Aspects of
Intrinsic Josephson Tunneling

D. Winkler,[1,2] A. Yurgens,[1] V.M. Krasnov,[1] Y.S. Sudershan,[1] T. Claeson,[1] E. J. Tarte,[3] M.G. Blamire[3]

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1) **Chalmers University of Technology and Göteborg University**
Department of Microelectronics and Nanoscience,
SE-412 96 Göteborg, Sweden

2) **Imego Institute**
Aschebergsg 46, Building 11, SE-411 33 Göteborg, Sweden

3) **IRC in Superconductivity, University of Cambridge**
Madingley Rd, Cambridge, CB3 0HE, UK

Contents

- Background and the system
- Ways of making small junctions
- The experimental ”toolbox”
- Recent work and some understanding
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- Interlayer coupling and pressure
- Bi2212 films
- Conclusions

KLEINER AND MÜLLER

VOLUME 68, NUMBER 15 PHYSICAL REVIEW LETTERS 13 APRIL 1992

Intrinsic Josephson Effects in $Bi_2Sr_2CaCu_2O_8$ Single Crystals

R. Kleiner, F. Steinmeyer, G. Kunkel, and P. Müller
Walther-Meissner-Institut, Walther-Meissner-Strasse 8, W-8046 Garching, Germany
(Received 21 August 1991; revised manuscript received 11 February 1992)

PHYSICAL REVIEW B VOLUME 49, NUMBER 2 1 JANUARY 1994-II

Intrinsic Josephson effects in high-T_c superconductors

R. Kleiner and P. Müller

FIG. 1. Superposition of the BSCCO crystal structure and a stack of Josephson junctions, whose electrodes are formed by CuO_2 double layers.

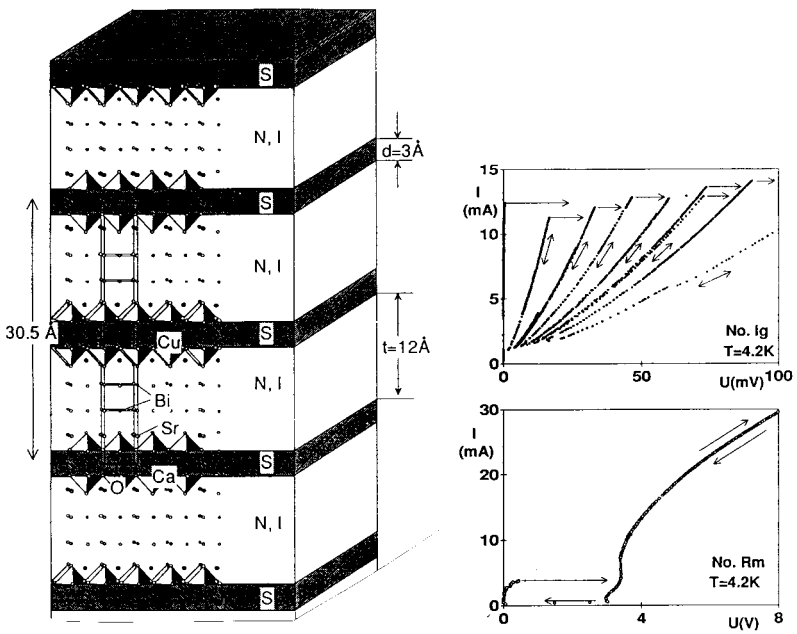

FIG. 5. *I-V* characteristics of Ar-annealed BSCCO crystals at different voltage scales. The multiple branches shown in the upper figure have not been traced out in the lower figure. The annealing conditions of the samples are 12 h, 600 °C (No. Ig) and 10 h, 550 °C (No. Rm). Contact resistances have been subtracted. Details of the *I-V* characteristics are described in the text.

VOLUME 68, NUMBER 15 PHYSICAL REVIEW LETTERS 13 APRIL 1992

2394 – 2397

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We have observed Josephson coupling between CuO double layers in $Bi_2Sr_2CaCu_2O_8$ single crystals by direct measurements of ac and dc Josephson effects with current flow along the *c* axis. The results show that a small $Bi_2Sr_2CaCu_2O_8$ single crystal behaves like a series array of Josephson junctions which can exhibit mutual phase locking.

PACS numbers: 74.50.+r, 74.60.Jg, 74.70.Jm

PHYSICAL REVIEW B VOLUME 49, NUMBER 2 1 JANUARY 1994-II

1327 – 1341

Intrinsic Josephson effects in high-T_c superconductors

R. Kleiner and P. Müller
Walther-Meissner-Institut, D-85748 Garching, Germany
(Received 19 July 1993)

We have investigated the coupling between CuO_2 layers in high-T_c superconductors by direct measurements of all dc and ac Josephson effects with current flow in the *c*-axis direction. The measurements have been performed on small single crystals of $Bi_2Sr_2CaCu_2O_8$, $(Pb_yBi_{1-y})_2Sr_2CaCu_2O_8$, $Tl_2Ba_2Ca_2Cu_3O_{10}$, and $YBa_2Cu_3O_{7-\delta}$ and on *a*-axis-oriented $YBa_2Cu_3O_7$ thin films. The results clearly show that all materials behave like stacks of superconductor-insulator-superconductor Josephson junctions. The current-voltage characteristics exhibit large hystereses and multiple branches, which can be explained by a series connection of highly capacitive junctions. From the modulation of the critical current in a magnetic field parallel to the layers, we infer a junction thickness of approximately 15 Å. In our microwave emission experiments we were able to prove explicitly that every pair of CuO_2 double or triple layers forms a working Josephson contact. An exception is $YBa_2Cu_3O_7$, where only flux-flow behavior has been observed.

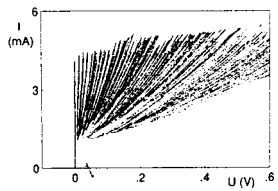


FIG. 1. *I-V* characteristic of sample *Fa* at $T = 4.2$ K. The contact resistance of 18 Ω is subtracted.

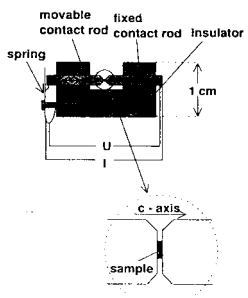


FIG. 4. Schematic view of the sample holder.

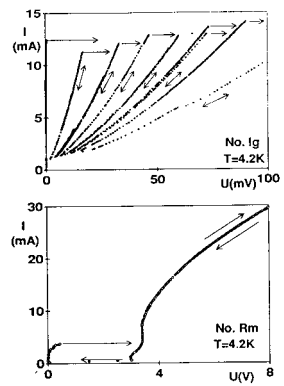
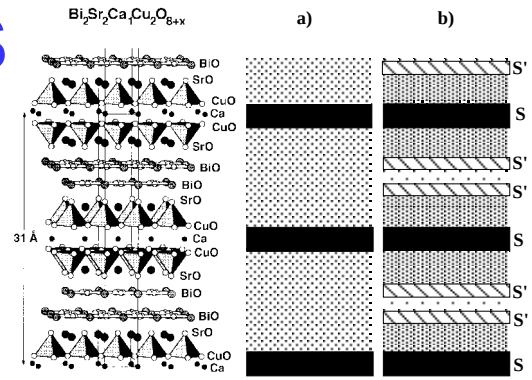
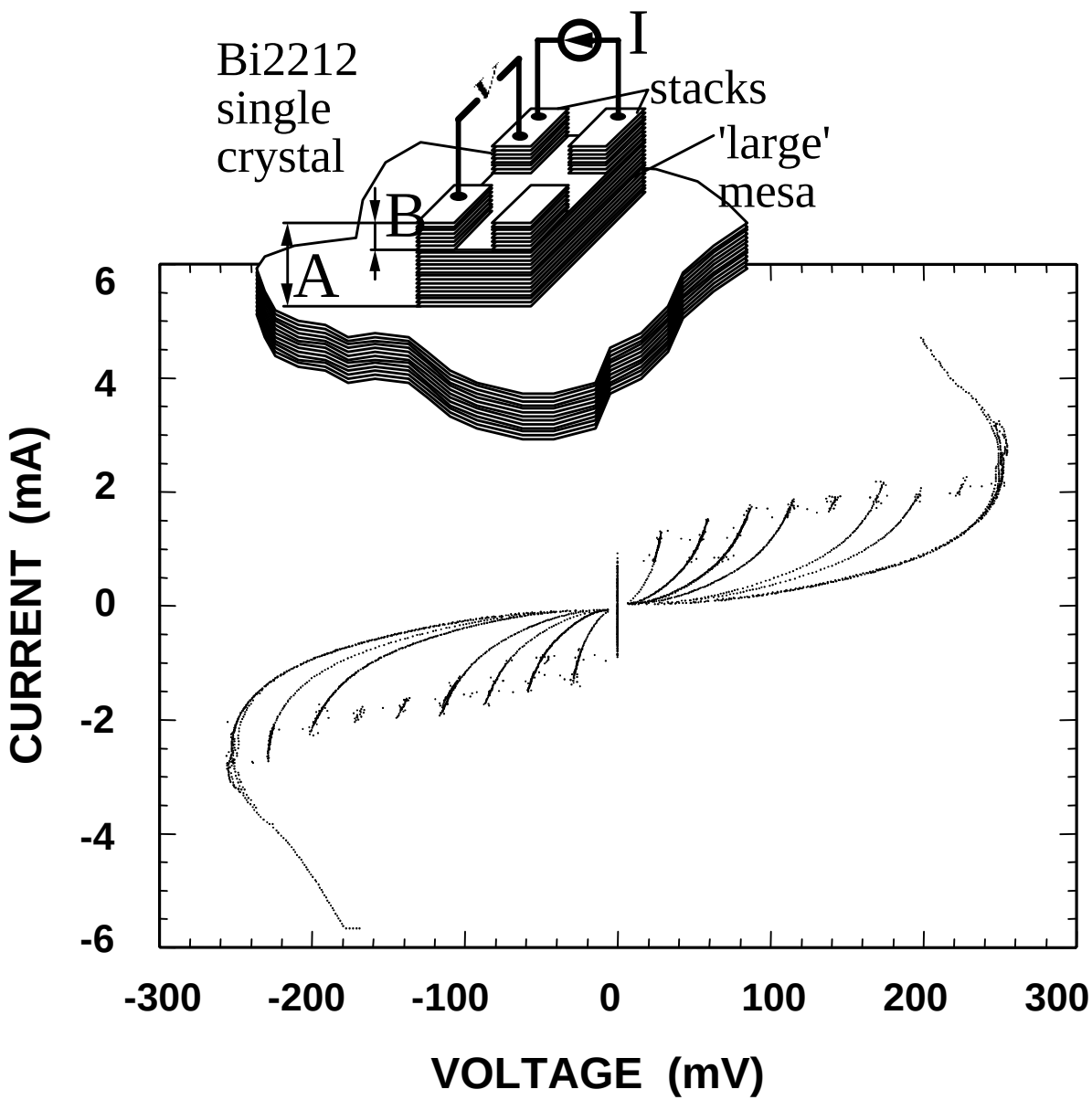
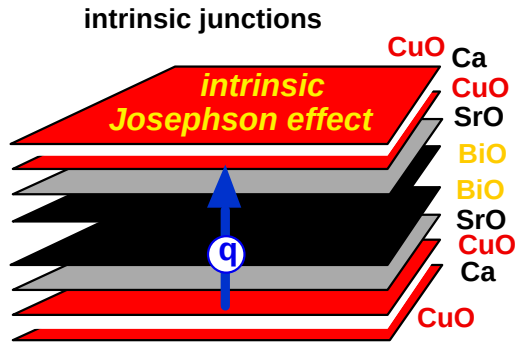


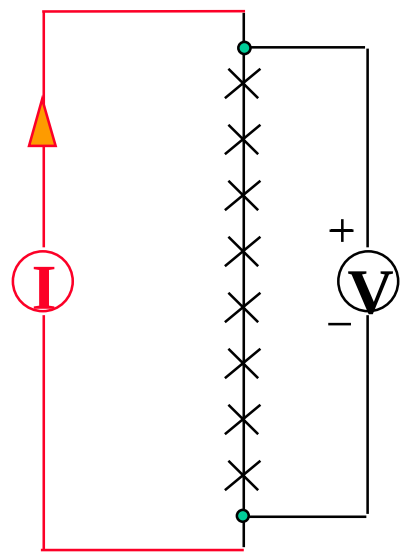
FIG. 5. *I-V* characteristics of Ar-annealed BSCCO crystals at different voltage scales. The multiple branches shown in the upper figure have not been traced out in the lower figure. The annealing conditions of the samples are 12 h, 600 °C (No. Ig) and 10 h, 550 °C (No. Rm). Contact resistances have been subtracted. Details of the *I-V* characteristics are described in the text.

