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STM/STS study of surface electronic density of states of Sr_2RuO_4 & Unconventional local transport characteristics in microfabricated Sr_2RuO_4-Ru eutectic crystals

AIST **Hiroshi Kambara**

AIST — Satoshi Kashiwaya

Tokyo Univ. of Sci. — Hiroshi Yaguchi

Hokkaido Univ. — Yasuhiro Asano

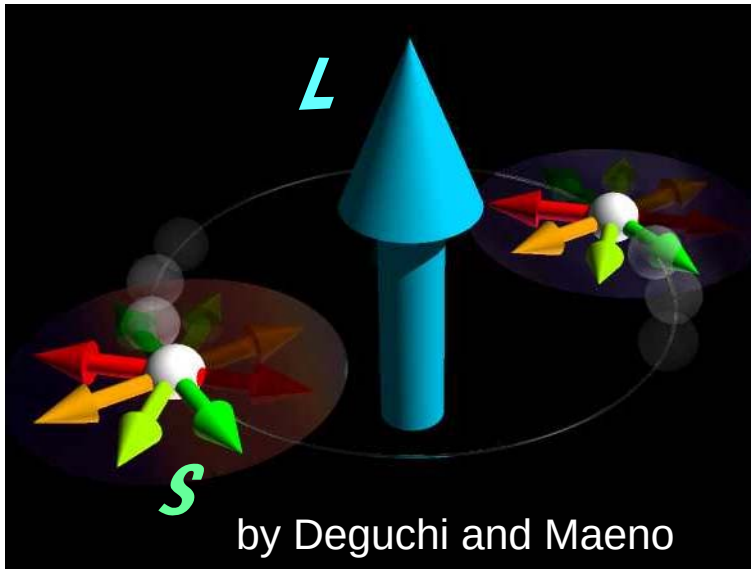
Nagoya Univ. — Yukio Tanaka

Kyoto Univ. — Yoshiteru Maeno

Univ. Tokyo — Hiroshi Fukuyama

Introduction

Sr_2RuO_4 (T_c = 1.5 K)



Chiral p-wave superconductor (spin-triplet pairing)

Time reversal symmetry breaking

$$\vec{d}(\vec{k}) = \underbrace{\hat{z}}_{\text{spin}}\Delta_0\underbrace{(k_x \pm ik_y)}_{\text{orbital}}$$

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

Existence of chiral domain

μSR 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

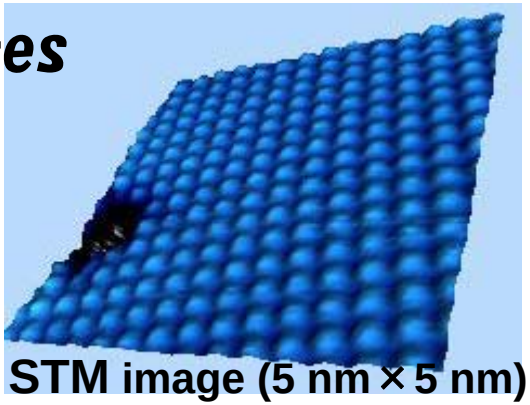
Outline

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.



STM image (5 nm × 5 nm)

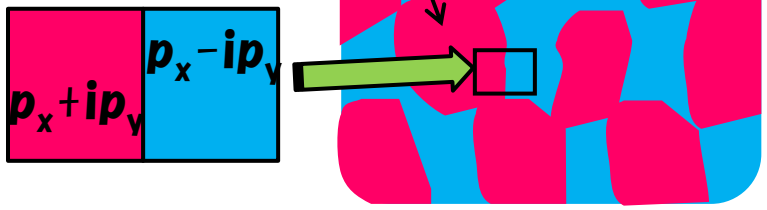
Sr_2RuO_4

2. Local transport characteristics of microfabricated crystals

   Surface insensitive

   Anomalous hysteretic feature in V-I characteristics suggests the existence of chiral domain

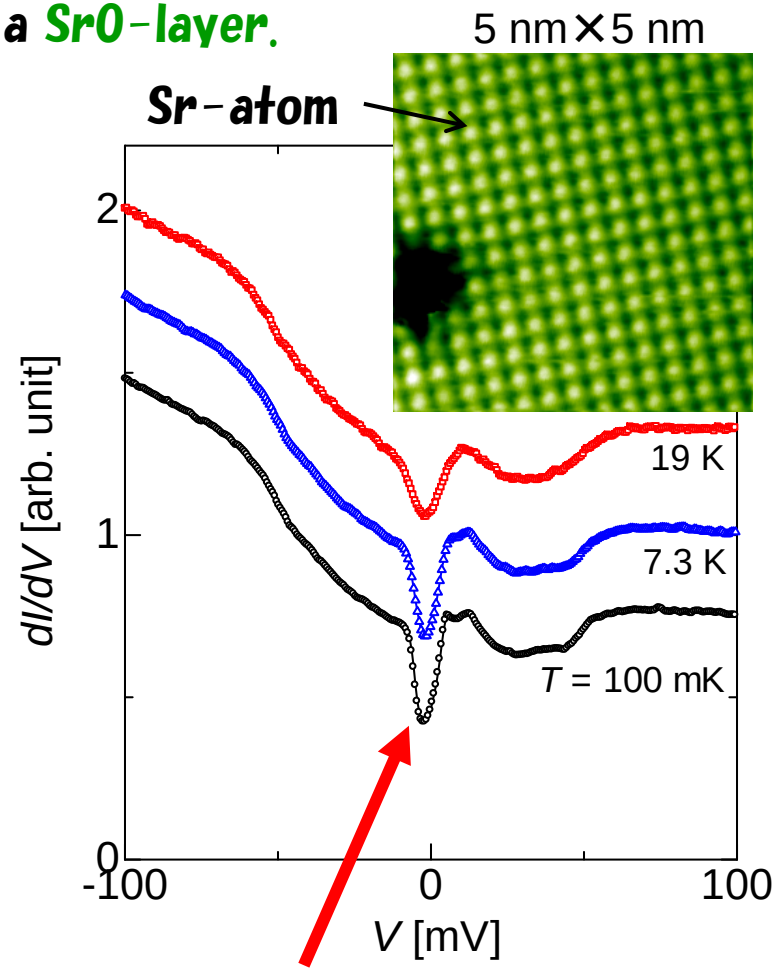
Local caracteristics extracted from bulk



