STM/STS Experiments of Sr_2RuO_4 and Related Compounds

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Sr_2RuO_4 single crystals are supplied by

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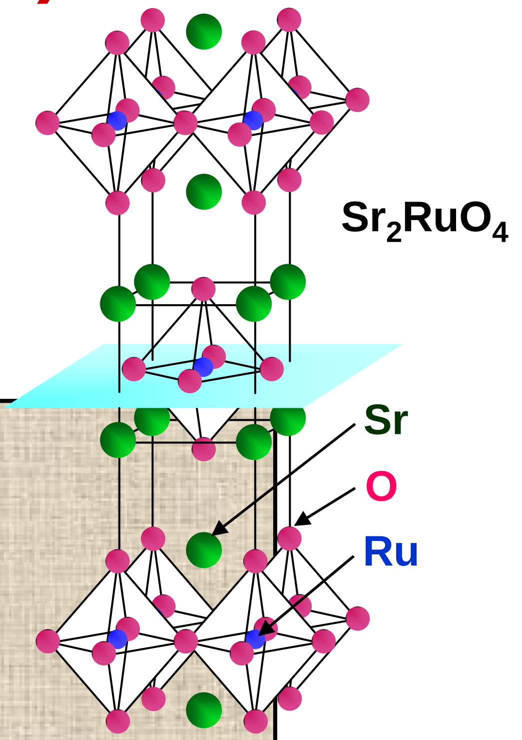
STM/STS for Sr_2RuO_4 and eutectics

Ultra Low Temperature Scanning tunneling Microscopy/Spectroscopy (STM/STS)

- high special resolution (~ 0.1 nm)
- high energy resolution (~ 10 μeV)

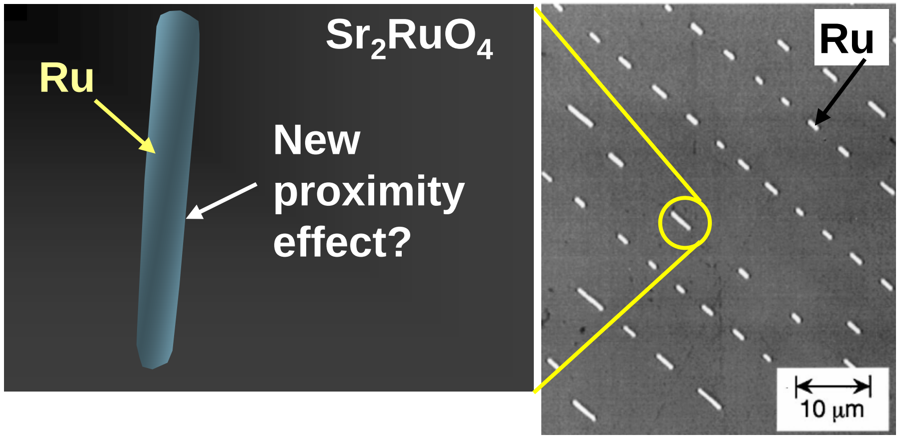
➡ **Observation of Local electronic density of states (LDOS)**



LDOS variations in p-wave spin triplet superconductor and related compounds

Sr_2RuO_4 (T_C = 1.5 K)
Sr_2RuO_4 - Ru (T_C = 3 K)
Sr_2RuO_4 – $Sr_3Ru_2O_7$ (SC - metamagnet)

Sr_2RuO_4 – Ru (3-K phase)

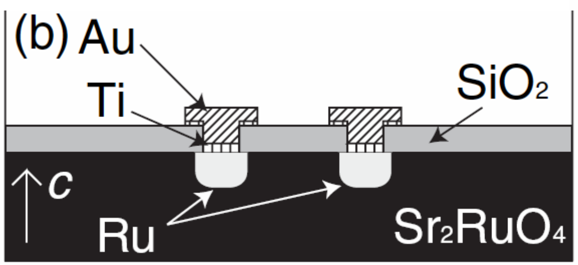


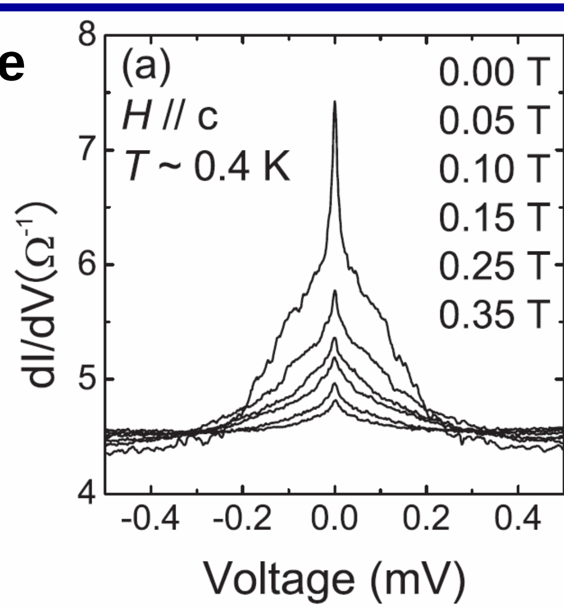
Maeno *et al*., PRL 81, 3765 (1998).

