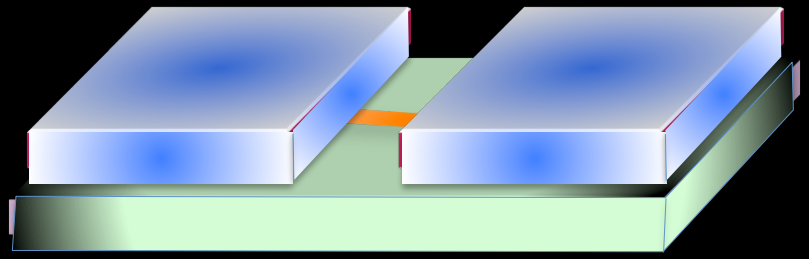
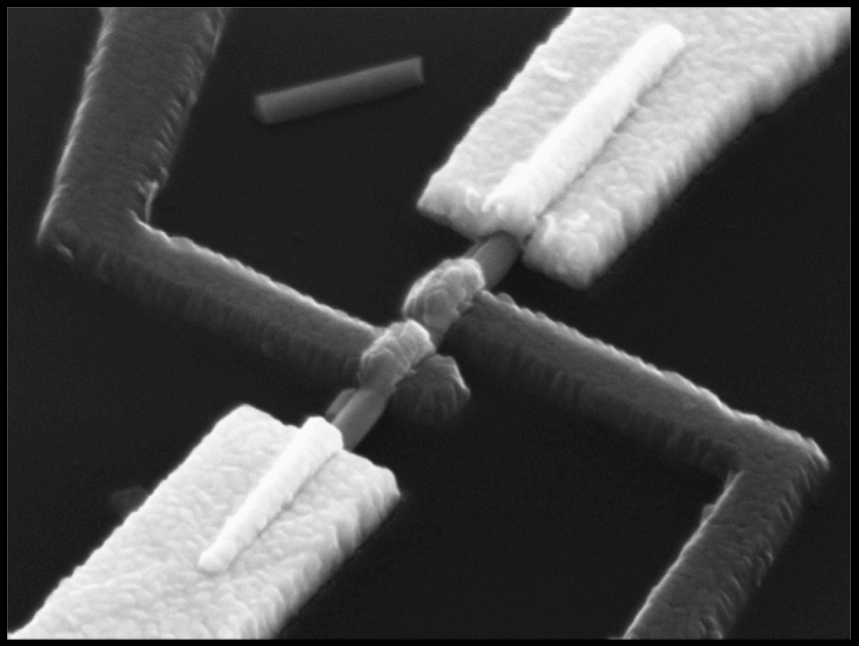
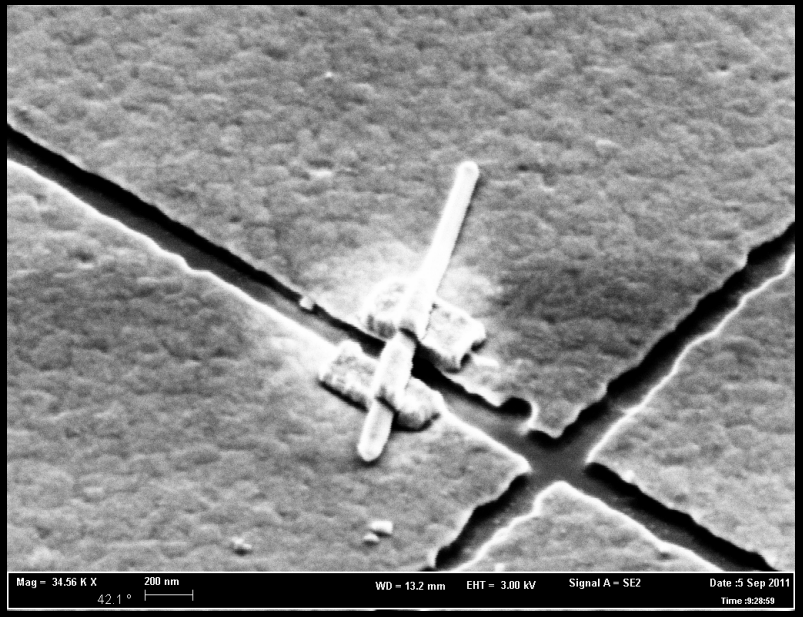
Hybrid structures with nanowires

