Josephson effects in iron-based superconductors

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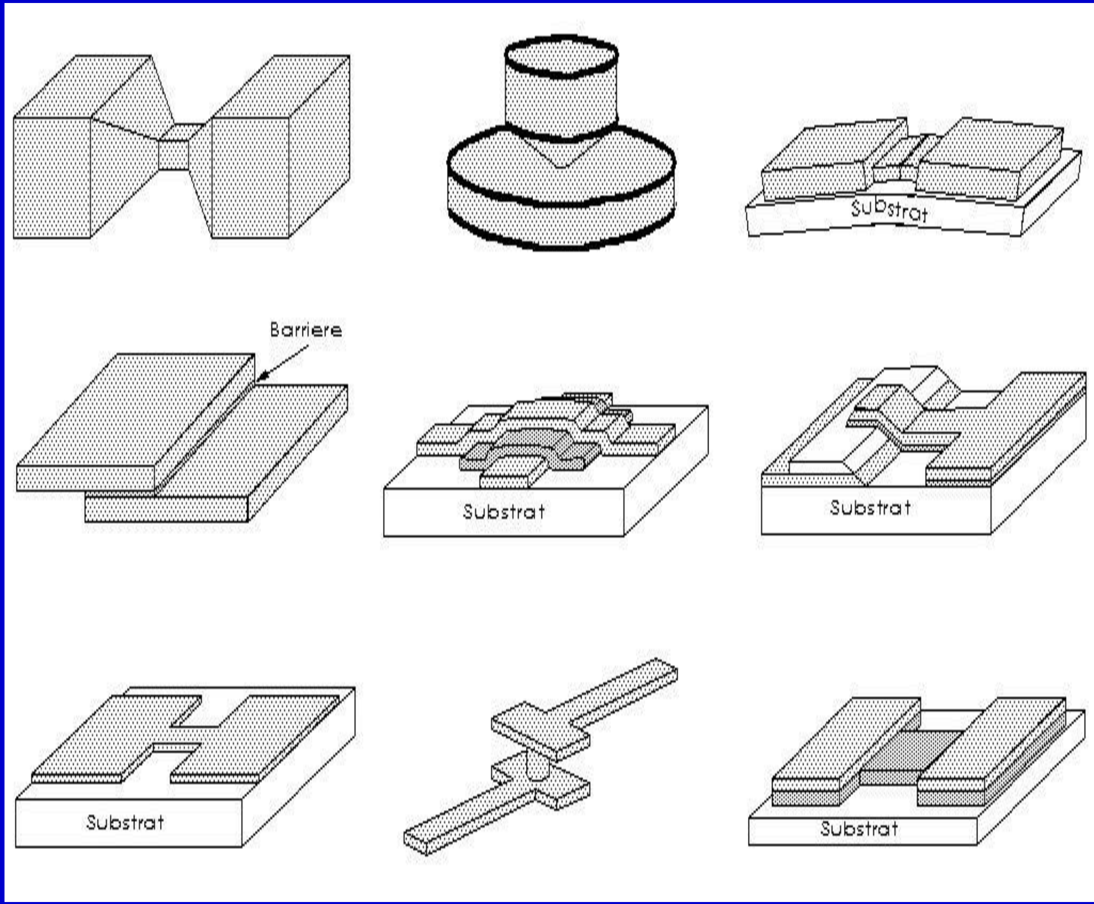
Many thanks to K. Iida, F. Kurth, M. Kidszun, S. Haindl, I. Mönch, L. Schultz, B. Holzapfel, IFW Dresden, Dresden, Germany

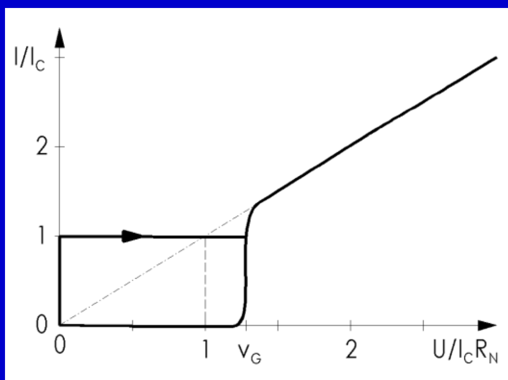
Content

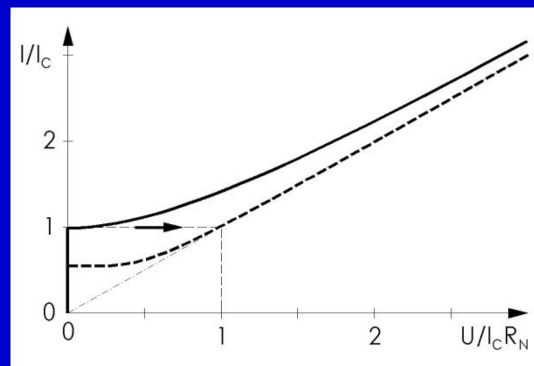
- 1. Josephson effects
- 2. Status of pnictide Josephson junctions
  - Native junctions
  - Thin film junctions (skipped to talk of S. Döring)
  - Grain boundary junctions
  - Intrinsic Josephson effect in pnictides
- 3. Corner junctions and SQUIDs

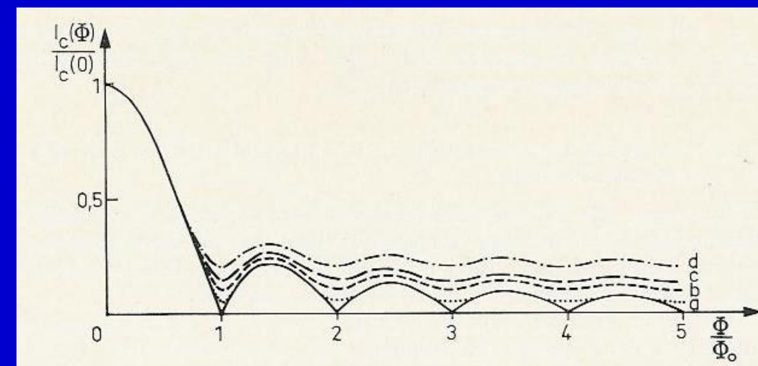
1. Josephson effects



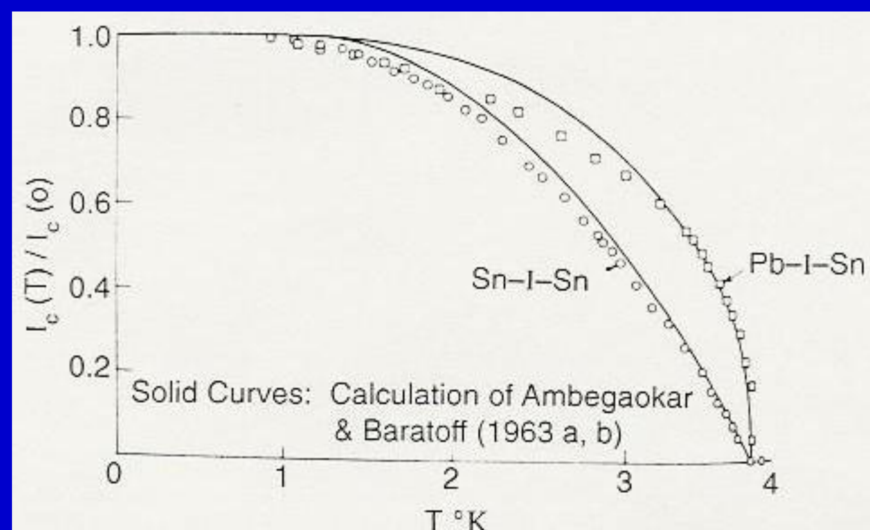
DC Josephson effect







$$I_C R_N = \frac{\pi}{2}\frac{\Delta}{e}$$



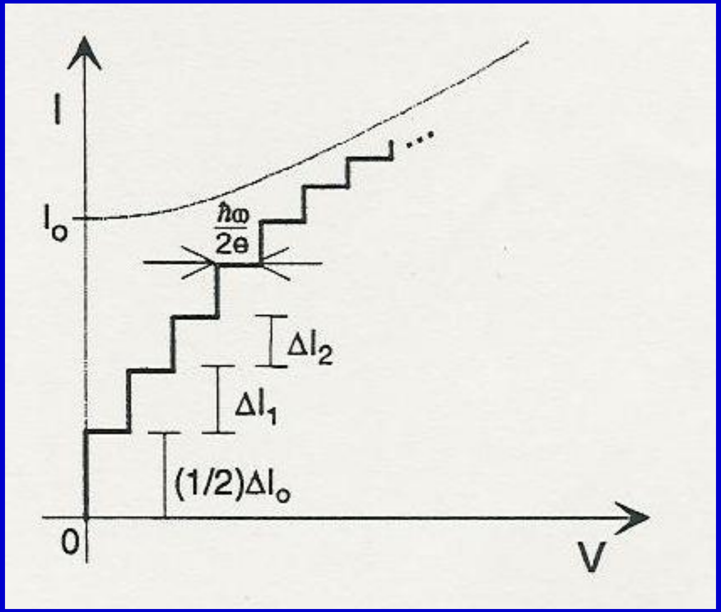
AC Josephson effect

$$V = \Phi_0 \cdot f \qquad \omega = \frac{2e}{\hbar} I_C R_N$$

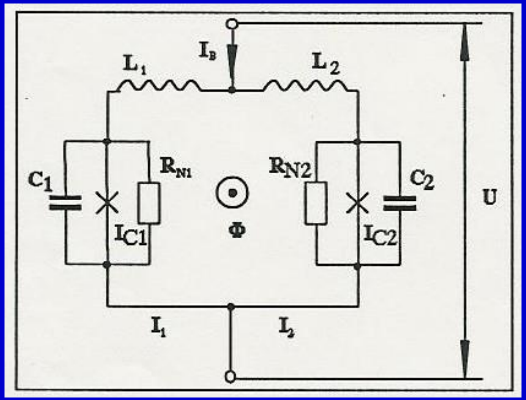
$$V_n = n\left(\frac{h}{2e}\right) f_{ex} = n\Phi_0 f_{ex}$$