Surface spin-triplet superconductivity

What is the enhancement mechanism in T_c?

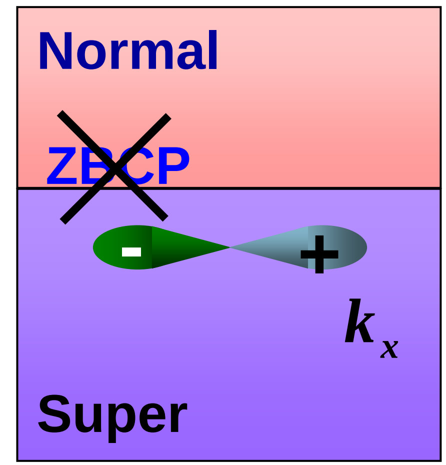
Tunneling at the interface between Sr_2RuO_4 - Ru

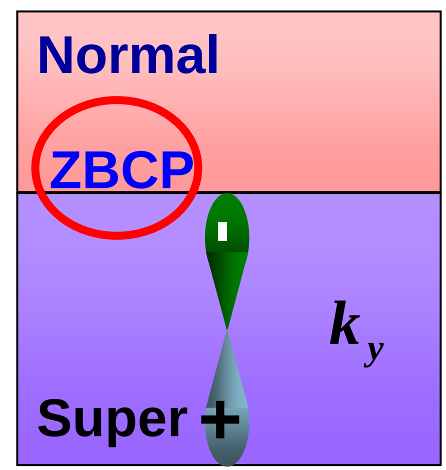




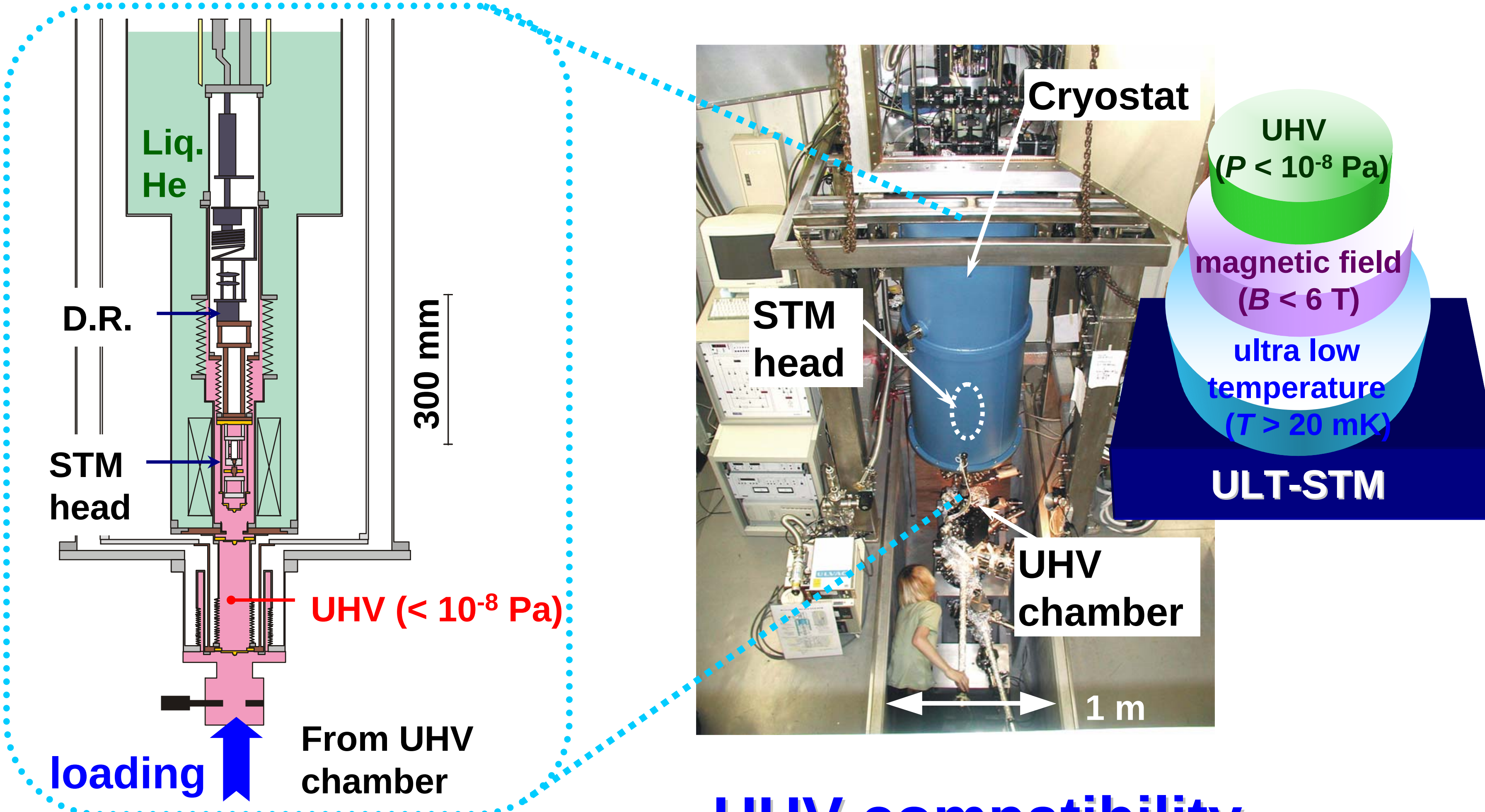
Kawamura *et al*.,
JPSJ 74, 531 (2005).