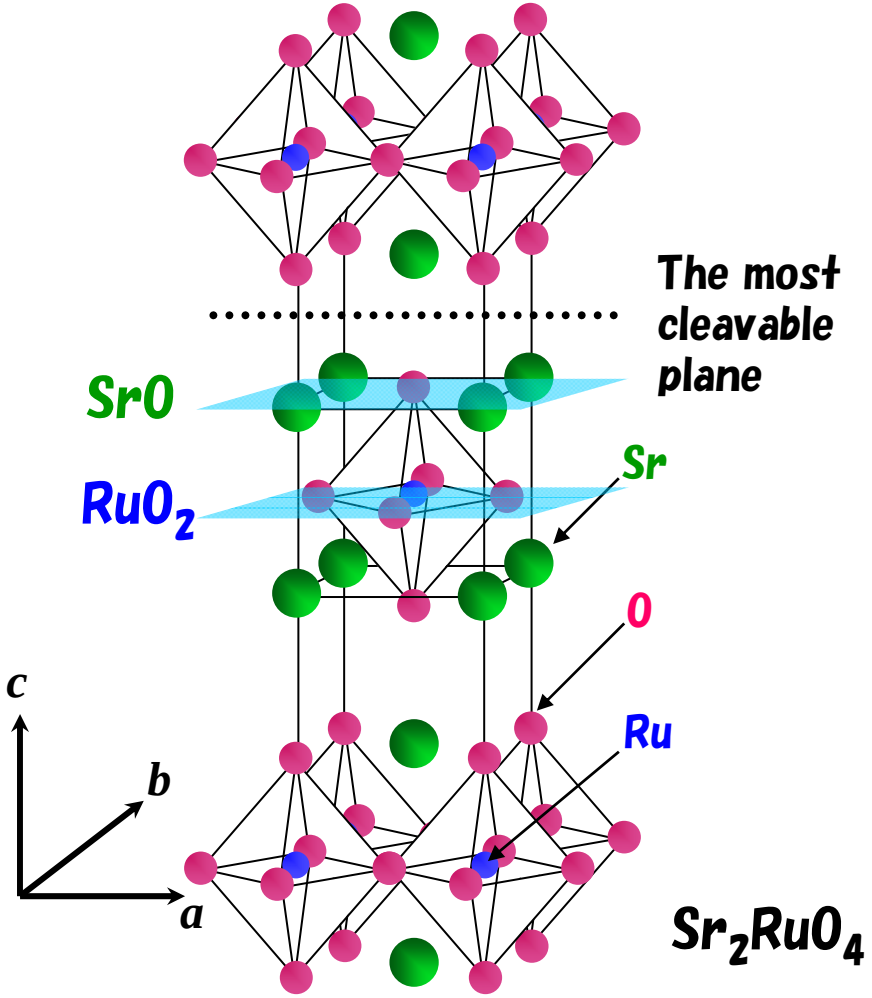
1.
STM/STS study of surface electronic density of states

STM and Tunnel spectra on a cleaved surface

Cleaved topmost surface is usually a SrO-layer.



Non-superconducting gap:
$\Delta \sim 5$ meV (~ 50 K)



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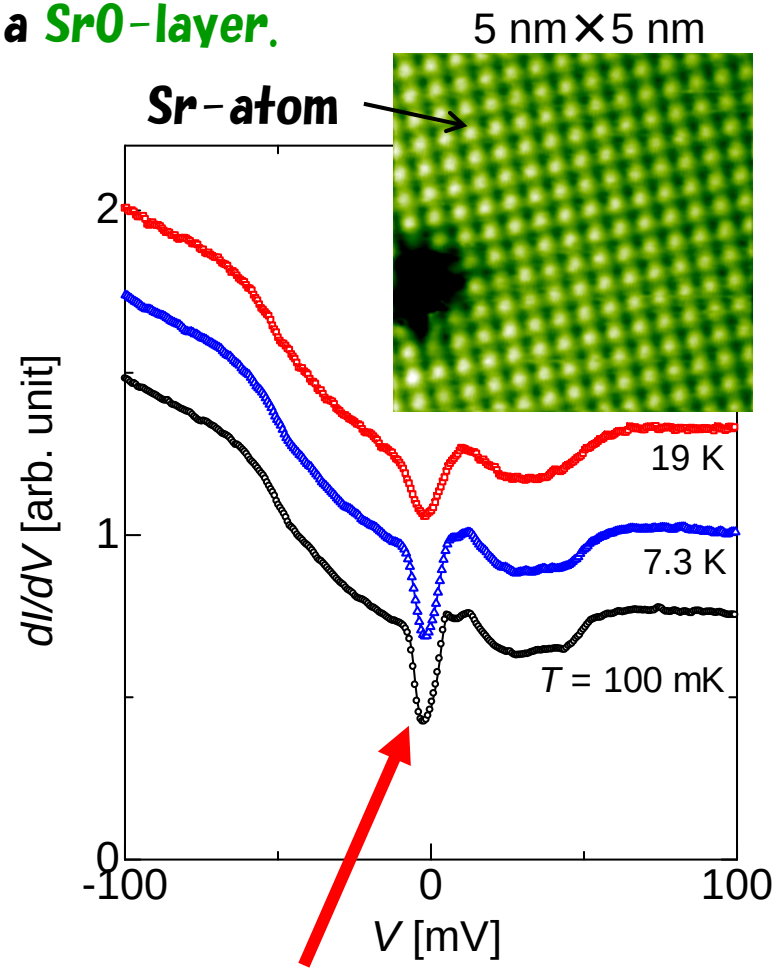

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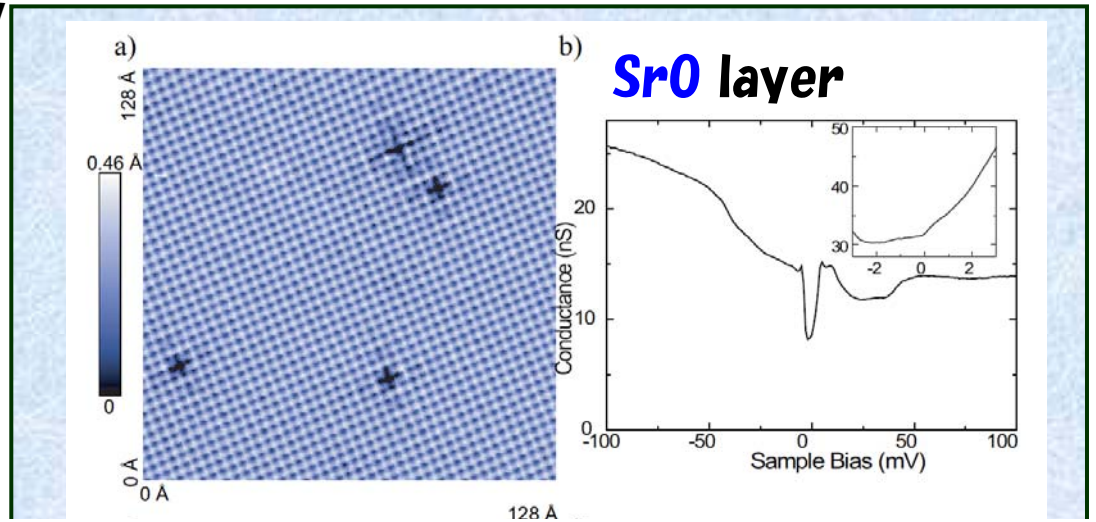
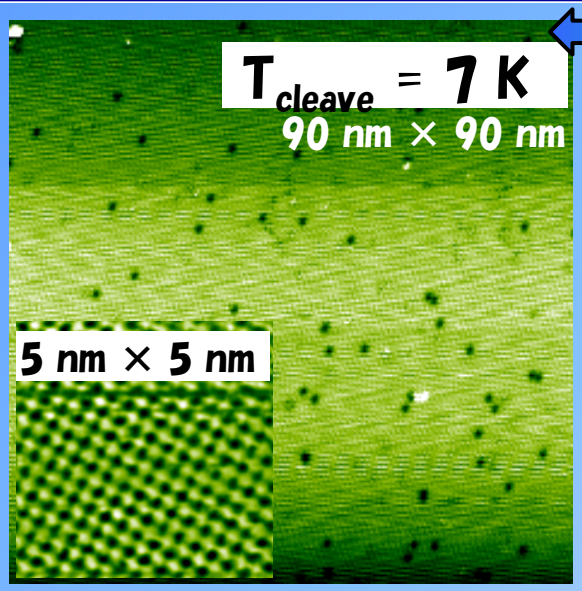


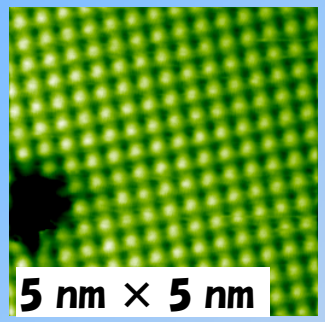
C. Lupien *et al.*, cond-mat/0503317.