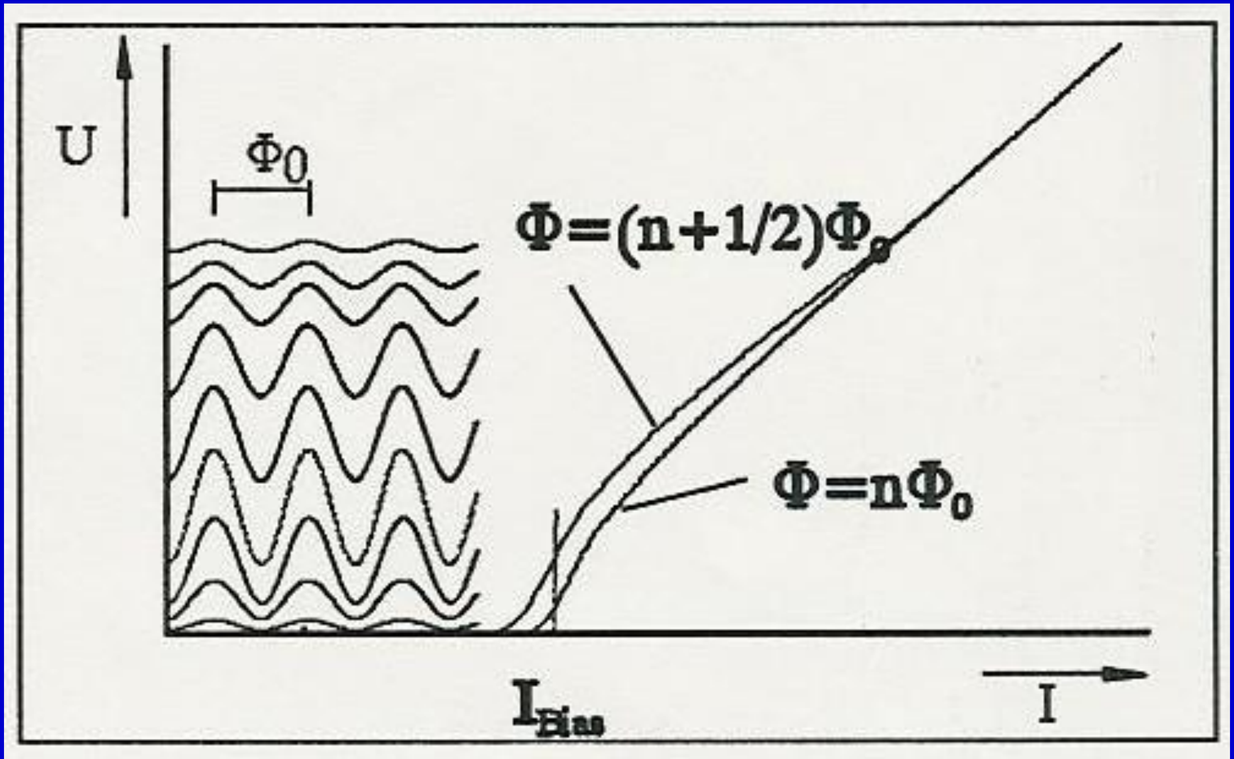
$$f / V = 483{,}6\, MHz / \mu V$$

$$\Omega = \frac{\omega_{ex}}{\omega_0}$$

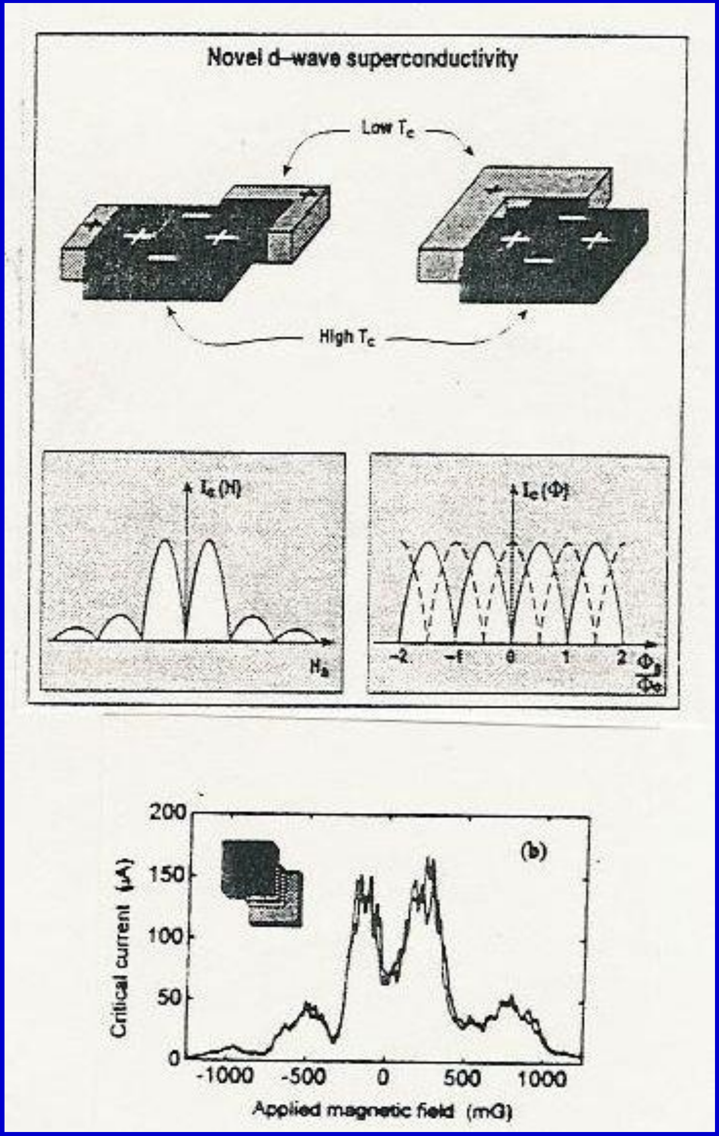


DC SQUID



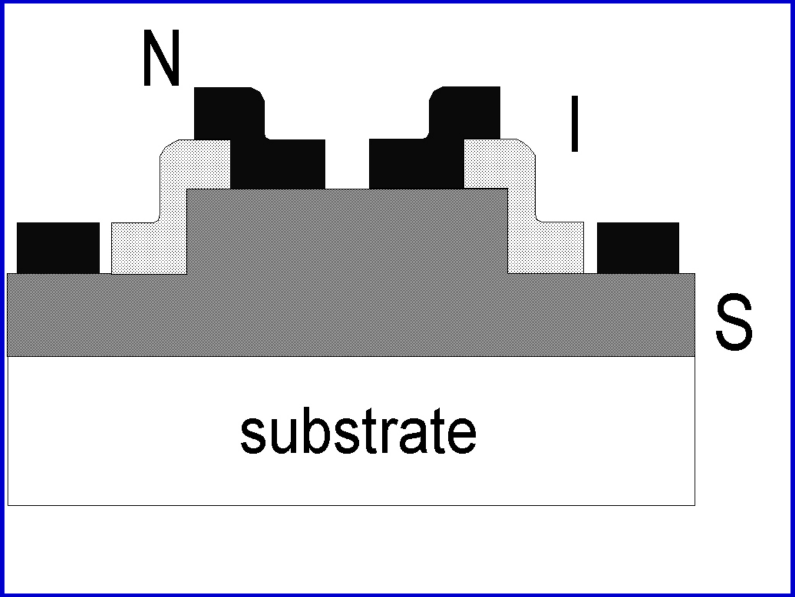


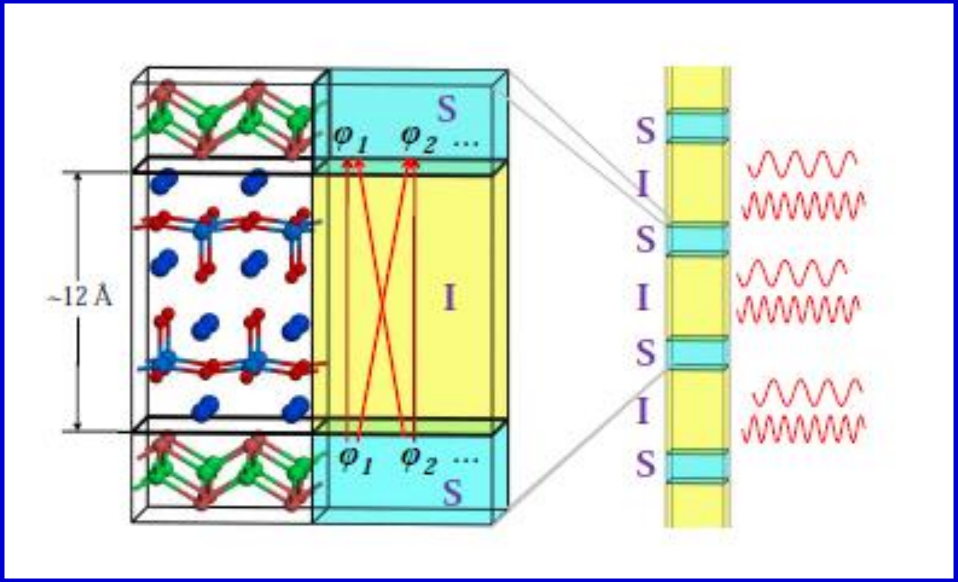
Corner junction



Π-SQUID

Intrinsic Josephson effect





H. Nakamura et al.

Main aims

- Realization of working types of tunneling and Josephson junctions
- Experimental verification of Josephson effects in the iron pnictides
- Comparison of main characteristics to conventional Josephson behaviour
- Determination of main parameters and dependencies incl. pairing symmetry
- Theoretical foundation and modelling

2. Status of pnictide Josephson junctions

IOP Publishing — Superconductor Science and Technology

Supercond. Sci. Technol. **24** (2011) 043001 (21pp) — doi:10.1088/0953-2048/24/4/043001

TOPICAL REVIEW

Josephson effects in iron based superconductors

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Trilateral Seminar on iron-based superconductors
October 2013

PRL **102,** 147002 (2009) PHYSICAL REVIEW LETTERS week ending 10 APRIL 2009

Observation of the Josephson Effect in $Pb/Ba_{1-x}K_xFe_2As_2$ Single Crystal Junctions

Xiaohang Zhang,[1] Yoon Seok Oh,[2] Yong Liu,[2] Liqin Yan,[2] Kee Hoon Kim,[2] Richard L. Greene,[1] and Ichiro Takeuchi[3]
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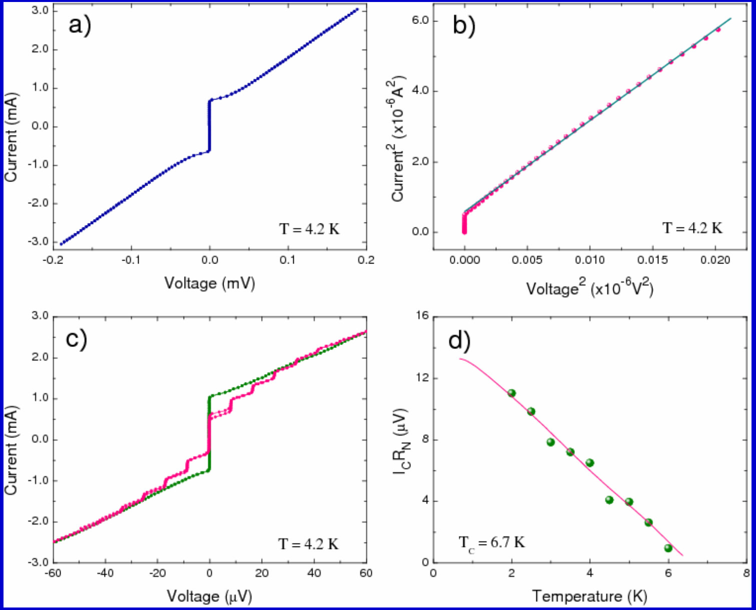
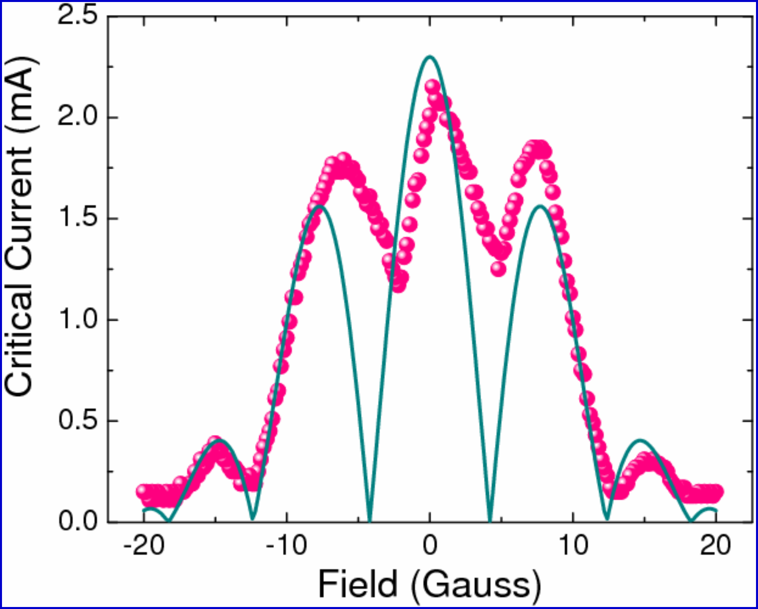
[2]*CSCMR & FPRD, Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Republic of Korea*
[3]*Department of Materials Science and Engineering, University of Maryland, College Park, Maryland 20742, USA*
(Received 15 December 2008; published 9 April 2009)





Trilateral Seminar on iron-based superconductors
October 2013

Corner junctions (d-wave)

Phase-Sensitive measurements on the corner junction of iron-based superconductor $BaFe_{1.8}Co_{0.2}As_2$

Yu-Rong Zhou[1], Yan-Rong Li[1,2], Jun-Wei Zuo[1], Rui-Yuan Liu[1], Shao-Kui Su[1], G. F. Chen[1], J. L. Lu[1], N. L. Wang[1], and Yun-Ping Wang[1*]
[1]*Beijing National Laboratory for condensed matter Physics, Institute of Physics, Chinese Academy of Sciences, P.O.Box 603, Beijing 100190, People's Republic of China*
and
[2]*Department of Physics, University of Science and technology of China, Hefei 230026, People's Republic of China*

(Dated: June 1, 2009)

We have made a phase-sensitive measurement on the corner junction of the iron-based superconductor $BaFe_{1.8}Co_{0.2}As_2$, and observed the typical Fraunhofer-like diffraction pattern. The result suggests that there is no phase shift between the *a*-*c* face and *b*-*c* face of a crystal, which indicates that the superconducting wave-function of the iron based superconductor is different from that of a cuprate superconductor.

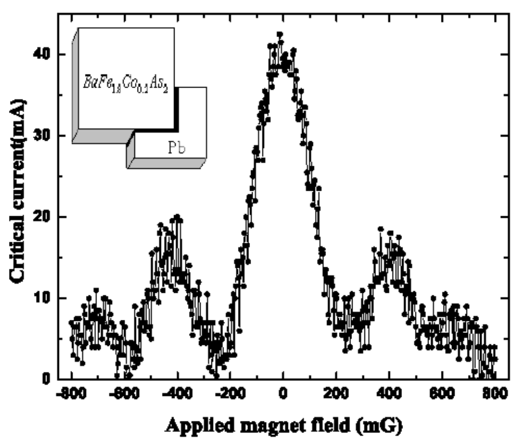


FIG. 3: The Fraunhofer diffraction pattern of the critical current as a function of magnetic field taken at 1.8K. Magnetic field is applied by a self-made NbTi superconducting coil, the maximum scanning range of magnetic field is -800mG~ 800mG, limited by the Joule heat in contacts.

