Spatial development of superconductivity in the \( \text{Sr}_2\text{RuO}_4 \)-Ru eutectic system

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We have clarified how the enhanced superconductivity, often referred to as the 3-K phase superconductivity, develops in the \( \text{Sr}_2\text{RuO}_4 \)-Ru eutectic system. From the detailed ac and dc susceptibility measurements on well-characterized crystals, we revealed strongly anisotropic shielding, governed by the direction of the screening current dominated within the RuO\(_2\) plane rather than by the orientation of the Ru lamellae. The onset temperature of the 3-K phase superconductivity probed by diamagnetic screening is as high as 3.5 K. The temperature dependence of the diamagnetic shielding above around 2 K is well ascribed by the interfacial screening among each Ru lamella. Below around 2 K, the rapid development of the shielding fraction as well as its peculiar response to ac and dc magnetic fields are explained by the formation of the Josephson network consisting of inter-lamellar supercurrents.

KEYWORDS: \( \text{Sr}_2\text{RuO}_4 \), ruthenate, eutectic crystal, proximity effect, diamagnetic shielding fraction

1. Introduction

The \( \text{Sr}_2\text{RuO}_4 \)-Ru eutectic system, in which Ru lamellae are regularly embedded with a stripe pattern in a \( \text{Sr}_2\text{RuO}_4 \) single crystal, is fascinating because the superconducting transition temperature \( T_c \) is largely enhanced over those of \( \text{Sr}_2\text{RuO}_4 \) and Ru. Pure \( \text{Sr}_2\text{RuO}_4 \) exhibits superconductivity at 1.5 K and is believed to be a spin-triplet \( p \)-wave superconductor with the vector order parameter \( d(k) = \Delta_0 (k_x + ik_y) \),\(^1,2\) and pure Ru metal is an \( s \)-wave superconductor with \( T_c = 0.49 \) K. Surprisingly, for \( \text{Sr}_2\text{RuO}_4 \)-Ru eutectic crystals, a broad superconducting transition with an onset temperature of nearly 3 K has been observed through resistivity \( \rho \) and ac susceptibility \( \chi_{ac} \) measurements.\(^3\) The \( \text{Sr}_2\text{RuO}_4 \)-Ru eutectic system with the enhanced \( T_c \) is referred to as the “3-K phase”.

Many interesting properties of the 3-K phase have been revealed, although the mechanism of the enhancement of \( T_c \) is still unknown. First, it has been proposed that the 3-K phase superconductivity occurs at the interface between \( \text{Sr}_2\text{RuO}_4 \) and Ru.\(^3\) Indeed, only a very tiny hump was observed in the specific heat.\(^4\) Secondly, the 3-K phase superconductivity is closely related to the triplet pairing of \( \text{Sr}_2\text{RuO}_4 \). For the 3-K phase, the upper critical field \( H_{c2} \) determined from resistance measurements has larger values for \( H \parallel ab \) than for \( H \parallel c \) (\( H_{c2ab}/H_{c2c} \approx 3.5 \) at 0 K),\(^5\) which is the same tendency as \( H_{c2} \) for pure \( \text{Sr}_2\text{RuO}_4 \) (\( H_{c2ab}/H_{c2c} \approx 20 \) at 0 K).\(^6\) In addition, tunneling measurements at the interface between \( \text{Sr}_2\text{RuO}_4 \) and Ru microinclusion have revealed the presence of a zero bias conductance peak,\(^7,8\) which is a hallmark of an unconventional superconductivity.\(^9\) Very recently, Kambara \( et al. \) observed an unusual hysteresis in the \( I-V \) characteristics of micro-fabricated channels of the 3-K phase,\(^10\) which indicates the existence of internal degrees of freedom in the superconducting order parameter. These results suggest that the 3-K phase superconductivity is unconventional and sustained in the \( \text{Sr}_2\text{RuO}_4 \) part of the interface rather than in the Ru part. Thirdly, the temperature dependence of \( H_{c2} \) in the 3-K phase is qualitatively different from that of \( \text{Sr}_2\text{RuO}_4 \). Especially, an unusual upturn curvature in \( H_{c2} \) is observed at temperatures below 2 K for \( H \parallel c \).\(^4\)

In order to explain these unusual features of the 3-K phase, Sigrist and Monien constructed a phenomenological theory which assumes a spin-triplet superconductivity occurring at the interface between \( \text{Sr}_2\text{RuO}_4 \) and Ru metal.\(^11\) They proposed that one of the two components of the superconducting order parameter, the component parallel to the interface, is stabilized at \( T_c \) of the 3-K phase in zero field and that the other component with the relative phase of \( \pi/2 \) emerges at a slightly lower temperature. Based on these experimental and theoretical works, the 3-K phase superconductivity is now believed to originate at the interface between \( \text{Sr}_2\text{RuO}_4 \) and Ru.