Electronic structure on a cleaved SrO-surface is different from that of superconductivity.

Cleaving-temperature dependence of Sr_2RuO_4

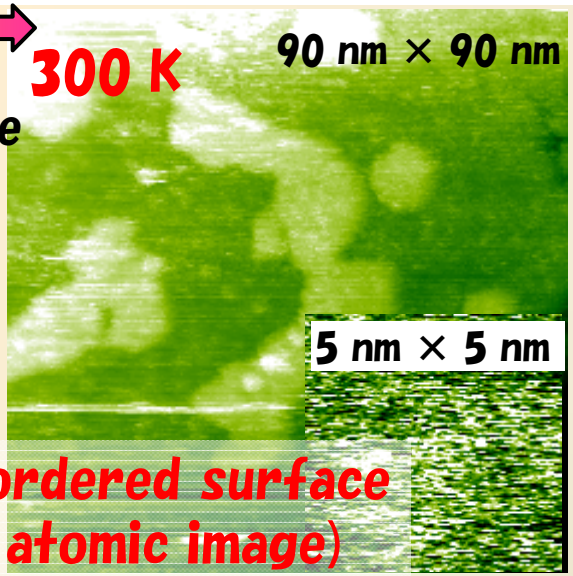


100 K



Cleaving temperature

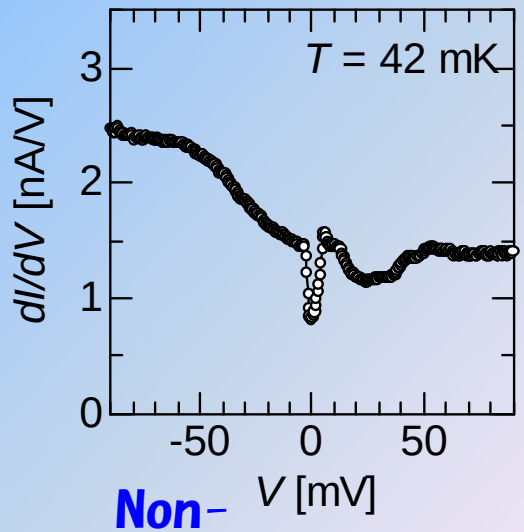
300 K



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

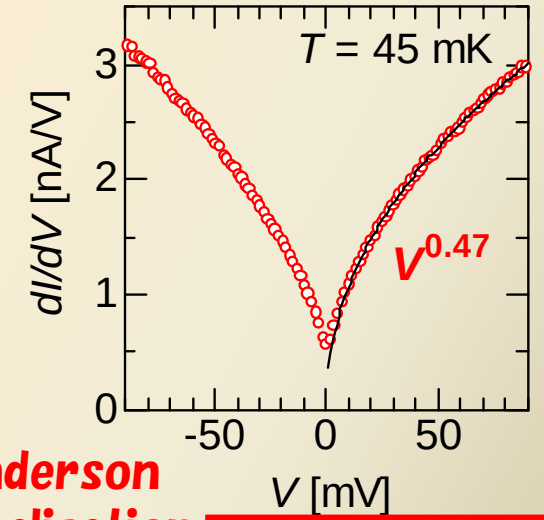
Recently, similar experiments were reported by Pennec *et al*., PRL (2008).

Flat surface with atomic resolution



Non-superconducting gap

Disordered surface (no atomic image)

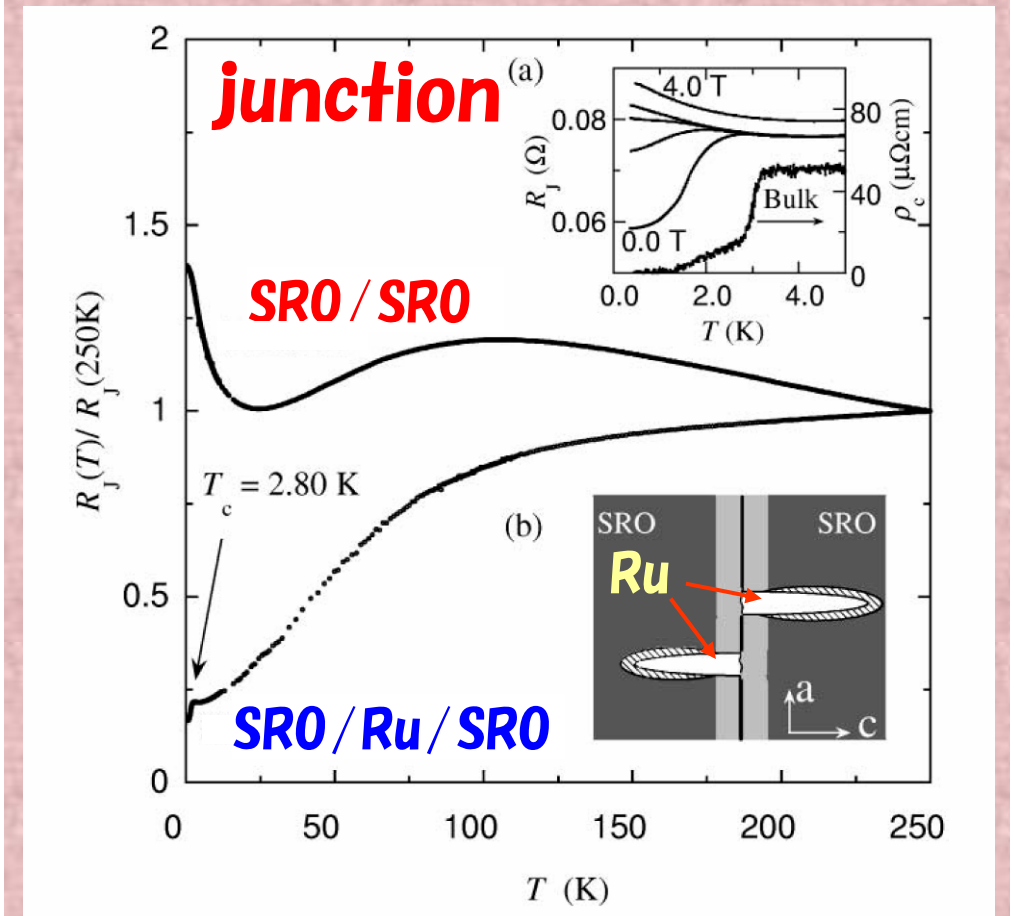


Anderson localization in 3D

$$\Delta\sigma \approx \sqrt{|E - E_F|}$$

Altshuler and Aronov, Solid State Commun. **30**, 115 (1979).

Non-superconducting surface of Sr_2RuO_4



Mao *et al.*, PRL **87**, 37003 (2001).