ArXiv: 0812.3295 (2009)

Up to now unpublished

Trilateral Seminar on iron-based superconductors
October 2013

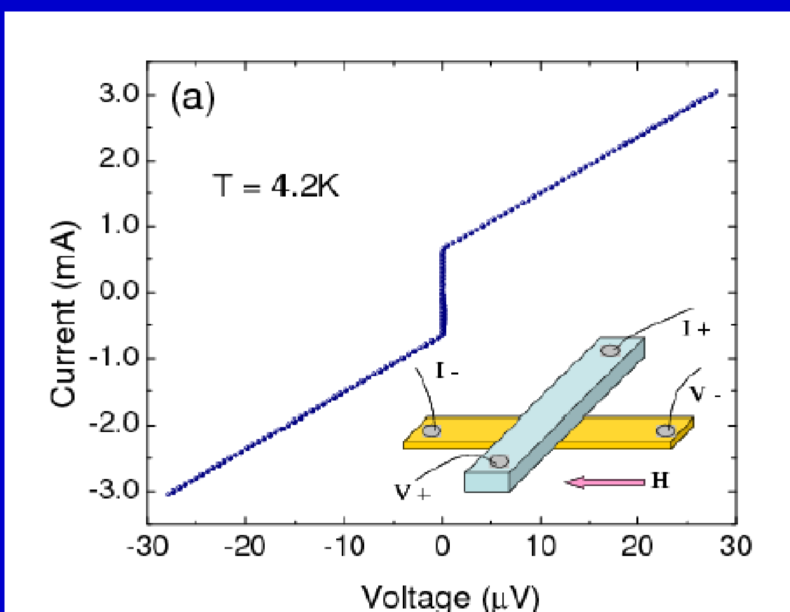
APPLIED PHYSICS LETTERS **95**, 062510 (2009)

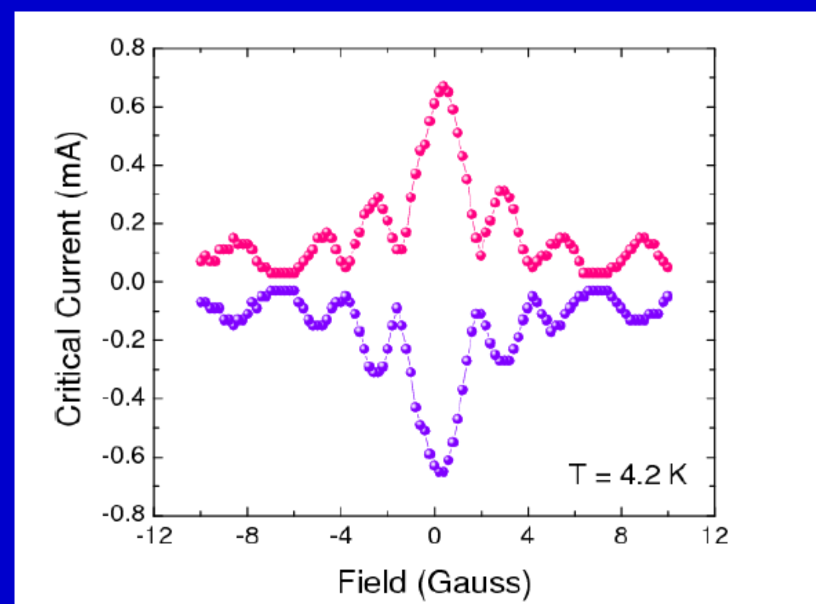
Josephson effect between electron-doped and hole-doped iron pnictide single crystals

Xiaohang Zhang,[1,a] Shanta R. Saha,[1] Nicholas P. Butch,[1] Kevin Kirshenbaum,[1] Johnpierre Paglione,[1] Richard L. Greene,[1] Yong Liu,[2] Liqin Yan,[2] Yoon Seok Oh,[2] Kee Hoon Kim,[2] and Ichiro Takeuchi[3]

[1]*Department of Physics and CNAM, University of Maryland, College Park, Maryland 20742, USA*
[2]*Department of Physics and Astronomy, CSCMR & FPRD, Seoul National University, Seoul 151-747, Republic of Korea*
[3]*Department of Materials Science and Engineering, University of Maryland, College Park, Maryland 20742, USA*

(Received 3 July 2009; accepted 24 July 2009; published online 14 August 2009)



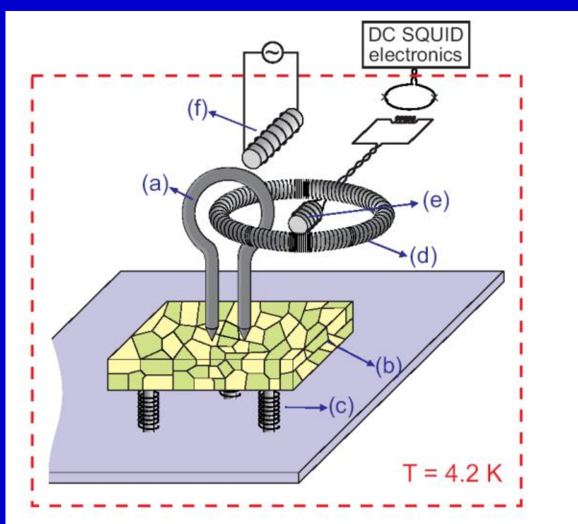


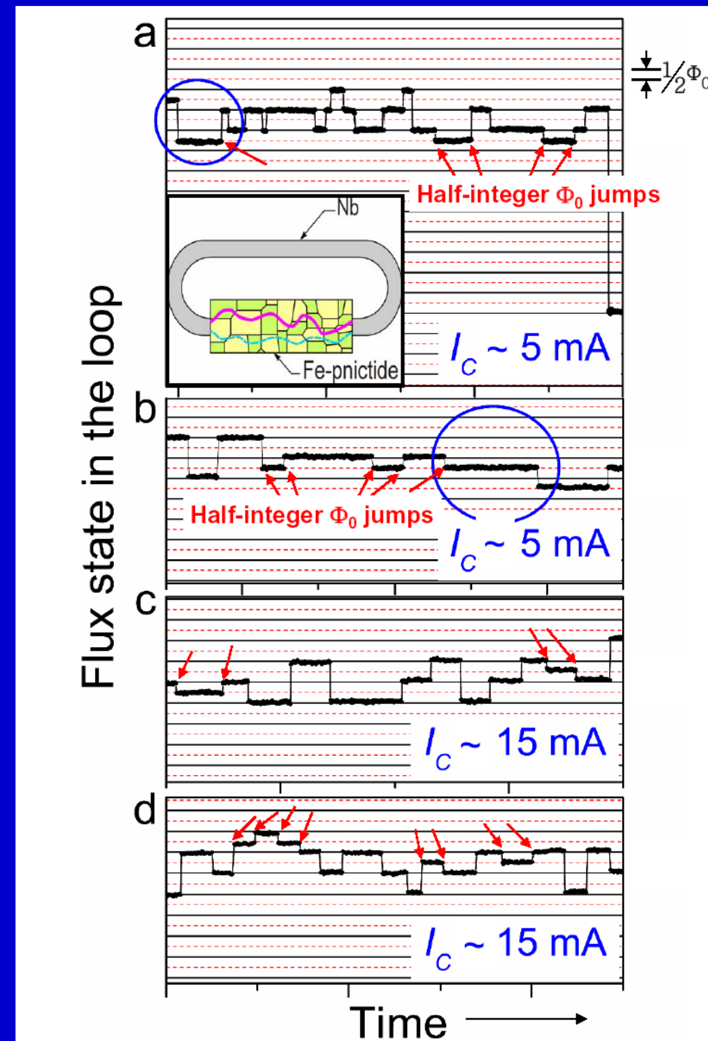
Integer and half-integer flux-quantum transitions in a niobium/iron-pnictide loop

C.-T. Chen[1], C. C. Tsuei[1], M. B. Ketchen[1], Z.-A. Ren[2] & Z. X. Zhao[2]

[1]*IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598, USA*

[2]*Institute of Physics and Beijing National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences, Beijing 100190, P. R. China*





Nature Physics 6 (2010) 260-264

Trilateral Seminar on iron-based superconductors
October 2013

Planar hybrid SNS' junctions

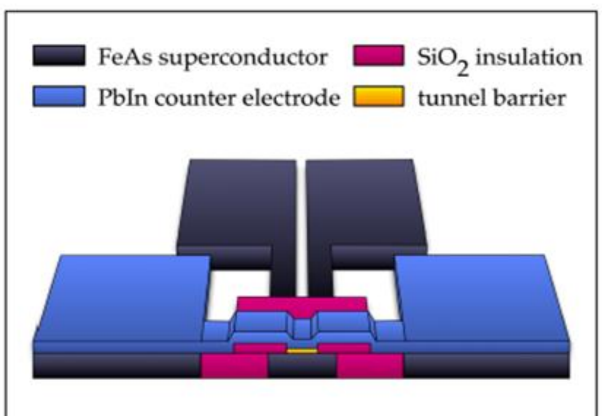
APPLIED PHYSICS LETTERS **97**, 172504 (2010)

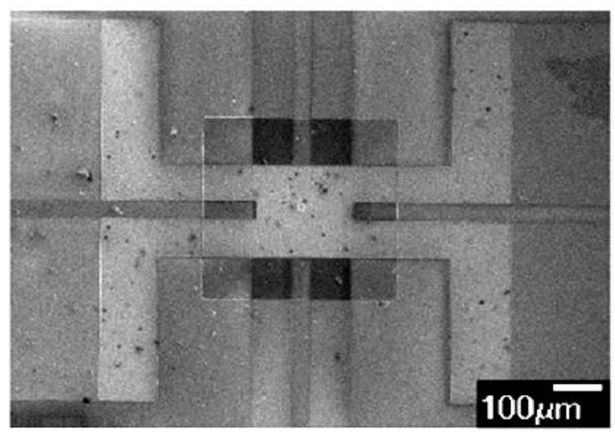
$BaFe_{1.8}Co_{0.2}As_2$ thin film hybrid Josephson junctions

S. Schmidt,[1] S. Döring,[1] F. Schmidl,[1] V. Grosse,[1] P. Seidel,[1,a)] K. Iida,[2] F. Kurth,[2] S. Haindl,[2] I. Mönch,[2] and B. Holzapfel[2]
[1]*Institut für Festkörperphysik, Friedrich-Schiller-Universität Jena, Helmholtzweg 5, 07743 Jena, Germany*
[2]*IFW Dresden, P.O. Box 270116, 01171 Dresden, Germany*

(Received 25 August 2010; accepted 5 October 2010; published online 28 October 2010)

Josephson junctions with iron pnictides open the way for fundamental experiments on superconductivity in these materials and their application in superconducting devices. Here, we present hybrid Josephson junctions with a $BaFe_{1.8}Co_{0.2}As_2$ thin film electrode, an Au barrier, and a PbIn counter electrode. The junction shows resistively shunted junction-like current-voltage characteristics up to the critical temperature of the counter electrode of about 7.2 K. The temperature dependence of the critical current shows nearly linear behavior near T_C. Well-pronounced Shapiro steps are observed at microwave frequencies of 10–18 GHz. Assuming an excess current of 200 μA at 4.2 K the effective $I_C R_N$ product calculates to 7.9 μV. © *2010 American Institute of Physics*. [doi:10.1063/1.3505526]





Hybrid edge-type junctions

Edge-type Josephson junctions with Co-doped Ba-122 thin films

S Döring[1], S Schmidt[1], F Schmidl[1], V Tympel[1], S Haindl[2], F Kurth[2], K Iida[2], I Mönch[2], B Holzapfel[2] and P Seidel[1]

[1] Institut für Festkörperphysik, Friedrich-Schiller-Universität Jena, Helmholtzweg 5, 07743 Jena, Germany
[2] Institut für metallische Werkstoffe, IFW Dresden, Postfach 270116, 01171 Dresden, Germany

