-quantized vortices and the other is the so-called giant vortex state (GVS) with one multiply-quantized vortex at the center of the disk.

In the case of a square, spontaneous nucleation of anti-vortex is also expected as well as MVS and GVS. It occurs when the total vorticity $N = 3$, for example, as a results of the confliction between the four-fold symmetry of the square and the symmetry of the vortex configuration. To adjust the four-fold symmetry, in this case, vortex-antivortex pair is spontaneously nucleated and four vortices occupy the four corner of the square and one antivortex is placed on the center. However, this antivortex is not stable against imperfections of the sample and the vortices are easily rearranged to the ordinary MVS. One way to stabilize the symmetry-induced antivortex is to enhance the four-fold symmetry of the sample by fabricating a hole at each corner of the square[3]. These holes also make it easy to detect an antivortex experimentally because they separate the corner vortices from the central antivortex.

Although recent experiments have verified the occurrence of these vortex states[4, 5], the quantitative method to measure the local field distribution, which is necessary to investigate the symmetry-induced antivortex, is still lacking. For this purpose, in this work we used a micro

Hall cross made of a semiconductor two-dimensional electron gas (2DEG). Because the Hall resistance of 2DEG is very sensitive to the change of magnetic field, a Hall cross device can be used as a magnetometer for quantitative detection of local magnetic field. If a superconducting square is fabricated on top of the Hall cross, the change of the distribution of magnetic field below the square due to the entrance or exit of a vortex can be detected as the change of Hall resistance of the Hall cross device[6].

The most of previous studies were limited to the measurement about the whole superconductor because each probe of Hall cross covered the whole superconductor. To improve this point, we fabricated a multi-probe Hall cross with several small arms around the square. As each probe covered only a part of the superconductor, we can detect the change of local field distribution by comparing the data obtained from various sets of the current and voltage probes, so that we may extract information relevant to the vortex configuration.

2. Experimental Method

2.1. Sample fabrication

Figure 1(a) shows the scanning electron microscope image of the sample. The micro Hall cross was made from GaAs/AlGaAs 2DEG and the Al square with small holes was fabricated on top of it. All fabrications were done by use of electron beam lithography.

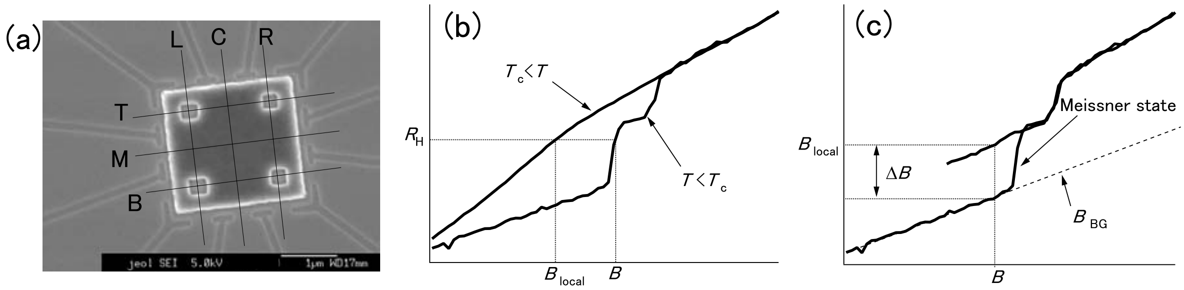

Figure 1. (a)Scanning electron microscope image of the sample. The radial trenches which look like spokes of a wheel define the multi-lead micro Hall cross made of GaAs/AlGaAs 2DEG. The square "hub" is the Al sample placed on top of the Hall cross. The correspondences of the labels and the choice of the probes are also shown. (b), (c)Schematic graphs of magnetic field dependence of (b)R_H above and below T_c of Al square and (c)B_local at $N = 0$ Meissner state and $N \neq 0$ state. The graphs also show the procedures of the conversion (b)from R_H to B_local and (c)from B_local to ΔB. Details of the conversions are written in the text.

A 240 nm thick Al square was deposited by vacuum evaporation and lift-off. The side of the square was 2.4 μm and each hole was 240 nm. The critical temperature $T_\mathrm{c} = 1.2$ K and $\xi(0) = 240$ nm were estimated from the Al film deposited simultaneously. $\lambda(0) = 300$ nm was then calculated under the assumption of dirty limit.