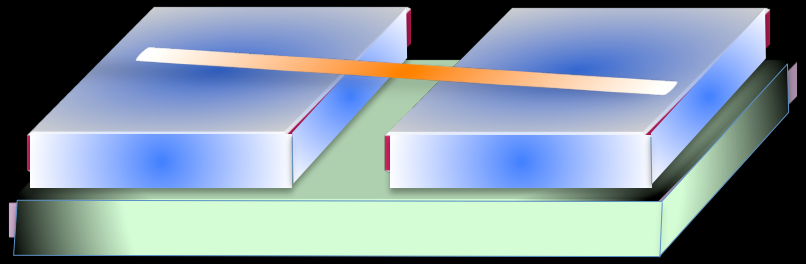
InAs nanowire /Al







InAs nanowire YBCO



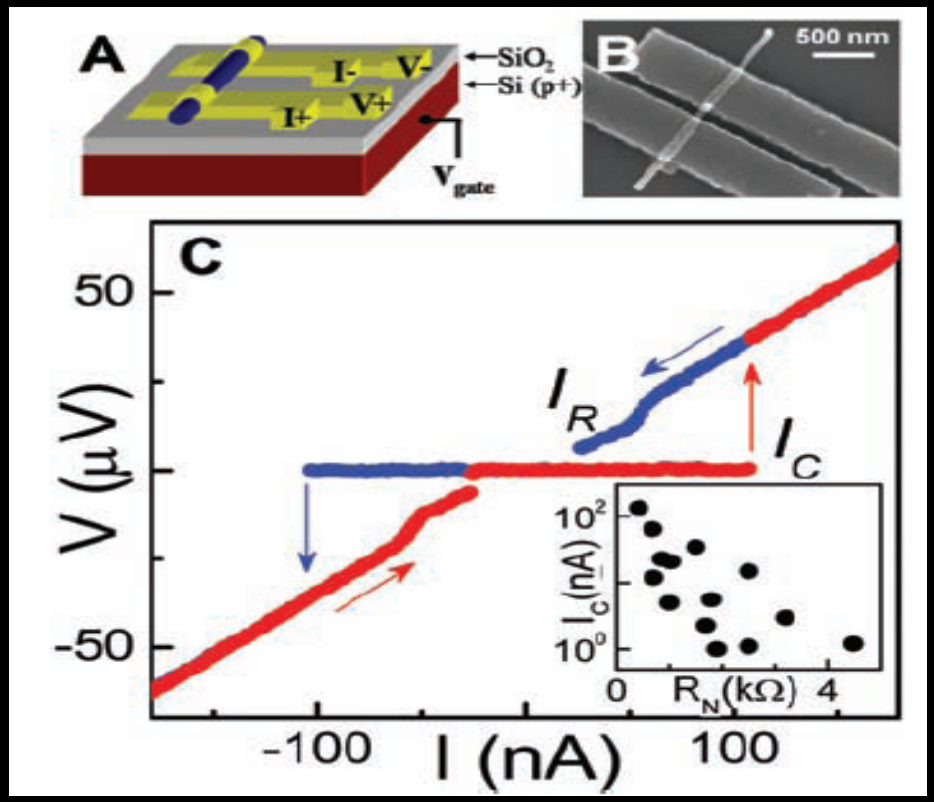
D. Montemurro et al J.Supercond. (2015)