Zero bias conductance peak (ZBCP)
→ *non-s*-wave SC





ULT-STM system



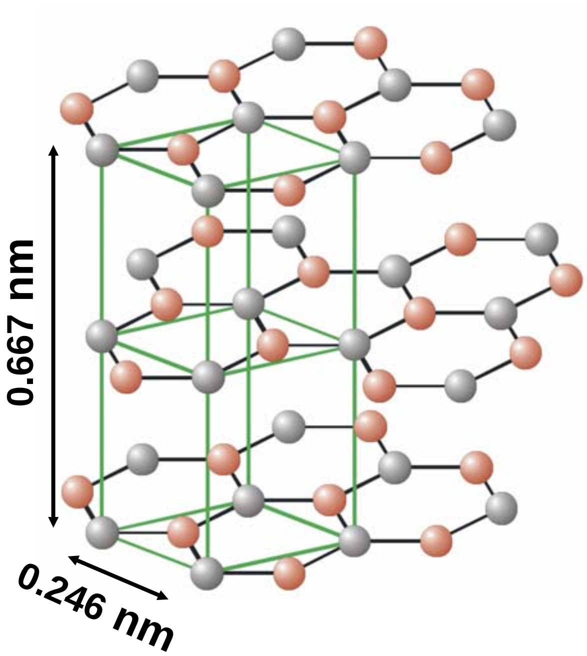
UHV compatibility

One can prepare and analyze clean sample surfaces which are not restricted to cleavable materials.

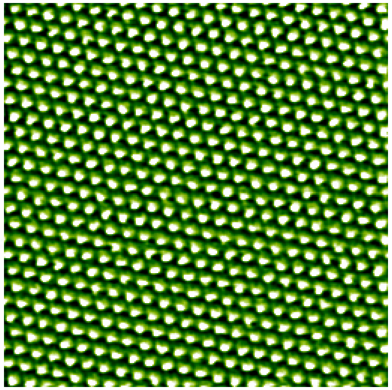
Quick turnaround

keeping LT and UHV by bottom loading mechanism

Performance of ULT-STM (Graphite)