INTRINSIC JOSEPHSON JUNCTIONS



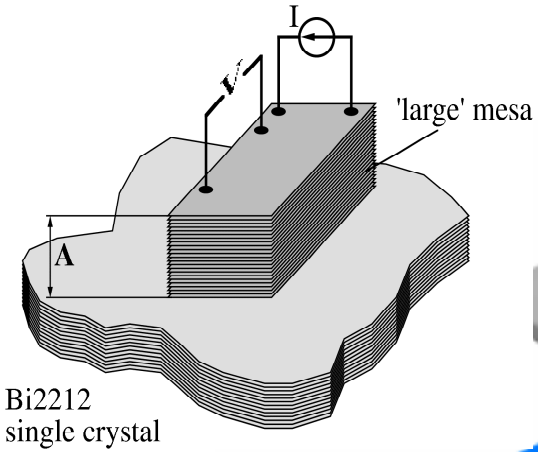


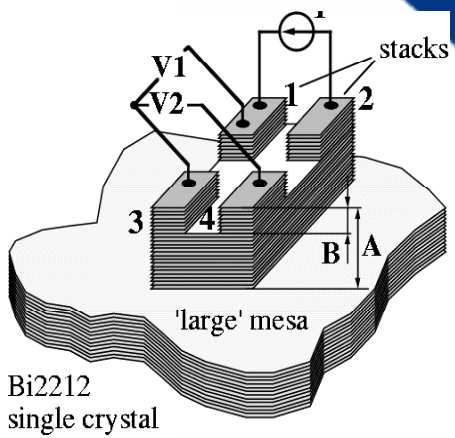


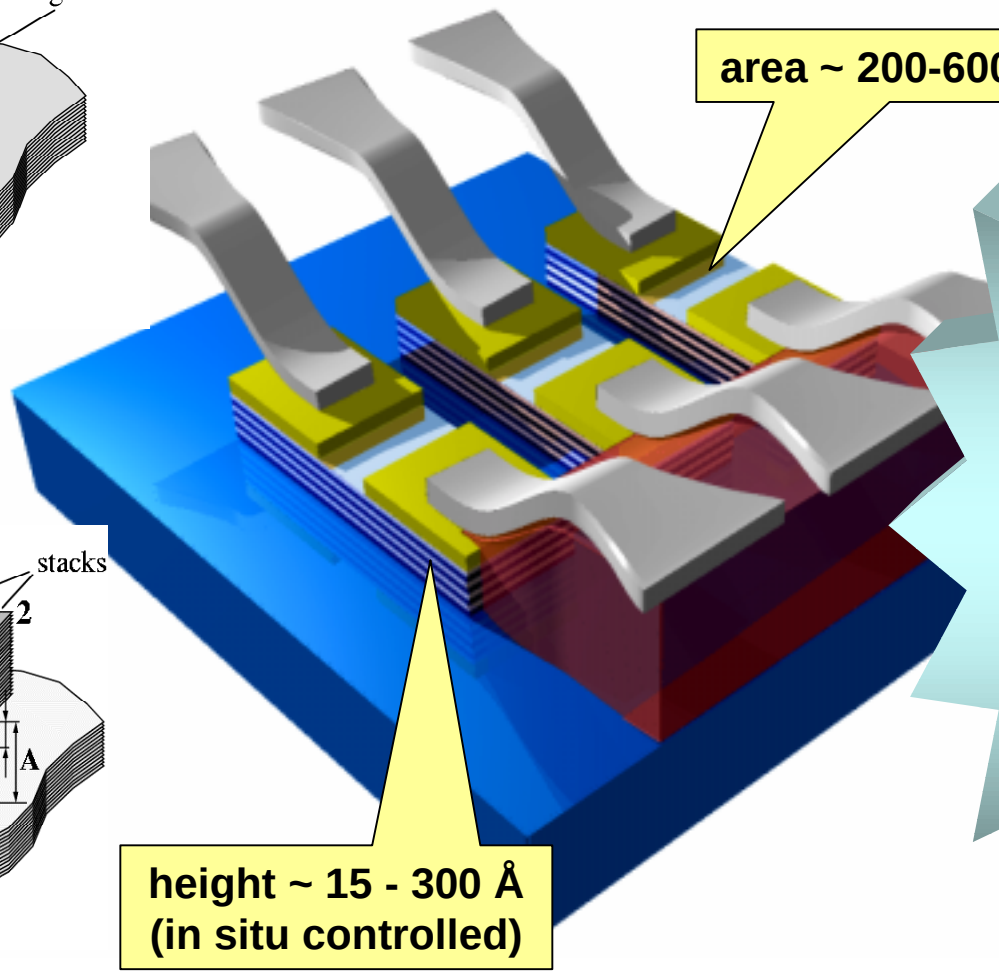


MESA STRUCTURES

- using photolithography







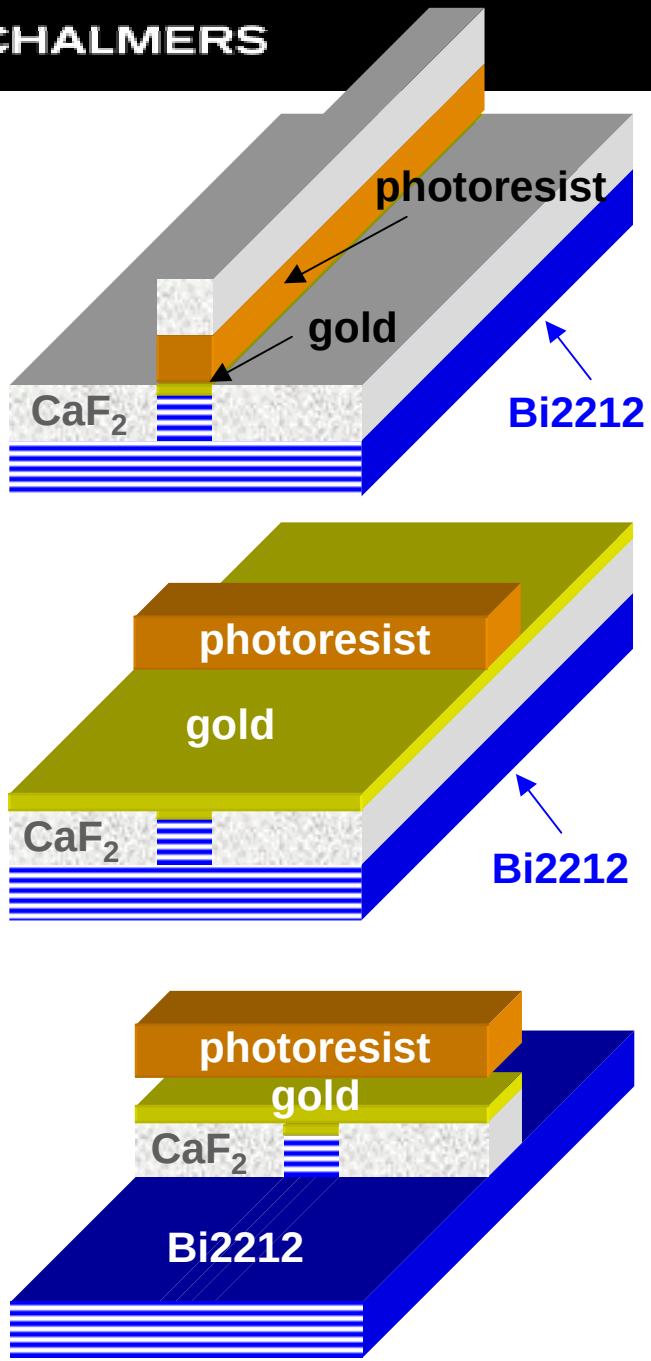
Advantages:
- **specified number of junctions**
- **small volume**
- **less defects**
- **less heating**

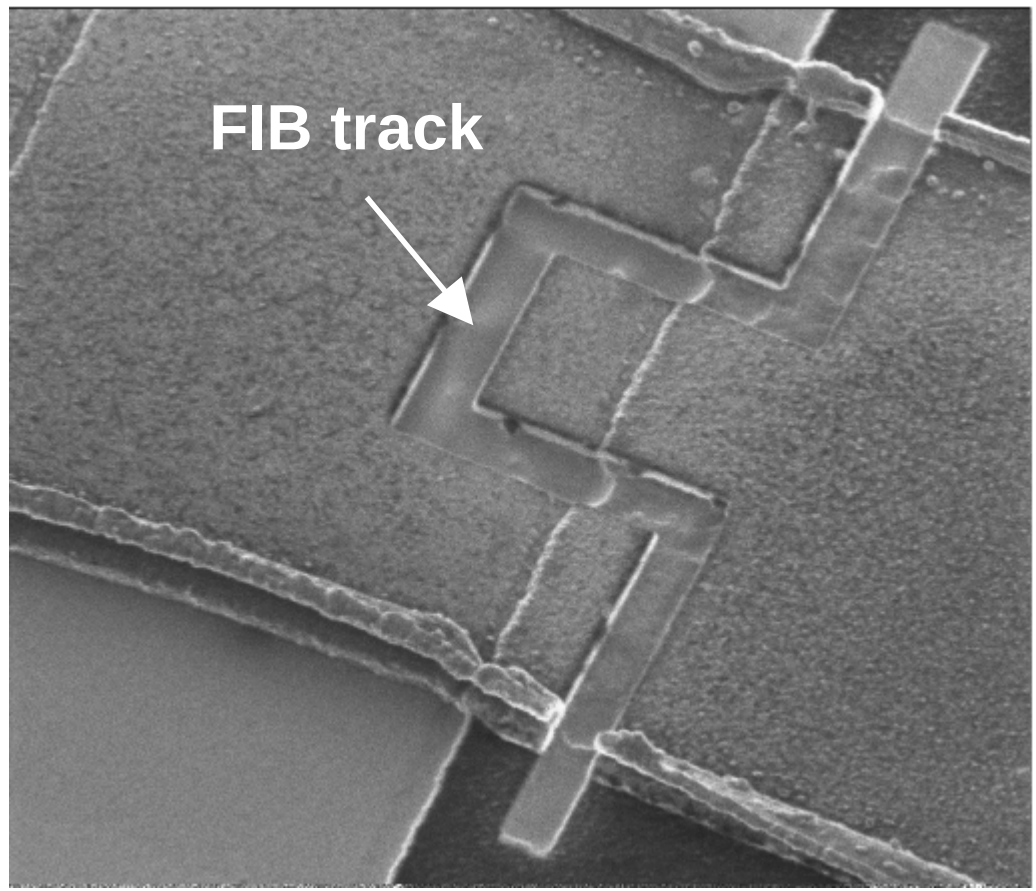
Ar ion etching or

Chemical etching (EDTA)

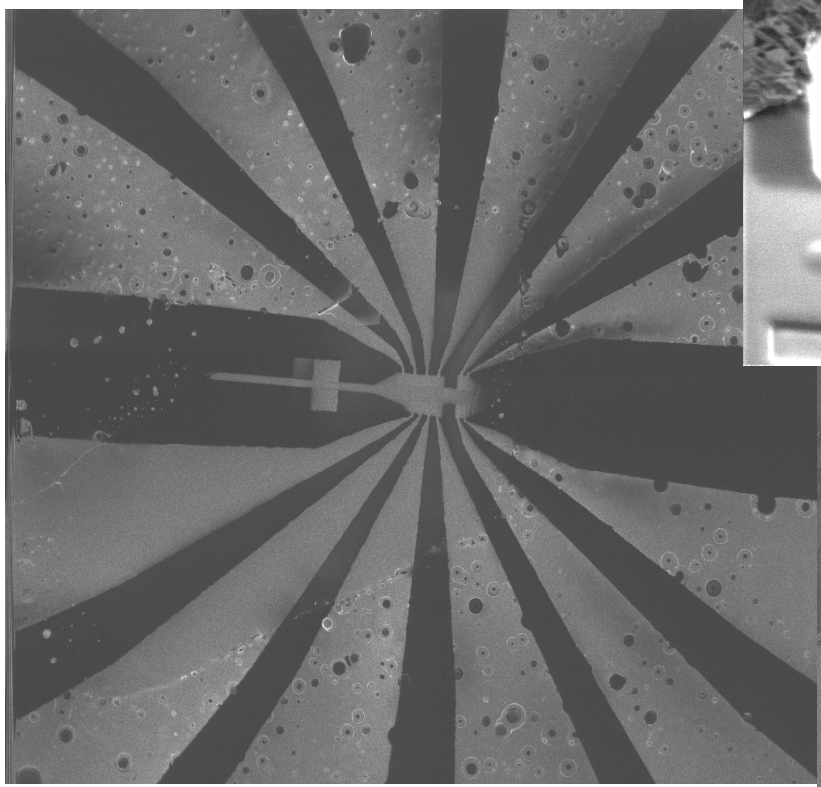
Appl. Phys. Lett. 70, 1760 (1997)