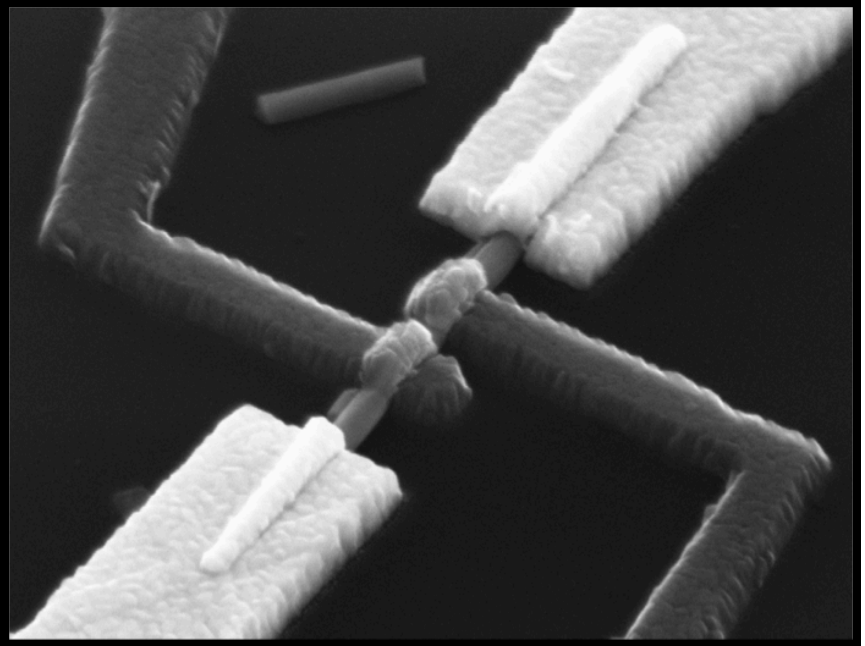
Hybrid structures with nanowires

8 JULY 2005 VOL 309 SCIENCE

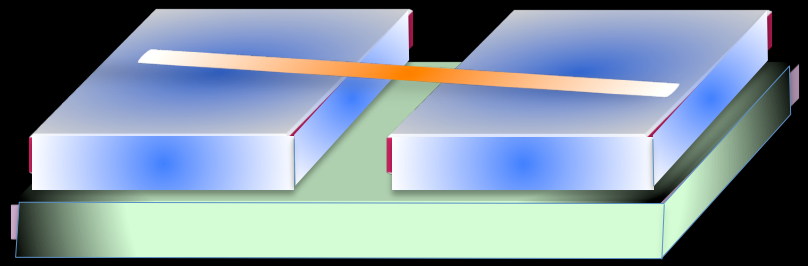
Tunable Supercurrent Through Semiconductor Nanowires

Yong-Joo Doh,[1*] Jorden A. van Dam,[1*] Aarnoud L. Roest,[1,2]
Erik P. A. M. Bakkers,[2] Leo P. Kouwenhoven,[1]
Silvano De Franceschi[1†]





InAs nanowire YBCO



D. Montemurro et al J.Supercond. (2015)

Search for Majorana Fermions in Superconductors

C.W.J. Beenakker

Annu. Rev. Condens. Matter Phys. 2013. 4:113–36

The *Annual Review of Condensed Matter Physics* is online at conmatphys.annualreviews.org

3.3. 4π-Periodic Josephson Effect

So far, I have discussed signatures of Majoranas in the electrical conduction out of equilibrium, in response to a voltage difference between the superconductor and a normal-metal electrode. In equilibrium, an electrical current (supercurrent) can flow between two superconductors in the absence of any applied voltage. This familiar DC Josephson effect (102) acquires a new twist (9, 18, 31, 32, 103–112) if the junction between the superconductors contains Majorana fermions, as in **Figure 2**.

Quite generally, the supercurrent I_J is given by the derivative

$$I_J = \frac{2e}{\hbar}\frac{dE}{d\phi} \qquad 11.$$

of the Josephson junction's energy E, with respect to the superconducting phase difference ϕ. Although in the conventional Josephson effect only Cooper pairs can tunnel (with probability $\tau \ll 1$), Majorana fermions enable the tunneling of single electrons (with a larger probability $\sqrt{\tau}$). The switch from $2e$ to e as the unit of transferred charge between the superconductors amounts to a doubling of the fundamental periodicity of the Josephson energy, from $E \propto \cos\phi$ to $E \propto \cos(\phi/2)$.

If the superconductors form a ring, enclosing a flux Φ, the period of the flux dependence of the supercurrent I_J doubles from 2π to 4π as a function of the Aharonov-Bohm phase $2e\Phi/\hbar$. This is the 4π-periodic Josephson effect (9, 103). As a function of the enclosed flux, I_J has the same h/e periodicity as the persistent current I_N through a normal-metal ring (radius L), but the size dependence is entirely different: Whereas I_N decays as $1/L$ or faster, I_J has the L-independence of a supercurrent.

Because the two branches of the E-ϕ relation differ by one unpaired quasiparticle (see **Figure 2**), external tunneling events that change the quasiparticle parity (so-called quasiparticle poisoning) restore the conventional 2π-periodicity (18). In a closed system, the 4π-periodicity is thermodynamically stable, provided that the entire ring is in a topologically nontrivial state (to prevent quantum phase slips) (108).

2. HOW TO MAKE THEM

- 2.1. Shockley Mechanism
- 2.2. Chiral *p*-Wave Superconductors
- 2.3. Topological Insulators
- 2.4. Semiconductor Heterostructures

3. HOW TO DETECT THEM

- 3.1. Half-Integer Conductance Quantization
- 3.2. Nonlocal Tunneling
- 3.3. 4π-Periodic Josephson Effect
- 3.4. Thermal Metal-Insulator Transition