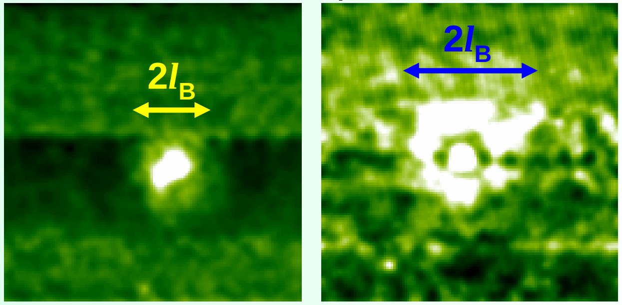


5 X 5 nm² (B = 6 T)



A-site
B-site

80 nm × 80 nm, T = 30 mK



6 T 36 meV 2 T 28 meV

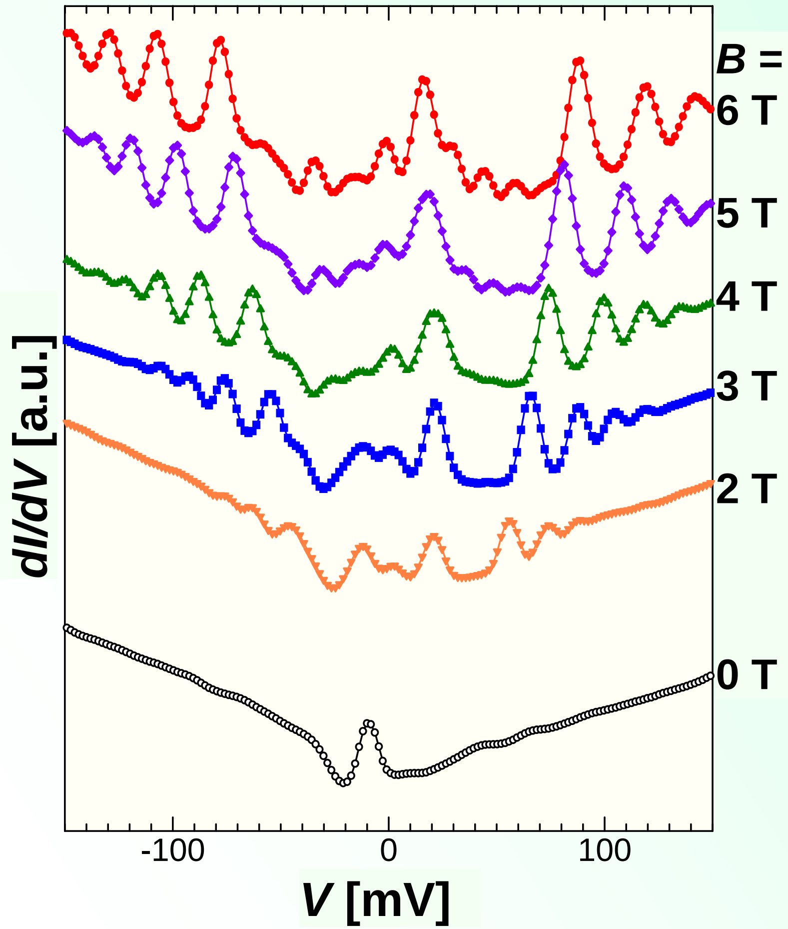
magnetic length

$$l_B = \sqrt{\frac{\hbar}{eB}}$$

***dI/dV* images around a point defect**

at valley energies between Landau levels

Landau quantization
($\omega_c = eB/m^*$, B // c)

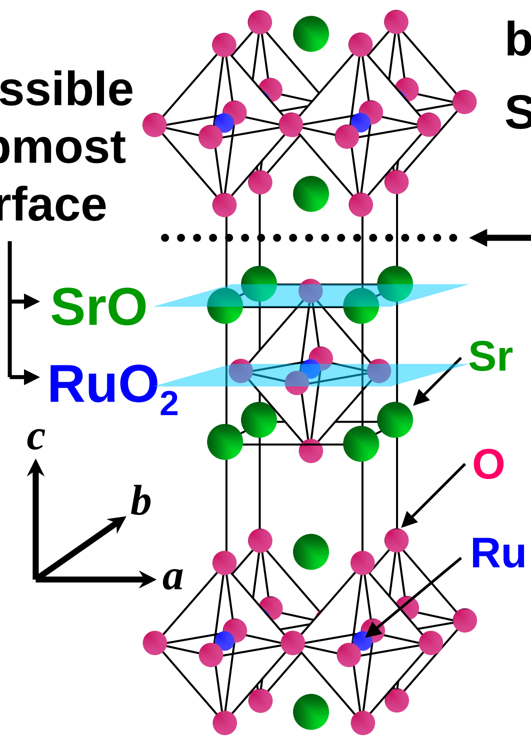


V = 182 mV, I = 0.2 nA, V_{mod} = 1 mV

Niimi *et al*., cond-mat/0511733.

STM on Sr_2RuO_4 surface (1.5-K phase)

Possible topmost surface



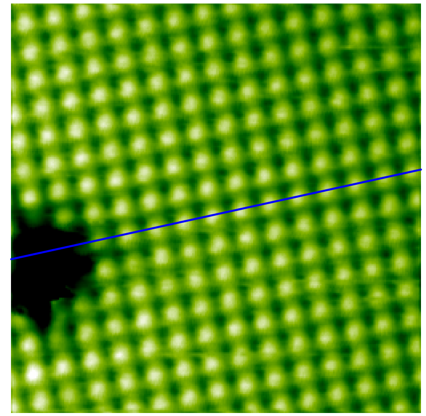
bonding

Sr-O < Ru-O

most likely cleavage

Crystal structure of Sr_2RuO_4

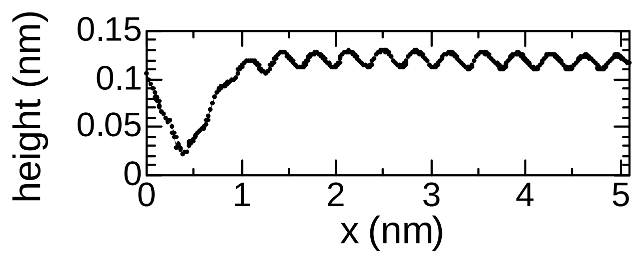
STM image



5 nm × 5 nm

V = –0.10 V, I =0.2 nA

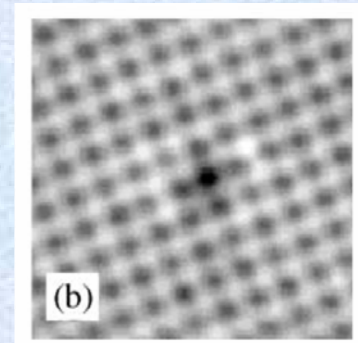
T = 47 mK



Density of point defects varies in every cleavage even in the same batch.

