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Observation of Quantum Fluctuation in Nano Sr$_2$RuO$_4$ p–wave Superconductors

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Abstract. We observed quantum fluctuations of the superconducting phase $\theta$ in single domain Sr$_2$RuO$_4$ single crystals using a transport measurement. The temperature dependence of the resistivity of submicron Sr$_2$RuO$_4$ shows that a finite resistivity below the superconducting transition temperature of $T_c = 1.69$ K. The results may suggest that the finite resistivity is occurred by the flow of vortices due to quantum fluctuations of the superconducting phase $\theta$ in the same way as one-dimensional Josephson junction array systems.

1. Introduction

A spontaneous symmetry breaking in condensed matter systems provides various order parameter fields. In particular, the quantum condensate of unconventional superconductivity [1], the superfluid of $^3$He [2] and the spinor Bose-Einstein condensate [3], which involve internal degrees of freedom of the order parameter, enrich the variety of topological phenomena. These $SU(2)$ gauge symmetry systems have produced novel physics with respect to unconventional vortices, chirality, spin supercurrent, particle statistics, etc. The results obtained with $SU(2)$ systems will be nontrivial than those provided by $U(1)$ gauge symmetry.

Sr$_2$RuO$_4$ [4] is a promising candidate of spin-triplet chiral-$p$ superconductor, (i.e., spin $S = 1$ and orbital angular momentum $L = 1$). Here bulk Sr$_2$RuO$_4$ is considered to have chiral domain structures which coexist with the two directions of $\pm \vec{l}$ of the pair angular momentum parallel to $c$ axis. Transport properties have been studied in relation to Josephson interferometry using bulk Sr$_2$RuO$_4$ crystals to determine the symmetry of Cooper pairs and measure the dynamics of chiral domains [5, 6]. These experimental data on bulk Sr$_2$RuO$_4$ should be considered as a result of ensemble averaging over possible chiral domain configurations. Thus we need to measure a small enough sample of Sr$_2$RuO$_4$ rather than the domain size to study peculiar phenomena to a single chiral domain such as dynamics of a single chiral domain, spin supercurrent, and unconventional vortices of magnetic spin vortices and half-quantum vortices [7, 8, 9]. Kerr effect measurements of Sr$_2$RuO$_4$ [10] and Josephson tunneling measurements [6] respectively suggested chiral domain size to be $50 \sim 100$ $\mu$m and 1 $\mu$m. However transport measurements have never been carried out yet in a single domain because it is also difficult to attach electrical contacts to submicron Sr$_2$RuO$_4$ crystals.

In this paper, we have studied transport properties in single domain Sr$_2$RuO$_4$ single crystals. For the submicron Sr$_2$RuO$_4$ identified as single crystals, the gold electrodes were fabricated. In four-terminal measurements, we observed the finite resistivity below the transition temperature...
Figure 1. The Figure (a) shows a micrograph of a submicron Sr$_2$RuO$_4$ single crystal. The red regions represent the crystal orientation is same direction. Figure (b) shows the micrograph of the submicron Sr$_2$RuO$_4$ fabricated the gold electrodes. The sample electrode spacing is 0.63 µm.

of $T_c = 1.69$ K by measuring temperature dependence of resistivity. The sample size is smaller or comparable to the penetration length $\lambda$. Vortices cannot be screened by the Meissner effect due to quantum fluctuations of the superconducting phase. Thus we suggest that the flow of vortices cause the finite resistivity.

2. Fabrication of submicron Sr$_2$RuO$_4$ single crystals
To obtain submicron Sr$_2$RuO$_4$ single crystals, we synthesized Sr$_2$RuO$_4$ with a solid phase reaction. Here we focus on Sr$_2$RuO$_4$ single crystals at the micro-nanoscale level. In the following methods, we selected Sr$_2$RuO$_4$ single crystals in the submicron range that had no grain boundaries and impurities. The samples were dispersed in dichloroethane by sonication and deposited on an oxidized Si substrate. We observed typical samples of about 50 nm $\sim$ 500 µm. Figure 1(a) shows a micrograph of a selected submicron Sr$_2$RuO$_4$. Energy dispersion spectroscopy (EDS;EX-64175 JMU, JEOL) was used to determine the components. The molar fraction of the Sr and Ru elements was 2 : 1. We observed the crystal orientation in all regions of the submicron crystals from the electron backscatter diffraction pattern (EBSP; OIM TSL [11]). The red regions of Fig. 1(a) show the crystal orientation is identified in $ab$ plane of Sr$_2$RuO$_4$. Thus the selected submicron Sr$_2$RuO$_4$ is single crystal that no grain boundaries and impurities.