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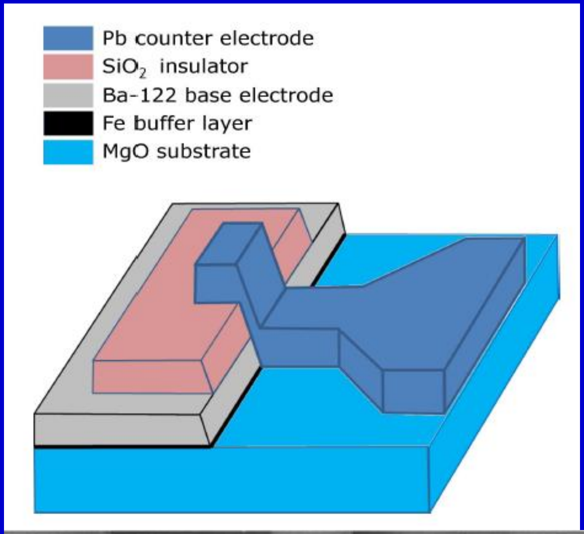
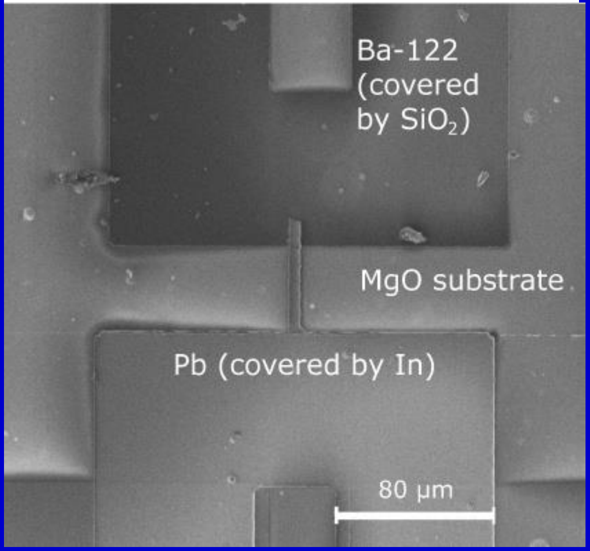
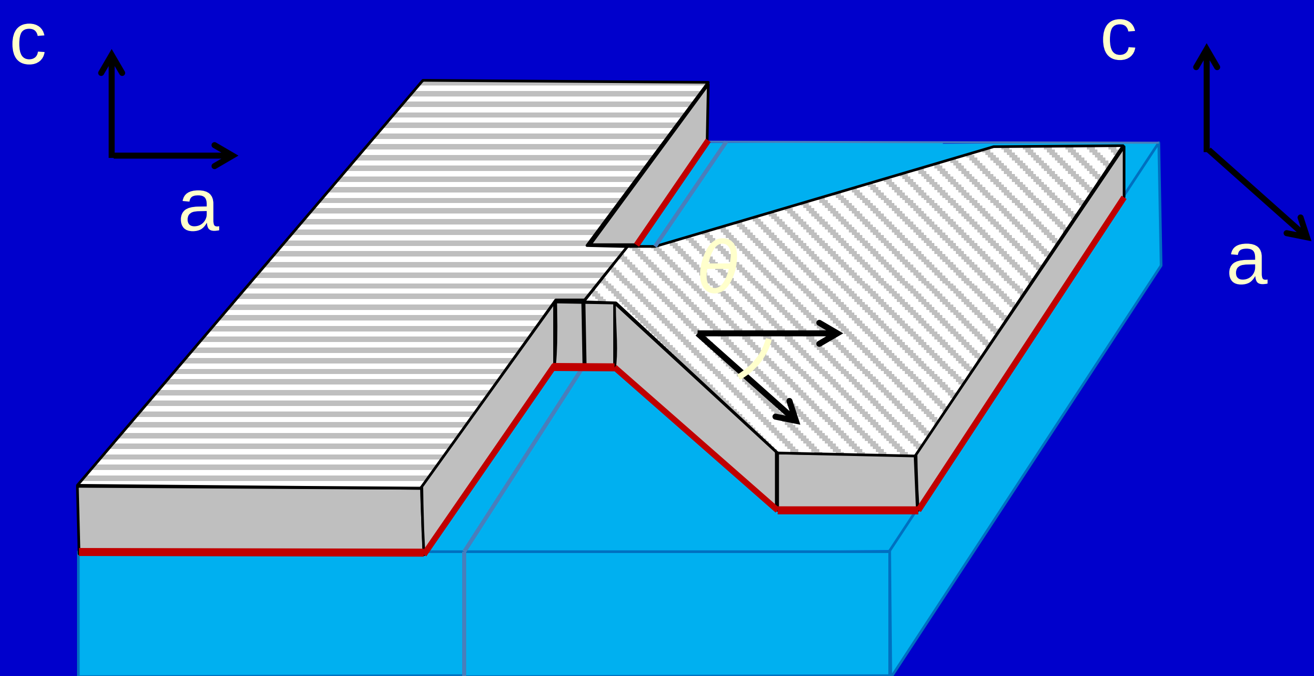
Online at stacks.iop.org/SUST/25/084020

Abstract
In this work we present preparation details and measurement results for an edge-type hybrid Josephson junction based on Co-doped $BaFe_2As_2$. The base electrode was formed by ion beam etching of a Ba-122 thin film, while the counter-electrode was patterned by evaporating lead. Finally, an indium protection layer was evaporated. The junction shows asymmetric *I–V*-characteristics with a total $I_C R_N$-product of about 12 μV. The characteristics can be fitted within a resistively shunted junction model assuming different fitting parameters for the positive and negative branches. There is a high excess current of unknown origin. The magnetic field dependence of the critical current indicates a non-homogeneous junction network and effects by flux trapping. It shows a variation of I_C in the positive as well as in the negative bias branch, but does not suppress it completely. Also the influence of microwave irradiation on the junctions is shown. Thereby I_C as well as the excess current can be suppressed, while first and higher order Shapiro steps can be observed.





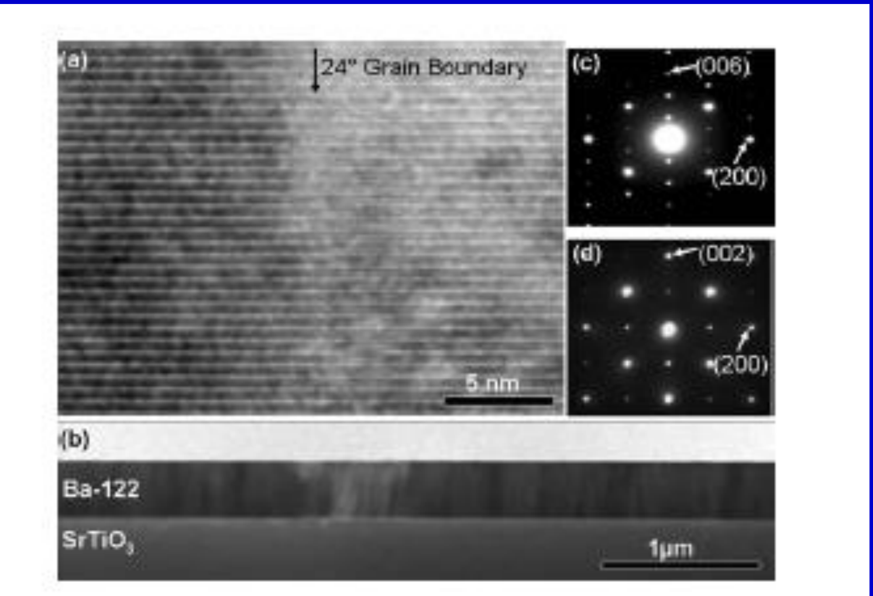
Grain boundary Bicrystal junctions

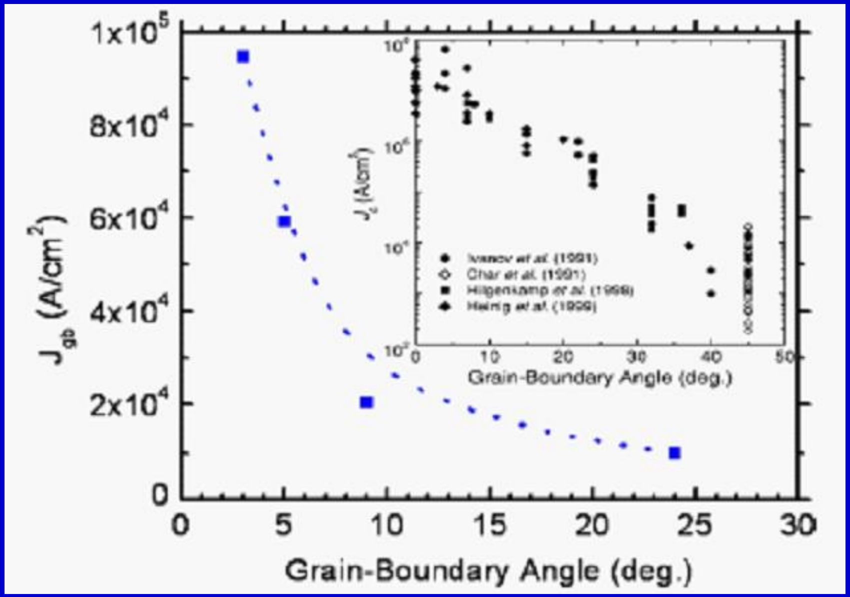


APPLIED PHYSICS LETTERS 95, 212505 (2009)

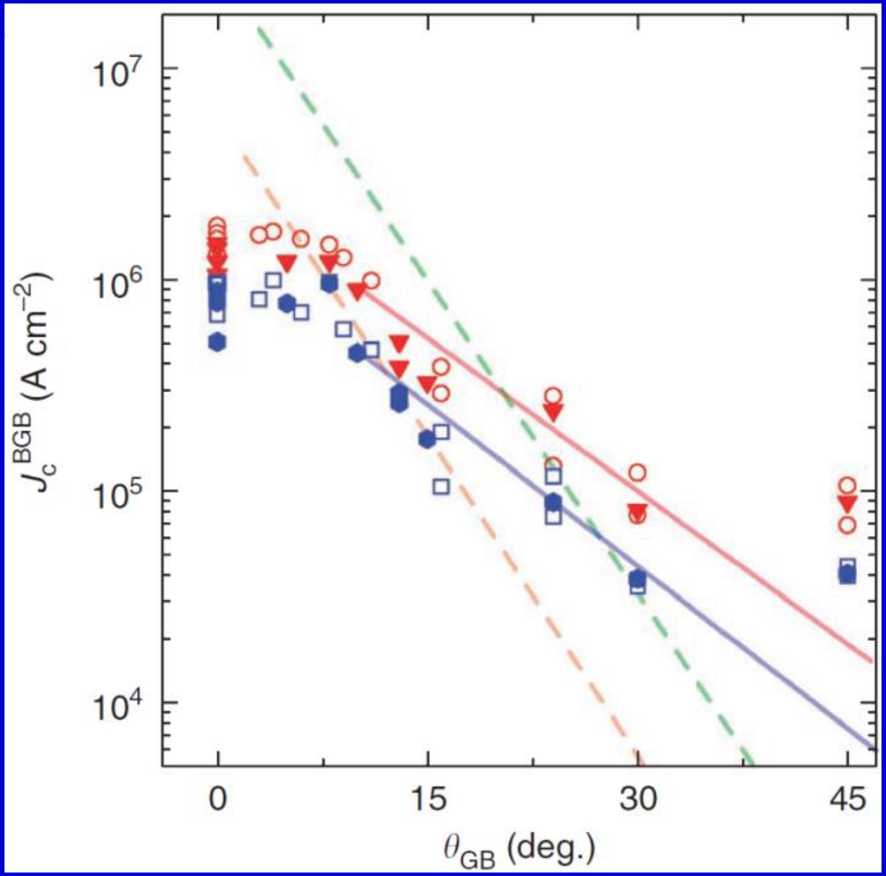
Weak-link behavior of grain boundaries in superconducting $Ba(Fe_{1-x}Co_x)_2As_2$ bicrystals

S. Lee,[1] J. Jiang,[2,a)] J. D. Weiss,[2] C. M. Folkman,[1] C. W. Bark,[1] C. Tarantini,[2] A. Xu,[2] D. Abraimov,[2] A. Polyanskii,[2] C. T. Nelson,[3] Y. Zhang,[3] S. H. Baek,[1] H. W. Jang,[1] A. Yamamoto,[2] F. Kametani,[2] X. Q. Pan,[3] E. E. Hellstrom,[2] A. Gurevich,[2] C. B. Eom,[1] and D. C. Larbalestier[2]