$Sr_2Ti_xRu_{1-x}O_4$

(x = 0.125%)



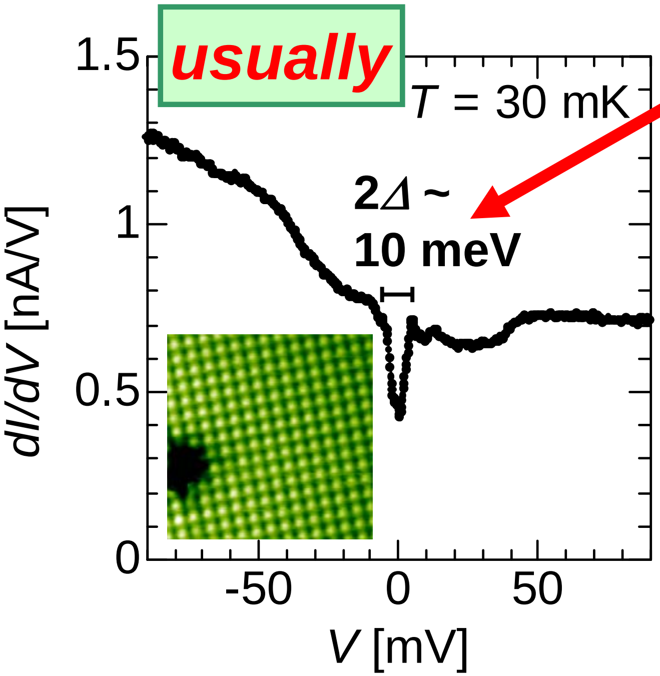
3.5 nm × 3.5 nm

V = –0.10 V, I =0.1 nA

Bright spot shows Sr-atom from Ti-substitution.

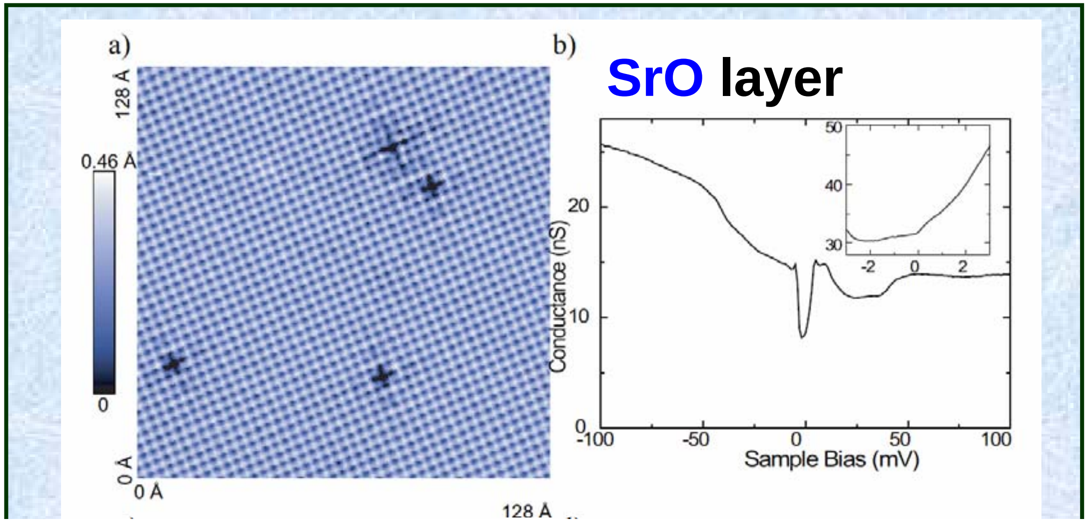
Barker *et al.*, Physica B **329–333**, 1334 (2003).

Tunnel spectra on Sr_2RuO_4 surface



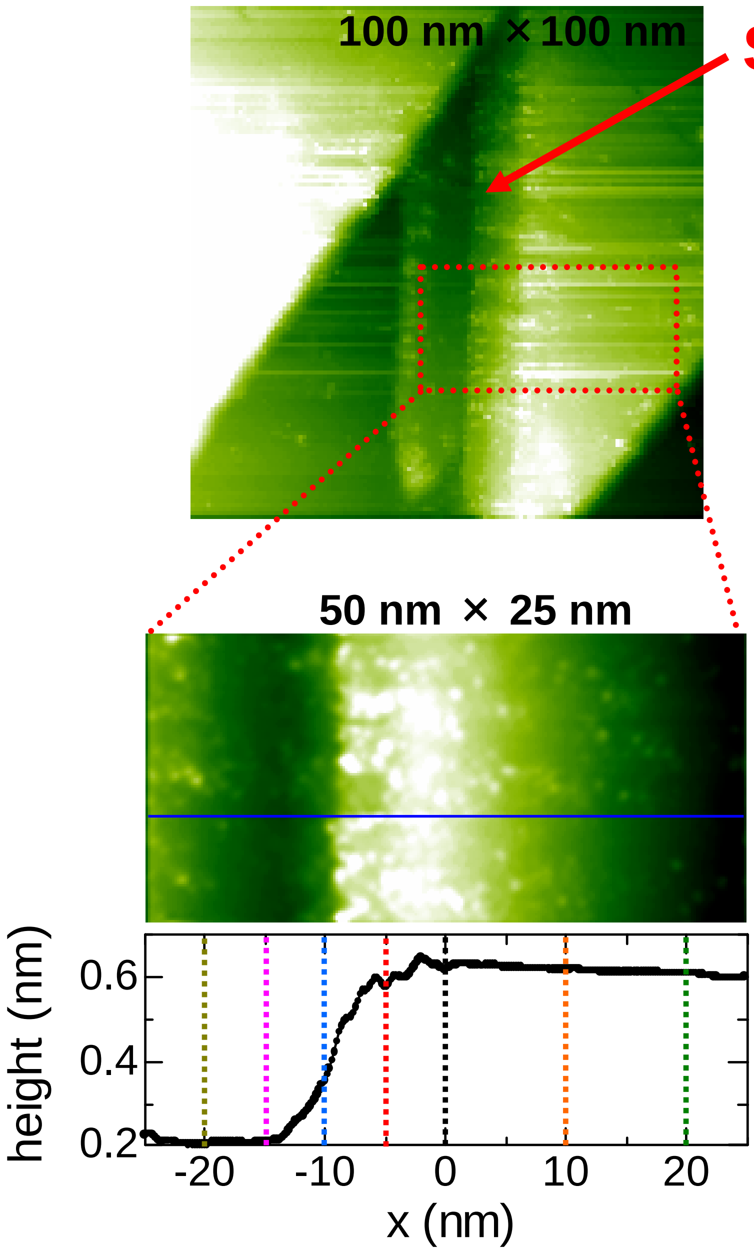
Normal gap : Δ ~ 5 meV (~ 50 K)