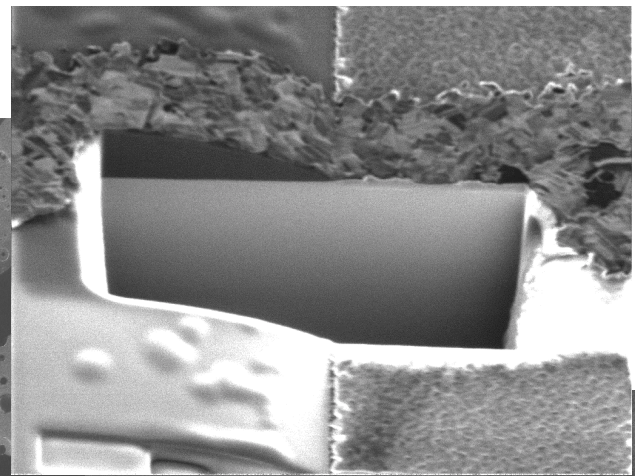
CROSS-BAR PHOTOLITHOGRAPHY

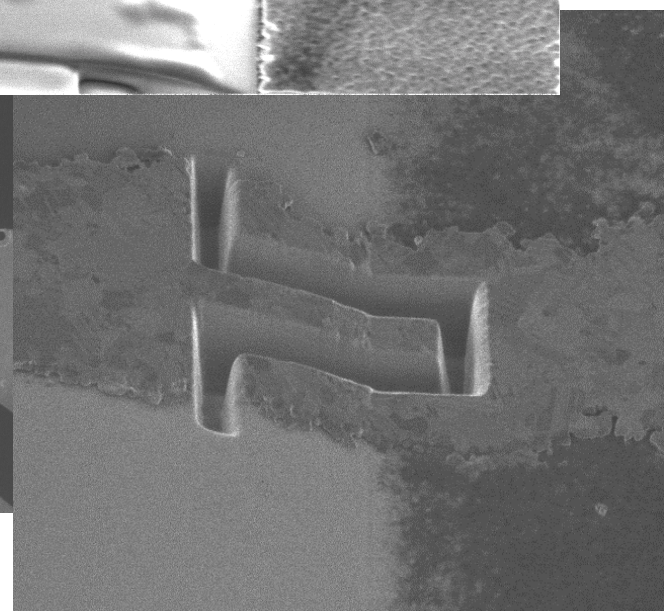




FABRICATION OF MESAS OF Bi2212 INTRINSIC JOSEPHSON JUNCTIONS USING A FOCUSSED ION BEAM



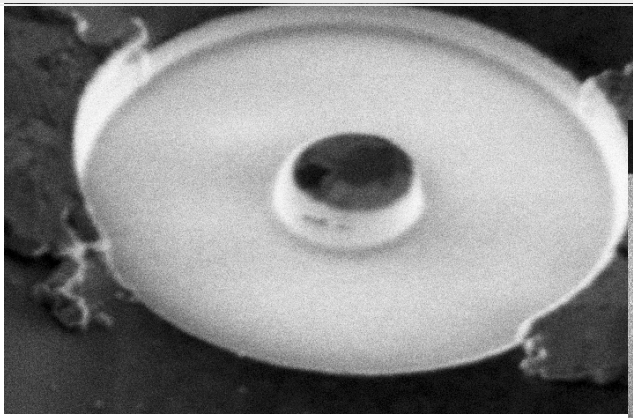


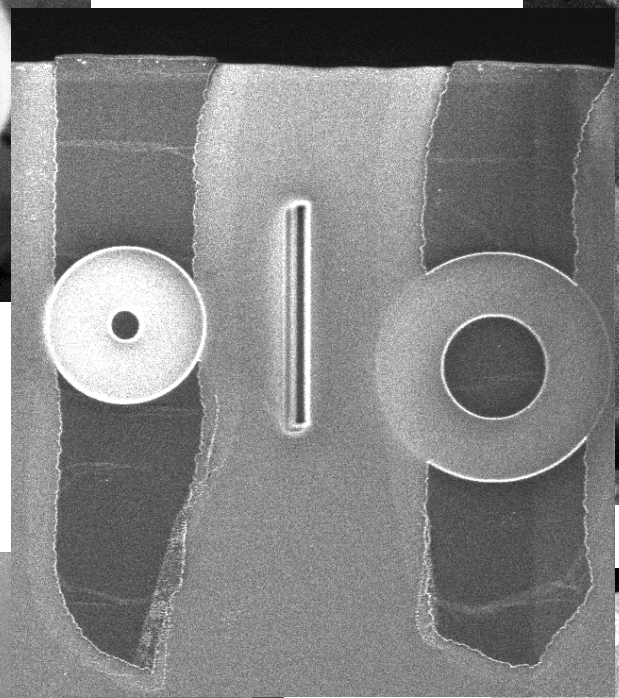


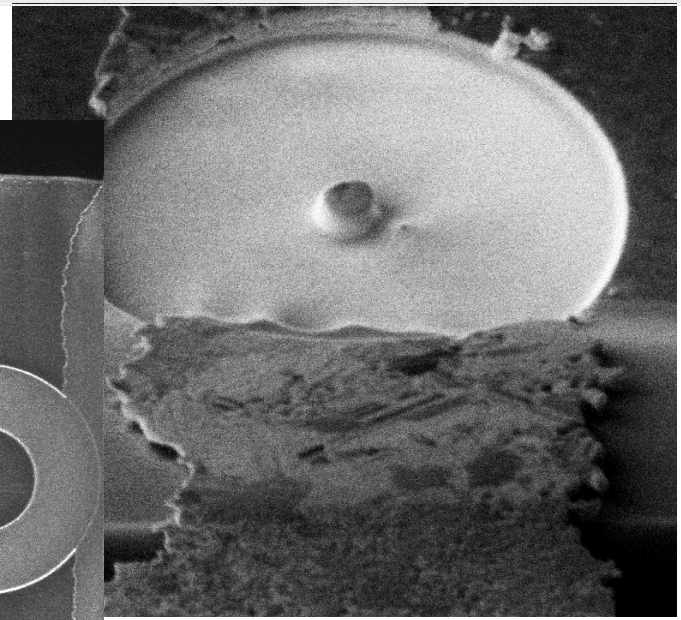
University of Cambridge
IRC in Superconductivity

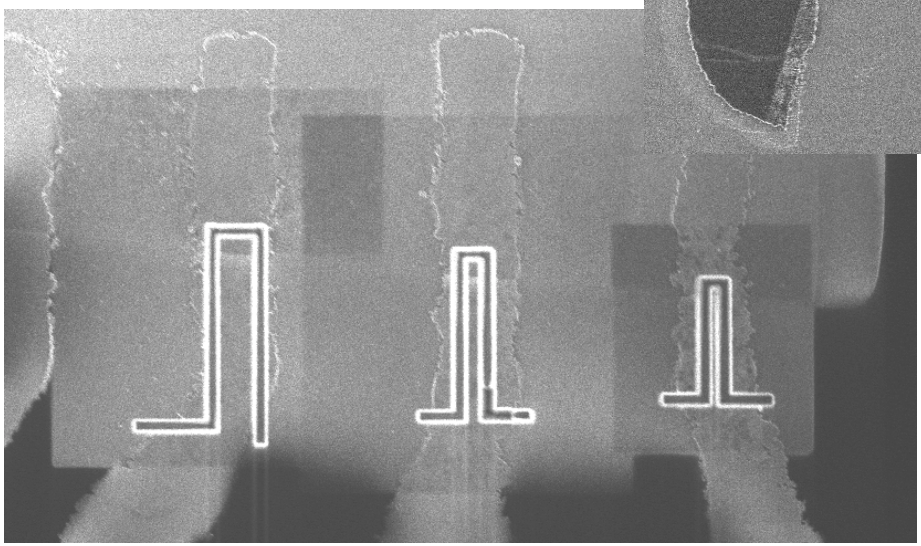
UNIVERSITY OF CAMBRIDGE

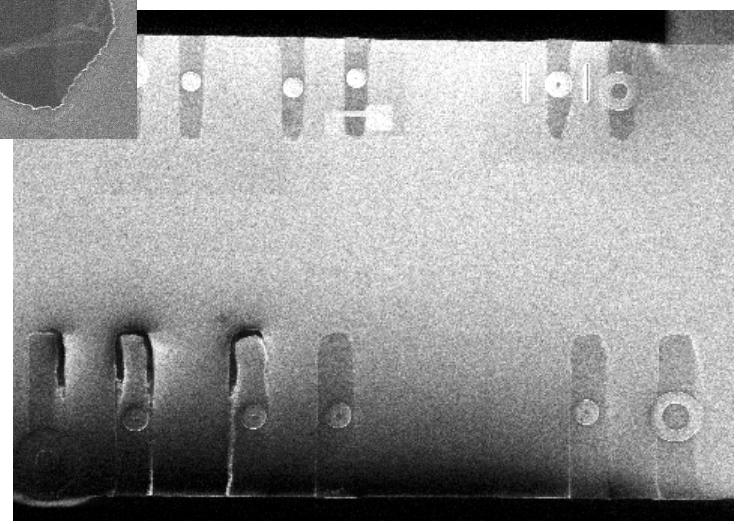
FABRICATION OF MESAS OF Bi2212 INTRINSIC JOSEPHSON JUNCTIONS USING A FOCUSSED ION BEAM











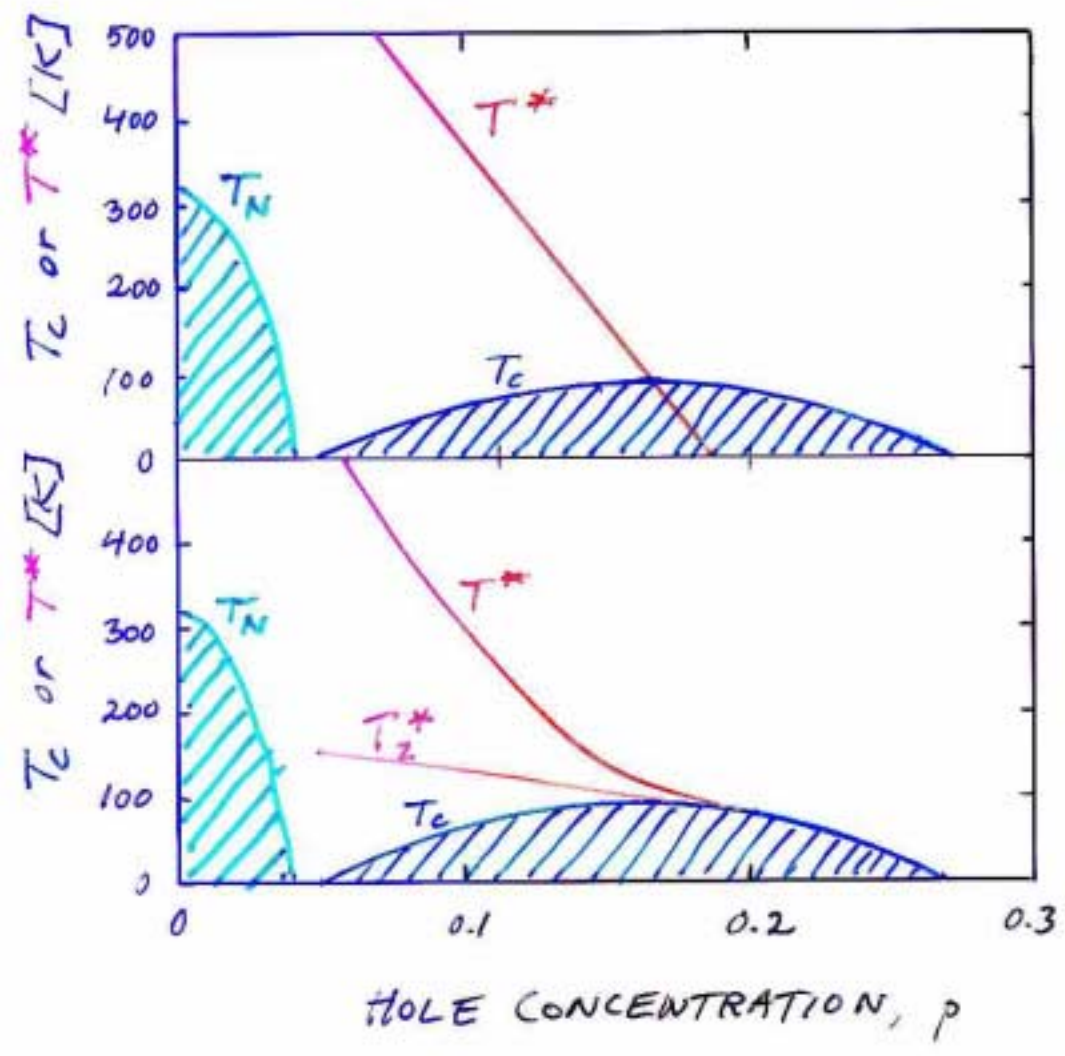
The experimental ”toolbox”

- Charge transport, current-voltage
- Temperature
- Magnetic field
- Pressure
- Intercalation
- Irradiation with heavy ions
- Light and microwaves
- Number of Cu-O planes