Junction resistance between SRO / SRO increases at $T < 25$ K

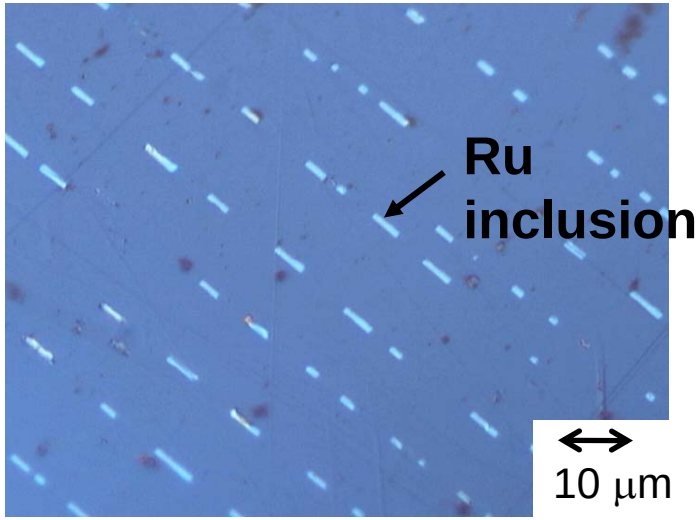
→ Non-superconducting surface layer

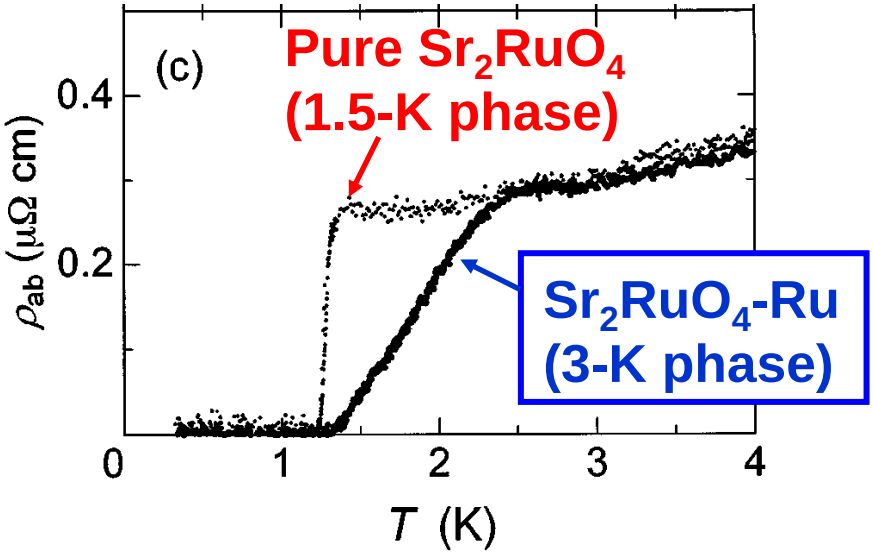
Surface-sensitive measurement is not straightforward to study the superconductivity of Sr_2RuO_4.

2.
Unconventional local transport characteristics in microfabricated Sr_2RuO_4–Ru eutectic crystals

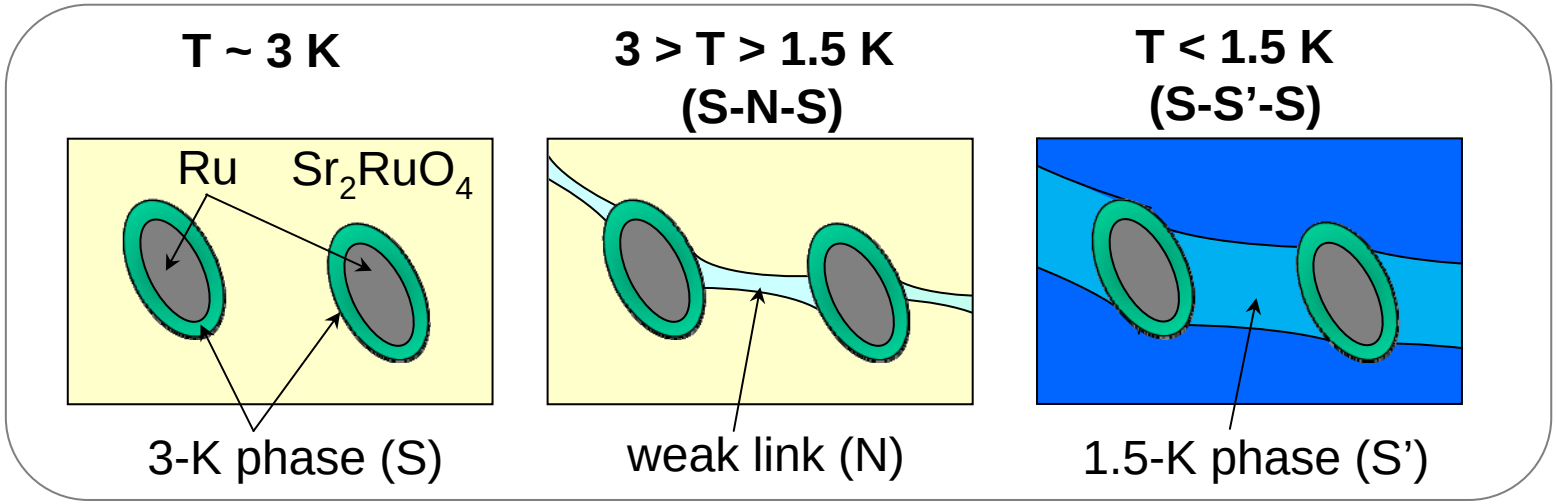
Sr_2RuO_4–Ru eutectic system ~3-K phase superconductivity~

Sr_2RuO_4 – Ru eutectics



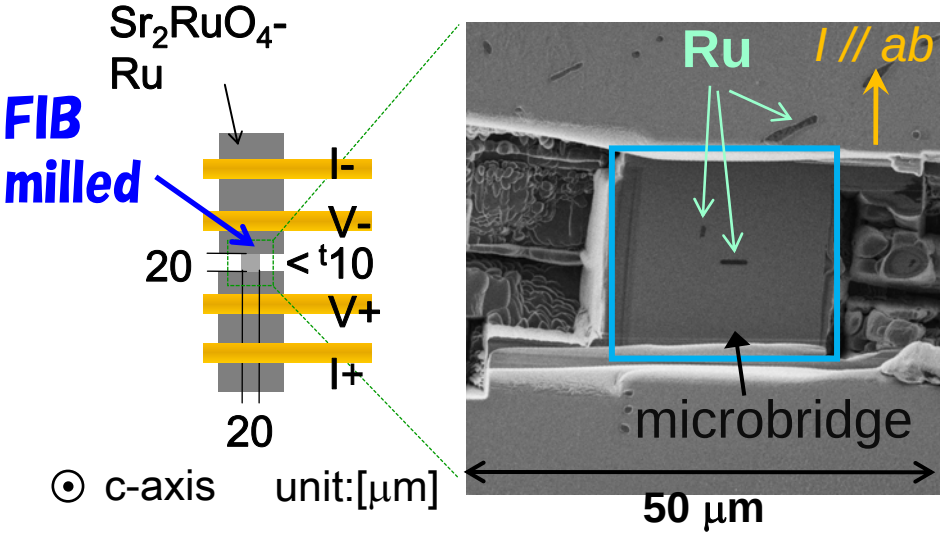


Maeno *et al.*, PRL **81**, 3765 (1998).

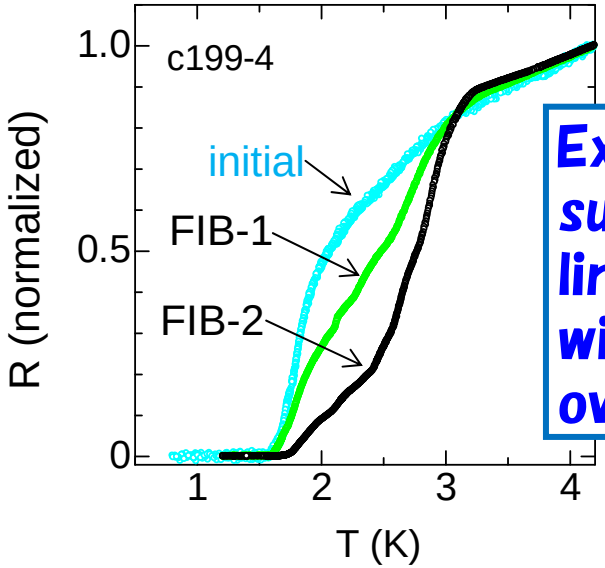


p-wave superconducting junctions are naturally formed.