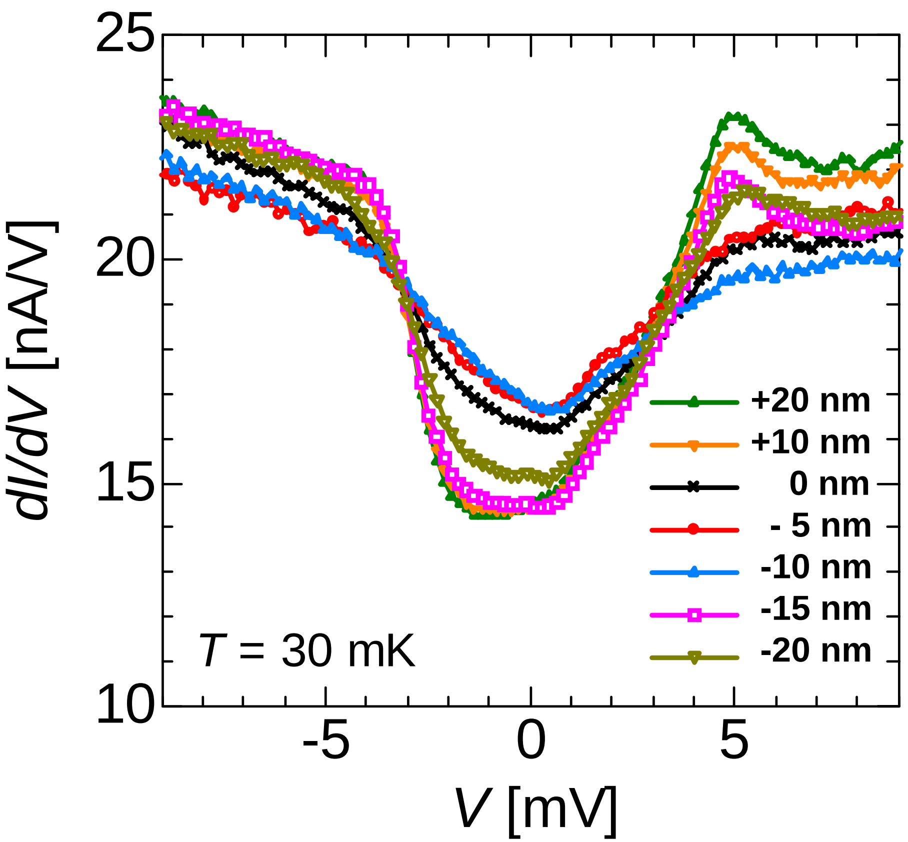
Not related with superconductivity



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

Spatial variations of the Normal gap





Only on the step edge, the normal gap is varied.

Classification of defects (1.5-K, 3-K phase)

STM image contrast

All STM images at V = –0.1 V, I = 0.2 nA.

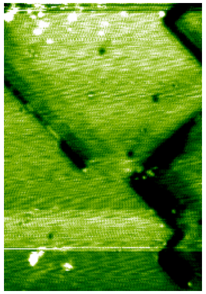
① STM image at V = –0.1 V

② STM image at V = –1.0 V

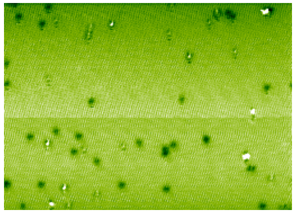
- Dark (①) → Dark (②) → **Type 1** / Point and line
- Dark (①) → Dark (②) → **Type 2** / Rectangular
- Dark (①) → Bright (②) → **Type 3** / Line
- Bright (①) → **Type 4** / Line (circuit)

Both 1.5-K and 3-K phase

Type 1
Point and line

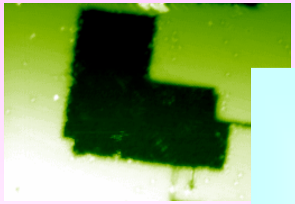


50 × 35 nm^2

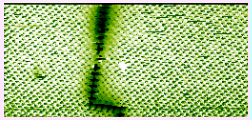


3-K phase only !