For the submicron Sr$_2$RuO$_4$ single crystals, we fabricated gold electrodes using standard overlay electron beam lithography. The inset (a) in Fig. 1 shows a micrograph of our samples. The sample size is 2.50 µm $\times$ 1.88 µm $\times$ 0.10 µm. The sample electrode spacing is 0.63 µm. In many cases, a crucial point is that it is difficult to form and electrical contact with fabricated submicron samples. This is because some of the polymethyl methacrylate resist used the process remains between the samples and the gold electrodes. Therefore we performed electron beam irradiation [12]. We heated each electrode on the sample for 15 s with a beam current irradiation of $2 \times 10^{-7}$ A. Using this process, we succeeded in greatly reducing the contact resistance below 10 Ω at room temperature.

3. Quantum fluctuations of the superconducting phase in submicron Sr$_2$RuO$_4$
The measurements were carried out in a dilution refrigerator (Kelvinox, Oxford) with a base temperature of 60 mK. All measurement leads were shielded. The lead lines were equipped with low pass RC filters. In the DC measurements, a bias current was supplied by a precise current
Figure 2. Temperature dependence of resistivity of submicron Sr$_2$RuO$_4$ in zero magnetic field (0 G) and in a magnetic field ($H = 3000$ G) applied parallel to $c$ axis. Flat tail resistivity can be seen at low temperatures below $T_c = 1.69$ K. The inset displays temperature dependence of the resistivity in the $ab$ plane from room temperature down to 4.2 K.

We measured the temperature dependence of the resistivity from room temperature to 63 mK. Figure 2 shows the residual resistivity $\rho_{ab}(4K) = 6.0 \mu\Omega$ cm. The ratio $\rho_{ab}(300K)/\rho_{ab}(4K) \sim 38$ in Fig. 2 and the inset is close to the ratio $\rho_{ab}(300K)/\rho_{ab}(4K) \sim 46$ of bulk Sr$_2$RuO$_4$ in Ref. [4]. Hence we consider there is no degradation of the sample by the solvent. Figure 2 also shows the decrease in resistivity at $T_c = 1.69$ K. In general, the resistivity of bulk Sr$_2$RuO$_4$ shows zero at superconducting transition temperature of 1.5K. However the resistivity of submicron Sr$_2$RuO$_4$ retained a finite resistivity of $\rho_{ab}(4K) = 4.5 \mu\Omega$ cm. There was no decrease in the resistivity at 1.69 K when magnetic field of 3000 G was applied parallel to the $c$ axis. Therefore we regard $T_c = 1.69$ K as the superconducting transition temperature of the sample.

Let us discuss the origin of the finite resistivity (flat tail) below $T_c$. If the finite resistivity is occurred by impurities, the resistivity decreases with decreasing temperature below $T_c$. In addition, the superconducting transition temperature is suppressed because the impurities destroy superconductivity. However the result of $T_c = 1.69$ K is just higher than $T_c = 1.5$ K of bulk Sr$_2$RuO$_4$. On the other hand, we should pay attention to another property for the transition temperature of bulk Sr$_2$RuO$_4$. The embedded ruthenium metals on the surface of bulk Sr$_2$RuO$_4$ enhance the transition temperature up to 3K [13]. However the result do not show the decrease of the resistivity from 3K to $T_c$ as shown in Fig. 2. We have no doubt that the selected submicron Sr$_2$RuO$_4$ can avoid these discussions in relation to the transition temperature because we check no impurities and the no ruthenium metals on the sample surface.

Here we suggest that the resistivity retains its flat tail owing to quantum fluctuations of the superconducting phase $\theta$. One-dimensional Josephson junction arrays and superconducting thin films is considered to take in the vortices in the superconductors because of the quantum fluctuations of the phase [14]. In a bulk superconductor, vortices is screened due to the Meissner
effect in zero magnetic field. When the sample size is smaller or comparable to the penetration length $\lambda$, such a sample accepts the vortices. We note that the distance between the electrode is 630 nm and $\lambda \approx 152$ nm. Hence the flow of vortices may cause the flat tail resistivity.

4. Summary
In summary, we observed the finite resistivity below the transition temperature in a submicron Sr$_2$RuO$_4$ single crystal by measuring temperature dependence of resistivity. Since the sample size is comparable to the penetration length $\lambda$, such a sample may accept the vortices in the sample due to quantum fluctuations of the superconducting phase. We consider the finite resistivity is occurred by the flow of vortices.

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