Although the typical distance between the nearest interfaces is approximately 10 \( \mu \)m, zero-voltage current was observed at temperatures well above \( T_c \) of the bulk \( \text{Sr}_2\text{RuO}_4 \), \( T_{c-bulk} \).\(^12\) This observation suggests that the supercurrent flows between different interfaces. In the present work, we performed detailed measurements of \( \chi_{ac} \) and dc magnetization \( M \) as a more direct approach to examine the spatial development of the 3-K phase superconductivity. We revealed that the diamagnetic signal in \( M \) for \( H_{dc} \parallel c \) becomes observable below approximately 3.5 K, while it becomes observable only below 3 K for \( H_{dc} \perp c \). The shielding fraction is also anisotropic with respect to the crystal structure of \( \text{Sr}_2\text{RuO}_4 \) rather than to the geometry of the interfaces. The value of the shielding fraction is at most 1.2% at 1.8 K, whereas the resistivity at this temperature becomes only 20% of the normal-state value.\(^4,10\) Further decreasing temperature, we found that the diamagnetic shielding fraction rapidly increases and reaches nearly 100% just above \( T_{c-bulk} \). This large shielding fraction is more easily suppressed by the ac mag-

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magnetic field $H_{ac}$ than by the dc magnetic field $H_{dc}$. These ac and dc magnetic field responses as well as the large shielding fraction suggest that the Josephson network is formed among different interfaces with a long-range proximity effect in which the proximity length diverges toward $T_c$-bulk.

2. Experimental

The 3-K phase samples used in our study were grown using a floating zone method with an excess amount of Ru. We performed measurements on more than five 3-K phase samples from different batches and obtained qualitatively the same behavior. In this paper, we focus on the results of two 3-K phase samples cut from different batches: Sample-1 and Sample-2. As depicted in Fig. 1 (a), Sample-1, whose dimensions are $1.85 \times 2.0 \times 0.85$ mm$^3$, has a thin-plate shape parallel to one of the ac planes of the tetragonal Sr$_2$RuO$_4$. The crystal axes were determined from Laue pictures. For convenience, we define one of the $a$ axes along the plate thickness as [010] and the other as [100]. Figures 1 (b)-(d) show polarized-light optical microscope images of the polished (001), (100), and (010) surfaces of Sample-1. The brighter and darker areas correspond to Ru and Sr$_2$RuO$_4$, respectively. From these pictures, we found that the typical dimensions of the Ru inclusion are approximately $10 \times 10 \times 1$ µm$^3$ with a thin-slab shape. As schematically illustrated in Fig. 1 (e), these Ru lamellae are probably aligned nearly, but not exactly, parallel to the (100) plane. The dimensions of Sample-2 are $1.8$ mm $\times 2.0$ mm in the $ab$ plane and $0.5$ mm along the $c$ axis, as shown in Fig. 1 (f). A polarized-light optical microscopic image of the polished (001) surface of Sample-2 is presented in Fig. 1 (g). Most regions of each surface of Sample-1 and Sample-2 show Ru stripe patterns similar to those shown in Fig. 1. The total area of the Ru inclusions is estimated as high as 5% of the area of the surface.

We measured $\chi_{ac} = \chi' - i\chi''$ by a mutual-inductance technique using a lock-in amplifier (LIA). The ac magnetic field $H_{ac}$ was applied with a small hand-made coil (40 µT / mA). The dc magnetic field $H_{dc}$ was generated by a 2-T magnet (Oxford Instruments), and was applied parallel to $H_{ac}$. When we measured $\chi_{ac}$ in zero dc field, we used a high-permeability-metal shield to exclude the geomagnetic field of about 50 µT. The values of $\chi_{ac}$ are obtained from the relation $\chi_{ac} = IC_1V_{LIA}/H_{ac} + C_2$, where $C_1$ and $C_2$ are certain coefficients and $V_{LIA}$ is the read-out voltage of LIA. We chose different values of $C_1$ and $C_2$ for each curve in Fig. 3, whereas we used the same values of $C_1$ and $C_2$ for all curves in Figs. 4 and 5. The samples were cooled down to 0.3 K with a $^3$He cryostat (Oxford Instruments, model Heliox VL). We measured $\chi_{ac}$ at different frequencies ranging from 17 Hz to 10 kHz. Although $\chi_{ac}$ of the 3-K phase superconductivity depends on frequency as reported in Ref. 14, we only present the data at 293 Hz since the behavior in $\chi_{ac}$ with different frequencies are qualitatively the same. We measured $M$ with a SQUID magnetometer (Quantum Design, model MPMS) from 1.8 K to 4.2 K in the zero-field-cooling condition.