RECENT WORK ON Bi2212 INTRINSIC JUNCTIONS

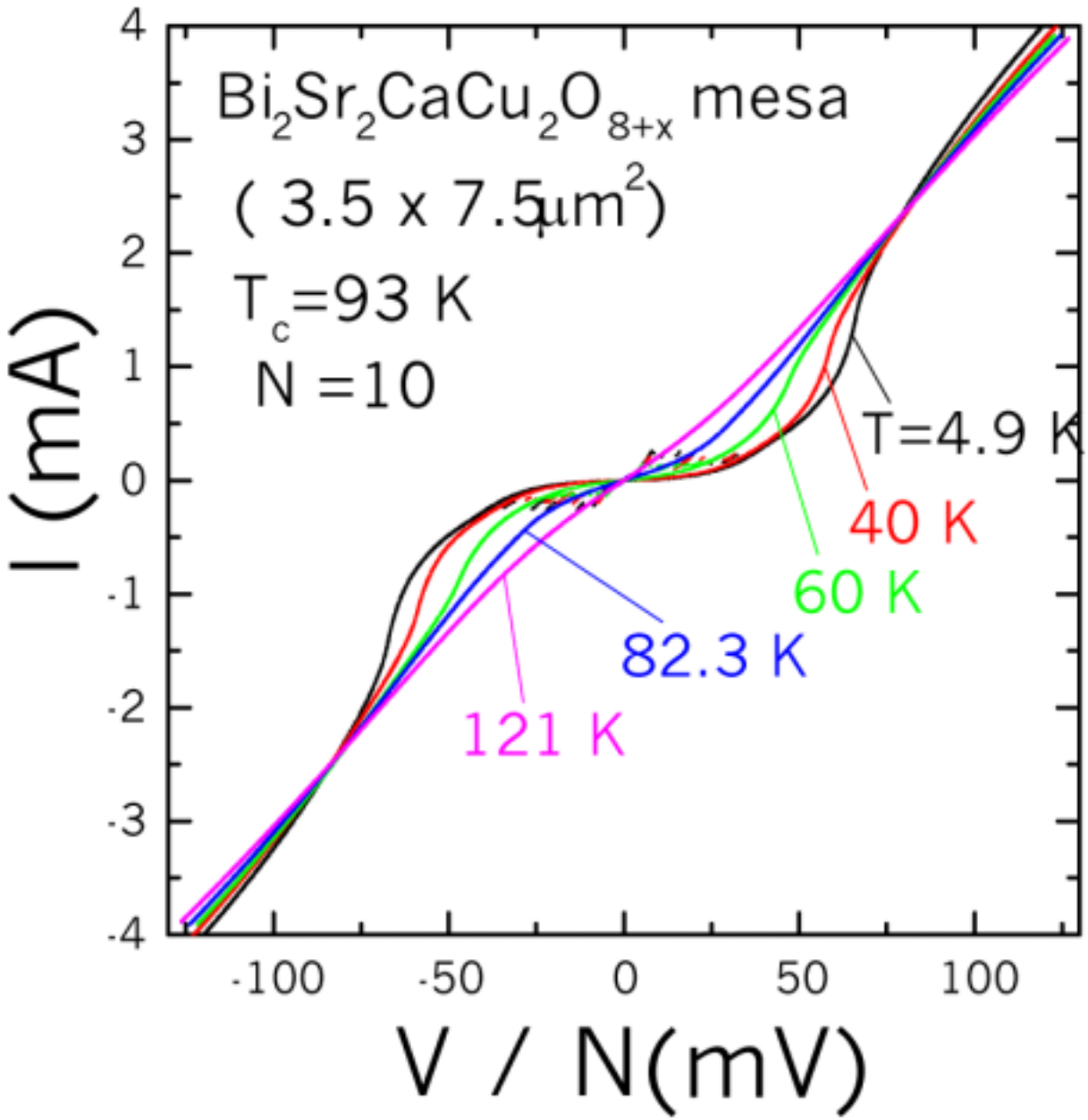
- **Pseudogap in the c-axis tunneling**
- **Interlayer coupling theory and intrinsic Josephson effects**
  - **A pressure-induced increase of 2 – 3 times in I_c of both Bi2212 and Bi2201- single crystals in contrast to 2-6% increase of T_c**
- **Vortex dynamics related work**
  - **The c-axis magnetoresistance peak effect in Bi2212 determined by the *zero-field* sub-gap current-voltage characteristics. 60-fold increase at 6 T.**
  - **Mapping the vortex magnetic phase diagram from I-V**
  - **The influence of 5 GeV Pb^+ ion radiation was studied. I_c has a peak at 1/3 of the matching field B_ϕ**
- **Multiple valued critical current**
  - **Zero-voltage-state lifetime measurements**
  - **Critical current switching distribution**
  - **Phase-locking between junctions in a stack**
  - **Comparison to numerical simulations**

PSEUDOGAP versus the SUPERCONDUCTING GAP – two scenarios...



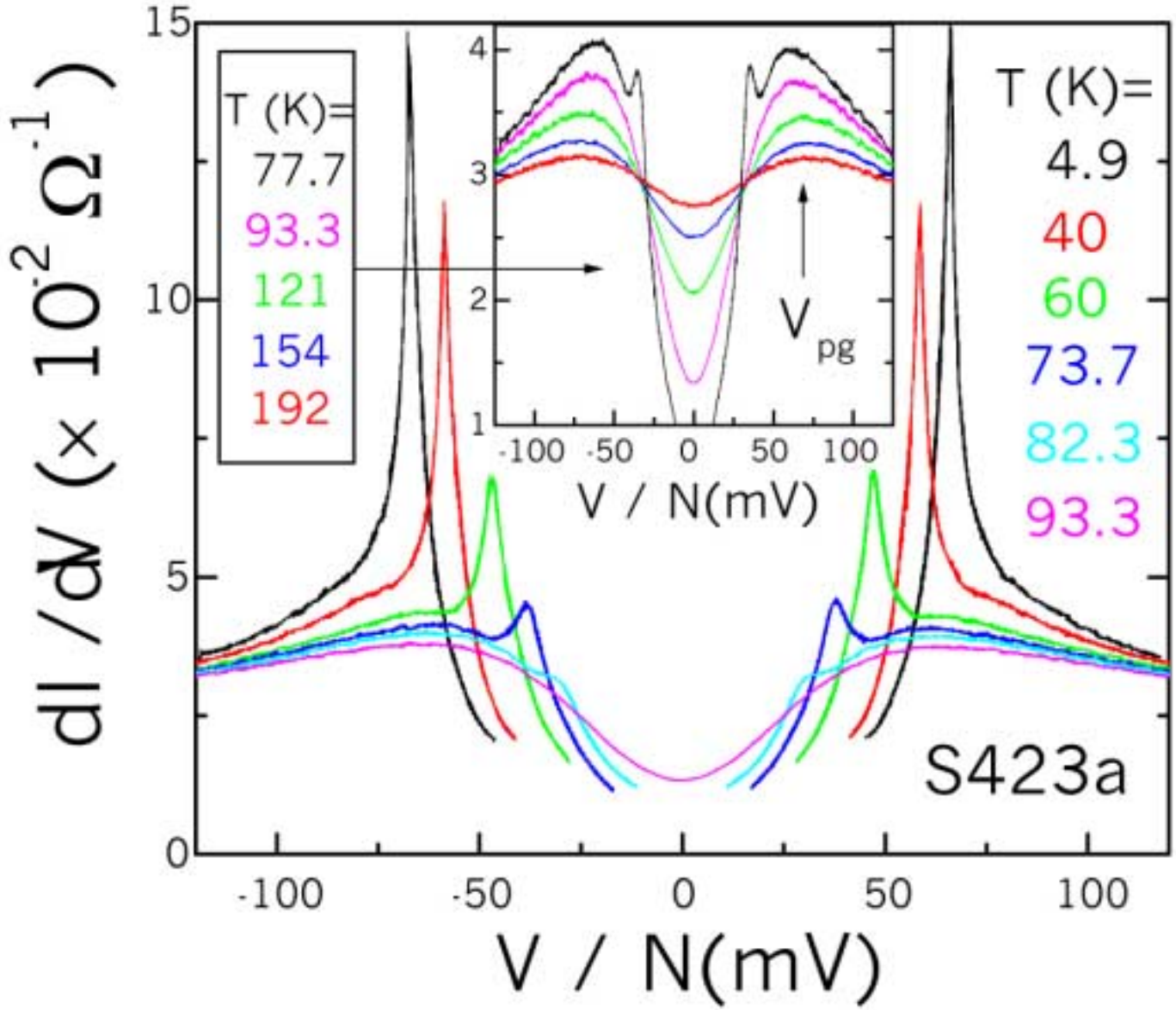
(From J.L. Tallon and J.W. Loram)

PSEUDOGAP

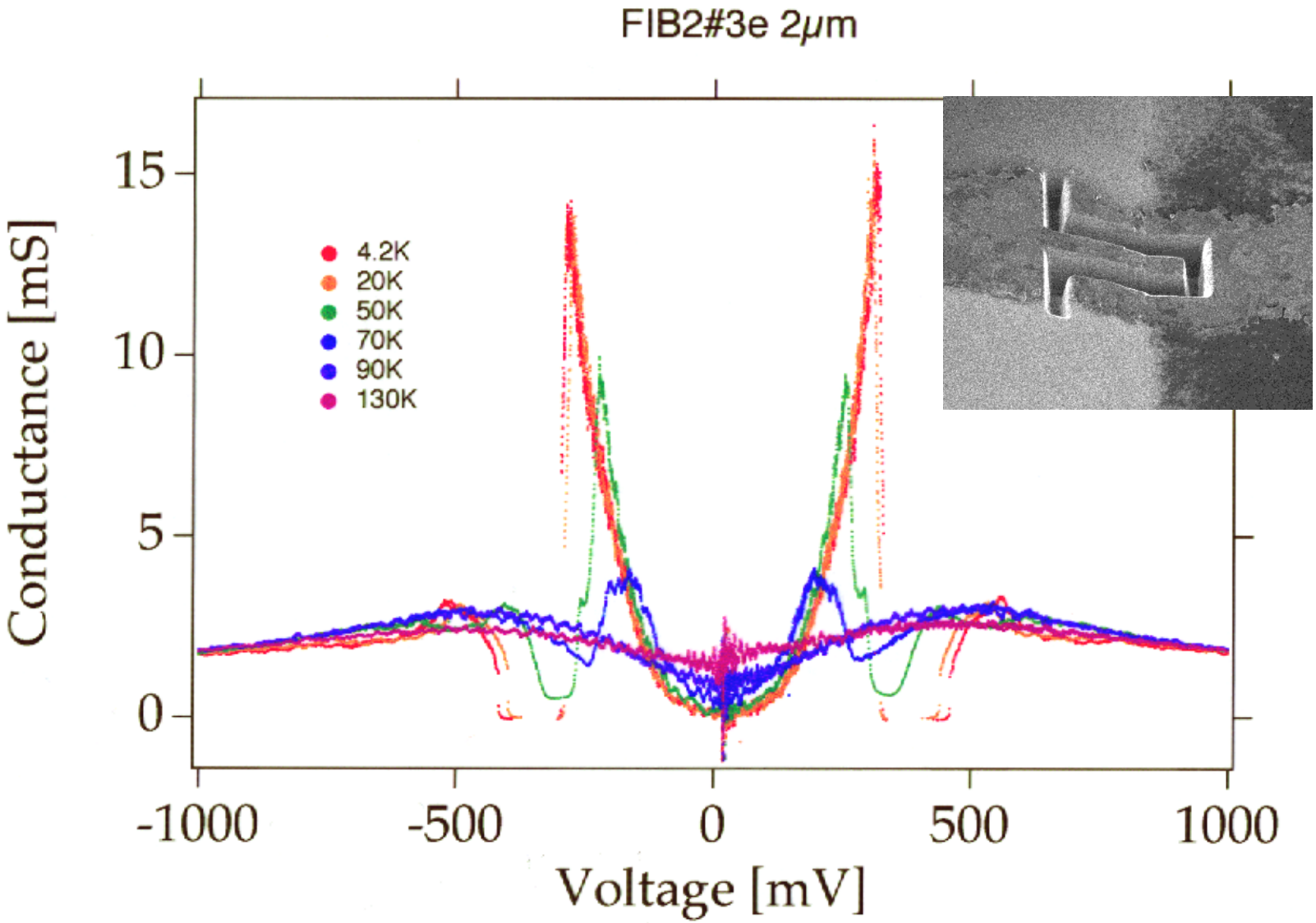


(Krasnov et al. PRL84, 5860 (2000))

dI/dV PSEUDOGAP

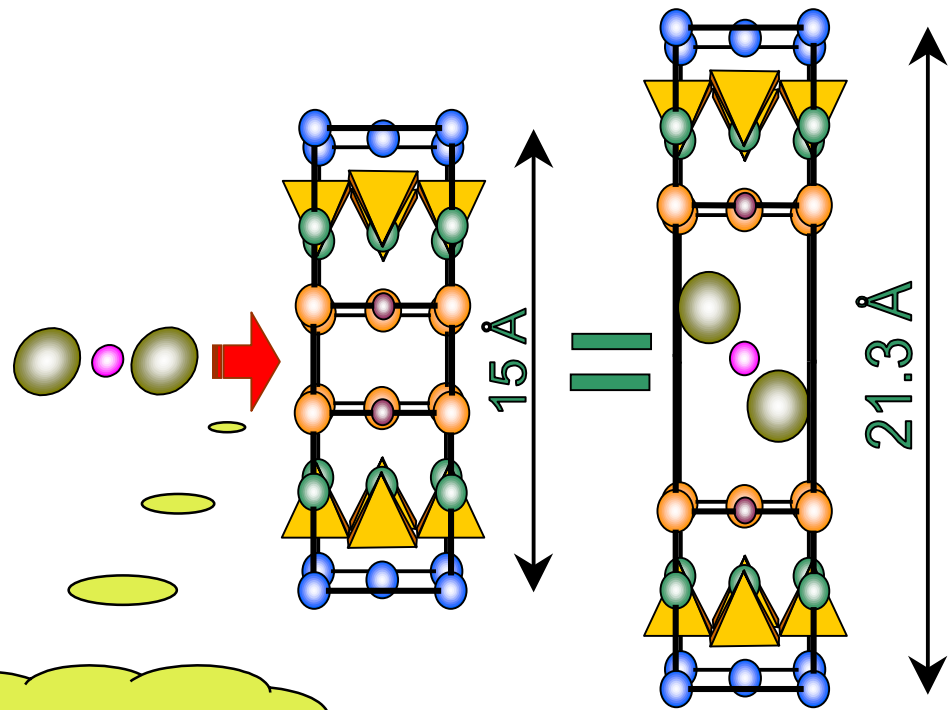


PSEUDOGAP



(Winkler et al., Supercond. Sci. Technol. 12, 1013-1015 (1999))