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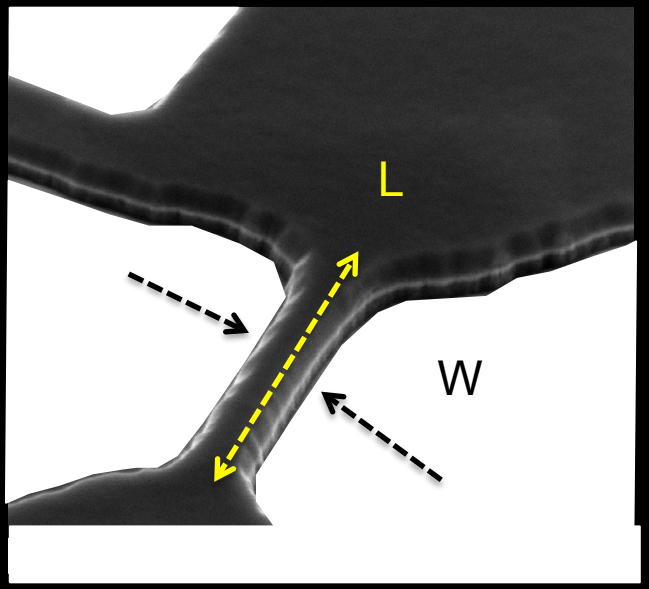
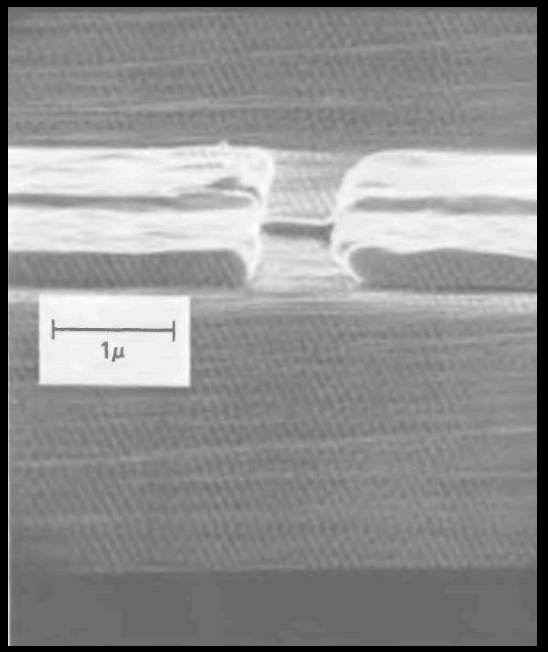
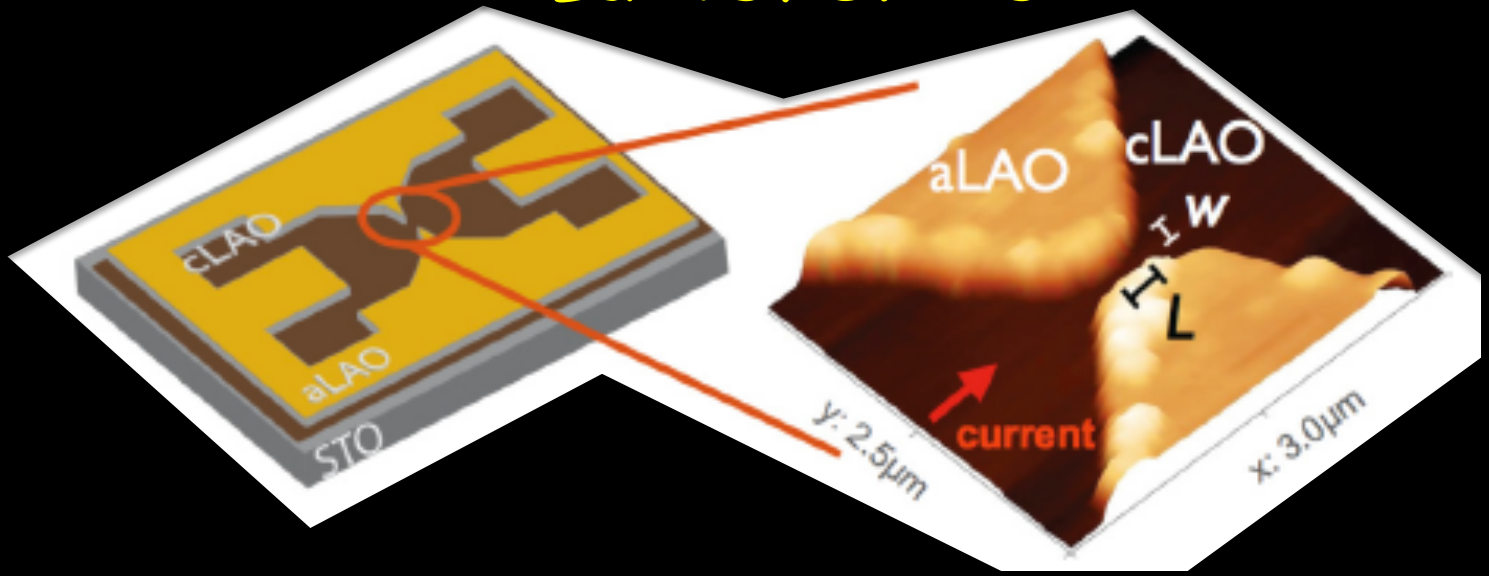
Weak links