Ba-122



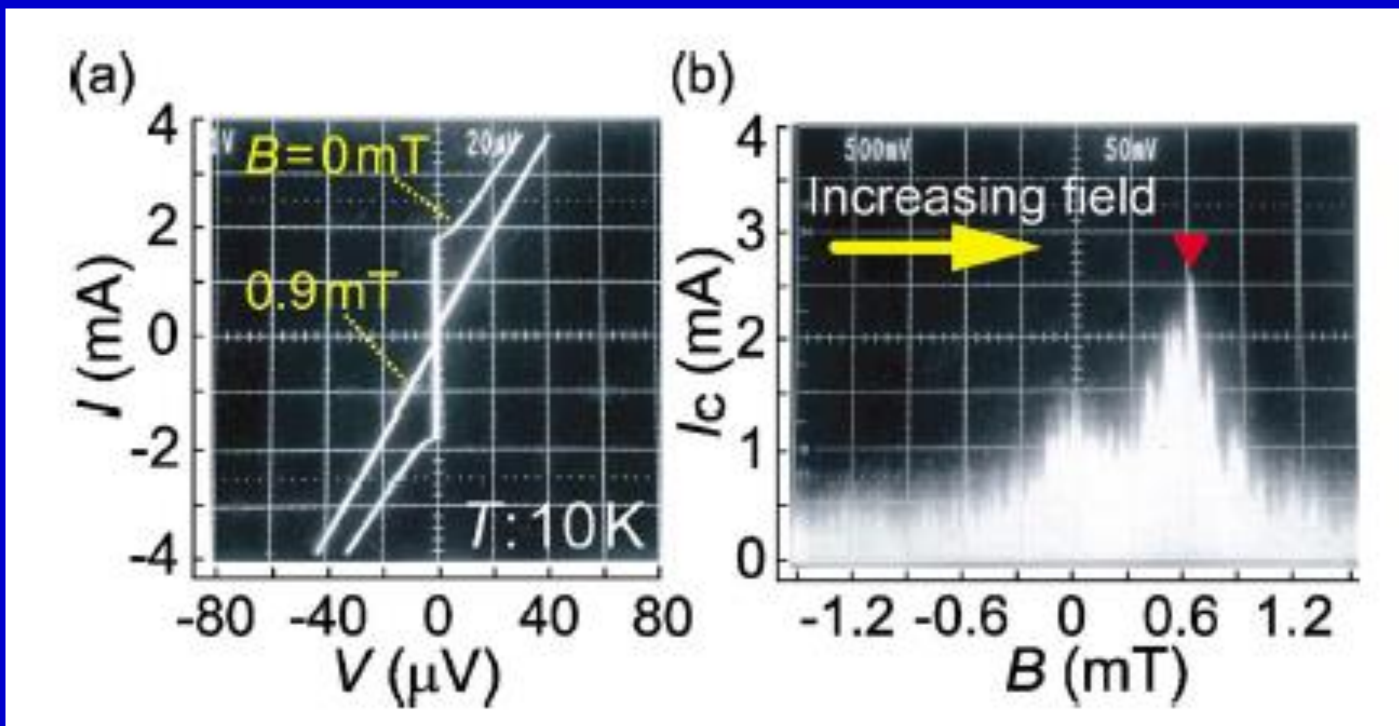
measurements on bicrystals
of MgO (open symbols)
and LSAT (closed symbols)

[Katase et al.]

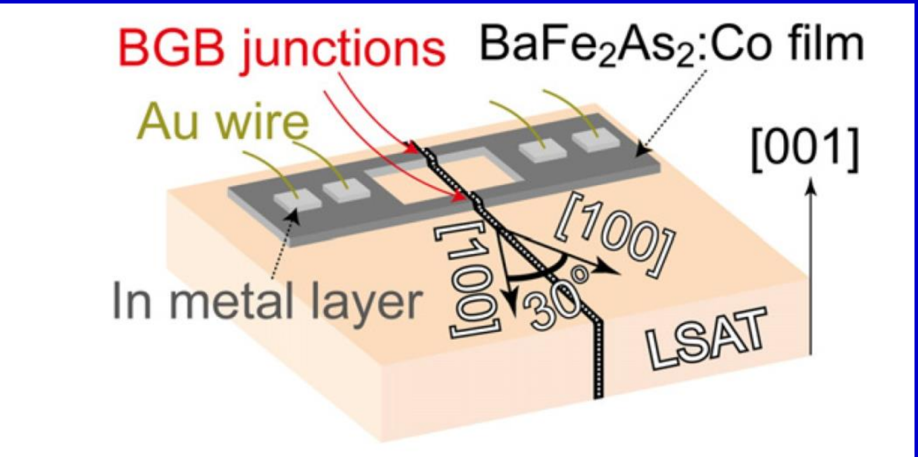
APPLIED PHYSICS LETTERS **96**, 142507 (2010)

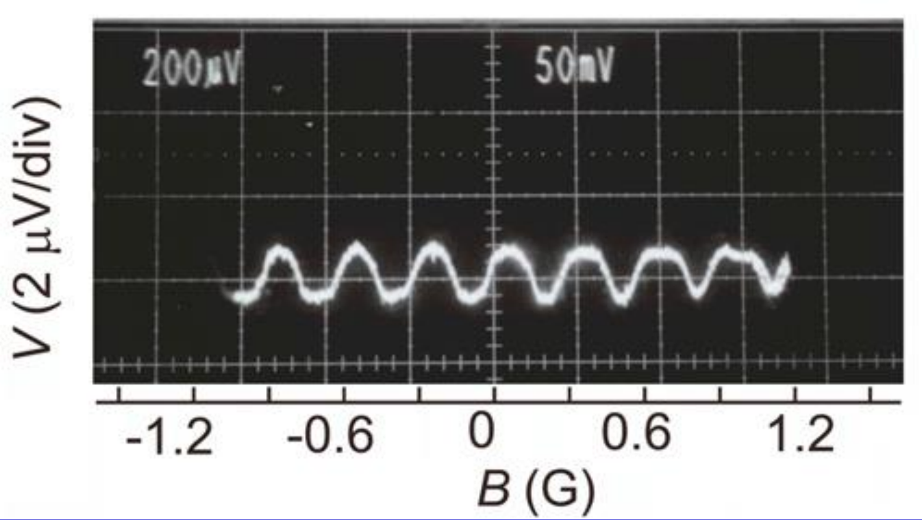
Josephson junction in cobalt-doped $BaFe_2As_2$ epitaxial thin films on $(La,Sr)(Al,Ta)O_3$ bicrystal substrates

Takayoshi Katase,[1,a)] Yoshihiro Ishimaru,[2] Akira Tsukamoto,[2] Hidenori Hiramatsu,[3]
Toshio Kamiya,[1] Keiichi Tanabe,[2] and Hideo Hosono[1,3]

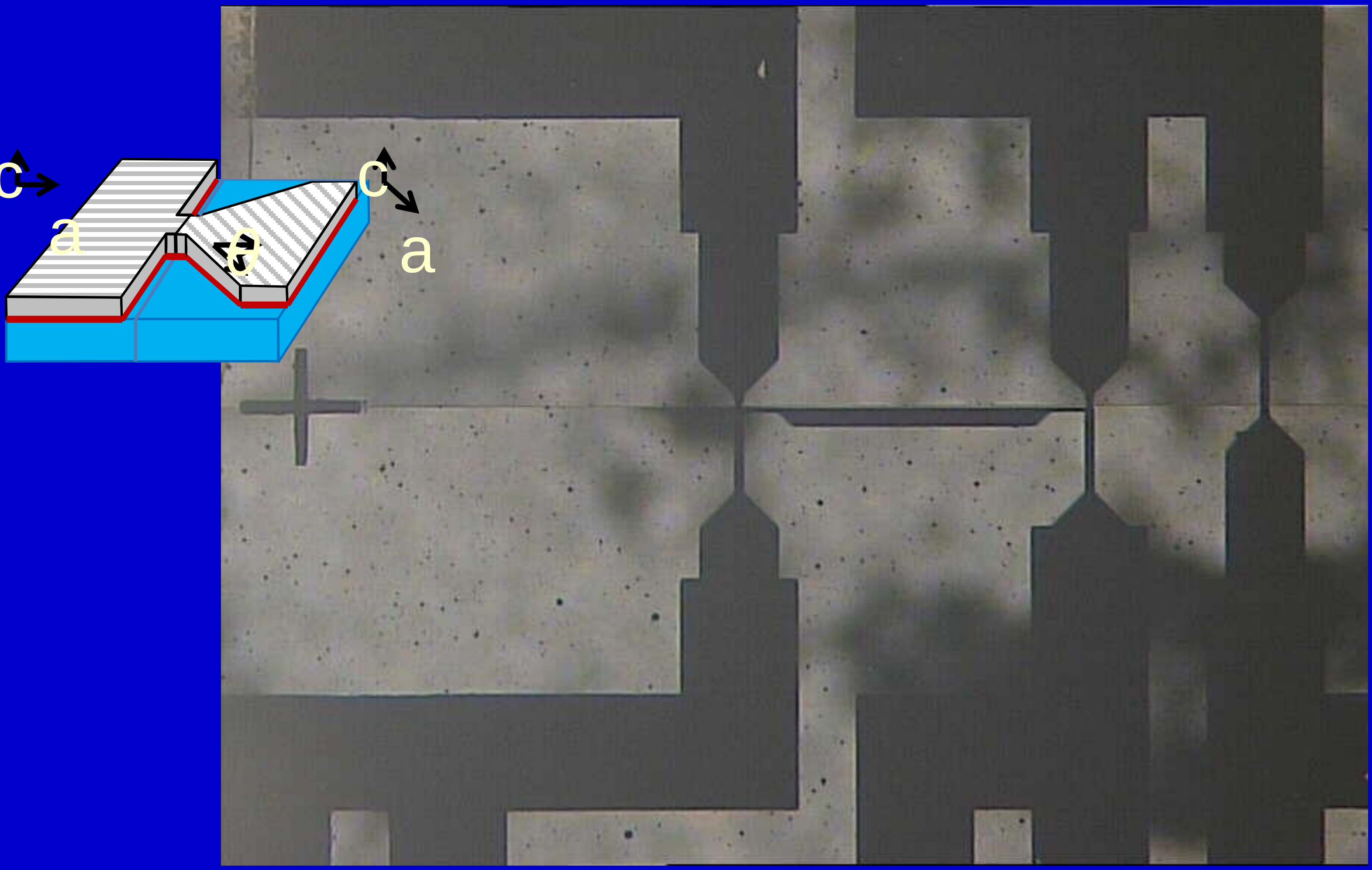


First SQUID





[Katase et al.]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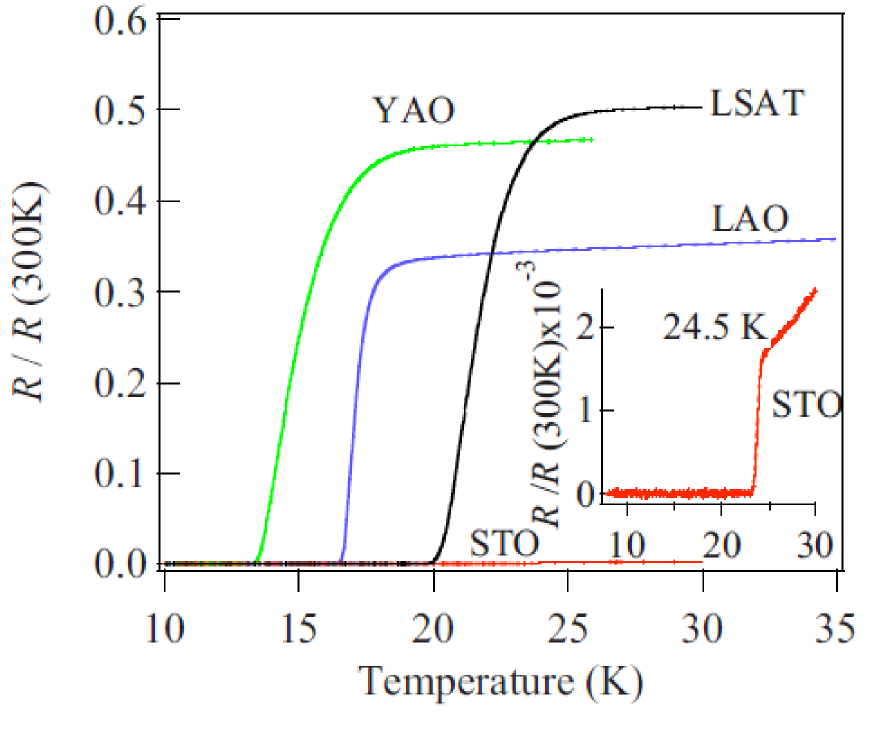
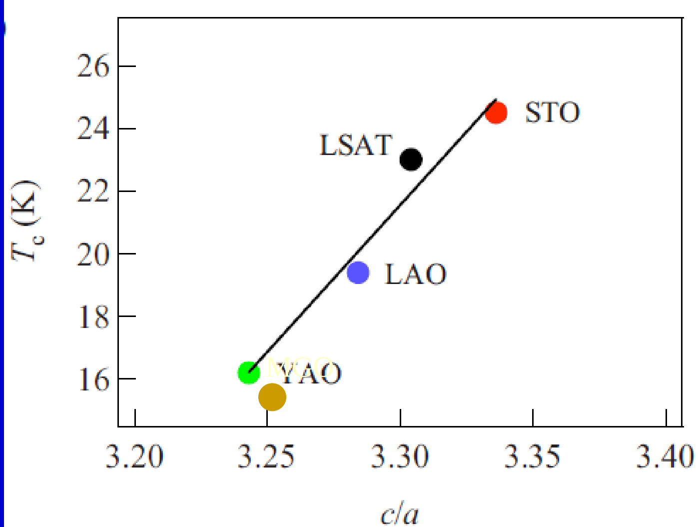
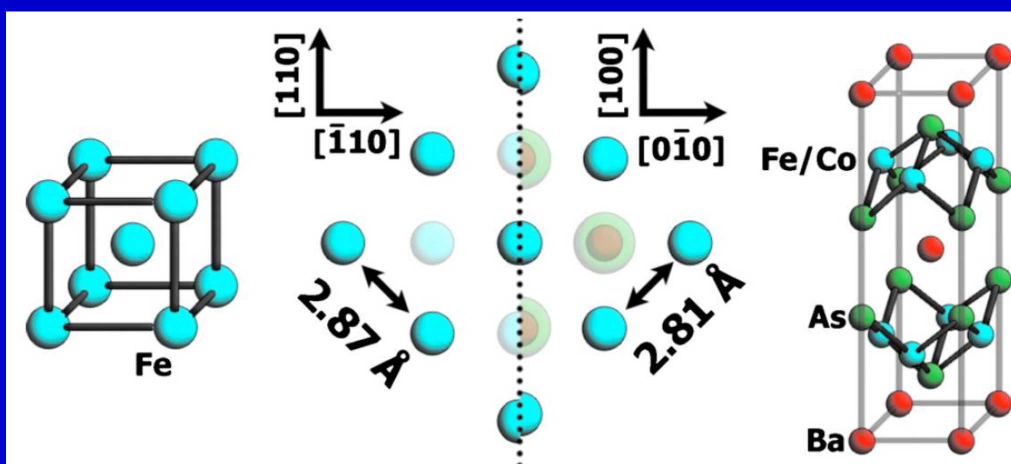
- STO is a better substrate material