3. Results

3.1 Anisotropy of the shielding fraction

We first present the result of the field-direction dependence of the 3-K phase superconductivity. Figures 2 (a) and (b) show the temperature dependence of the dc shielding fraction $\Delta M/H_{dc}$ in $\mu_0 H_{dc}$ of 2 mT along the [001], [100], and [010] axes. In these figures, we normalize $M/H_{dc}$ by the ideal value calculated for the full Meissner state without the demagnetization correction. Remarkably, from Fig. 2 (a), we found that $M$ for $H_{dc} \parallel c$ starts to decrease with the onset temperature of 3.5 K, which is apparently higher than the onset temperature reported in the out-of-plane resistance $\rho_c$ measurements (at most 3 K) but is comparable to that reported in the in-plane resistance measurement (above 3 K). In contrast, the diamagnetic signal becomes observable only below 3 K for $H_{dc} \parallel ab$, which is consistent with the onset temperature reported in the $\rho_c$ measurements. These results suggest that the 3-K phase superconductivity is highly two dimensional above 3 K. As shown in Fig. 2 (b), the anisotropy of the dc shielding fraction is also striking. We found that the dc shielding fraction in the measurement temperature range
strongly depends on the field direction with respect to the Sr$_2$RuO$_4$ crystal axes rather than to the geometry of the Ru lamellae (cf. Figs. 1 (a)–(e)). The dc shielding fraction at 1.8 K is much larger for $H_{dc} \parallel c$ than for $H_{dc} \parallel ab$, indicating that the screening current mainly flows within the $ab$ plane. We note that the effect of the demagnetization factor of Sample-1 should be comparable between the fields along the [010] and [001] axes.

As shown in Fig. 3, we also measured $\chi_{ac}$ of Sample-1 with $\mu_0 H_{ac}$ of 10 $\mu$T-rms along the [001], [010], and [100] axes in zero dc field. The values of $C_1$ and $C_2$ for each curve are chosen so that $\chi'(3 \text{ K}) = 0$ and $\chi'(0.3 \text{ K}) = -1$. We note that these $\chi_{ac}$ measurements cover lower temperatures than the $M$ measurements whereas its experimental resolution is relatively lower. Although the onset between 2 and 3.5 K observed in $M$ is too small to be detected in $\chi_{ac}$, an anisotropic shielding fraction similar to that observed in the $M$ measurements was observed below 2 K. Near $T_{c-bulk}$, the shielding fractions for the three field directions reach 100% and the anisotropy apparently disappears. This result indicates that the magnetic fluxes are excluded from most of the sample area even above $T_{c-bulk}$, though it contains a large fraction of the normal-state Sr$_2$RuO$_4$ regions. These results suggest that the anisotropy associated with the RuO$_2$ plane plays an essential role in the spatial development of the 3-K phase superconductivity.

We should here remind the fact that the in-plane$^{10}$ as well as the out-of-plane$^3$ resistivity decrease by nearly 80% even at 2.5 K from the normal-state value. The observed shielding fraction, at most 1.2% at 1.8 K for any field direction, seems to be apparently inconsistent with the decrease of the resistivity. We will discuss the origin of this apparent inconsistency in Sec. 4.