$HgBr_2$ intercalation



about one week at 230-240 C

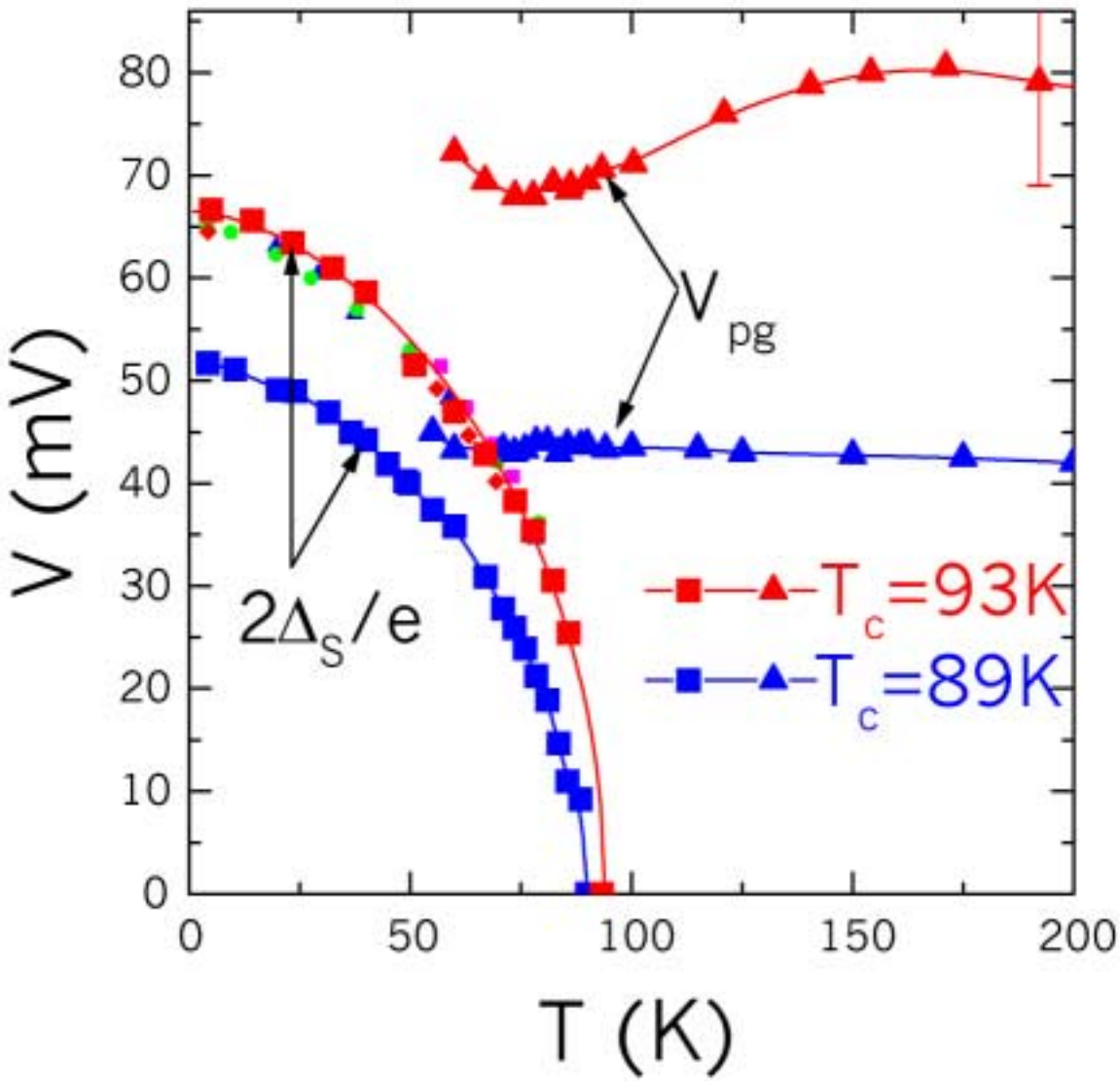
Decrease of the c-axis critical current

less heating

Jin-Ho Choy, Seong-Ju Hwang, and Nam-Gyu Park

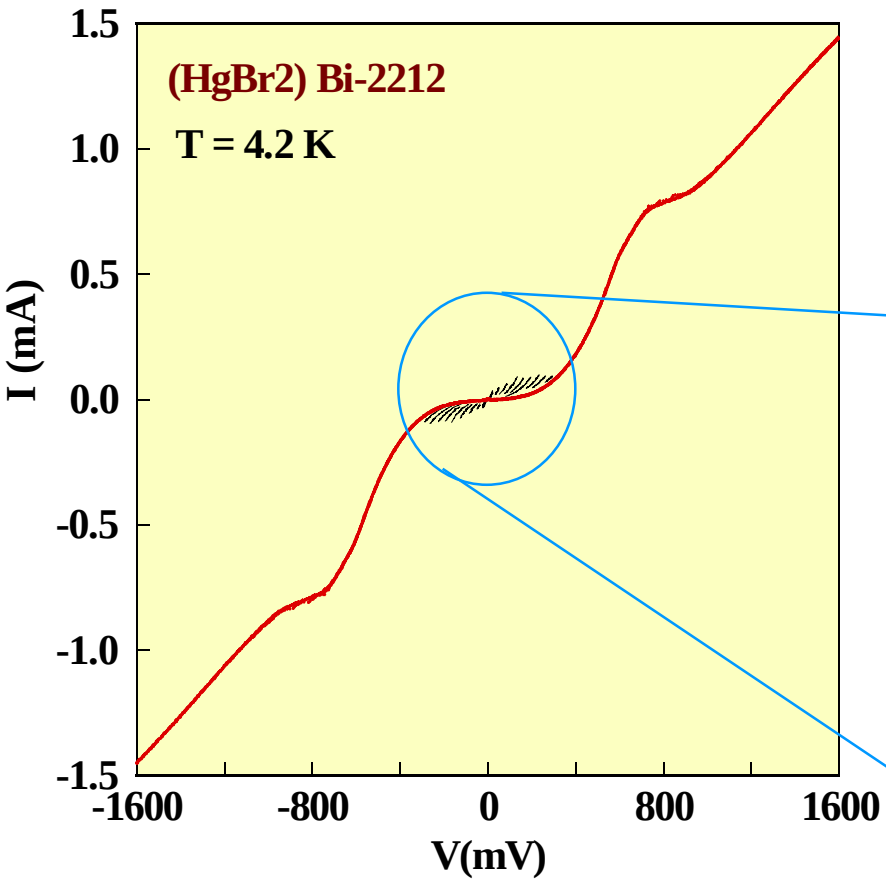
J. Am. Chem. Soc. 119, 1624 (1997)

PSEUDOGAP

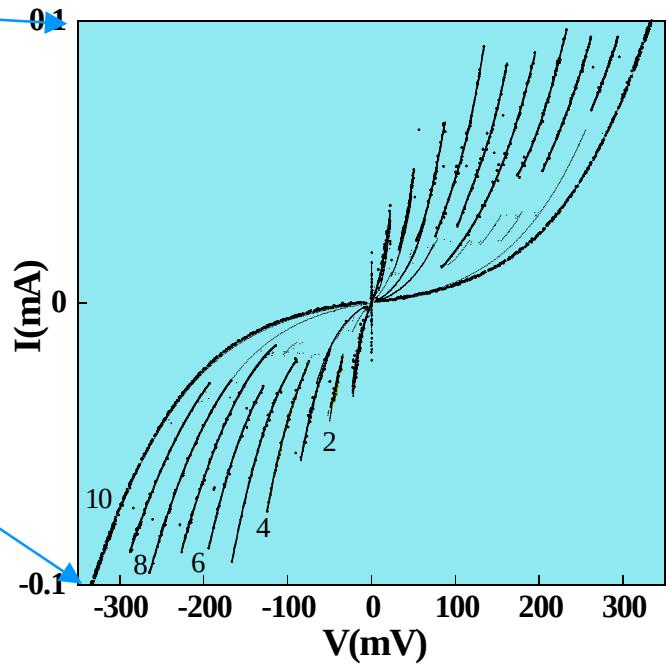


(Krasnov et al. PRL84, 5860 (2000))

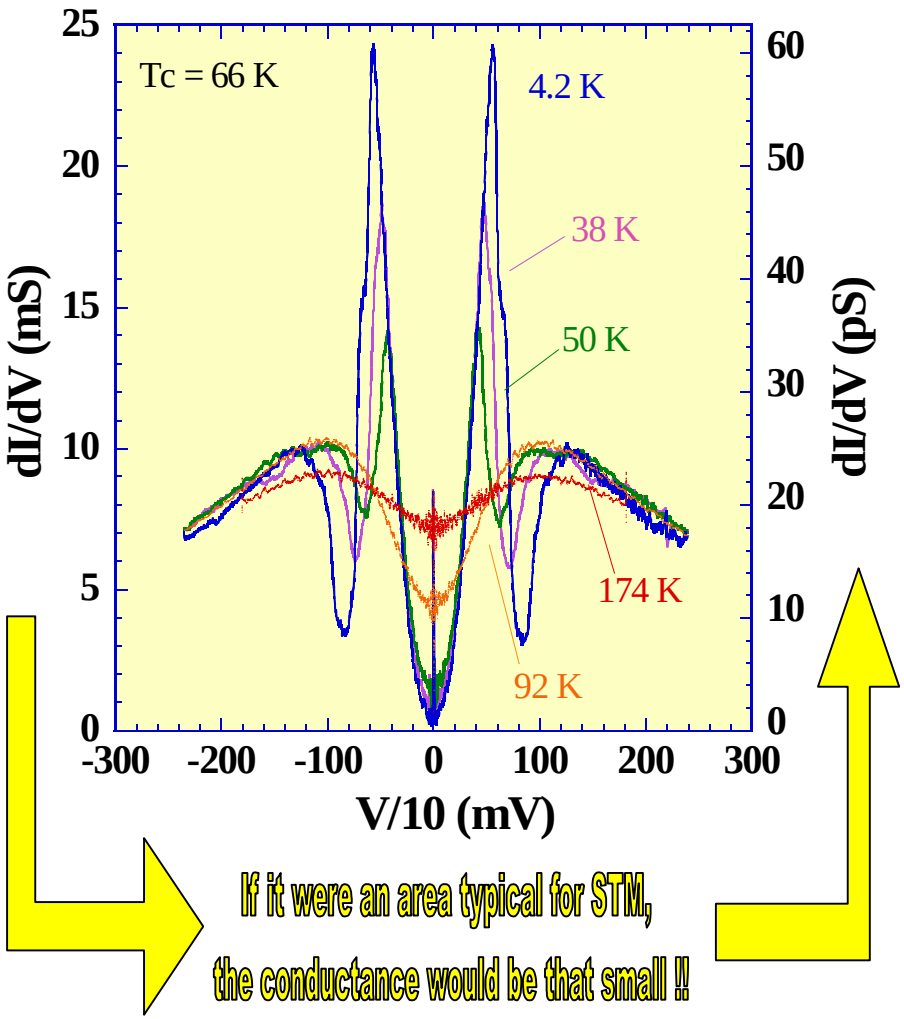
10 intrinsic Josephson junctions

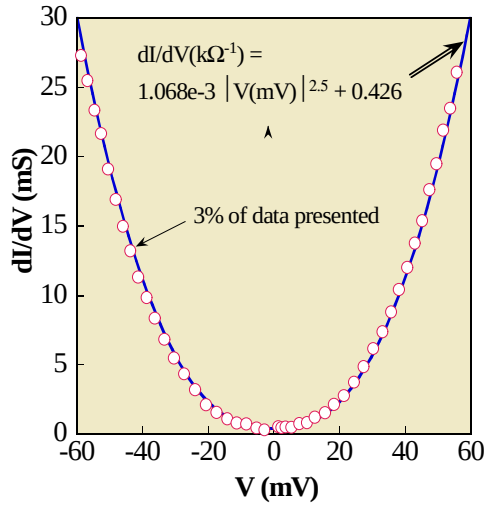


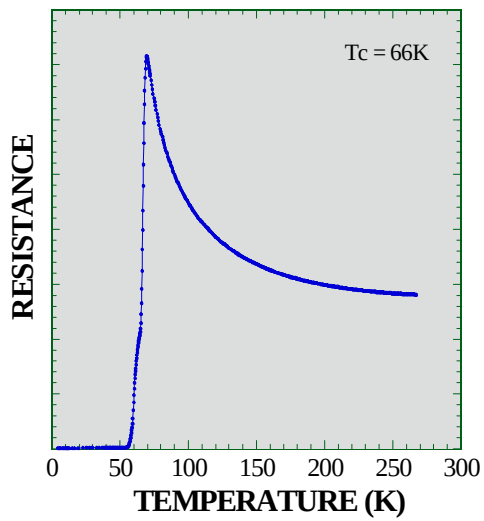
10 intrinsic Josephson junctions



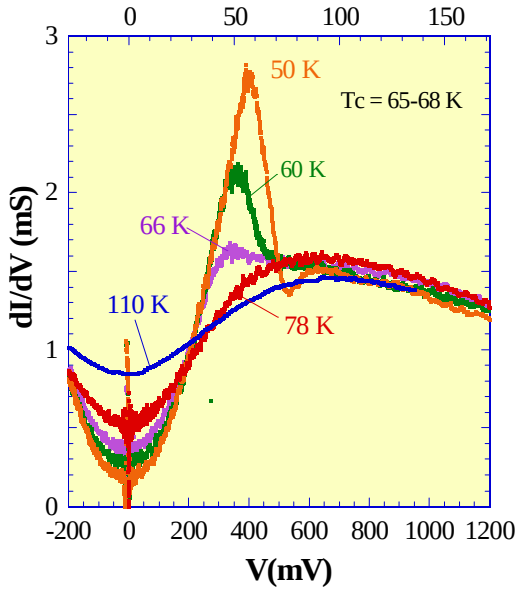
The intercalation does not change the quality of I-V's

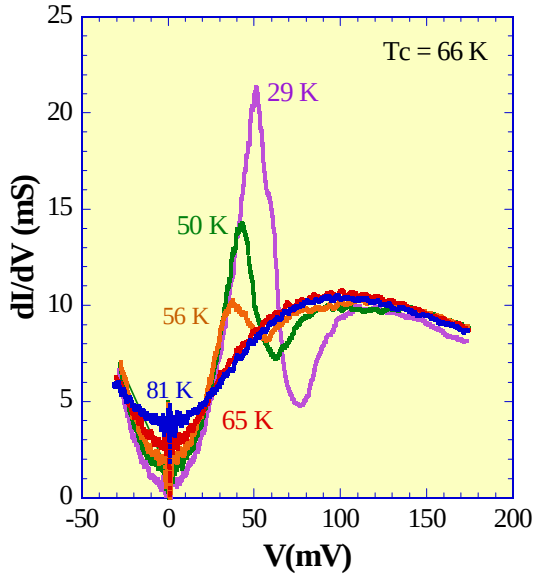

Tc = 66 K
4.2 K
38 K
50 K
174 K
92 K
dI/dV (mS)
dI/dV (pS)
V/10 (mV)
If it were an area typical for STM,
the conductance would be that small !!