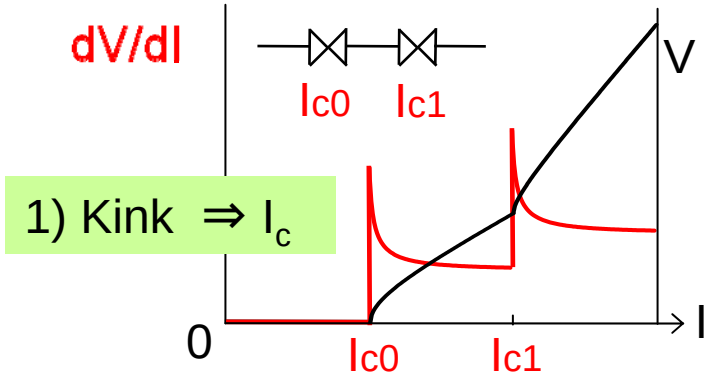
Transport characteristics in microfabricated Sr_2RuO_4–Ru junction



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

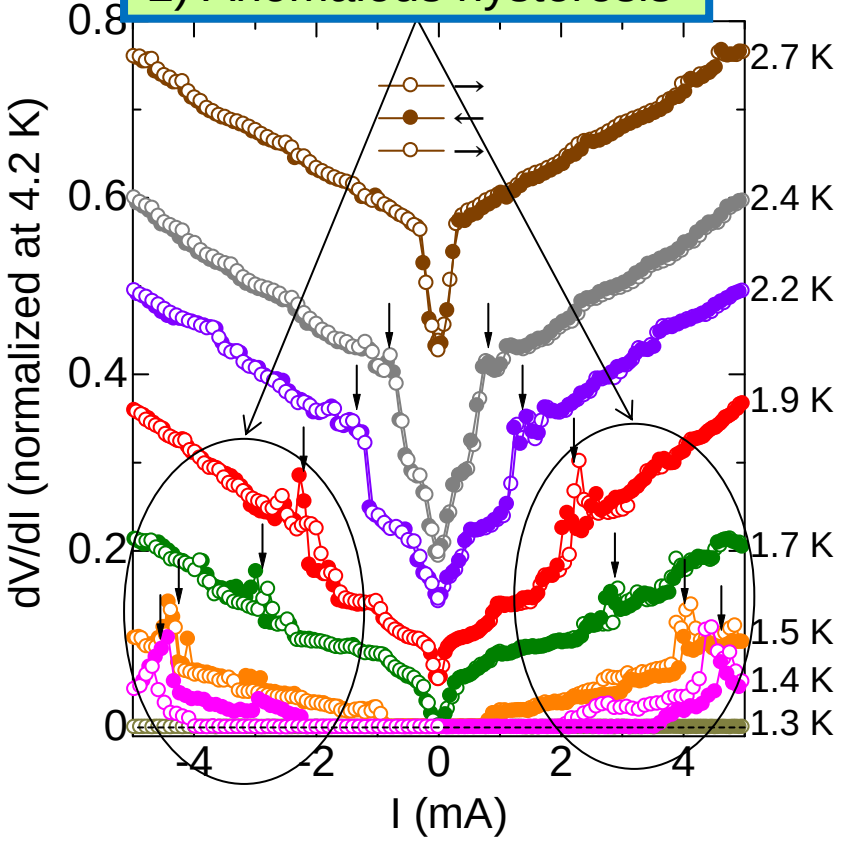


Extraction of superconducting linkage channels without averaging over bulk sample



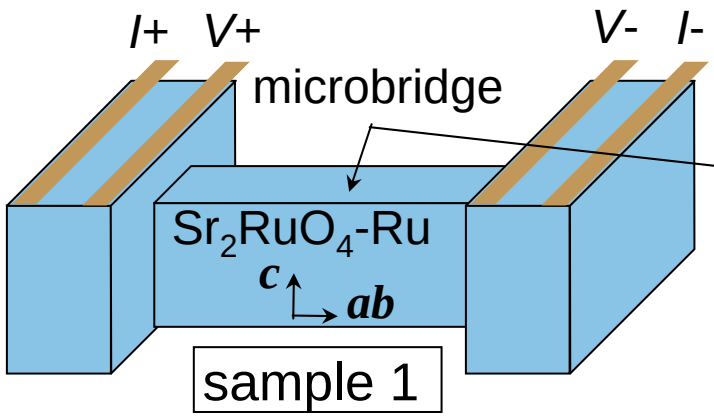
1) Kink ⇒ I_c

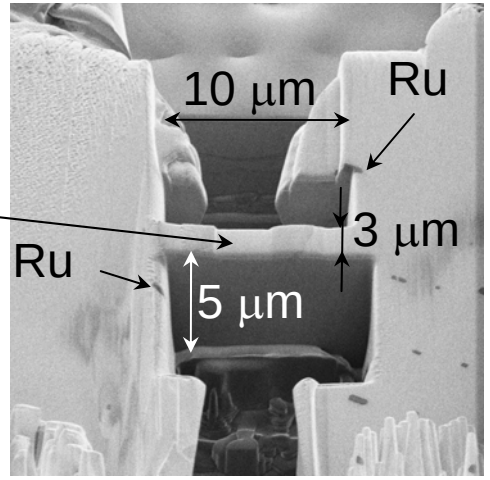
2) Anomalous hysteresis



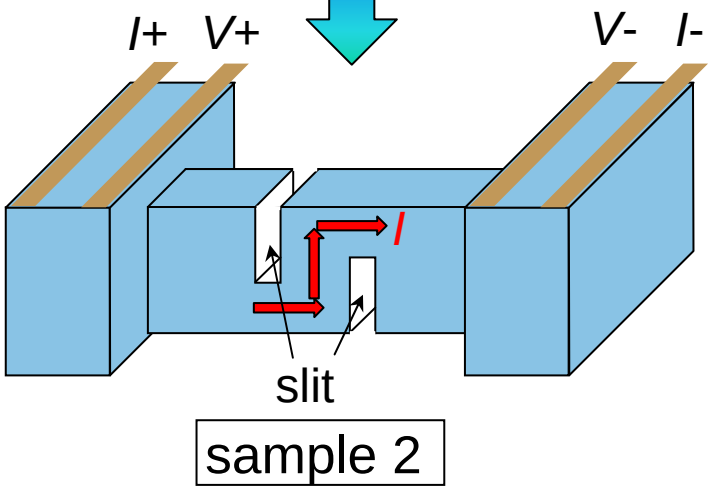
Sample configurations (I // ab and I // c)