In variable thickness bridge



LaAlO/SrTiO



LAO/STO 2-d systems

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **95**, 140502(R) (2017)

Signatures of unconventional superconductivity in the $LaAlO_3/SrTiO_3$ two-dimensional system

D. Stornaiuolo,[1,2,*] D. Massarotti,[1,2] R. Di Capua,[1,2] P. Lucignano,[2] G. P. Pepe,[1,2] M. Salluzzo,[2] and F. Tafuri[3]

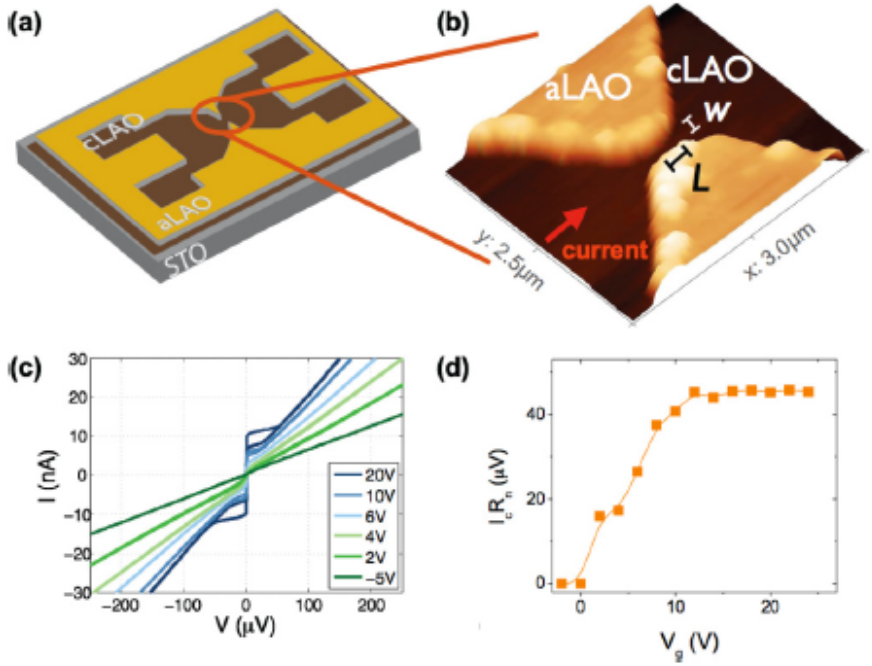
[1]*Dipartimento di Fisica "E. Pancini", Università di Napoli Federico II, Monte S. Angelo-Via Cintia, I-80126 Napoli, Italy*

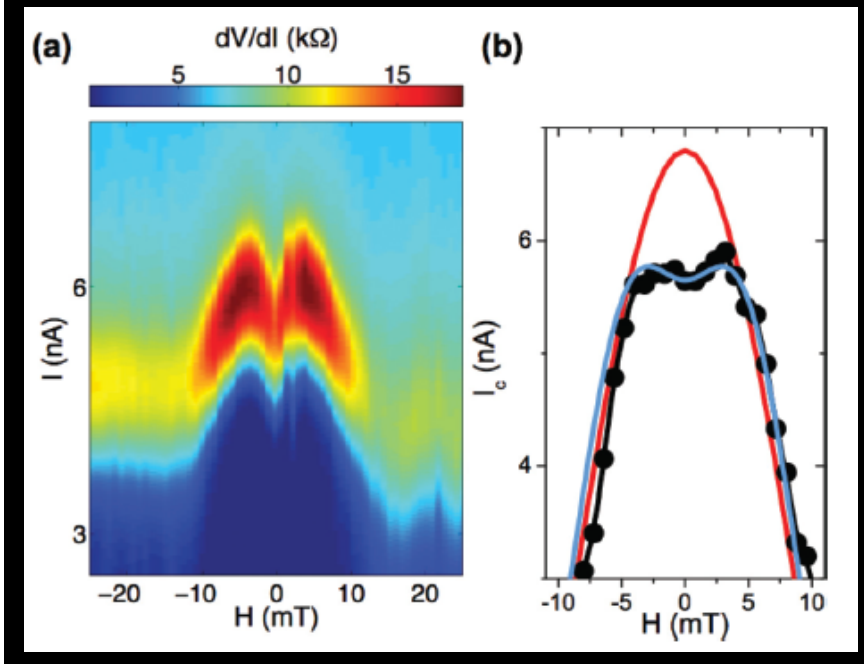
[2]*CNR-SPIN UOS Napoli, Monte S. Angelo-Via Cintia, I-80126, Napoli, Italy*