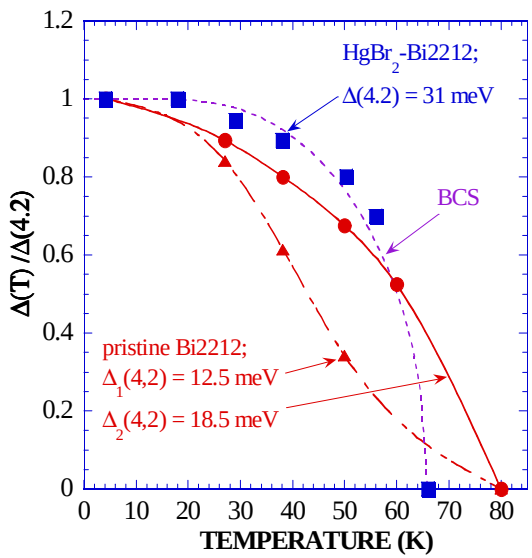

dI/dV(kΩ-1) =
1.068e-3 |V(mV)|2.5 + 0.426
3% of data presented
dI/dV (mS)
V (mV)


Tc = 66K
RESISTANCE
TEMPERATURE (K)

Two intercalated samples







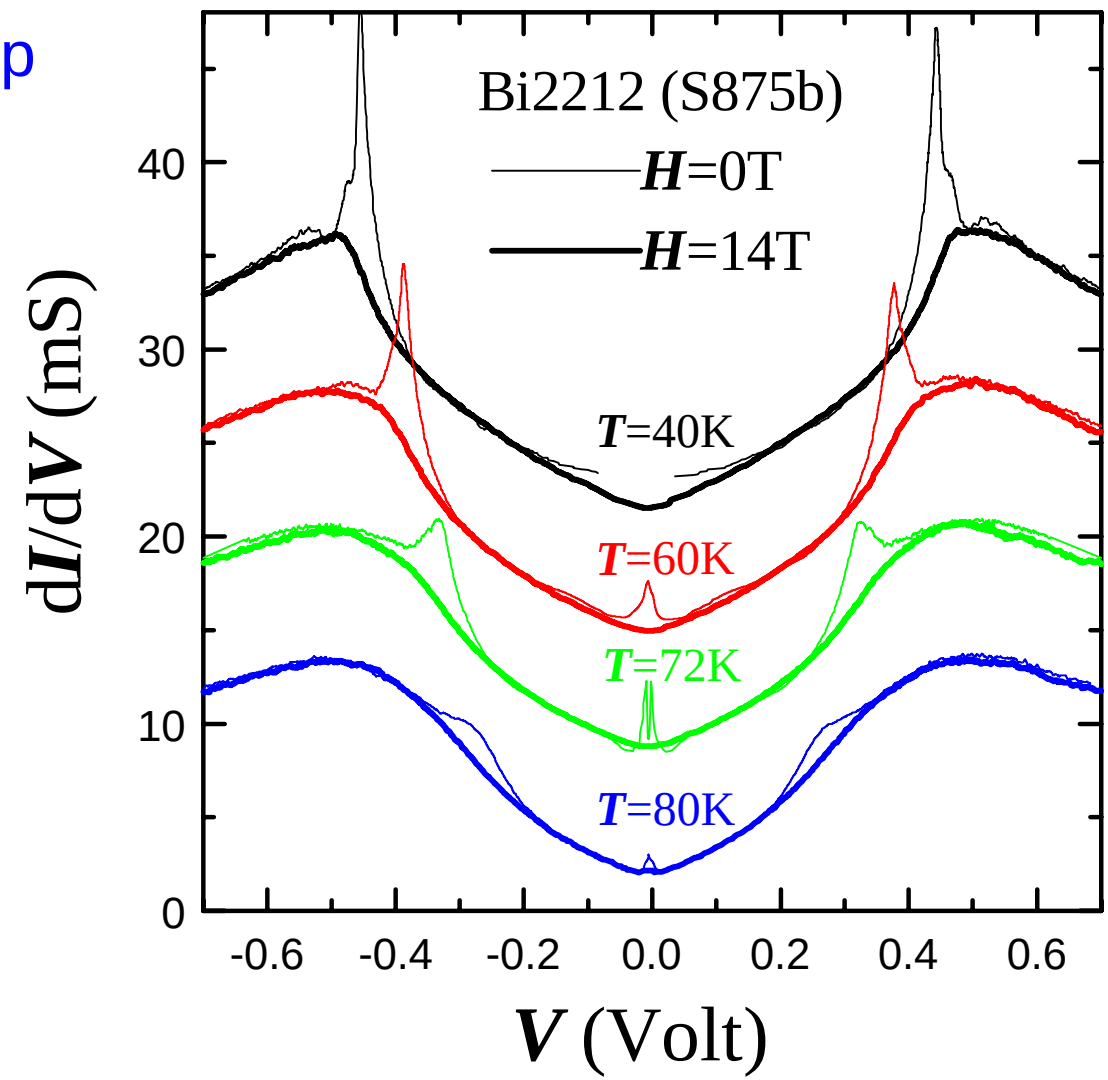
Superconducting & pseudogap structures

Magnetic field dependence H || I || c for Bi2212

Superconducting gap

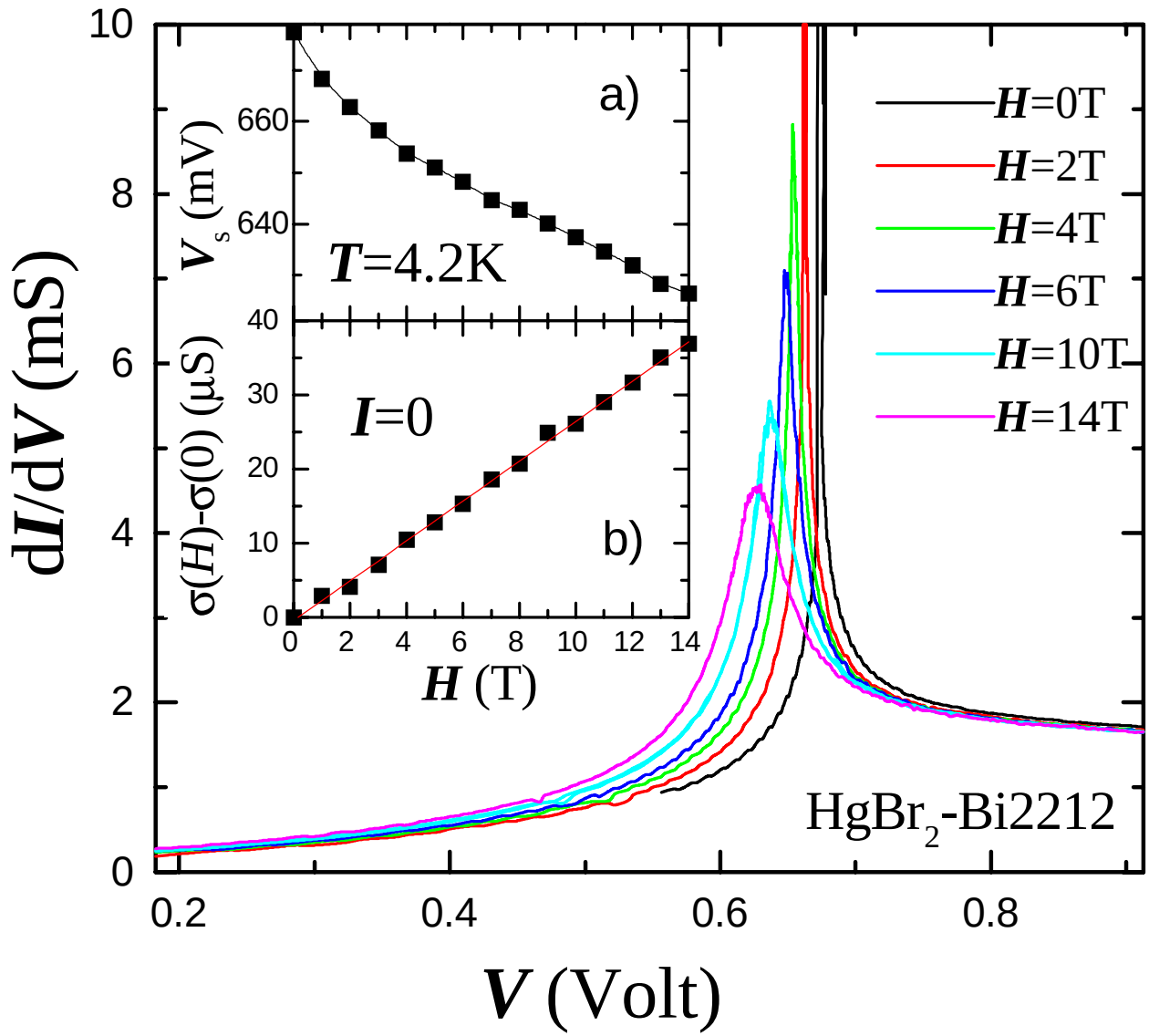
and

pseudogap

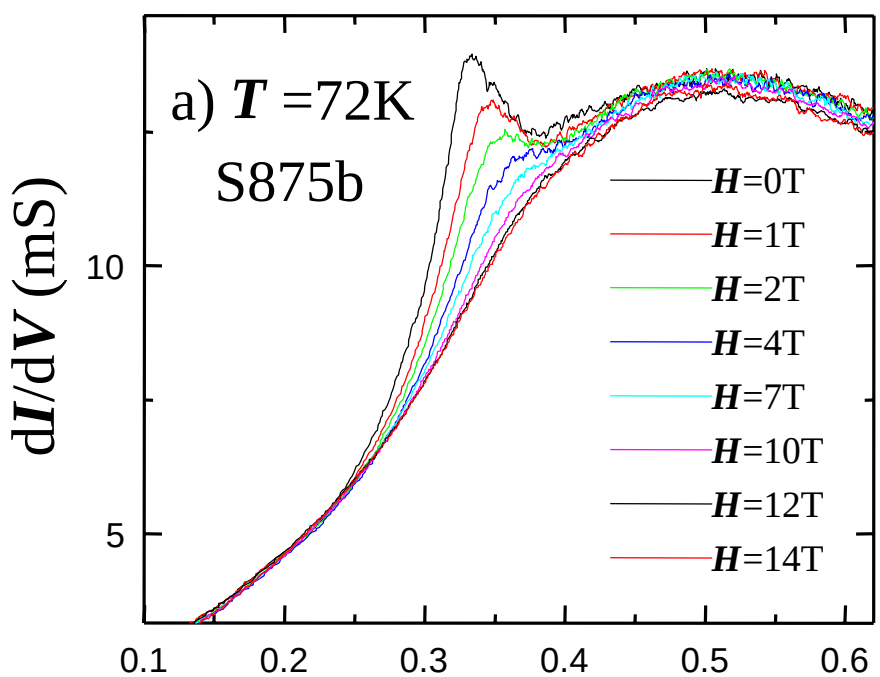


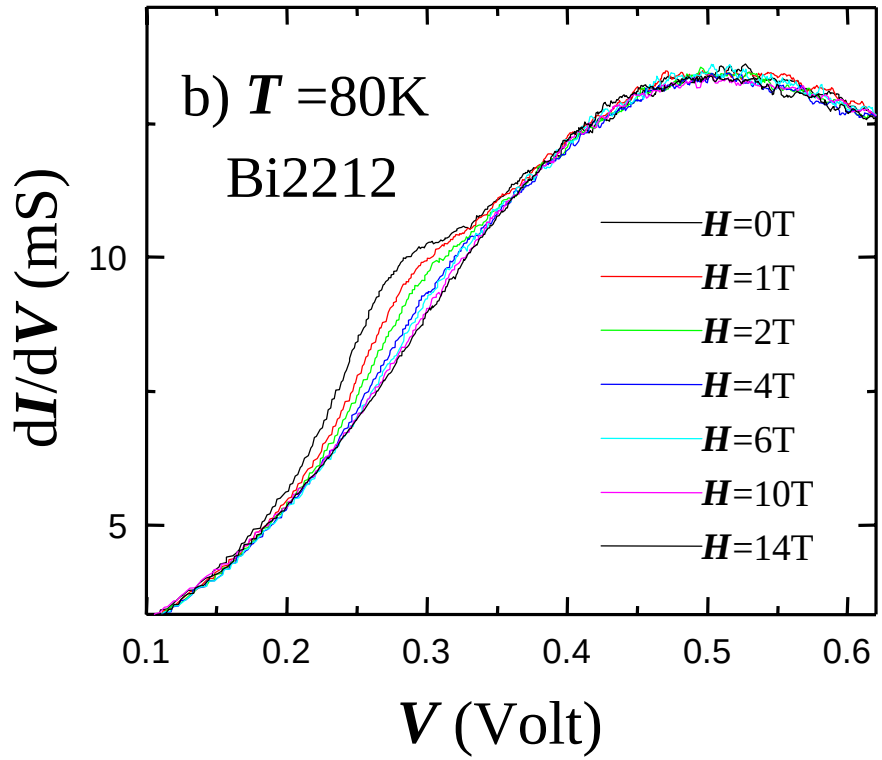
(Krasnov et al. cond-mat/0006479, 29 June 2000)