3.2 Field-magnitude dependence of $\chi_{ac}$

In order to further investigate the development of the 3-K phase superconductivity, we compare the $H_{ac}$ and $H_{dc}$ dependence of the $\chi_{ac}(T)$ curve for $H_{ac} \parallel H_{dc} \parallel c$ using Sample-2. We choose the values of $C_1$ and $C_2$ so that $\chi'$ at 3 K becomes 0 and $\chi'$ at 0.3 K becomes −1 for the 0.1 $\mu$T-rms curve; we use the same $C_1$ and $C_2$ throughout the curves in Figs. 4 and 5. We first focus on the result for $\mu_0 H_{ac} = 0.1$ $\mu$T-rms and $\mu_0 H_{dc} = 0$ T (the red curve in Fig. 4). Two anomalies were observed: the sharp drop at 1.4 K (= $T_{c-bulk}$) due to the bulk superconducting transition of Sr$_2$RuO$_4$ and the broad decrease between 1.4 K and 2 K corresponding to the 3-K phase superconductivity. Just above $T_{c-bulk}$, $\Delta \chi' = \chi'(3 \text{ K}) - \chi'(T)$ reaches 70% of $\Delta \chi'$ in the full Meissner state below 1.3 K. Probably, $\Delta \chi'$ just above $T_{c-bulk}$ corresponds to the volume fraction of the 3-K phase in the samples.

We next give attention to the $H_{ac}$ dependence of $\chi_{ac}$ of the
large ac shielding fraction is observed just above $T_{c \rightarrow \text{bulk}}$. (ii) The shielding fraction for any field direction is at most 1.2% at 1.8 K, seemingly inconsistent with the decrease of resistivity. (iii) The 3-K phase superconductivity above $T_{c \rightarrow \text{bulk}}$ has a strong anisotropy against the field direction with respect to the Sr$_2$RuO$_4$ crystal axes rather than to the orientation of Ru lamellae: The shielding fraction as well as the onset temperature of the observable diamagnetic signal is enhanced for $H \parallel c$ than for $H \parallel ab$. (iv) Above $T_{c \rightarrow \text{bulk}}$, $\Delta \chi'$ is more easily suppressed by $H_{ac}$ than by $H_{dc}$, suggesting a formation of a “weak” superconductivity. This feature is observed for both $H_{ac} \parallel c$ and $H_{ac} \parallel ab$.

In the following, we discuss the origin of these interesting features observed in the 3-K phase.

The first possible scenario is based on a model in which there are many Ru lamellae enough to cover the whole sample if we were to see through the sample from the applied field direction. In other words, this scenario assumes that the large shielding fraction originates only from individual interface between Sr$_2$RuO$_4$ and Ru. This scenario is similar to the scenario proposed for the origin of the superconductivity observed in the Sr$_2$Ru$_2$O$_7$ region cut out from the Sr$_2$Ru$_2$O$_7$-Sr$_2$RuO$_4$ eutectic system. In the Sr$_2$Ru$_2$O$_7$ region, Sr$_2$RuO$_4$ thin slabs embedded as stacking faults were observed with a transmission electron microscope and it is suggested that these thin slabs become superconducting and contribute to the large shielding fraction. Although this scenario can explain the features (i) and (iv), it is difficult to explain the feature (iii): If this scenario were the case, the anisotropy of the shielding fraction would be governed by the geometry of the Ru inclusions rather than the crystal structure of Sr$_2$RuO$_4$. Therefore, this scenario is not suitable for the 3-K phase.

The second possible scenario is that a Josephson network induced by the proximity effect of the interfacial superconductivity is formed and that the Josephson screening current connecting the lamellae produces the large shielding fraction. In this scenario, we assume that the 3-K phase (probably p-wave) superconductivity occurring at the interfaces penetrates into the normal-state Sr$_2$RuO$_4$ due to the proximity effect and forms Josephson-type weak links among different interfaces. Indeed, a strong $H_{ac}$ dependence of the $\chi_{ac}(T)$ curve being similar to the feature (iv) has been observed in materials with such a Josephson network (e.g. Ref. 19). This scenario also seems to be consistent with the other present observations as discussed below.

In the proximity-induced Josephson network scenario, the observed large shielding fraction above $T_{c \rightarrow \text{bulk}}$ (feature (i)) indicates that the proximity length should be comparable to or even larger than the inter-Ru distances (typically 10 µm). The observation of the zero-voltage current above $T_{c \rightarrow \text{bulk}}$ also suggests a long proximity length. It is known that the proximity length $\xi_p$ in a clean metal connected to a superconductor with its transition temperature $T_c$ is given by

$$\xi_p(T) = \frac{h \nu_f}{2 \pi k_B T},$$

where $h$ is Planck’s constant, $\nu_f$ is the frequency of the ac field, and $k_B$ is Boltzmann’s constant.
where $\hbar$ is the Dirac constant, $v_F$ is the Fermi velocity of the normal metal, and $k_B$ is the Boltzmann constant. If the normal metal is also a superconductor with a transition temperature $T_{cn}$ lower than $T_{cs}$, eq. (1) is modified using the Eilenberger formalism,\cite{20} in the clean limit and in the temperature range $T_{cn} < T < T_{cs}$,