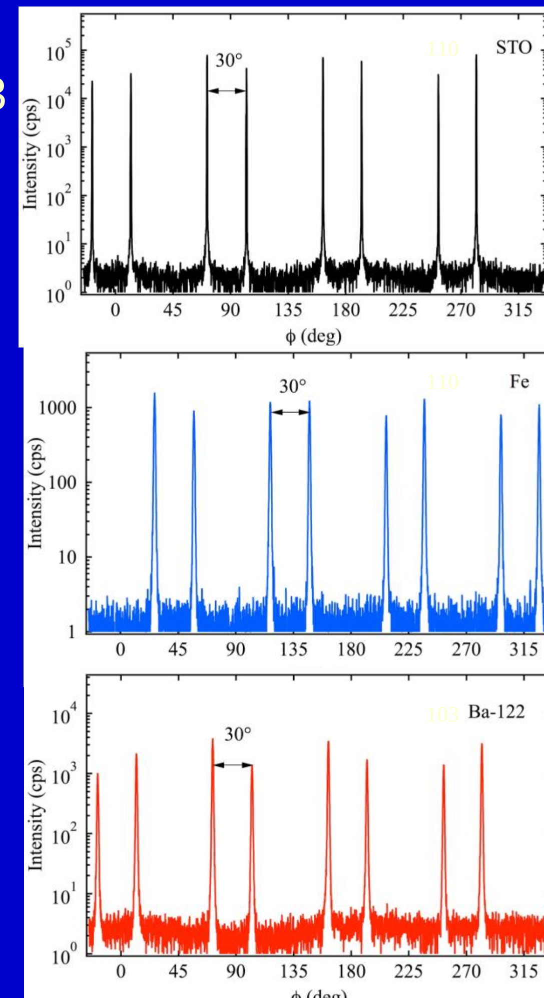




K. Iida et al.
Appl. Phys. Lett. 95 (2009) 192501

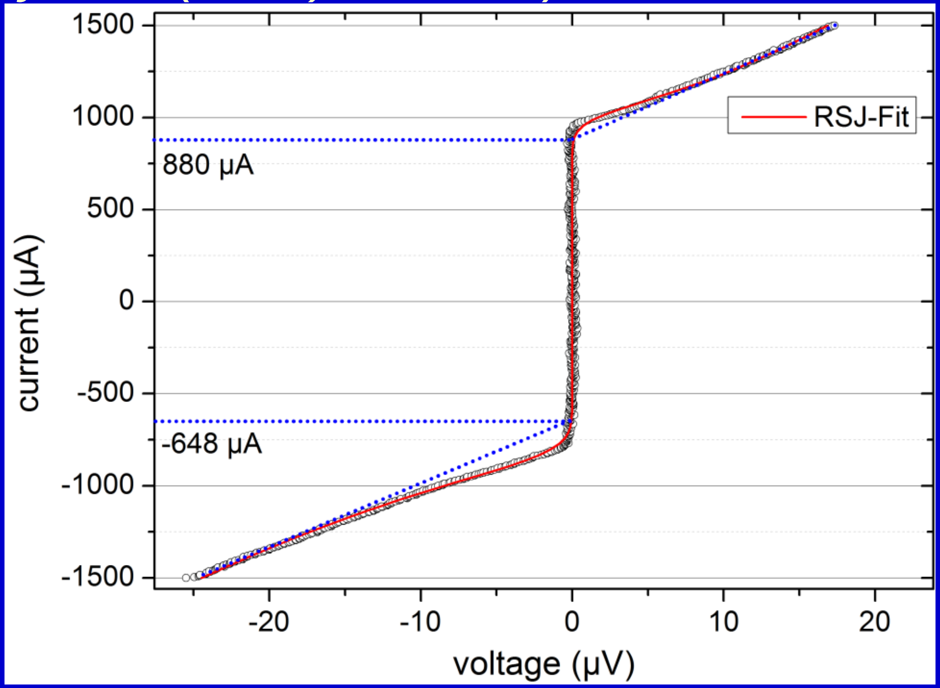
- Substrate material: [100]-tilt $SrTiO_3$
- $MgAl_2O_4$ buffer (10nm)
- Fe buffer layer (20nm)
- $Ba(Fe_{0.84}Co_{0.16})_2As_2$ (100nm)





T. Thersleff et al.
Appl. Phys. Lett. 97 (2010) 022506

- I-V curve with RSJ-Fit
  (fitted as in P.A. Lee, *J. Appl. Phys. 42 (1971) 325-334*)
  → Asymmetric
  → Excess current I_{ex}



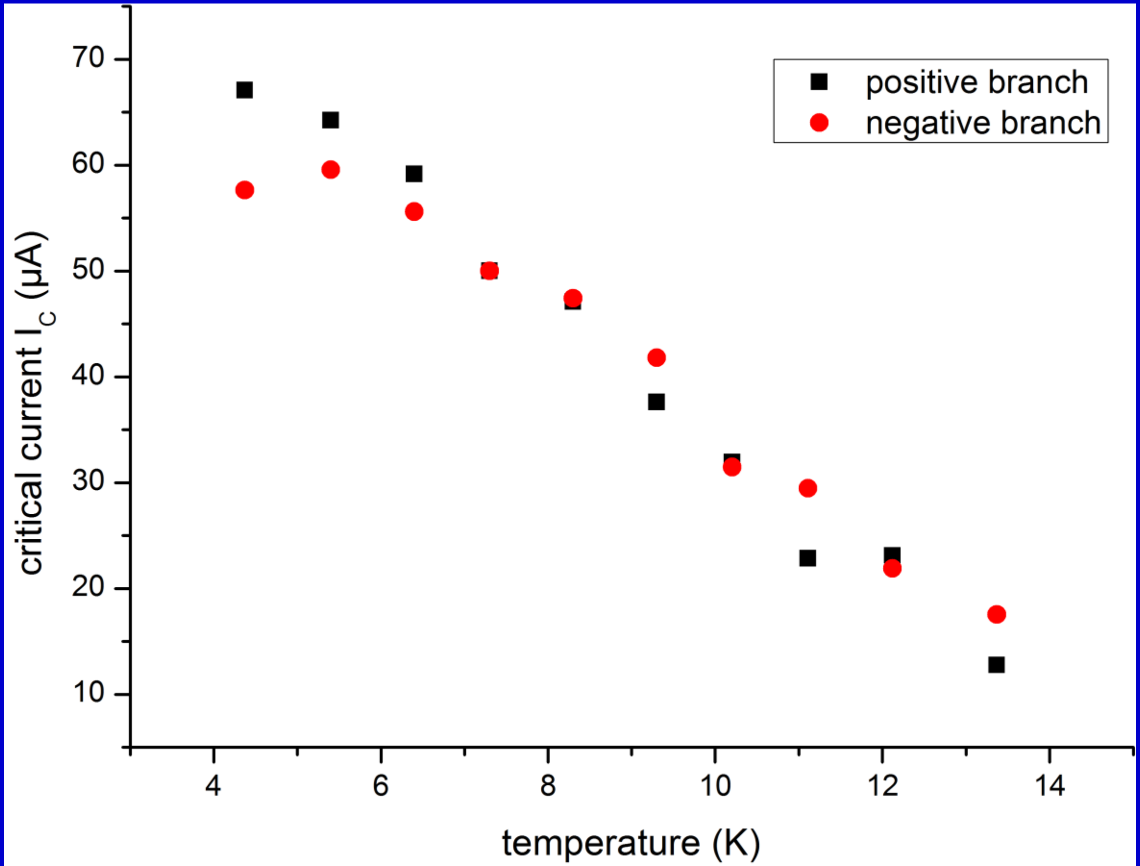
- $I_C R_N$ products:
  19.9 µV (incl. I_{ex})
  6.3 µV (corrected)

- Corrected j_C of 6.8 $*10^4$ A/cm² (bridge width 14µm)

temperature dependence

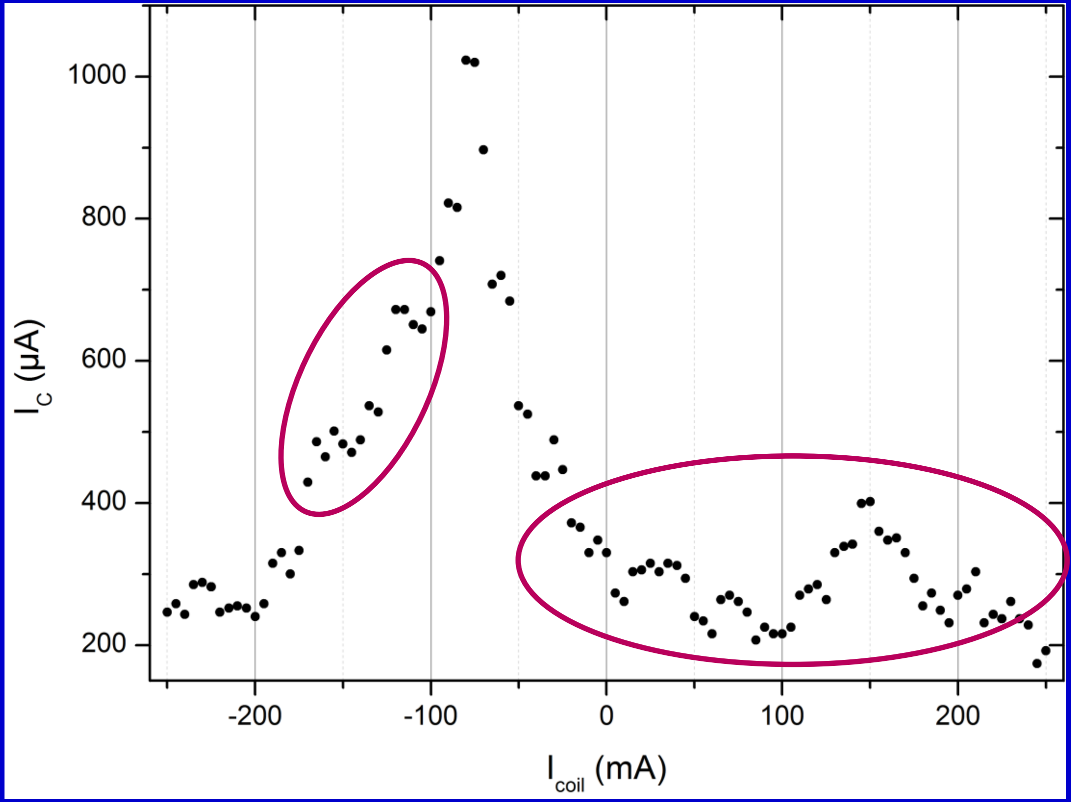
- Almost linear decrease of the critical current
  (after IBE treatment to remove gold shunt)