[3]*Dipartimento di Ingegneria Industriale e dell'Informazione, Seconda Università di Napoli, I-81031 Aversa (CE), Italy*

(Received 19 January 2017; published 7 April 2017)

We study the superconducting state of the two-dimensional electron gas (2DEG) at the $LaAlO_3/SrTiO_3$ interface using Josephson junctions as spectroscopic probes. The transport properties of these devices reveal the presence of two superconducting gap structures and of an unconventional superconducting π channel. These features provide evidence of an unconventional superconducting ground state, possibly related to the interplay between superconductivity and the large Rashba spin-orbit coupling in the 2DEG.





Journal of Low Temperature Physics, Vol. 16, Nos. 1/2, 1974

Phase-Slip Centers and Nonequilibrium Processes in Superconducting Tin Microbridges*

W. J. Skocpol,† M. R. Beasley, and M. Tinkham

Journal of Low Temperature Physics, Vol. 27, Nos. 5/6, 1977

Regimes in the Behavior of Superconducting Microbridges

T. M. Klapwijk, M. Sepers, and J. E. Mooij

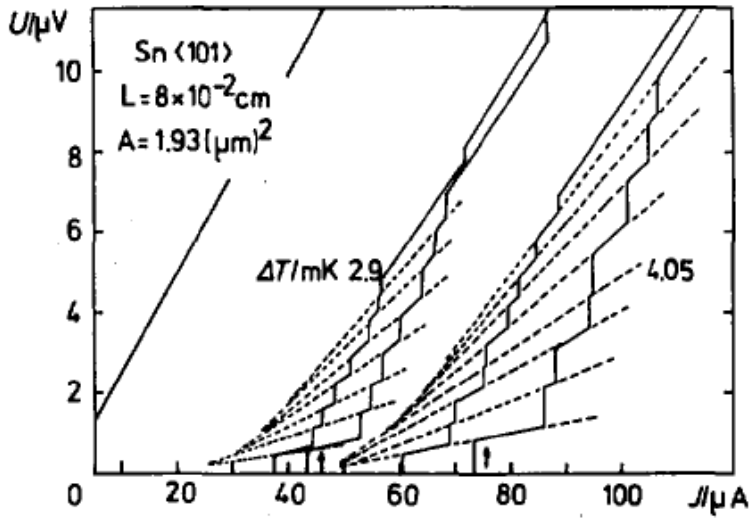
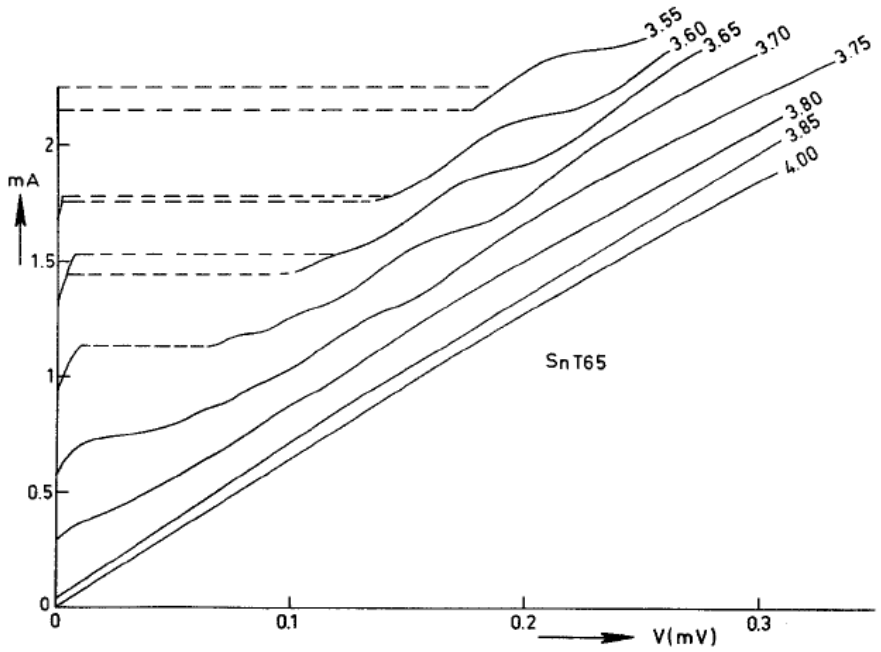
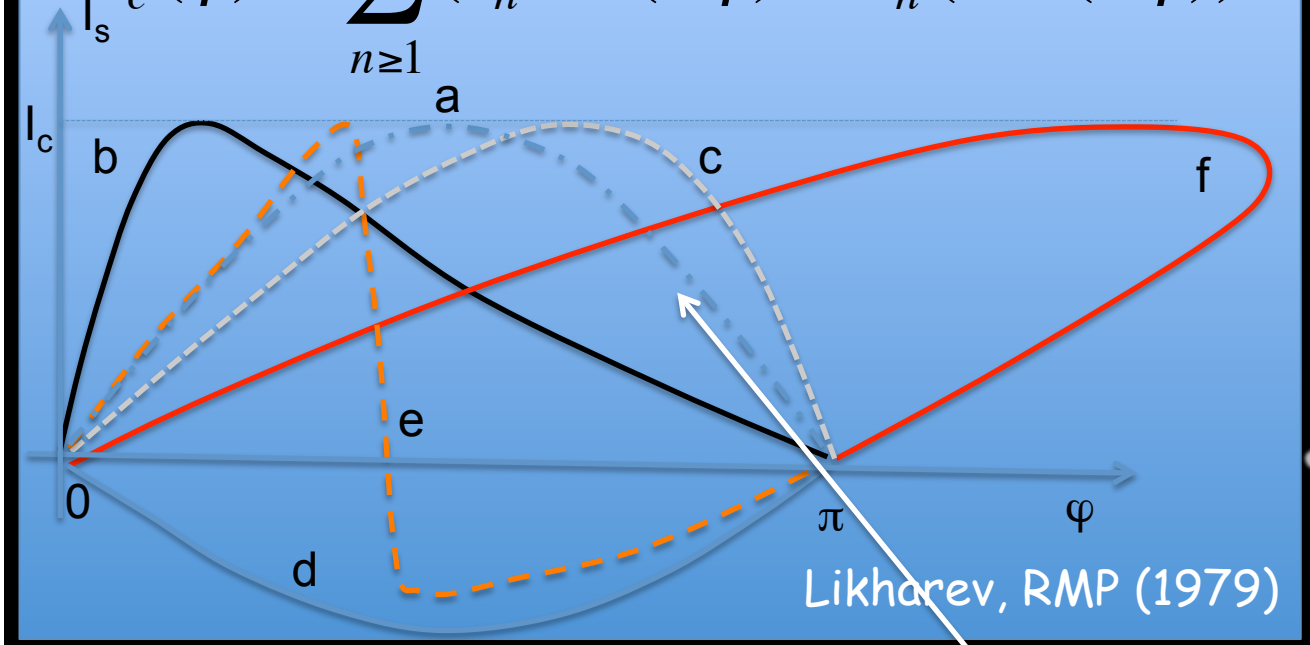


