Majorana-Weyl fermions in (2+1)-dimensional superconductors

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Abstract. We found Majorana-Weyl fermions in the (2+1)-dimensional superconductor Sr\textsubscript{2}RuO\textsubscript{4}. The current-voltage (\(I-V\)) curves show an anomalous behavior. The induced voltage is an even function of the bias current in four terminal measurements. The parity-violating \(I-V\) curves are dependent on the direction of the applied magnetic field parallel to \(c\) axis. The result revealed spontaneous magnetization and a change in the chirality of the single domain Sr\textsubscript{2}RuO\textsubscript{4}. We suggest the excitation of the Majorana-Weyl fermions along the closed chiral edge current of the single domain under bias current.

1. Introduction
Parity violation provides important insights into physical phenomena of particle physics and condensed-matter physics. As for the parity violation, at least two different mechanisms are known. The first is due to a quantum anomaly in Dirac fermions of (2+1)-dimensional quantum electrodynamics [1, 2]. Intriguingly, a quantum Hall conductivity in graphene of which electrical properties are described by Dirac fermions reveals the parity violation [3, 4] and propels an excellent analogue to (2+1)-dimensional quantum electrodynamics. The other mechanism is theoretically predicted to be caused by (2+1)-dimensional Majorana fermions, where a particle is identified to its own antiparticle. However the parity-violating Majorana fermions have never been found yet.

Sr\textsubscript{2}RuO\textsubscript{4} [5] is a promising candidate of Majorana fermions in superconductors. Since the ground states are two-fold degenerate with different chirality, millimeter-scale Sr\textsubscript{2}RuO\textsubscript{4} is considered to have chiral domain structures [6, 7]. The data of the millimeter-scale Sr\textsubscript{2}RuO\textsubscript{4} should be considered as a result of ensemble averaging over possible chiral domain configurations. Hence transport measurements of the single domain Sr\textsubscript{2}RuO\textsubscript{4} are very important in order to study gapless excitations [8], unconventional vortices [9, 10], and quantum Hall effects [11]. In this work, we performed transport measurements for edges of the chiral single domain Sr\textsubscript{2}RuO\textsubscript{4} because the topological nature appears in the edge [12].
Figure 1. (a) Temperature dependence of resistivity of microscale Sr$_2$RuO$_4$ in zero magnetic field. The inset shows a micrograph of a microscale Sr$_2$RuO$_4$ single crystal. (b) Voltage $V$ is plotted as a function of bias current $I$ at 96 mK and 4.2 K in zero magnetic field.

2. Experiment

To obtain microscale Sr$_2$RuO$_4$ single crystals, we synthesized Sr$_2$RuO$_4$ crystals with a solid phase reaction, and then selected microscale Sr$_2$RuO$_4$ single crystals from the results of chemical composition and crystallinity [13]. We fabricated gold electrodes to the sample edges using overlay electron beam lithography. The inset of Fig. 1(a) shows a micrograph of the measured sample. Electric transport properties were measured by four-terminal methods using a dilution refrigerator.

3. Results and Discussion

Figure 1(a) shows the superconducting transition temperature $T_c = 1.59$ K with the transition temperature width $\Delta T \approx 30$ mK. The resistivity is estimated from the size of 4.0 $\mu$m (length) $\times$ 5.0 $\mu$m (width) $\times$ 0.3 $\mu$m (thickness). From the results, the temperature dependence of the resistivity in the microscale Sr$_2$RuO$_4$ was consistent with that of bulk crystals.

We found the parity-violating $I-V$ curves for the microscale Sr$_2$RuO$_4$ in zero magnetic field below $T_c$. Figure 1(b) shows $I-V$ characteristics at 96 mK and 4.2 K. In general, the voltage $V$ is always odd function of bias current $I$, which is a result of parity conservation. The $I-V$ curve at 4.2 K is odd function of $I$. Surprisingly, the $I-V$ curve at 96 mK shows that $V$ has anomalous components which are even function of $I$. This implies the parity violation of $I-V$ characteristics.

Figure 2(a) shows $I-V$ curves for several magnetic fields applied parallel to $c$ axis at 96 mK. It can be found that all of the $I-V$ curves are symmetric with respect to the zero bias current: $V(+I) = V(-I)$ or $-V(+I) = V(-I)$. Applying the magnetic field from zero magnetic field to 1200 Oe, the resistance $R$ on a bias current $I > 0$ changes from a positive ($R > 0$) to a negative ($R < 0$). On the other hand, for a bias current $I < 0$, a negative $R$ changes to a positive $R$.