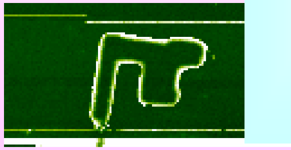
Type 2
Rectangular

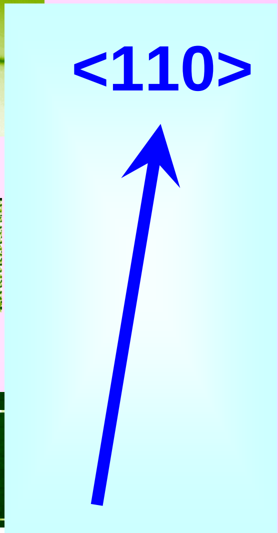


Type 3
Line

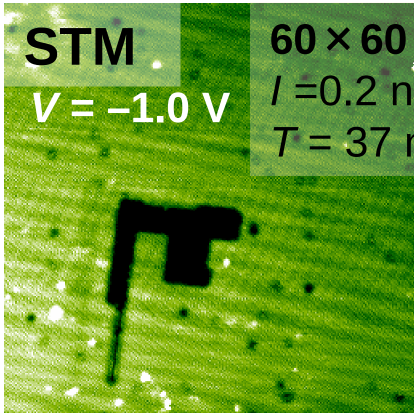


Type 4
Line (circuit)



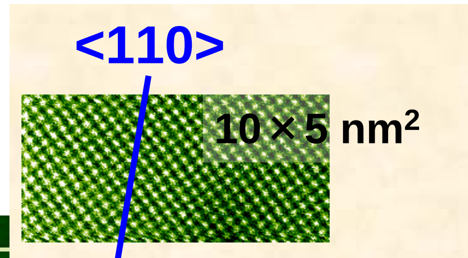


LDOS around circular defects (3-K phase, Type4)

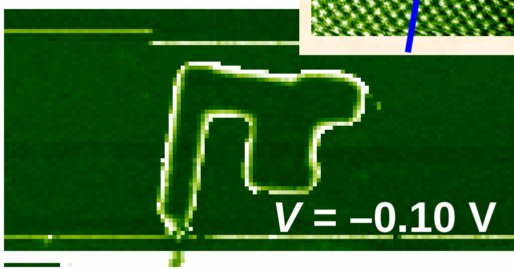


Line defects // <110>

LDOS varies in the width of ~ 1 nm



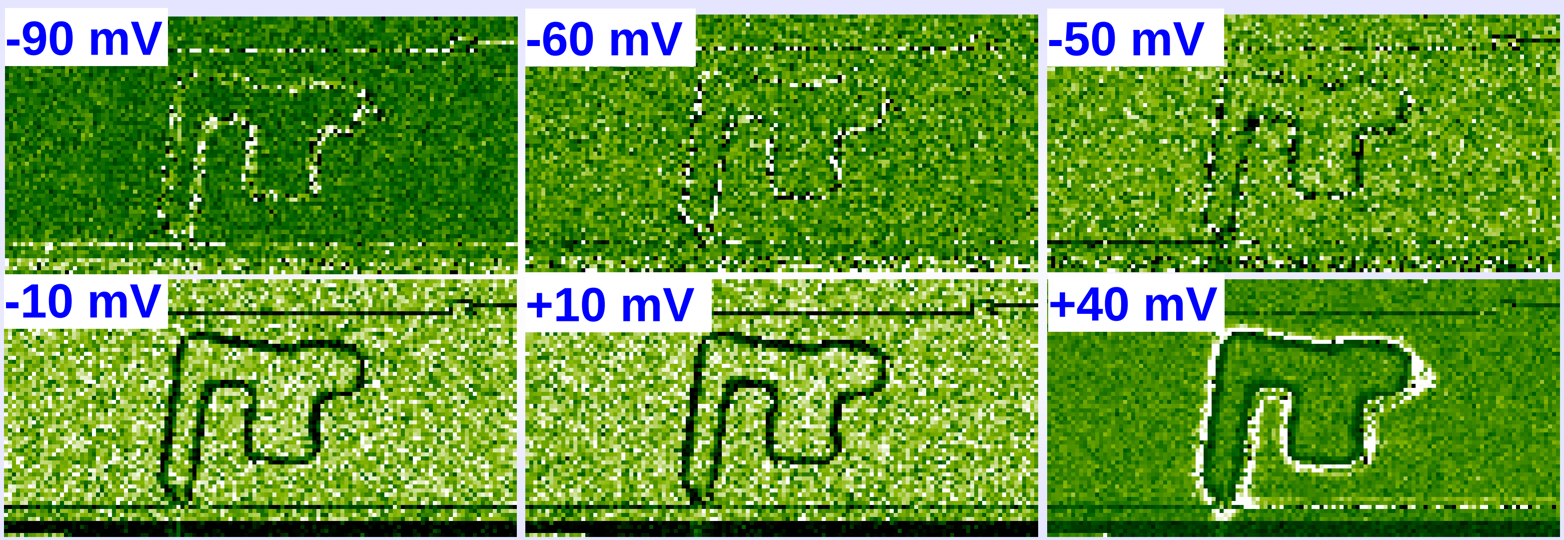
STM



50 × 25 nm²

I =0.2 nA

dI/dV



Summary

1. **“Normal” gap (Δ ~ 5 meV) is observed on the SrO plane in agreement with the data of Davis’ group. But the origin of the gap is still unknown.**