$$\xi_s^{2D}(T) = \xi_0(T) \frac{1 + 2/\ln(T/T_{cn})}{1 + 4/\ln(T/T_{cn})}$$

(2)

for a two-dimensional system, and

$$\frac{1}{2} \ln \frac{T}{T_{cn}} = \frac{\xi_s^{3D}(T)}{\xi_0(T)} - \text{arctanh} \left( \frac{\xi_s^{3D}(T)}{\xi_0(T)} \right) - 1$$

(3)

for a three-dimensional system. In these equations, $\xi_0(T)$ is given by eq. (1). We plot in Fig. 6 (a) the temperature dependence of $\xi_0$ (diverging at 0 K) and $\xi_s^{2D}$ (diverging at $T_{cn}$) calculated using $v_{Flab} = 5.5 \times 10^4$ m/s for the $y$ band of Sr$_2$RuO$_4$ and $T_{cn} = T_{c-bulk} = 1.4$ K. Equations (2) and (3) lead to the divergent behavior $\xi_s^{2D}(T) \propto v_F/(T - T_{cn})^{1/2}$ near $T_{cn}$. We note that $\xi_s^{3D}(T)$ in the dirty limit also exhibits $v_F/(T - T_{cn})^{1/2}$ behavior near $T_{cn}$.\cite{20}

It is clear in Fig. 6 (a) that the long-range proximity length discussed above for the normal-state Sr$_2$RuO$_4$ in the 3-K phase is not consistent with eq. (1), but can be explained by eq. (2) or (3).

Within this Josephson network scenario, the origin of the feature (iii), the anisotropy of the shielding fraction reflecting the layered crystal structure of Sr$_2$RuO$_4$, is ascribable to the anisotropy of the proximity length $\xi_{prox}^{2D} \gg \xi_{prox}^{3D}$ resulting from the fact $v_{Flab} \gg v_{F|c}$.\cite{2} Because of this anisotropy, the 3-K phase superconductivity penetrates more deeply into the normal-state Sr$_2$RuO$_4$ region along the $ab$ plane than along the $c$ axis.

Here, we discuss the origin of the feature (ii), the small shielding fraction above 2 K. One possible scenario is that most of the interfaces become superconducting, leading to the large reduction in the resistivity, while these interfacial regions cannot prevent magnetic fields from penetrating into the Ru metal inside. Let us calculate the temperature dependence of $M$ near the onset temperature with a model that Ru metal is cylindrical along the $c$ axis with the radius $R_0 = 1$ μm ($R_0 \gg \xi_0^{2D}$) and quantized vortices are pinned only in the region $R_0 < r < R_0 + \xi_0^{2D}(T)$. (For simplicity, we represent by $\xi_0^{2D}$ the region of both the interfacial superconductivity and the proximity effect.) To this interfacial region, we apply the critical state model\cite{22} represented by the homogeneous critical current $J_c(r, T) = J_c(T) = -dH(r)/dr$, as illustrated in the inset of Fig 6 (b). Then, the magnetic flux density $B(r, T)$ in the Ru metal is given by

$$B(r, T)|_{r \leq R_0} = \mu_0(H_{dc} - J_c(T)\xi_0^{2D}(T)).$$

(4)

We assume that $J_c(T)$ behaves as $J_c(0)(1 - T/T_{cs})^2$, adopting the same temperature dependence in the weak superconducting region in a granular superconductor.\cite{19} The diamagnetic magnetization per unit volume is expressed as

$$\Delta M(T) = \frac{\langle B(T) \rangle}{\mu_0} - H_{dc}.$$  

(5)

Here, $\langle B(T) \rangle$ is the spatial average of the magnetic flux density in the bulk of the sample. Because of the condition $R_0 \gg \xi_0^{2D}$, $\langle B(T) \rangle$ is approximated as

$$\langle B(T) \rangle \approx f_{Ru} B_{Ru}(0, T) + (1 - f_{Ru})\mu_0 H_{dc},$$

(6)

where $f_{Ru}$ is the volume fraction of Ru inclusions in the sample. From eqs. (4)–(6), we obtain

$$\Delta M(T) \approx f_{Ru} J_c(0) \left(1 - \frac{T}{T_{cs}}\right)^2 \xi_0^{2D}(T).$$