To analyze the result of Fig. 2(a), we plotted magnetic field dependence of conductivity for bias current $I > 0$ or $I < 0$ as shown in Fig. 2(b). The conductivity of conventional superconductors with a magnetic field has symmetric curves with respect to zero magnetic field and shows infinite one at zero magnetic field. Figure 2(b), however, shows that the sample has a finite conductivity at the zero magnetic field, and a divergent point of conductivity is shifted to a finite $H \approx 450$ Oe. Furthermore, the reflection of the sign of conductivity around 450 Oe is observed. In contrast, the conductivity is robust against the magnetic field applied to opposite
To understand the physical origin of the parity-violating $I − V$ characteristics, we discuss the dependence of the chirality of the single domain of Sr$_2$RuO$_4$ on an external magnetic field. The chiral domain can explain the shift of the singular point of the conductivity and the change of its sign in Fig. 2(b). Let us suppose that a chiral vector of a single domain, $+\vec{l}$, spontaneously points to $+z$ direction ($c$ axis) in zero magnetic field as shown in the left panel of the inset of Fig. 2(b). The vector $\vec{l}$ represents the pair angular momentum parallel to $c$ axis. Assuming that an magnetic field $H_{ex}$ applied to the $−z$ direction (opposite to $+\vec{l}$) would suppress the chirality of the domain, the chiral vector of the domain would eventually point to the opposite direction (i.e., $−\vec{l}$) in a positive effective magnetic field $H_{eff} > 0$, where the effective magnetic field are defined as $H_{eff} = (H_{ex} − 450 \text{ Oe})$. In contrast, if the assumption is correct, the magnetic field applied to the $+z$ direction is expected to affect a change of the chiral domain with $+\vec{l}$, and the exchange of the sign of the conductivity does not occur in $H_{eff} < 0$. Actually, according to Fig. 2(b), the assumption seems to be valid. Our sample size $\sim 10 \mu m$ is comparable to the single domain size, so that the sample should exhibit properties in a single domain structure. Thus the microscale Sr$_2$RuO$_4$ itself is the chiral single domain with spontaneous magnetization and the applied magnetic field causes the chirality of the domain to change.

How can we understand the anomalous $I − V$ curves from the viewpoint of the peculiar transport phenomena in the chiral single domain? In what follows, we focus on an existence of Majorana-Weyl fermions in the edge of Sr$_2$RuO$_4$. The parity-violating $I − V$ curves can be understood as the result of the selective excitation of Majorana-Weyl fermions along the closed edge of the single domain under the bias current direction (i.e., $I > 0$ or $I < 0$). As shown in Fig. 3, we suppose that each region of the $I − V$ curve can be related to the paths of quasielectron or quasihole carrying the current: The panels (A)-(D) respectively correspond to the regions (A)-(D) shown in Fig. 2(b). Here we assume that the chiral edge supercurrent of the $+\vec{l}$ domain flows clockwise for $+z$ direction along the boundary even in the absence of the bias current. On a bias current $I > 0$, when right-handed quasielectrons are created by low-energy excitation from the Fermi surface (point), they circulate along the closed line (Fig. 3(A)). On the contrary, for a bias current $I < 0$, the right-handed quasiholes created by the excitation circulate oppositely (Fig. 3(B)). As a consequence, the anomalous induced voltage of $V(+I) = V(−I)$ was observed. Furthermore, similarly to the above explanation, when the $−\vec{l}$ domain which has the chiral edge...
Figure 3. A circulating model of Majorana-Weyl fermions along the closed edge of the sample and energy spectrum in chiral edge states.

supercurrent flowing counterclockwise produce the left-handed quasielectrons and quasiholes, the voltage of $-V(+I) = -V(-I)$ is induced as shown in Figs. 3(C) and (D). The excitation of quasiholes to the negative energy is considered as the same excitation of quasielectrons to the positive energy in Majorana fermions. The excitation is determined by the bias current and the direction of the applied magnetic field. In this manner, the parity-violating $I-V$ curves can be understood as relating to the excitation of the Majorana-Weyl fermions.

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