Intercalated HgBr2- Bi2212 mesa at 4.2 K



H || I || c – pure Bi2212





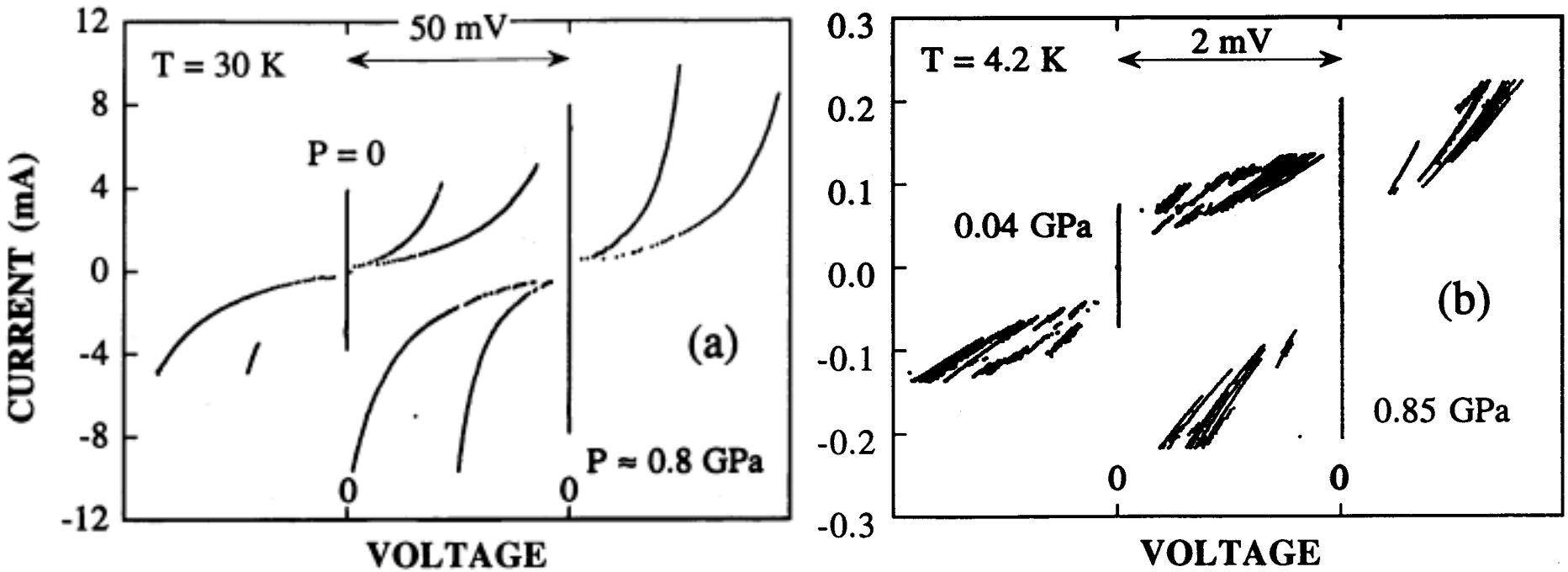
INTERLAYER COUPLING AND PRESSURE

VOLUME 82, NUMBER 15 PHYSICAL REVIEW LETTERS 12 APRIL 1999

Interlayer Coupling and Superconducting Critical Temperature of $Bi_2Sr_{1.5}La_{0.5}CuO_{6+\delta}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$: Incommensurate Effects of Pressure

A. Yurgens,* D. Winkler, and T. Claeson
Department of Microelectronics and Nanoscience, Chalmers University of Technology and Göteborg University, S-41296 Göteborg, Sweden

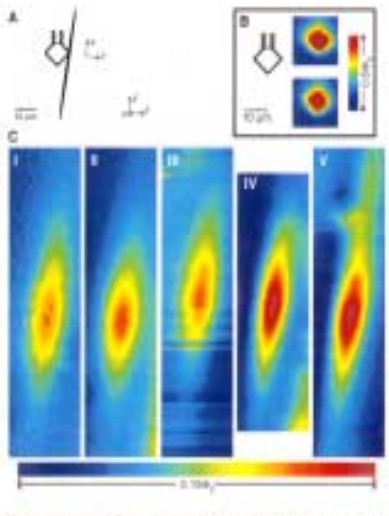
T. Murayama and Y. Ando
Electrical Physics Department, Central Research Institute of Electric Power Industry, 2-11-1 Iwato-kita, Komae, Tokyo 201-8511, Japan
(Received 5 January 1998; revised manuscript received 30 November 1998)



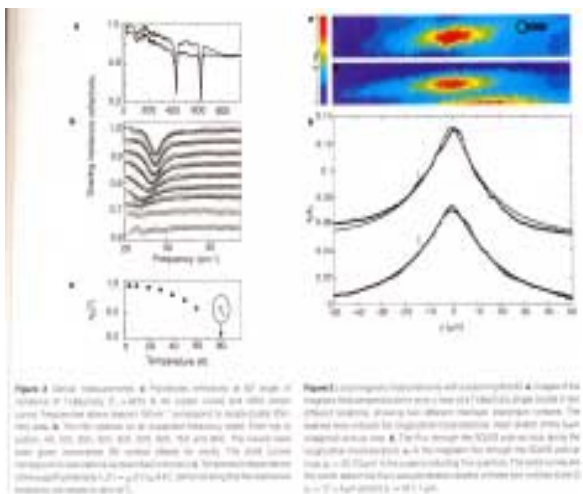
PENETRATION DEPTH

$$\lambda_c = \sqrt{\frac{c\Phi_0}{8\pi^2 s J_c}}$$

K.A. Moler et al., Science 279, 1193 (1998)



T1-2201



A.A. Tsvetkov et al., Nature 395, 360 (1998)

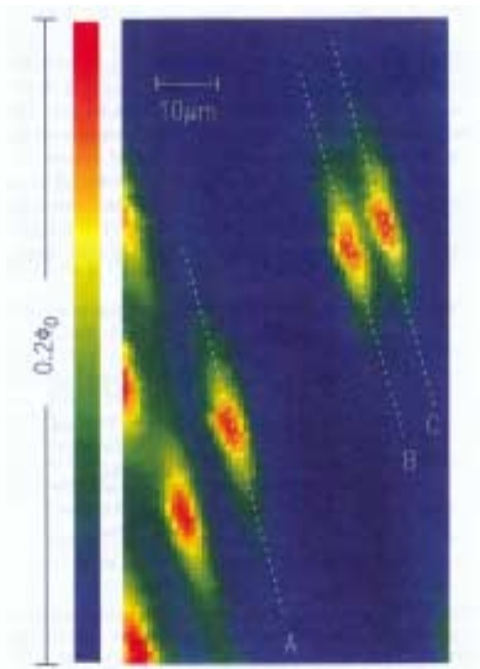
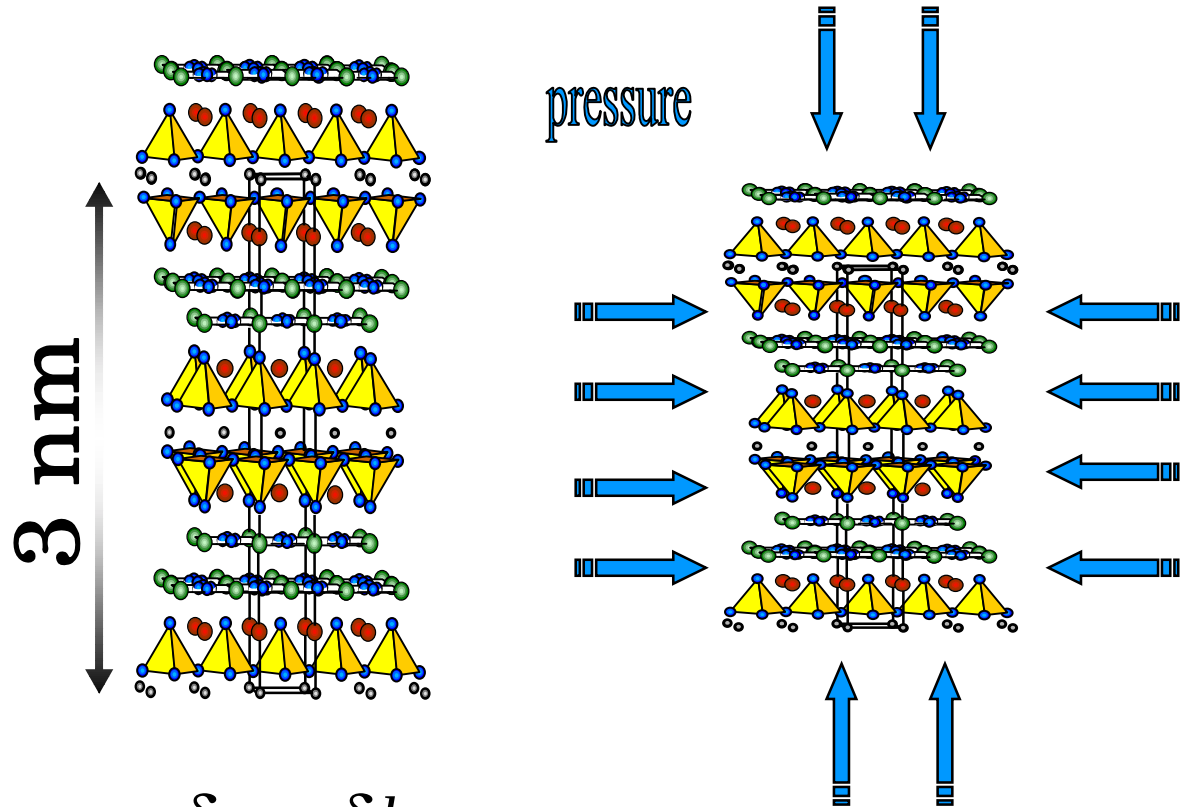


FIG. 2(color). Expanded view of a 54 × 100 μm area of the image of Fig. 1. The dashed lines indicate the paths of cross sections through the data parallel to the planes displayed in Fig. 3.

J.R. Kirtley et al., PRL 81, 2140 (1998)

Hg-1201

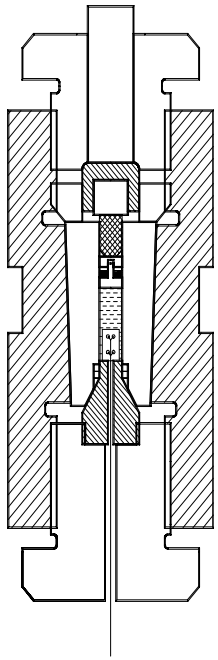
PRESSURE



$$\frac{\delta a}{a} = \frac{\delta b}{b} = 0.2\,\%\ \mathrm{GPa}^{-1}$$

$$\frac{\delta c}{c} = 0.6\,\%\ \mathrm{GPa}^{-1}$$

HIGH PRESSURE CELL

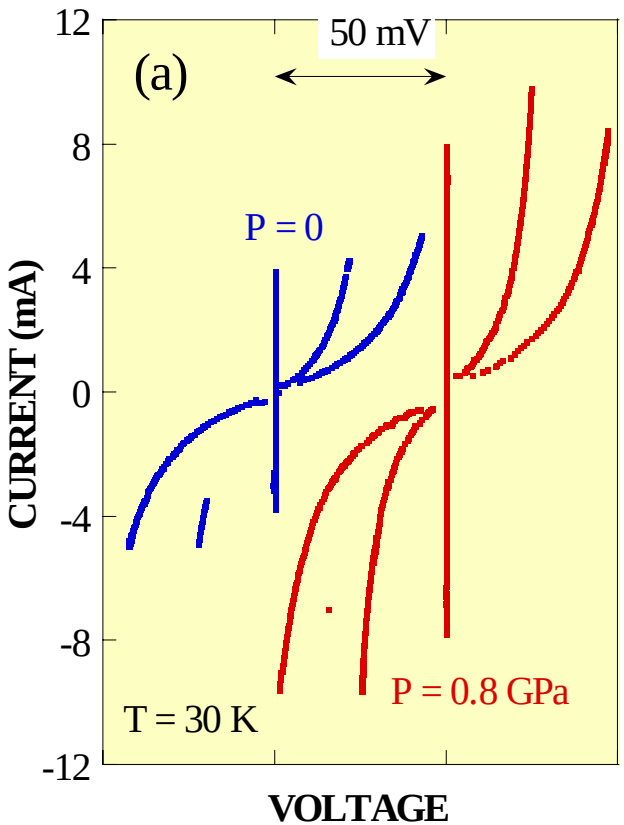


Option	#1	#2	#3
Pressure range, *GPa*	1.0	2.0	3.0
Outer diameter, *mm*	30	40	60
Inner diameter, *mm*	8	6	6
Working volume at max pressure, *ccm*	1	0.35	0.35
Weight, *kg*	1.0	1.7	2.7

