Giant vortex and multivortex states under local supercurrent injection in a mesoscopic superconducting square

S Hatsumi$^{1,2}$, Y Kuroda$^{1,2}$, Y Ootuka$^{1,2}$, A Kanda$^1$

$^1$Institute of Physics, University of Tsukuba, Tsukuba 305-8571, Japan
$^2$Tsukuba Research Center for Interdisciplinary Materials Science (TIMS), University of Tsukuba, Tsukuba 305-8571, Japan

E-mail: hatsumi@lt.px.tsukuba.ac.jp

Abstract. We experimentally study giant vortex states (GVSs) and multivortex states (MVSs) in a mesoscopic superconducting square under local supercurrent injection. By using the multiple-small-tunnel-junction measurement, we find that the magnetic field for the transition between a GVS and an MVS with a fixed vorticity depends on the magnitude of the injected supercurrent. This result indicates the possibility of manipulating quantum vortex states with supercurrent injection.

1. Introduction
Mesoscopic superconductors have sizes comparable to the superconducting coherence length $\xi$ and/or the magnetic penetration length $\lambda$. In such small superconductors, confinement of supercurrent dramatically modifies superconducting properties. In particular, vortex configuration strongly reflects the sample geometry, leading to formation of novel vortex states such as multi vortex states (MVSs) and giant vortex states (GVSs). In MVSs, repulsive interaction between a vortex and the shielding supercurrent flowing along the sample boundary forces the vortex arrangement to fit the sample geometry. On the other hand, when the shielding current is large enough and/or the sample size is small enough, the resultant strong confinement effect stabilizes the GVS, in which multiple singly-quantized vortices merge into a multiply-quantized giant vortex. These two novel vortex states were theoretically predicted for a long time [1, 2, 3, 4, 5, 6], but have been experimentally confirmed just recently.[7, 8, 9, 10]

It should be noted that in most of the experimental studies reported so far, transitions between different vortex states have been induced by magnetic field sweep, which is not so convenient for the manipulation of the vortex states because fast sweep of magnetic field is accompanied by a large eddy current. In this study, we try to induce vortex state transitions by applying local supercurrent into the superconductor. Some of the main results are already published elsewhere.[11, 12] Here we report transitions between giant vortex and multivortex states with a fixed vorticity $L$ (the change of the phase of the order parameter around the sample divided by $2\pi$) under local supercurrent injection.

In order to distinguish between GVSs and MVSs, we have developed the multiple-small-tunnel-junction (MSTJ) method.[7, 13] In a sample for the MSTJ measurement, multiple small
superconductor-insulator-normal metal (SIN) junctions are attached to symmetrical positions of a mesoscopic superconductor. It is well known that when a small current is applied to the SIN junction, the measured voltage reflects the superconducting energy gap underneath the junction, which changes sensitively with the local supercurrent density. So, by comparing the junction voltages, one can obtain (partial) information about the supercurrent distribution, which is closely related to the vortex configuration. Particularly, when the voltage of each junction placed at symmetrical positions take the same value, the vortex state is potentially the GVS, while when they are different to each other, the vortex state is definitely an MVS.[7]
Figure 2 shows the typical magnetic field dependence of the junction voltage. There are two origins for the voltage change: one is related to the smearing of the gap structure in the density of states by magnetic field and the other is the decrease of the superconducting energy gap by supercurrent flowing underneath the junction.[14] Especially, a large voltage jump corresponds to a drastic change of supercurrent, presumably due to vortex penetration/expulsion. We are able to determine the vorticity $L$, as shown in Fig. 2, by taking into account the fact that vortices penetrate into (or, is expelled from) the sample one by one.

Figure 3 shows the junction voltages $V_1$ and $V_2$ for the whole $L=3$ state at 0.7 K under several injection currents, $I_t = 10\,\mu A$, $5\,\mu A$, $0\,\mu A$, and $-5\,\mu A$. The directions of the positive injection current and the magnetic field are indicated in Fig. 1(b). We compensated the

2. Measurements and Results

The sample is an Al square with side of 1.1 $\mu m$ and thickness of 40 nm, which was fabricated by using $e$-beam lithography followed by the angle deposition of Al and Cu. Figure 1 shows a scanning electron microscope (SEM) image and a schematic view of the sample. Two Cu leads are connected to symmetrical positions in the top side of the sample through Al-AlO$_x$-Cu SIN tunnel junctions. In addition, three Al leads are attached to the center of the sides directly. In the measurement, the bottom lead is used for the current injection and the right lead is connected to the ground. The left lead is left unconnected. The sample was cooled in a dilution refrigerator. A fixed current of 1 nA is injected to each SIN junction, and the junction voltages, $V_1$ and $V_2$, were measured simultaneously as a function of the perpendicular magnetic field. We estimated the coherence length $\xi(0)$ to be $150 - 190$ nm and the superconducting critical temperature $T_c$ was 1.35 K.
difference of the offset voltages of the voltage amplifiers in the measurement system by assuming that the voltages $V_1$ and $V_2$ take the same values at the highest magnetic field of the $L = 3$ state, i.e., the vortex state is the GVS close to the vortex penetration. This assumption for $I_t = 0$ (Fig. 3(c)) is justified by the numerical simulation based on the Ginzburg-Landau theory.[12] In Fig. 3(c), we notice that $V_1$ and $V_2$ takes almost the same value above $B = 11.6$ mT (indicated by an arrow), while their difference becomes wider with decreasing magnetic field below 11.6 mT. Here, we can distinguish between MVS and GVS by comparing between junction voltages $V_1$ and $V_2$ in the case of $L = 3, I_t = 0$ [9]; in GVSs, a giant vortex is situated at the center of the sample, leading to the quadruple symmetry in the distribution of supercurrent. As a result, voltages of junctions attached to symmetric positions of the sample, $V_1$ and $V_2$, are equal to each other. On the other hand, in the $L = 3$ MVSs, vortex configuration does not have such quadruple symmetry, so $V_1$ and $V_2$ take different values. For this reason, we can guess that vortex state is the GVS at high magnetic fields ($B > 11.6$ mT) and an MVS at low magnetic field ($B < 11.6$ mT). Thus an MVS-GVS transition occurs at 11.6 mT. Here we note that both the $V_1$ curve and the $V_2$ curve have a kink at 11.6 mT, indicating the change of the vortex structure.

