STM/STS study of surface electronic density of states of Sr$_2$RuO$_4$ & Unconventional local transport characteristics in microfabricated Sr$_2$RuO$_4$–Ru eutectic crystals

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**Introduction**

$\text{Sr}_2\text{RuO}_4$ ($T_c = 1.5$ K)

Chiral $p$-wave superconductor (spin-triplet pairing) by Deguchi and Maeno

Time reversal symmetry breaking

$$\vec{d}(\vec{k}) = \hat{z} \Delta_0 (k_x \pm ik_y)$$

Spin orbital

$$(k_x + ik_y), (k_x - ik_y)$$

Existence of chiral domain

$\mu$SR Luke et al. (1998)

Kerr effect Xia et al. (2006)

Rich internal degrees of freedom in the Cooper pair!

Novel phenomena are predicted theoretically:

half quantum vortex, anomalous proximity effect, etc.

challenging subjects
Outline

What are the local electronic states and properties?

1. STM/STS study of local density of states
   - Surface sensitive
     - A cleaved surface (SrO-layer) does not show superconductivity.
   - Local characteristics extracted from bulk

2. Local transport characteristics of microfabricated crystals
   - Surface insensitive
     - Anomalous hysteretic feature in V-I characteristics suggests the existence of chiral domain

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Sr$_2$RuO$_4$

STM image (5 nm × 5 nm)
1. STM/STS study of surface electronic density of states
STM and Tunnel spectra on a cleaved surface

Cleaved topmost surface is usually a SrO-layer.

Non-superconducting gap: $\Delta \sim 5$ meV ($\sim 50$ K)
STM and Tunnel spectra on a cleaved surface

Cleaved topmost surface is usually a SrO-layer.

Non-superconducting gap: \( \Delta \sim 5 \text{ meV} \sim 50 \text{ K} \)

Electronic structure on a cleaved SrO-surface is different from that of superconductivity.
Cleaving-temperature dependence of Sr$_2$RuO$_4$

All samples were cleaved at ultrahigh vacuum. STM images were obtained at T~40 mK.

Recently, similar experiments were reported by Pennec et al., PRL (2008).

\[ T_{\text{cleave}} = 7 \, \text{K} \]

Flat surface with atomic resolution

Non-superconducting gap

\[ \Delta \sigma \approx \sqrt{|E - E_F|} \]

Anderson localization in 3D

Non-superconducting surface of Sr$_2$RuO$_4$

Junction resistance between SRO/SRO increases at $T < 25$ K
→ Non-superconducting surface layer


Surface-sensitive measurement is not straightforward to study the superconductivity of Sr$_2$RuO$_4$. 
2. Unconventional local transport characteristics in microfabricated \( \text{Sr}_2\text{RuO}_4 \)-Ru eutectic crystals
**Sr$_2$RuO$_4$ - Ru eutectic system ~3-K phase superconductivity~**

**Sr$_2$RuO$_4$ - Ru eutectics**

Ru inclusion

10 µm

Maeno et al., PRL 81, 3765 (1998).

**T ~ 3 K**

3-K phase (S)

**T > 3 K**

3 > T > 1.5 K

(S-N-S)

weak link (N)

**T < 1.5 K**

(S-S'-S)

1.5-K phase (S')

$p$-wave superconducting junctions are naturally formed.
Transport characteristics in microfabricated \( \text{Sr}_2\text{RuO}_4\)-Ru junction

The surface state does not influence this 4-probe configuration.

Extraction of superconducting linkage channels without averaging over bulk sample.
**Sample configurations** \((I \parallel ab \text{ and } I \parallel c)\)

**I \parallel ab**

- Microbridge
- \(\text{Sr}_2\text{RuO}_4\)-Ru
- Sample 1

**I \parallel c**

- Slit
- \(\text{Sr}_2\text{RuO}_4\)-Ru
- Glue
- Sample 2

SIM image obtained after the top and side surfaces were slightly milled. FIB milling was done after transport measurements.
Anomalous hystereses are observed for both I//ab and I//c directions.

V-I & dV/dI-I characteristics (Anomalous hysteresis)

Negative dV/dI is not observed $\rightarrow$ switching phenomena

Anomalous hystereses are observed for both I//ab and I//c directions.
How are V-I characteristics anomalous?

Anomalous features

1. Voltage decreases at $I_{sw}$.
2. It switches to a lower $R_n$ (normal resistance) branch with larger $I_c$.
3. Opposite hysteresis loop compared to typical Josephson junction (JJ) s.

Sr$_2$RuO$_4$-Ru

Usual switching

Intrinsic JJs in Bi2212

NOT usual JJs!
Magnetic field effect

The curves are offset by -0.5 unit for clarity.

Anomalous hysteresis is NOT due to a magnetic vortex!

cf) $H_{c1}(0) \approx 70$ G (1.5-K phase)  
Deguchi, Mao, Maeno, JPSJ(2004).
**Anomalous $J_c$ enhancement**

In usual case,

$$R_{bridge} = \rho \frac{L}{S}$$

$$S = Wt$$

Critical current density: $J_c$

$$J_c = \frac{I_c}{S} = \text{const.}$$

 usual

Unusual!

Jc increases for small S.

In usual case,

- High $J_c$ along edge
- Low $J_c$ inside

Edge channels seem to be formed.

$\star J_c$ is not $J_c(0)$ at $T = 0$. 

**Graphs:**

- Variation in thickness and width
- $L/R_{bridge}$ vs. $L/R_{bridge}$
- $J_c$ vs. $S$ for different temperatures

**Notes:**

- $J_c(0) = 500$ A/cm$^2$ for bulk pure Sr$_2$RuO$_4$ (by Deguchi and Maeno)

**Equations:**

- $S = Wt$
- $J_c = I_c/S = \text{const.}$
- $R_{bridge} = \rho \frac{L}{S}$

**Variables:**

- $L$: length
- $R_{bridge}$: bridge resistance
- $\rho$: resistivity
- $S$: area
- $W$: width
- $t$: thickness
- $I_c$: critical current
- $J_c$: critical current density
- $T$: temperature
- $k_x$, $k_y$: wavevectors
Possible origin of the anomalous hysteresis

**Chiral domain wall motion through the 3-K phase \(k_x\) and 1.5-K phase \(k_x \pm i k_y\) coexistence region**

(1) Initial state

(2) \(I > 0\)

Domain wall moves under DC current.

(3) \(I = I_{sw1}, I_{sw2}\)

\(k_x\)-phase flips

Frustration

No frustration

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Frustration

pair potential for \(x\)

No frustration

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\[ V \]

\[ I \]

\[ I_{c0} \]

\[ I'_{c0} \]

\[ I''_{c0} \]
STM/STS at Sr$_2$RuO$_4$ surface

- Low temperature (T<100 K) cleaved surface (SrO-layer) shows non-superconducting gap. Room temperature cleaved surface shows disordered electronic states. The surface electronic states are different from those of bulk superconductivity.

Local transport measurement for microfabrication sample

- Microfabrication technique with FIB was applied to Sr$_2$RuO$_4$-Ru eutectic crystals. Local superconducting channels were successfully extracted.

- Anomalous hysteresis of V-I characteristics was observed for both I//ab and I//c directions. It suggests that internal degrees of freedom of the chiral p-wave state, Chiral domain wall motion by DC current is a possible origin of the anomalous hysteresis.