(7)

Equation (7) gives a good fitting to the data of $M$ for $H_{dc} = 2$ mT above 2.1 K, as plotted in Fig. 6 (b). The resultant fitting parameters are $f_{Ru} J_c(0) = 25$ A/cm$^2$ and $T_{cs} = 3.3$ K. If we adopt the ratio of total Ru area to the area of the $ab$ surface, approximately 0.05, as $f_{Ru}$, $J_c(0)$ becomes 500 A/cm$^2$. This value of $J_c(0)$ seems reasonable because it is comparable to the experimental value ($J_c(0) \sim 800$ A/cm$^2$).\cite{12} Below 2.1 K, the fitting is less satisfactory: the experimental shielding fraction is more pronounced than our calculation. This deviation is attributable to the additional shielding by the inter-Ru supercurrent forming the Josephson network, which is not included in our calculation.

Summarizing the discussion above, we elucidate the spatial development of the 3-K phase superconductivity. As presented in Fig. 2 (b), we revealed that the onset temperature in $M$ for $H_{dc} \parallel c$ is as high as 3.5 K. It should be emphasized that $M$ for $H_{dc} \perp c$ as well as the out-of-plane resistance\cite{5} exhibit clear superconducting signals only below 3 K. These results suggest that, as temperature decreases, the 3-K phase superconductivity above 3 K is confined within each RuO$_2$ plane at the Ru interface and is highly two dimensional. When temperature further decreases, the 3-K phase superconductivity extends also along the $c$ axis. At around 2.5 K, most of the interfacial regions exhibit non-bulk superconductivity, lead-
ing a large drop in resistivity. This non-bulk superconductivity penetrates into the normal-state Sr$_2$RuO$_4$ region due to the proximity effect. Below around 2 K, the proximity-induced Josephson network possibly develops connecting different interfaces and extends more widely within the $ab$ plane than along the $c$ axis, leading to the large and anisotropic shielding fraction.

According to the theoretical analysis by Sigrist and Monien, the one-component $p$-wave order parameter with its node perpendicular to the interface would be stabilized at the interface near the 3-K onset temperature. If weak links between different interfaces are formed with the one-component $p$-wave order parameter, it is not possible that all links have zero phase shifts in the order parameter: some links must have $\pi$ phase shifts. This situation results in a frustration in the system because the links with the $\pi$ phase shift, $\pi$-junctions, have slightly higher energy than the links with the zero phase shift. In our ac-susceptibility study, however, we have not obtained any experimental hints indicating a formation of such a $\pi$-junction network, e.g. paramagnetic signals associated with a spontaneous current in $\pi$-junction loops. When the temperature is lowered, the other component is expected to emerge in the 3-K phase superconductivity leading to the chiral state $k_x + ik_y$. Based on the observation of the zero-bias conductance peak, it has been suggested that the two-component state appears below about 2.3 K.$^{31}$ Since our experimental results indicate that the Josephson network is formed mainly below 1.8 K, it probably consists of the two-component $p$-wave order parameter in the chiral state $k_x + ik_y$. Whether or not the frustration occurs in the Josephson network needs to be further investigated both experimentally and theoretically.

5. Conclusion

We have clarified the process of spatial development of the 3-K phase superconductivity. By precise magnetization measurements, we revealed that the onset temperature of the 3-K phase superconductivity is as high as 3.5 K. The observation of the diamagnetic shielding above 3 K only for $H_{dc} \parallel c$ implies that the shielding current originating from the 3-K phase superconductivity flows only within the RuO$_2$ planes. Below 3 K, the diamagnetic signal associated with the shielding current along the $c$ axis also becomes observable. The small shielding fraction above around 2 K is explained by a scenario that the interfacial superconducting regions are too thin to exclude magnetic fields from Ru inclusions. By ac susceptibility measurements, we revealed that the shielding fraction in the temperature range $T_{c-bulk} < T < 2$ K is easily destroyed by $H_{dc}$ and is anisotropic with respect to the crystal structure of Sr$_2$RuO$_4$. In the vicinity of $T_{c-bulk}$, the shielding fraction for all field directions reaches nearly 100%. Based on these experimental results, we suggest the formation of the Josephson network in the 3-K phase. The proximity length diverging toward $T_{c-bulk}$ enables the formation of weak links among well separated Ru metals. Although the microscopic origin of the enhancement of $T_c$ remains an open question, the present results provide a basis for future theoretical and experimental studies.

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