The 2DEG was located 60 nm below the surface of GaAs/AlGaAs substrate. The electrical contact pads were made of AuGeNi alloy. The carrier mobility μ and the carrier density n of the 2DEG at 1.6 K were 64 m^2/V·s and 3.8×10^{15} m^{-2}, respectively. The mean free path ℓ of the 2D electrons was calculated as 6.5 μm. Therefore our Hall cross was in the so-called ballistic regime with the system size smaller than ℓ. The probes were defined on the substrate by wet-etching. The typical width of each probe was about 300 nm.

Hereafter, the choice of the current and voltage probes is indicated by two letters. First letter represents the choice of the current leads and second letter represents the voltage probes. The correspondence between the pair of probes and the each letter B, M, T, L, C and R is shown in Fig. 1(a). For example, TL means that the current is passed between the topmost horizontal pair and the voltage is measured by the leftmost vertical pair. The label also defines the active area of the Hall cross as the cross-section of the two lines.

2.2. Local field measurement
In general, the magnetization of the mesoscopic superconductor shows hysteresis due to the surface barrier. We measured the minor loops of the Hall resistance R_{H} by the following procedure.

(i) Set the magnetic field at the starting field.
(ii) Sweep up/down to the target field.
(iii) Repeat (i) and (ii) for different values of the starting field.

Data was recorded only during the sweep (ii).

The measured R_{H} was converted into the local magnetic field B_{local} averaged over the active area of the Hall cross. For this conversion, we assumed that R_{H} depends only on B_{local} and its dependence on B_{local} is the same as the dependence $R_{\mathrm{H}}(B)$ when Al square is in the normal state ($T > T_{\mathrm{c}}$). B_{local} can be derived as the magnetic field which gives the same value of R_{H} for $T > T_{\mathrm{c}}$, as shown in Fig. 1(b).

Note that although most of previous studies assumed the linear relation $R_{\mathrm{H}} \propto B_{\mathrm{local}}$, it is not valid for a ballistic 2DEG even under a homogeneous magnetic field[7] due to the collimation effect *etc.* The procedure adopted here is to take these effects into account.

The contribution of vortices to B_{local} is obtained by $\Delta B = B_{\mathrm{local}} - B_{\mathrm{BG}}$, where B_{BG} corresponds to the magnetic flux density for the completely flux-expelled state, and is given by a linear extrapolation of Meissner state as shown in Fig. 1(c). ΔB means the increment of B_{local} due to the presence of vortices.

All measurements were conducted in a ^{3}He cryostat. The minimum temperature was below 350 mK and the stability of the temperature better than 5 mK was attained by a feedback circuit.

3. Results
Figure 2(a) shows the field dependence of ΔB at $T \sim 350$ mK. The probed area for each graph is indicated by the two-letter-label (*e.g.* TC) mentioned earlier. Only the up-sweep traces are shown for clarity. Each one of the branches corresponds to the different vortex state and a larger spacing between successive curves corresponds to a large change of magnetic field in the detected area, most likely caused by entrance(exit) of a vortex to(from) that area.

Next step is to assign the vortex configuration according to the magnetic field distribution. Figure 2(b) summarizes the possible vortex configurations for up and down sweep at $T \sim 350$ mK and $T \sim 700$ mK.

Every paths consists of six steps from $N = 7$ MVS to $N = 0$ Meissner state. The first and last three steps are in common while the second and third steps have a choice between two configulations.

The choice at the second step between 2 and 2' is between two different configurations of $N = 6$ MVS. Because these two vortex states are not different so much, the observed vortex state was changed even for the different sweep direction.

The choice at the third step between 3 and 3' is between $N = 3$ MVS and $N = 3$ MVS. The fact that two states with different N are equally stable suggests that $N = 3$ MVS is stable and two additional vortices in $N = 5$ MVS are very easy to get out of the square. It also suggests the existence of particularly strong pinning site at the position of third vortex. The repulsive force exerted by the third vortex appears to be so strong as to hinder the next vortices to occupy the (otherwise stable) hole sites.