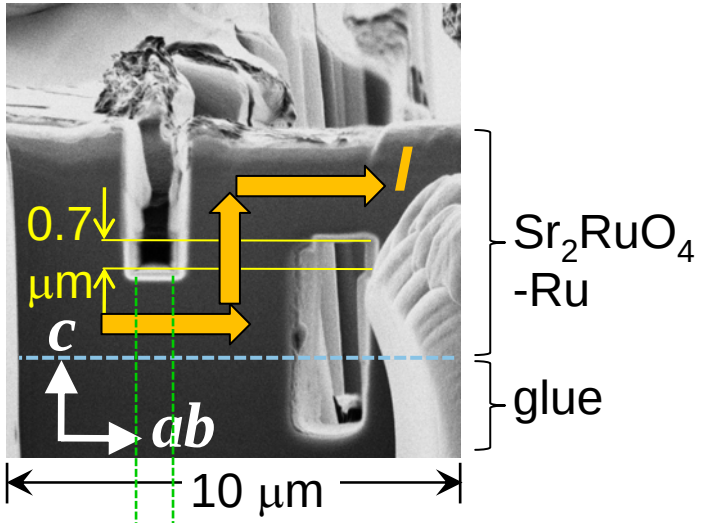
I // ab



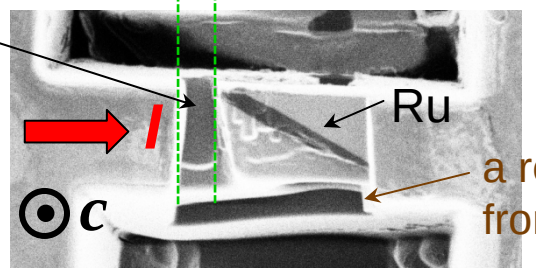


I // c

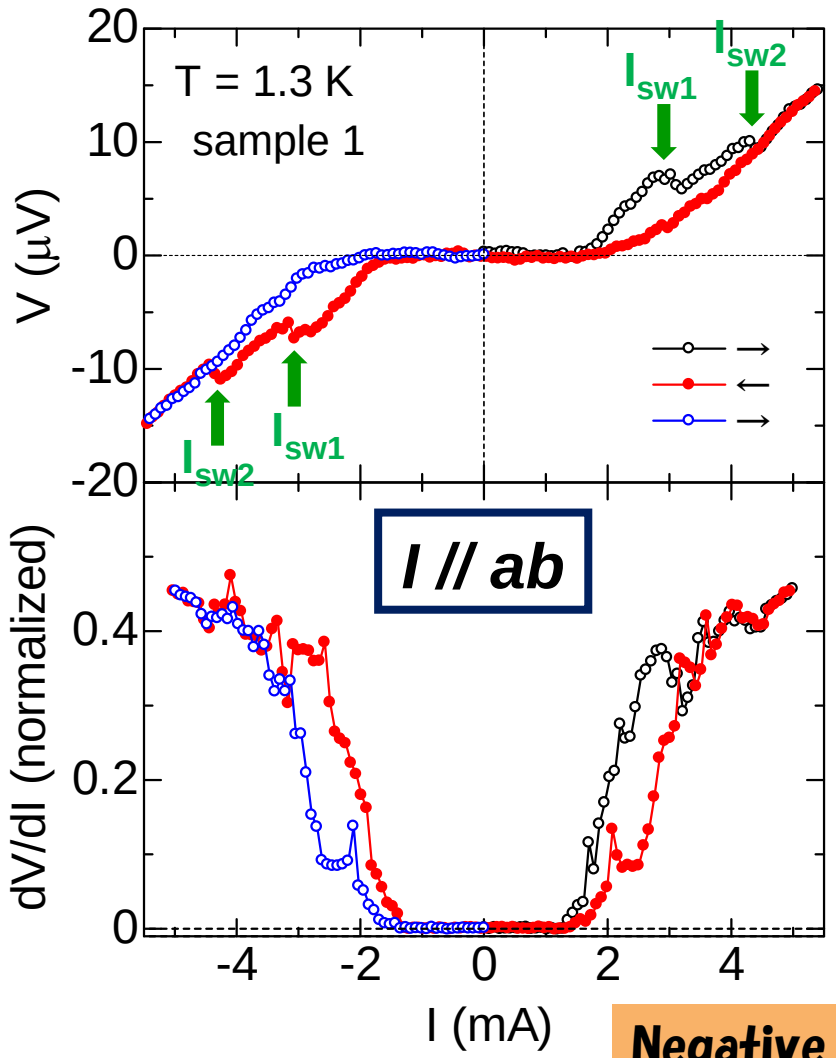


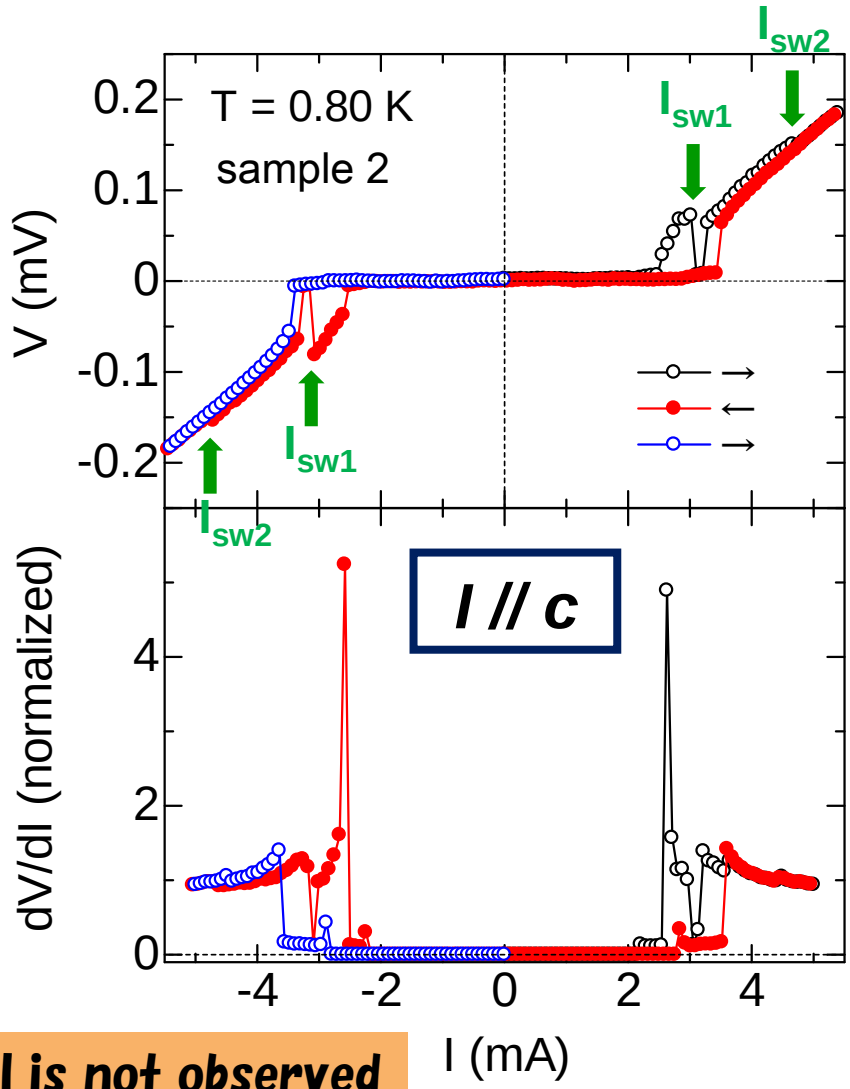


SIM image obtained after the top and side surfaces were slightly milled. FIB milling was done after transport measurements.



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



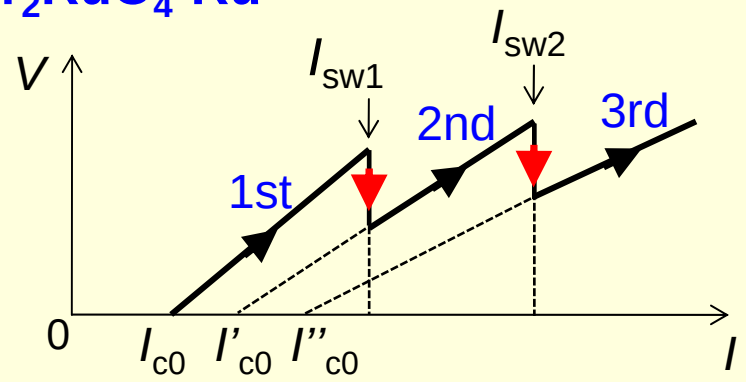


Negative dV/dI is not observed
→ switching phenomena

Anomalous hystereses are observed for both I//ab and I//c directions.

How are V-I characteristics anomalous?