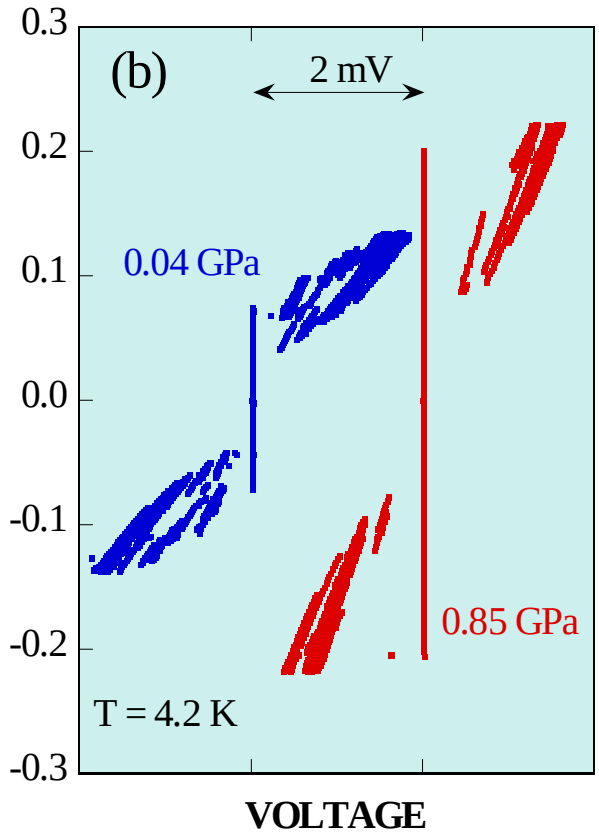
Institute for High Pressure Physics Tel. (7-095) 3340582
142092 TROITSK Moscow Reg. RUSSIA Fax. (7-095) 3340012

TWO OR ONE PLANE

Bi-2212

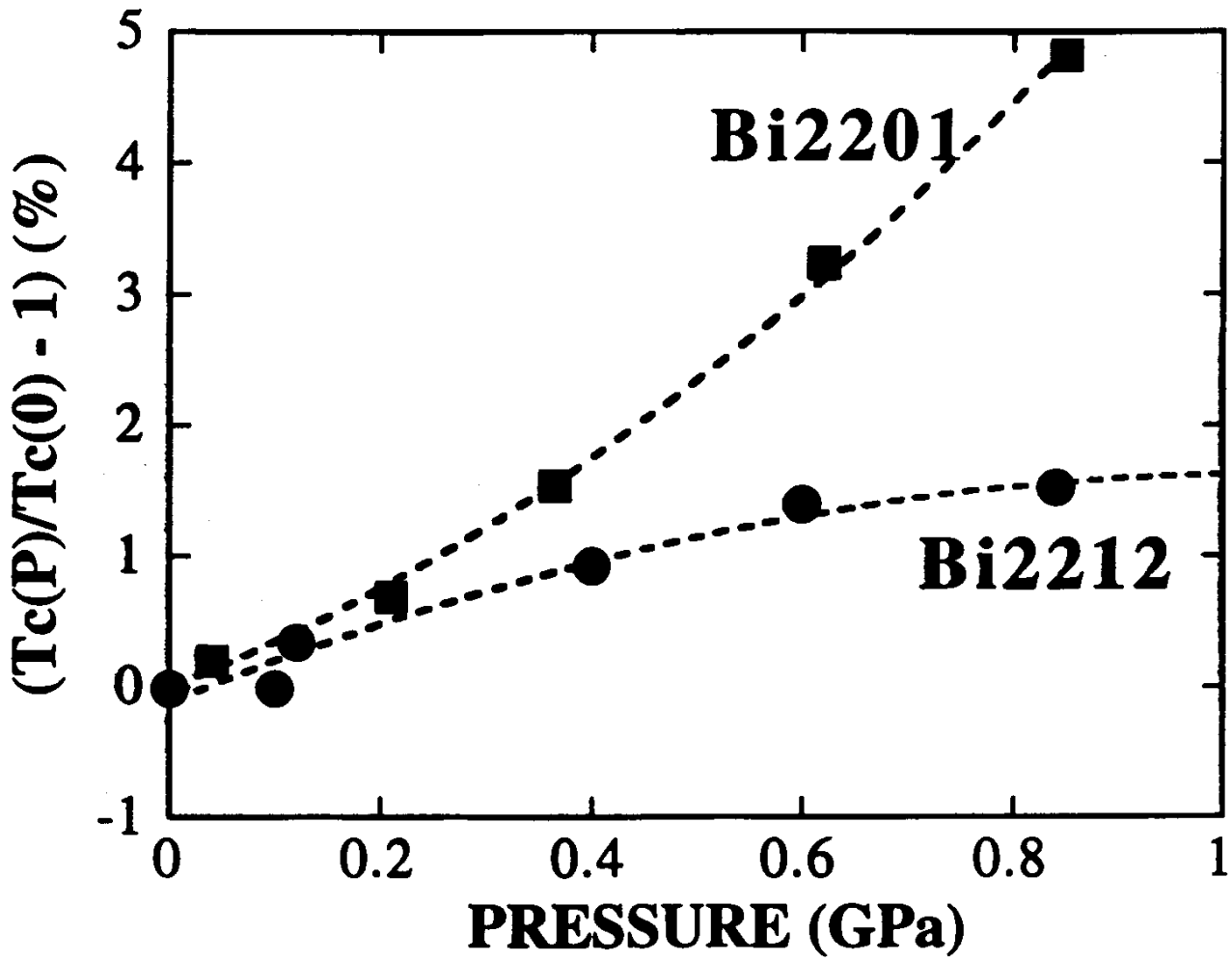


Bi-2201



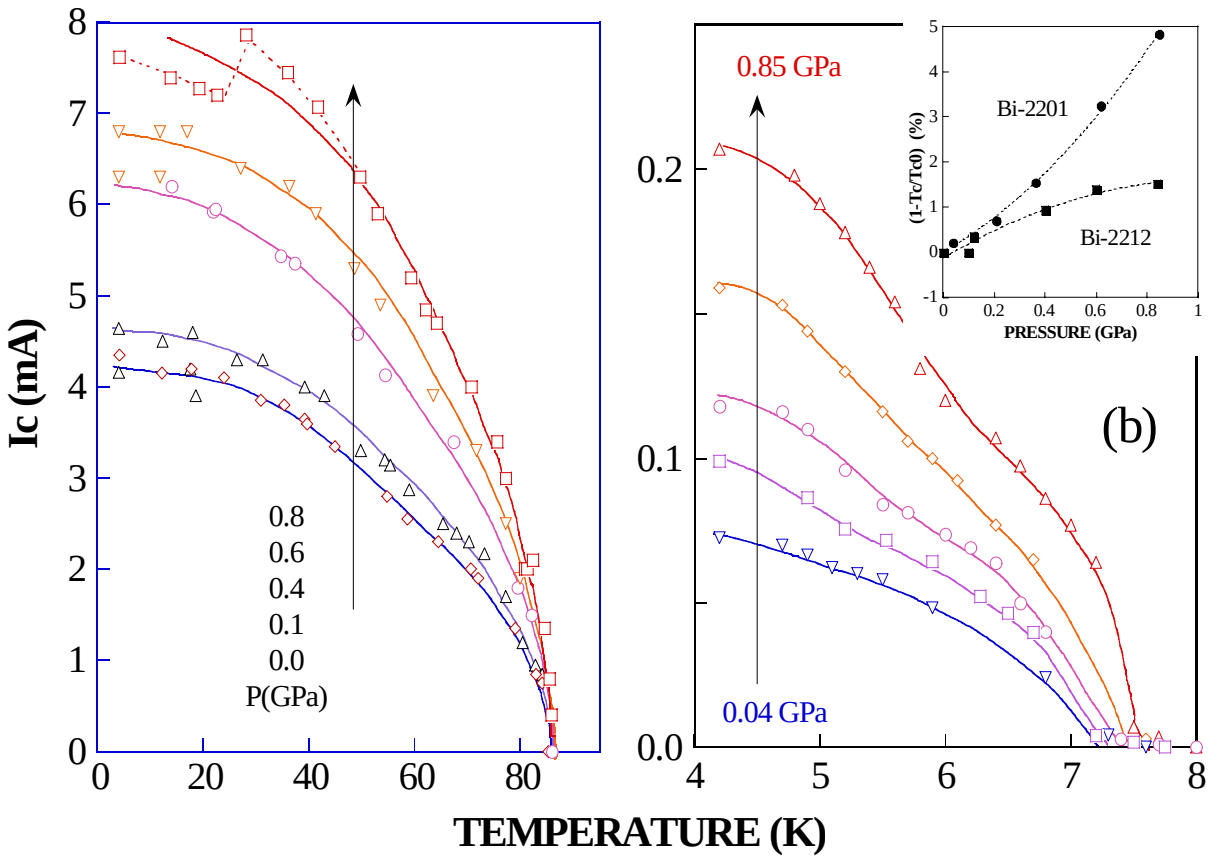
No change in shape of I-V´s

INTERLAYER COUPLING AND PRESSURE



PRESSURE EFFECTS

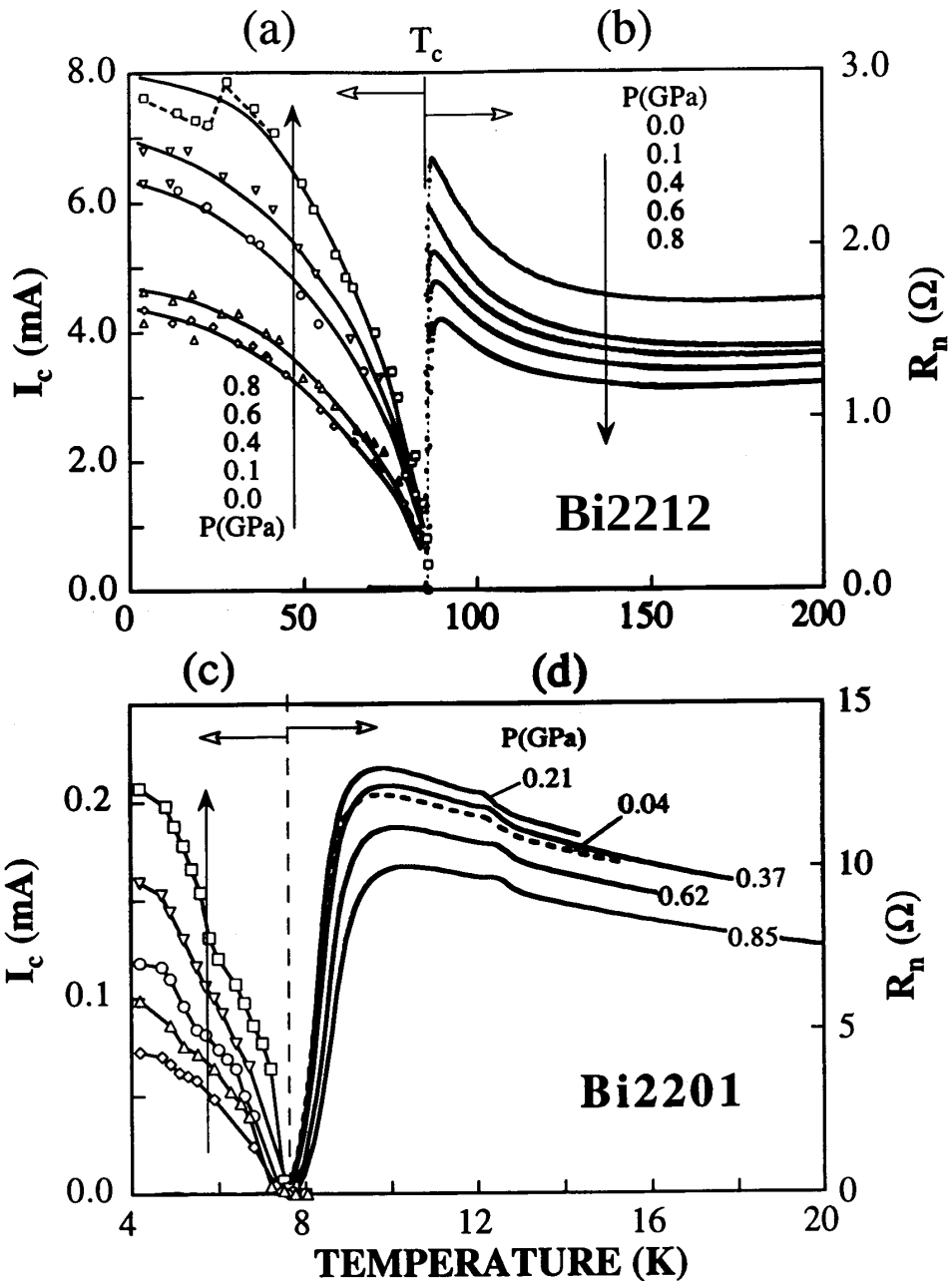
Bi-2212 Bi-2201



The pressure affects the c-axis transport but not the superconducting transition

INTERLAYER COUPLING AND PRESSURE

I_c goes up with pressure, but T_c remains about the same



CONCLUSIONS

- Fabrication – several methods
- Pseudogap and the superconducting gap seem to coexist – T, H, $HgBr_2$, pressure,...
- No evidence for the interlayer coupling theory for HTS from experiments on Bi2212 and Bi2201
- Intrinsic Josephson effect and vortex matter
- Multiple valued critical current

REFERENCES AND FURTHER READING

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- http://fy.chalmers.se/~winkler/
- http://fy.chalmers.se/~yurgens/ijj.html
- http://fy.chalmers.se/~krasnov/