- Very small I_C



magnetic field dependence

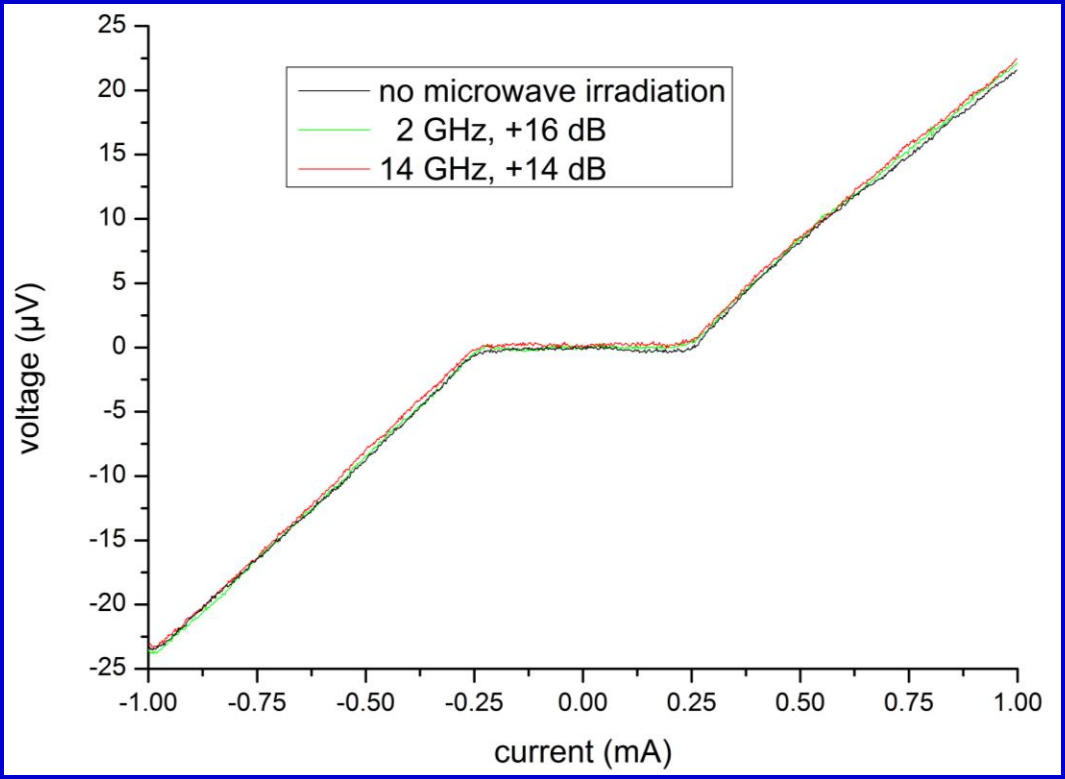
- Fraunhofer-similar pattern
  → excess current
  → asymmetric



- Long junction?
- Influence of Fe-buffer layer?

microwave irradiation studies

- No Supression of I_C, no Shapiro steps



- Samples are shunted through **gold cap layer**
  → IBE treatment influences BGB dramatically!
  → gold etching rates are being examined

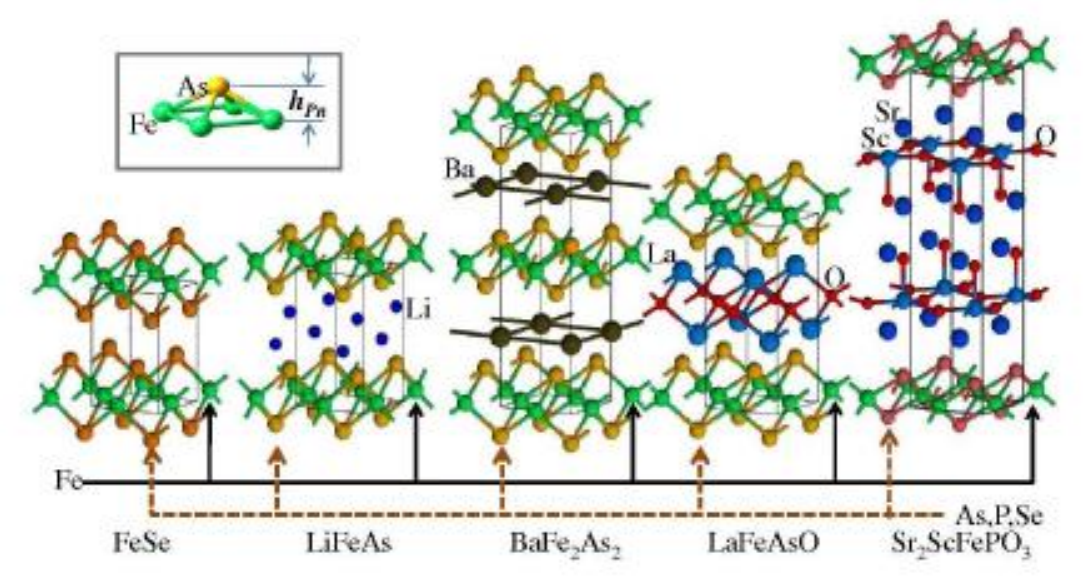
- Samples are shunted through **iron buffer layer**
- Unknown magnetic influence of iron thin films
  → not avoidable on STO substrates
  → CaF_2 substrates/substrate coatings are promising

Trilateral Seminar on iron-based superconductors
October 2013

Intrinsic JJ ?

TABLE I: Lattice constants a and c, the height h_{Pn} of As, P , or Se ions from the Fe-plane, and the anisotropy parameters of the resistivity and the penetration depth at zero temperature. a, c, and h_{Pn} are experimental values as the input parameters for the first-principles calculations, and γ_ρ and γ_λ are the calculated ones.

	a[Å]	c[Å]	h_{Pn}[Å]	$\gamma_\rho(0)$	$\gamma_\lambda(0)$
FeSe	3.7738	5.5248	1.4652	18.44	4.29
LiFeAs	3.7914	6.3639	1.6769	9.06	3.01
$BaFe_2As_2$	3.9625	13.0168	1.3602	10.69	3.27
LaFePO	3.9636	8.5122	1.1398	17.34	4.16
LaFeAsO	4.020	8.7034	1.3238	116.8	10.81
$Sr_2ScFePO_3$	4.016	15.543	1.1984	6.19×10^5	248



H. Nakamura et al.

APPLIED PHYSICS LETTERS **96**, 202504 (2010)

C-axis critical current of a $PrFeAsO_{0.7}$ single crystal

H. Kashiwaya,[1,a)] K. Shirai,[1,2] T. Matsumoto,[1] H. Shibata,[1] H. Kambara,[1] M. Ishikado,[1,3,4] H. Eisaki,[1,4] A. Iyo,[1,4] S. Shamoto,[3,4] I. Kurosawa,[2] and S. Kashiwaya[1]
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[2]*Japan Women's University, Tokyo 112-8681, Japan*
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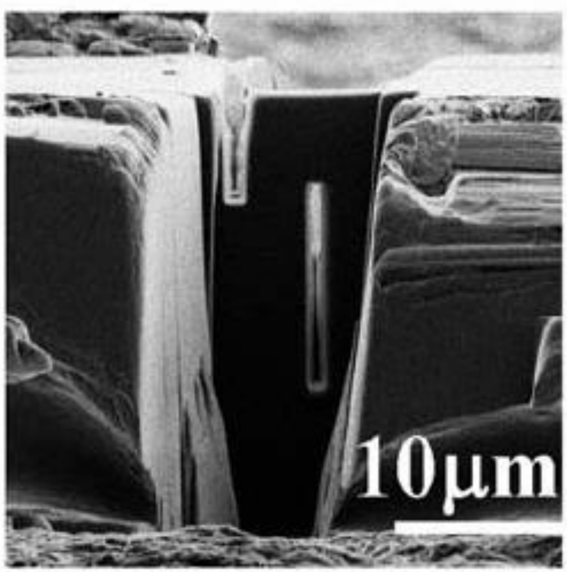

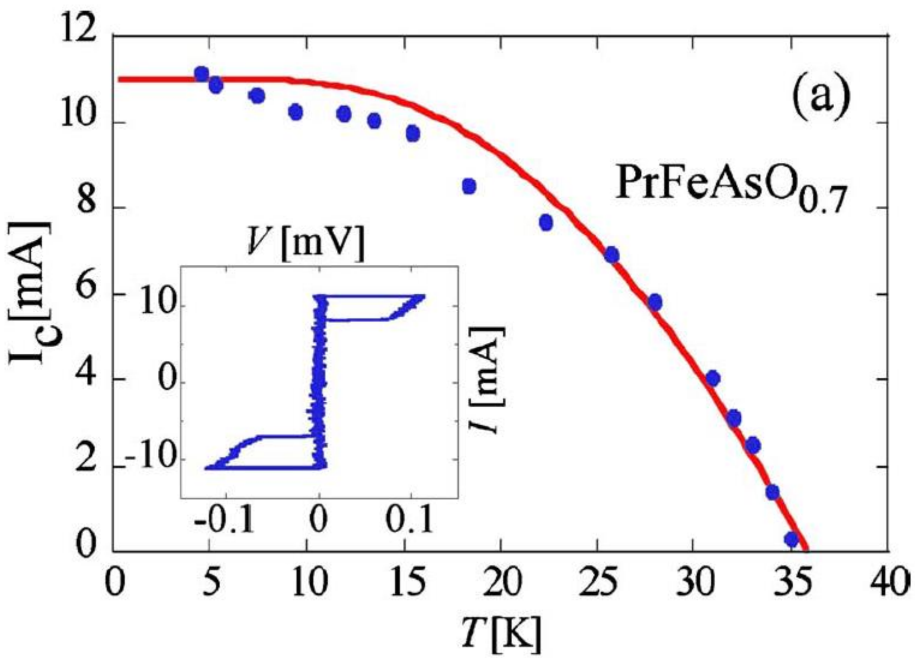

Trilateral Seminar on iron-based superconductors
October 2013

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Absence of a Tunneling Character in c-axis Transport of $SmFeAsO_{0.85}$ Single Crystals

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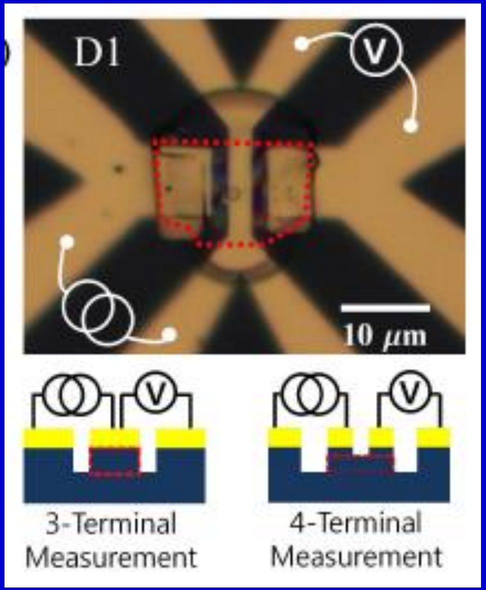
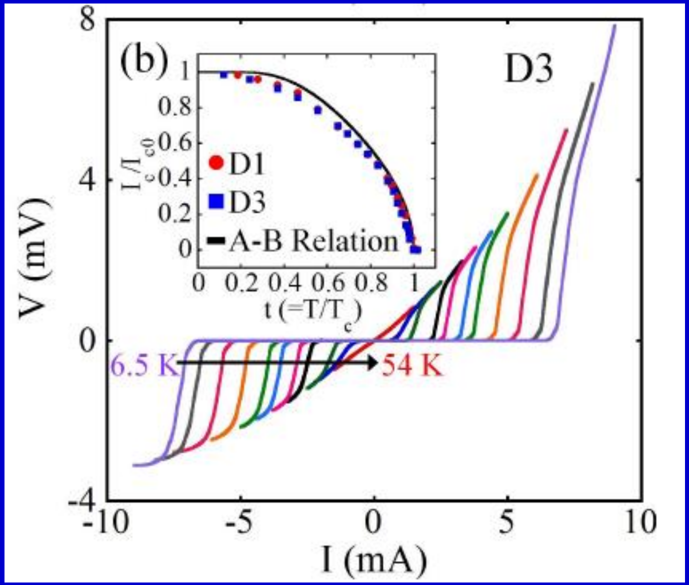
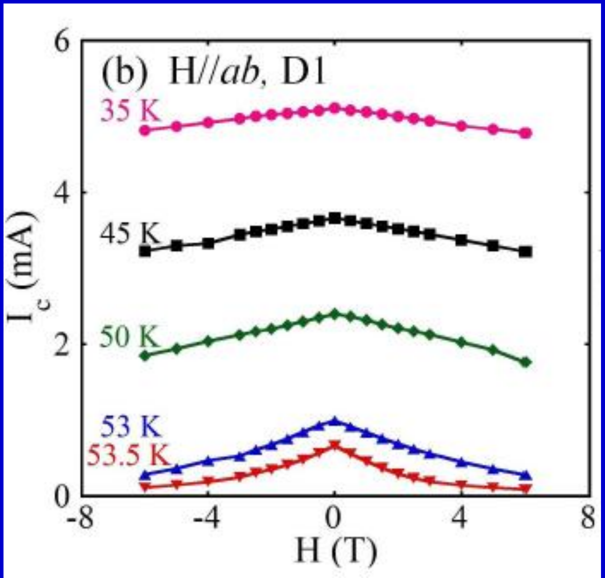
$\gamma = 5$