In the case of $I_t \neq 0$, the symmetry of supercurrent distribution is broken by the injected supercurrent even in GVSs, so strictly speaking, we can’t use the MSTJ method for the distinction between MVSs and GVSs. However, the behavior seen in Figs. 3(a), 3(b) and 3(d) is similar to that of Fig. 3(c), i.e., $V_1$ almost equals $V_2$ above a magnetic field at which clear kinks are seen both in $V_1$ and $V_2$, suggesting the GVS in this magnetic field range. The magnetic field for the MVS-GVS transition is not necessarily the same as that of Fig. 3(c): 11.0 mT, 11.3 mT, and 11.6 mT in Figs. 3(a), 3(b) and 3(d), respectively, as indicated by arrows. These results demonstrate that the MSTJ measurement is still valid under supercurrent injection as shown in Fig. 3, although the core of a GVS is expected to be shifted from the sample center due to the Lorentz force exerted by the injected supercurrent and the symmetry of the supercurrent distribution is supposed to be broken. Notice that when the magnetic field is fixed at a value between 11.0 mT and 11.6 mT, an MVS-GVS transition is expected under the sweep of the injected supercurrent $I_t$, which is consistent with the observation by the temperature dependence of the vortex expulsion fields.[8, 9, 12] Also note that in Fig. 3(a), $V_2$ is larger than $V_1$ in the MVS, while in other cases (Figs. 3(b), 3(c) and 3(d)), $V_2$ is smaller than $V_1$ in the MVS. This shows that the vortex configuration at $I_t = 10\mu$A is different from that in $I_t < 5\mu$A. Such a kind of MVS-MVS transitions at a fixed vorticity is discussed in more detail elsewhere.[12]

3. Conclusion
We studied vortex states in a mesoscopic superconducting square under local supercurrent injection by using the MSTJ method. We find that the MVS-GVS transition occurs at the $L = 3$ state, and the magnetic field at which the MVS-GVS transition occurs depends on the injected supercurrent. The result supports the existence of the MVS-GVS transition as a function of the locally injected supercurrent. This result indicates the possibility of manipulating quantum vortex states with supercurrent injection.

Acknowledgments
This work was supported by the Kurata Memorial Hitachi Science and Technology Foundation. AK greatly acknowledges M. V. Milošević, F. M. Peeters, and M. Hayashi for discussions.

References
[1] Moshchalkov V V, Qiu X G and Bruyndoncx V 1997 Phys. Rev. B 55 11793
[2] Schweigert V A, Peeters F M and Deo P S 1998 Phys. Rev. Lett. 81 2783.
[3] Palacois J J 1998 Phys. Rev. B 58 (1998) 5948(R)
[4] Palacois J J 2000 Phys. Rev. Lett. 84 1796
[5] Baelus B J and Peeters F M 2002 Phys. Rev. B 65 104515
[6] Baelus B J, Cabral L R E and Peeters F M 2004 Phys. Rev. B 69 064506
[7] Kanda A, Baelus B J, Peeters F M, Kadowaki K and Ootuka Y 2004 Phys. Rev. Lett. 93 257002
[8] Baelus B J, Kanda A, Peeters F M, Ootuka Y and Kadowaki K 2005 Phys. Rev. B 71 140502(R)
[9] Baelus B J, Kanda A, Shimizu N, Tadano K, Ootuka Y, Kadowaki K and Peeters F M 2006 Phys. Rev. B 73 024514
[10] Grigorieva I V, Escoffier W, Misko V R, Baelus B J, Peeters F M, Vinnikov L Y and Dubonos S V 2007 Phys. Rev. Lett. 99 147003
[11] Hatsumi S, Ootuka Y and Kanda A 2009 Physica C 469 1080
[12] Milošević M V, Kanda A, Hatsumi S, Peeters F M and Ootuka Y 2009 Phys. Rev. Lett. 103 217003
[13] Kanda A and Ootuka Y 2004 Physica C 404 205
[14] Tinkham M 1996 Introduction to Superconductivity 2nd ed. (New York: McGraw-Hill) chapter 10