2. **The normal gap is spatially uniform except near the step structure.**

3. **It is not easy to observe the superconducting gap.**

4. **Several point and line defects are observed for both 1.5-K and 3-K phase samples. These defects are classified into four categories by bias-dependent STM images.**

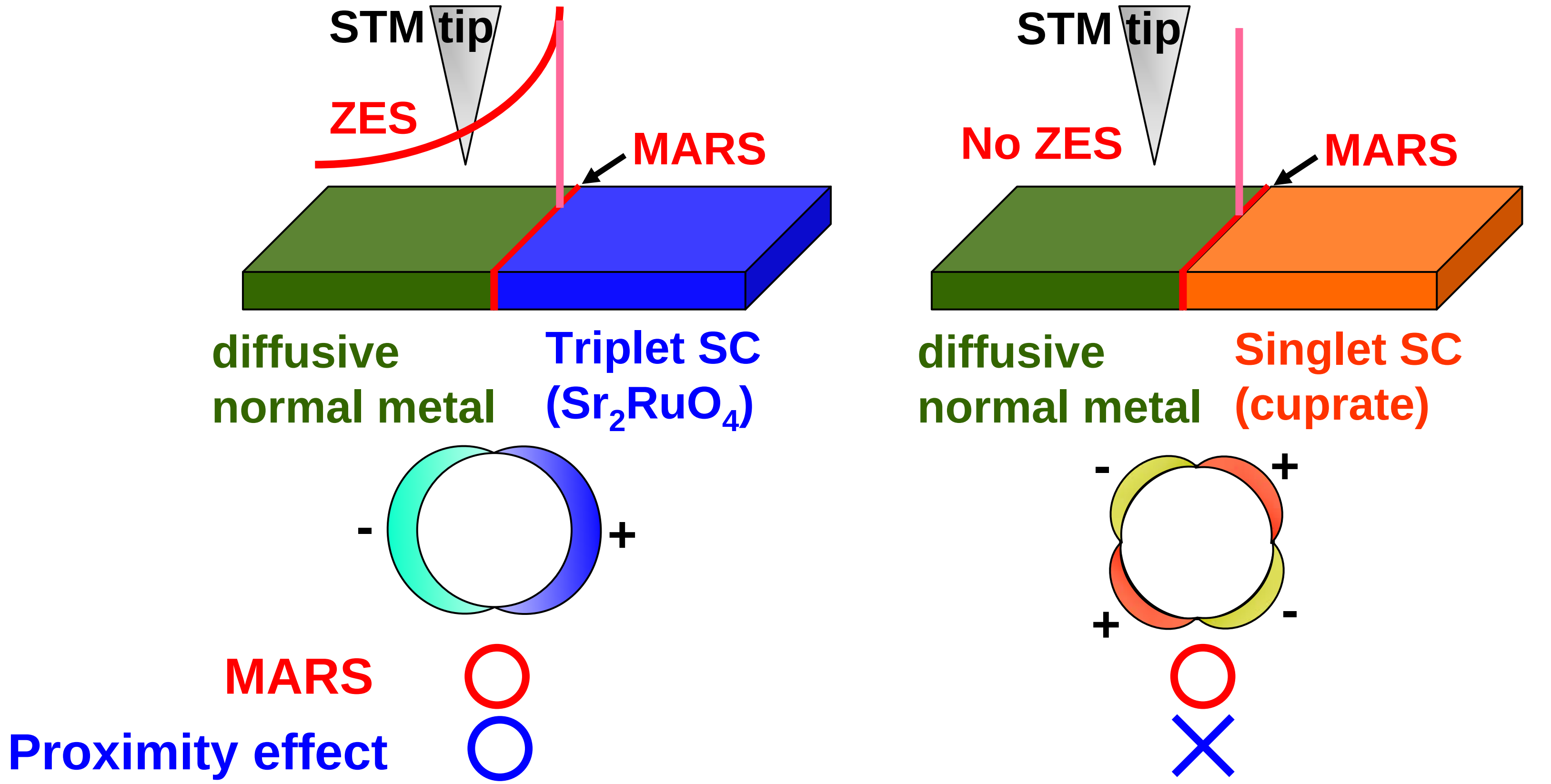
5. **The line defects always go along the <110> directions. LDOS varies only in the width of 1 nm.**

6. **Type 2~4 defects exist in only 3-K phase. These defects may be seeds of the Ru-lamellae?**

Future work

Search for new superconducting phenomena
in *spin triplet superconductor – normal metal junctions by STS*

As one of the subjects, detection of enhanced proximity effect by midgap Andreev resonant state (MARS) predicted theoretically



Tanaka, Kashiwaya and Yokoyama, PRB 71, 094513 (2005).
Tanaka and Asano, Solid State Physics 40, 683 (2005).