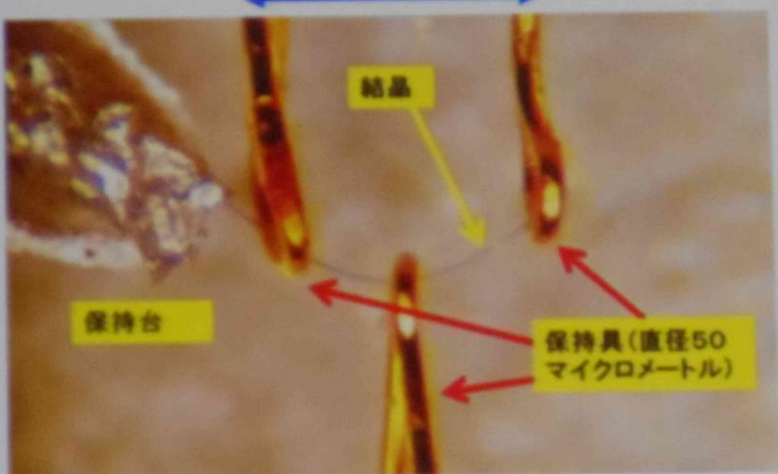






$Ca_{10}(Pt_4As_8)(Fe_{1.8}Pt_{0.2}As_2)_5$

1 mm

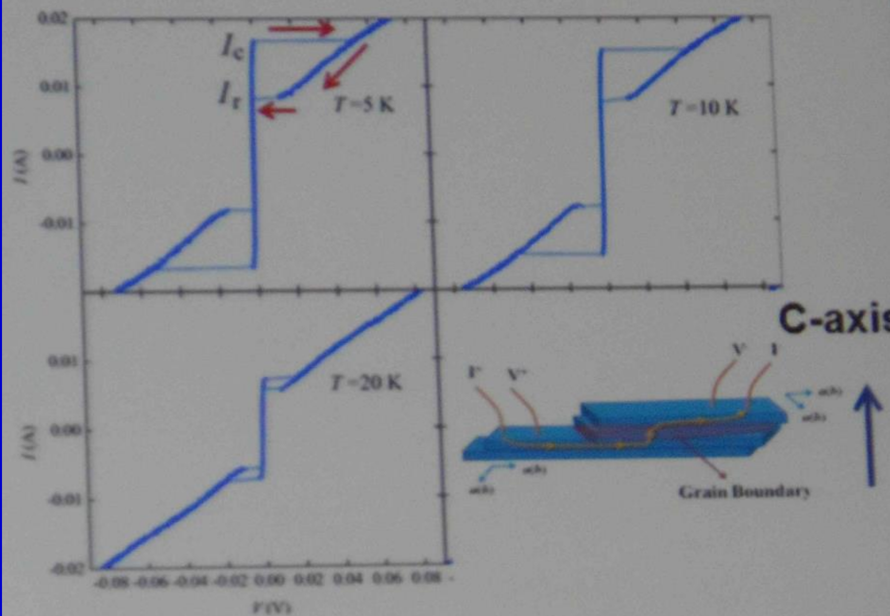


$Ca_{10}(Pt_4As_8)(Fe_{1.8}Pt_{0.2}As_2)_5$

Diameter $< 1\ \mu m$

Length ~ 2 mm

Intrinsic JJ



SIS Josephson Junction (diameter $\sim 2 \mu m$), clear hysteresis in J-V curve

NIMS Muromachi G. JACS (2012)

[Hosono]

Status:Pnictide JJs

Pnictide electrode	Weak link	Counter-electrode	IV	$I_c R_N$ (4.2 K) (μV)	$I_c(T)$	$I_c(H)$ FH-like	MW f (GHz)	Reference
122 sc	Native	Pb tip or Pb film	RSJ	3–300	Linear	Yes	4	[103]
122 sc	Native	Pb film				Yes		[104]
122 sc	Native	122 sc (crossed)	RSJ			Yes	2.5, 4	[107]
122 film	GBJ	122 film	RSJ	50–60	Linear	No		[109]
122 film	Au	PbIn film	RSJ + excess	8–20	Linear		10–18	[106]
1111 sc	Intrinsic	1111 sc	Hyst.	10	AB			[111]
1111 sc	Intrinsic	1111 sc	Hyst.	125	AB			[112]

[P. Seidel, Supercond. Sci. Technol. 24 (2011) 043001]

4. Corner junctions and SQUIDs

PRL **102,** 227007 (2009) PHYSICAL REVIEW LETTERS week ending 5 JUNE 2009

Possible Phase-Sensitive Tests of Pairing Symmetry in Pnictide Superconductors

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(Received 23 December 2008; published 5 June 2009)

The discovery of the new class of pnictide superconductors has engendered a controversy about their pairing symmetry, with proposals ranging from an extended *s* wave or "$s_{\pm}$" symmetry to nodal or nodeless *d*-wave symmetry to still more exotic order parameters such as *p* wave. In this Letter, building on the earlier, similar work performed for the cuprates, we propose several phase-sensitive Josephson interferometry experiments, each of which may allow resolution of the issue.

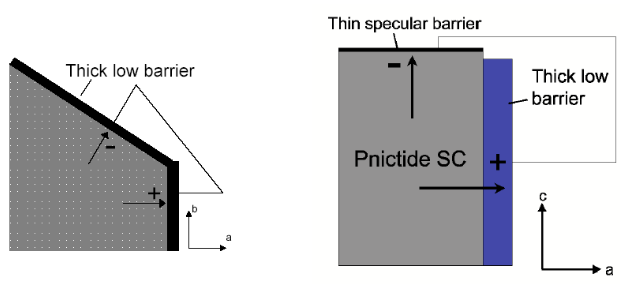
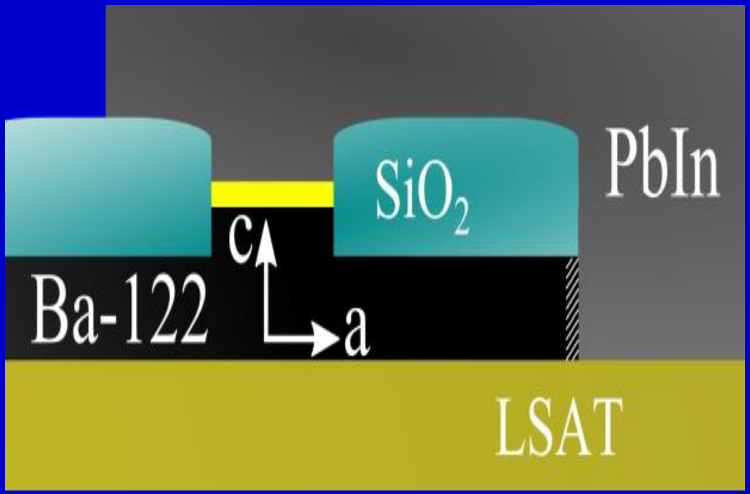


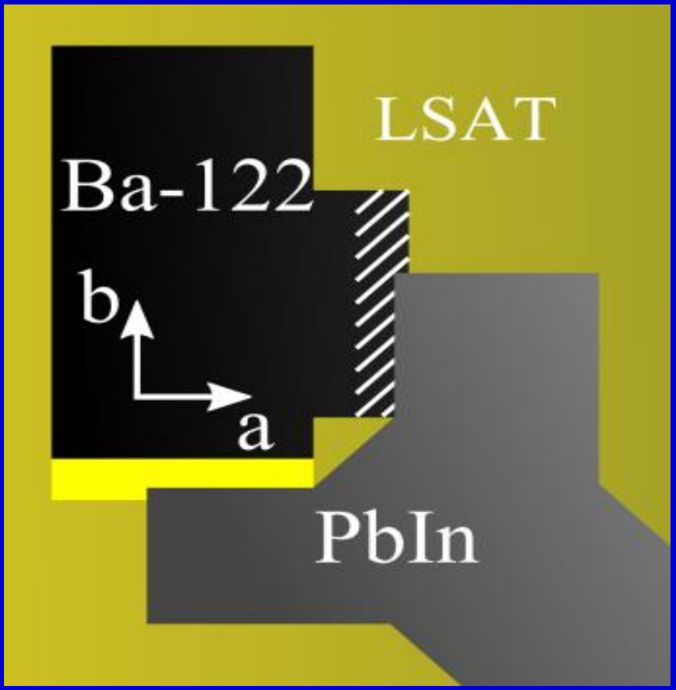
FIG. 2: A schematic view of tunneling geometry for two possible experiments: left, a (100) -near-(110) orientation, right, an ac orientation with specular and thick barriers as indicated.

Test for extended s-wave

- No combination of tunneling directions (a and b equivalent)
- Specular (infinitely thin) barrier can give no result (all wavevectors contribute)
- Thick barriers ! (tunneling normally to interface is prefered!)
- 1) Angles of about 30 degrees
- 2) Corner junction with different barriers

Layouts for phase-sensitive corner junctions





Döring et al. *Phys. Proc.* **27** (2012) 296

New proposals by Golubov & Mazin

APPLIED PHYSICS LETTERS **102**, 032601 (2013)

Designing phase-sensitive tests for Fe-based superconductors

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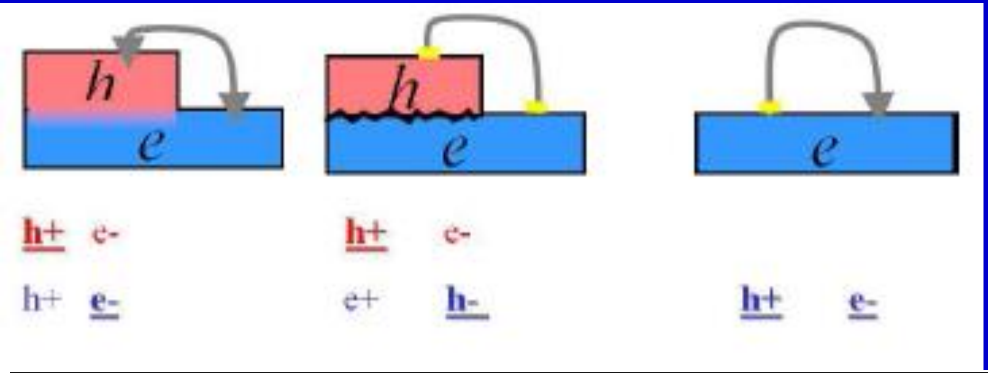
(Received 12 September 2012; accepted 3 January 2013; published online 22 January 2013)

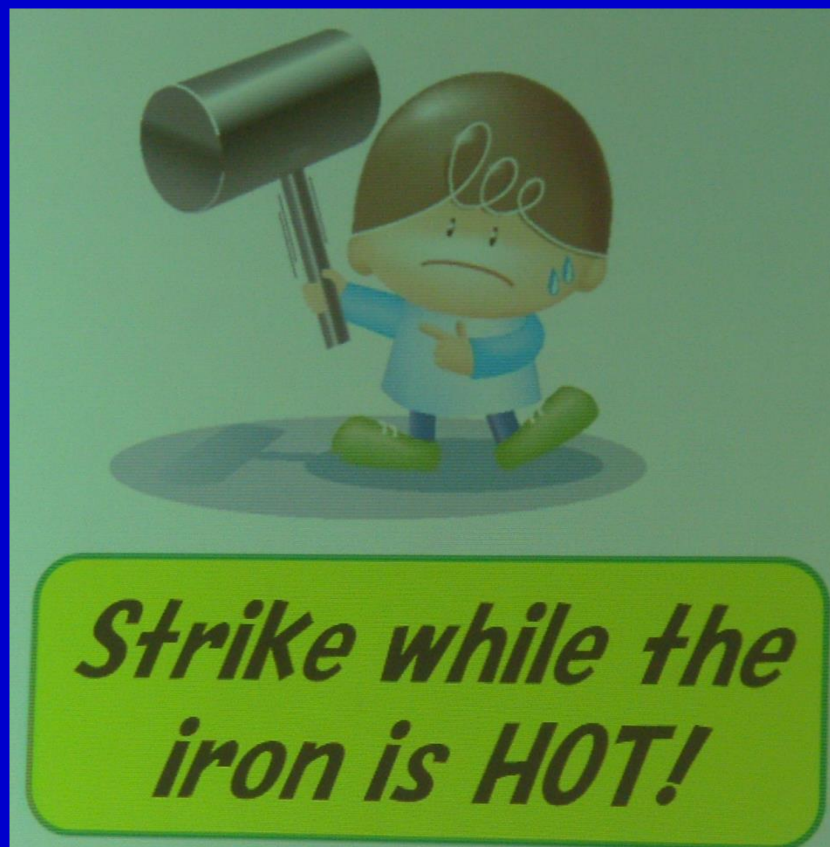
We suggest experimental designs suitable to test pairing symmetry in multiband Fe-based superconductors. These designs are based on combinations of tunnel junctions and point contacts and should be accessible by existing sample fabrication techniques. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4788720]

New proposals by Golubov & Mazin



Design			
Fig. 1 panel	Left	Middle	Right
Upper/left contact	Point	Tunnel	Tunnel
Lower/right contact	Point	Tunnel	Point
Upper Δ_{hole}	$-$	$+$	$+$
Upper Δ_{elec}	$+$	$-$	$-$
Interface	Epitaxial	Rough	n/a
Lower Δ_{hole}	$-$	$-$	n/a
Lower Δ_{elec}	$+$	$+$	n/a
Upper contact current dominated by	Electrons	Holes	Holes
Lower contact current dominated by	Holes	Holes	Electrons

Thank you !



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