Sr_2RuO_4-Ru



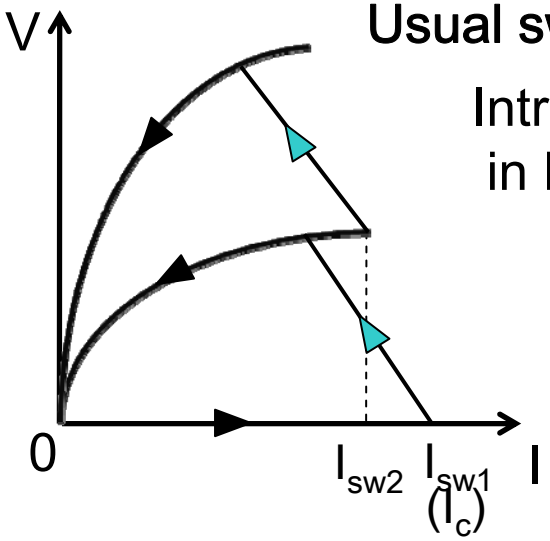
Anomalous features

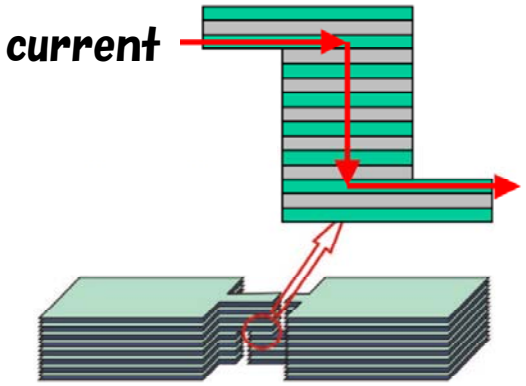
(1) Voltage *decreases* at I_{sw}.

(2) It switches to a *lower* R_n (normal resistance) branch with larger I_c.

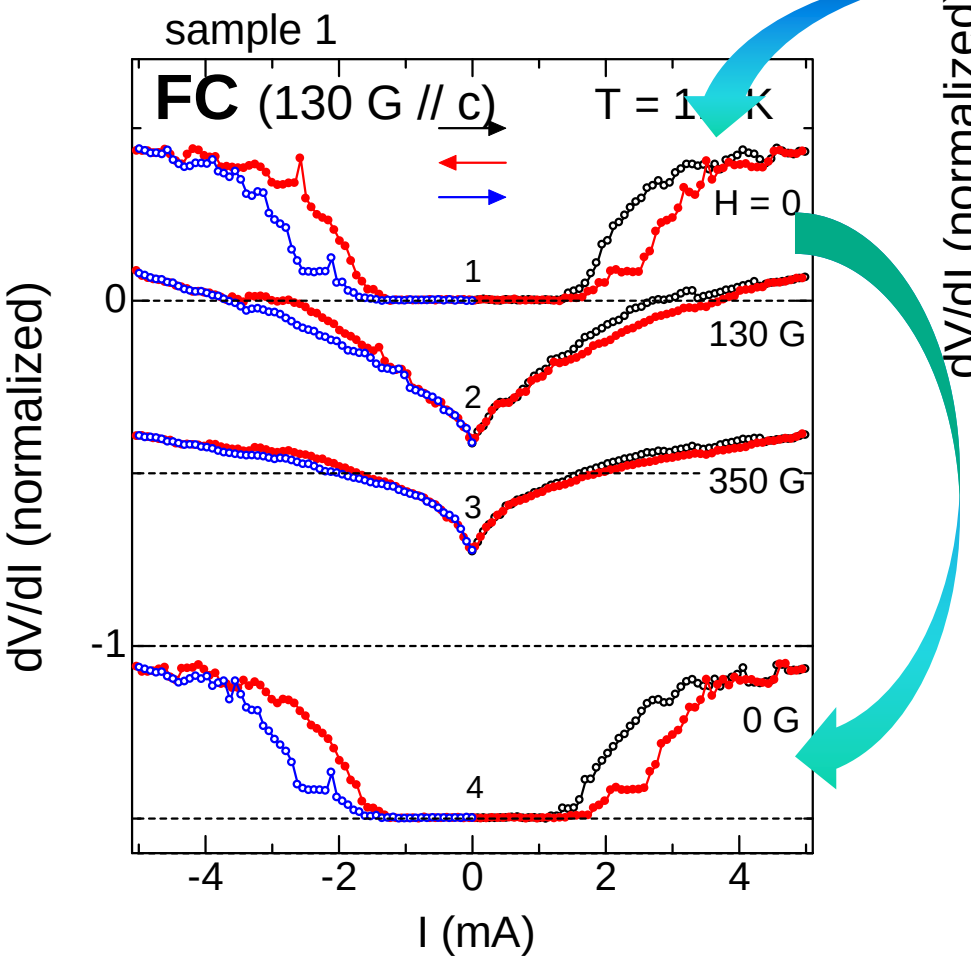
(3) *Opposite* hysteresis loop compared to typical Josephson junction (JJ) s.

NOT usual JJs!

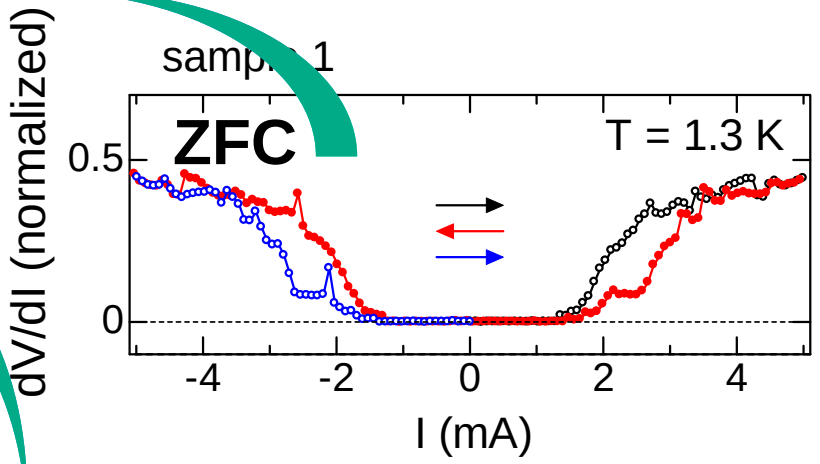




Magnetic field effect



The curves are offset by -0.5 unit for clarity.



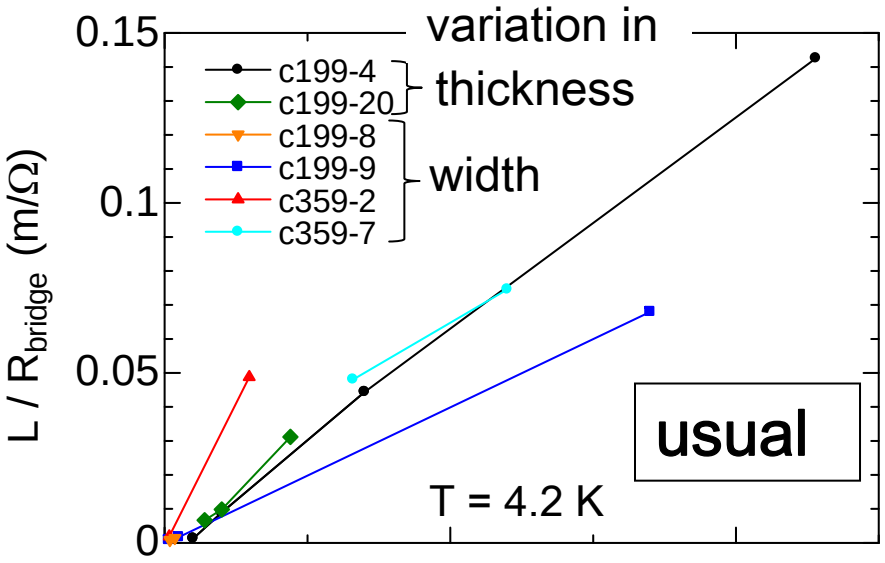
No change !