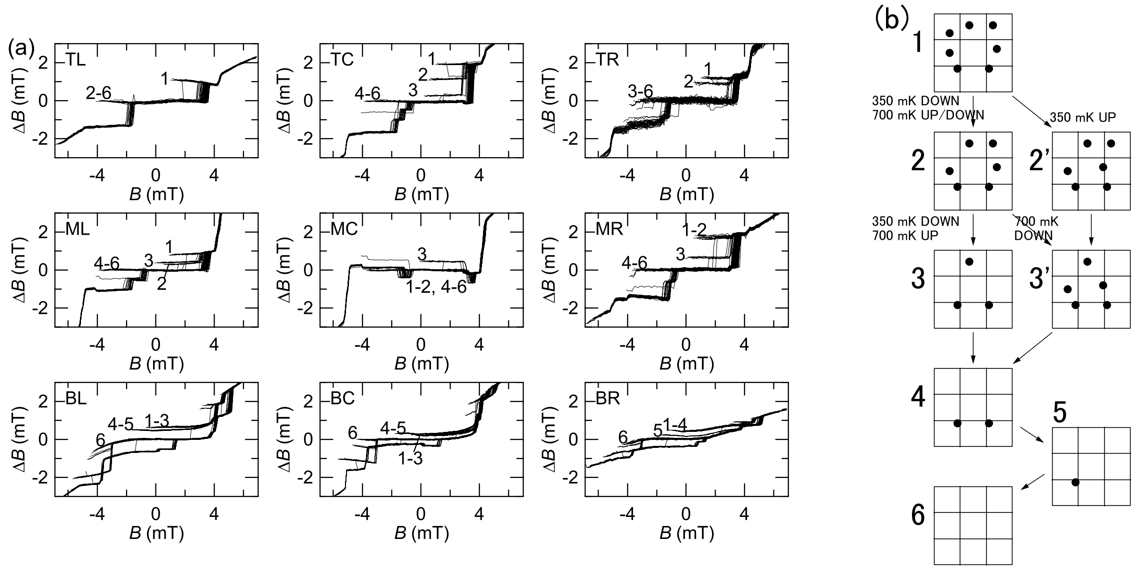

Figure 2. (a)The magnetic field dependence of ΔB in the labeled area at $T \sim 350$ mK. Each curve corresponds to the vortex state labeled by the same number in (b). (b)The change of vortex configuration according to decreasing magnetic field. The changes for both up and down sweep at $T \sim 350$ mK and $T \sim 700$ mK are summarized.

Although the negative signal of ΔB was observed in MC area, it is too speculative to say the signal is related to the nucleation of antivortex. Actually, the additional pinning site mentioned above would be too strong to nucleate a symmetry-induced antivortex. More detailed studies are necessary to reveal the origin of this negative signal.

4. Conclusion

In this study, we investigated the changes of vortex configuration in mesoscopic Al square samples with a hole at each corner by use of micro Hall cross magnetometry. We observed the change of vortex states and speculated the vortex configuration for the different sweep direction and temperature. Because the four-fold symmetry of the sample has been destructed by additional pinning sites, a symmetry-induced antivortex was not observed.

Acknowledgments

One of the authors (H.S.) appreciates the support by the Japan Society for the Promotion of Science (JSPS) fellowship. This work is supported by Grant-in-Aid for Scientific Research from JSPS.

References

[1] Schweigert V A, Peeters F M and Deo P S 1998 *Phys. Rev. Lett.* **81** 2783
[2] Chibotaru L F, Teniers G, Ceulemans A and Moshchalkov V V 2004 *Phys. Rev.* B **70** 094505
[3] Geurts R, Miloevi M V and Peeters F M 2006 *Phys. Rev. Lett.* **97** 137002
[4] Kanda A, Baelus B J, Peeters F M, Kadowaki K and Ootuka Y 2004 *Phys. Rev. Lett.* **93** 257002
[5] Grigorieva I V, Escoffier W, Richardson J, Vinnicov L Y, Dubonos S and Oboznov V 2006 *Phys. Rev. Lett.* **96** 077005
[6] Geim A K, Grigorieva V, Dubonos S, Lok J G S, Maan J C, Filipov A E and Peeters F M 1997 *Nature* **390** 259
[7] Roukes M L, Scherer A, Allen Jr S J, Craighead H G, Ruthen R M, Beebe E D and Harbison J P 1987 *Phys. Rev. Lett.* **59** 3011