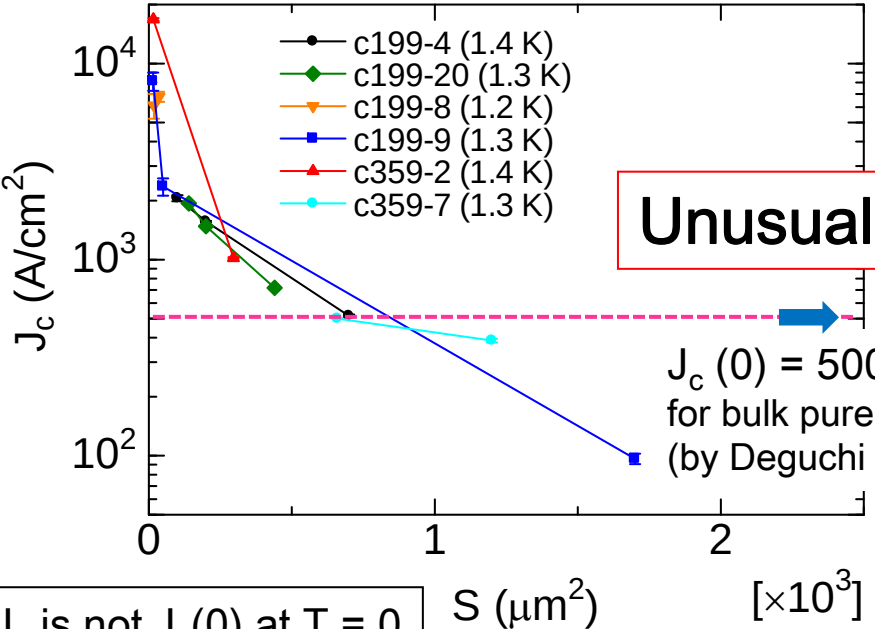
No change !

Anomalous hysteresis is NOT due to a magnetic vortex!

cf) $H_{c1}(0) \cong 70$ G (1.5-K phase)
Deguchi, Mao, Maeno, JPSJ(2004).

Anomalous J_c enhancement





Unusual !

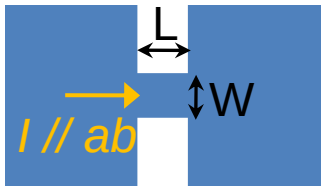
J_c increases for small S.

J_c (0) = 500 A/cm^2
for bulk pure Sr_2RuO_4
(by Deguchi and Maeno)

※ J_c is not $J_c(0)$ at T = 0.

In usual case,

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



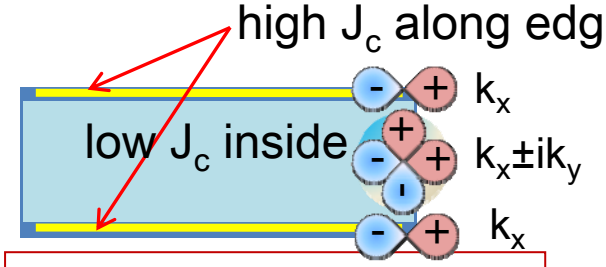
S = Wt

t:
thickness

Critical current density: J_c

$$J_c = I_c / S = const.$$

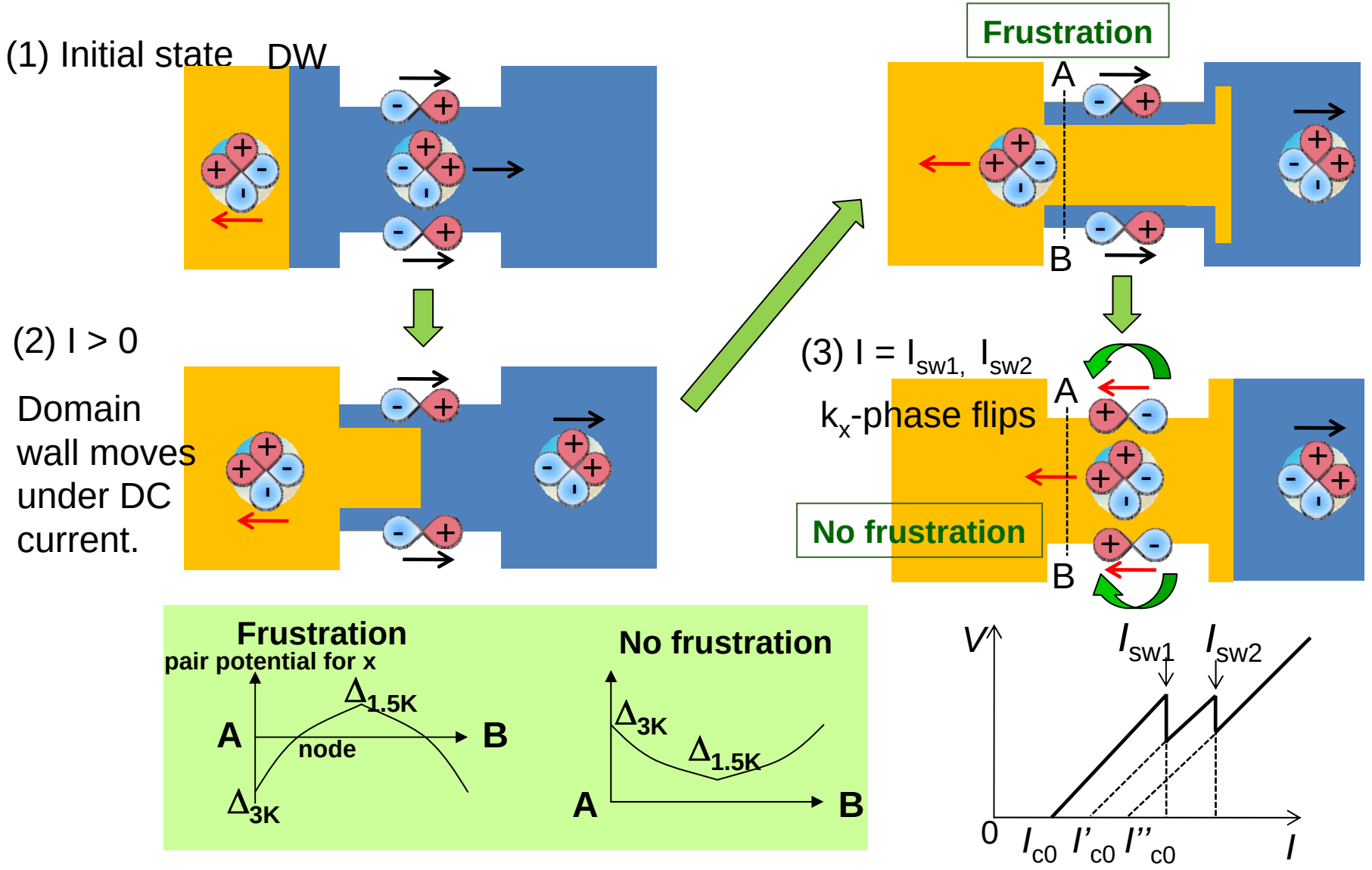
➡ S-independent



Edge channels seem
to be formed.

Possible origin of the anomalous hysteresis

Chiral domain wall motion through the 3-K phase (k_x) and 1.5-K phase ($k_x \pm ik_y$) coexistence region



Summary

STM/STS at Sr_2RuO_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_2RuO_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.