Fig. 8. Current–voltage characteristics for tin whisker crystals, showing the same behavior discussed here for tin microbridges (from Meyer[5]).

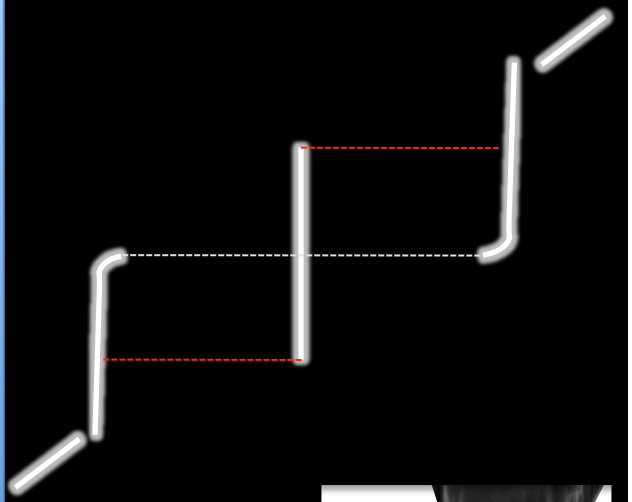


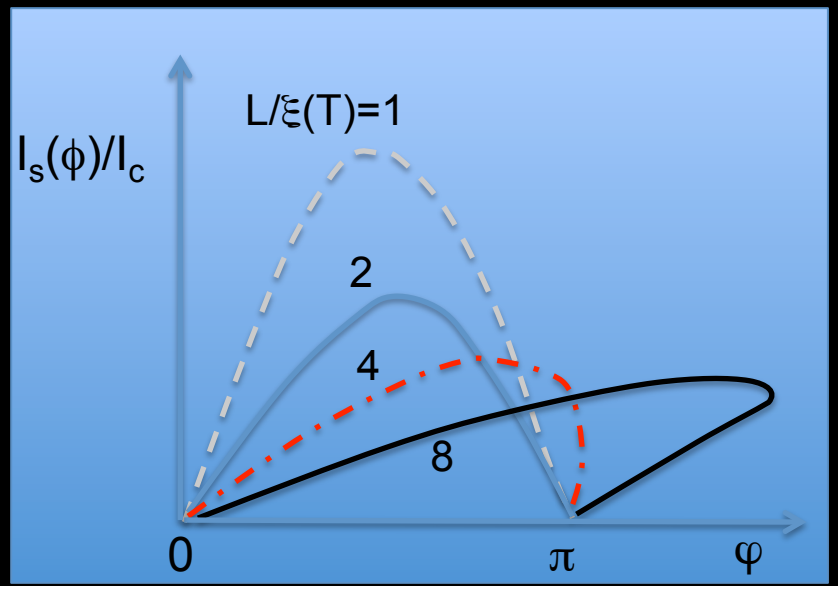
The Josephson effect: the general $I_c(\varphi)$ relation

$$I_c(\varphi) = \sum_{n\geq 1} (I_n \sin(n\varphi) + J_n(\cos(n\varphi))$$

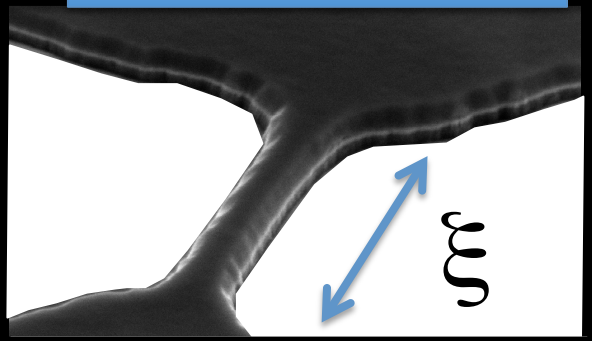


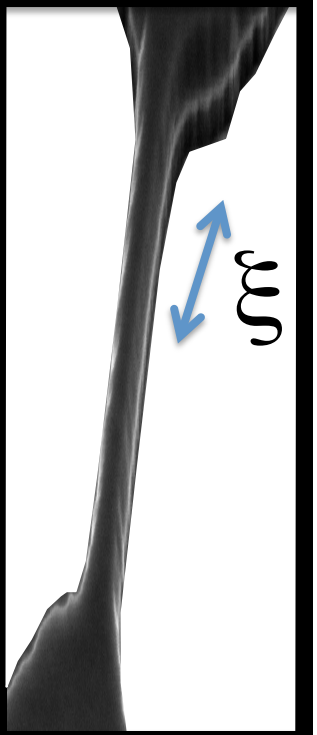
Likharev, RMP (1979)



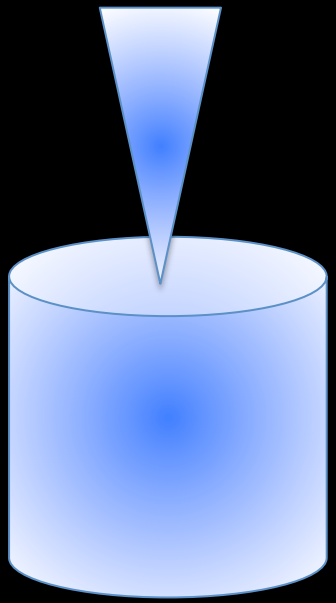


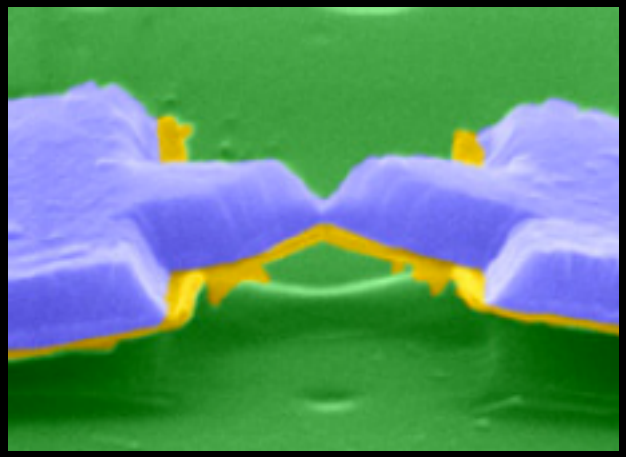
$$E_J(\varphi) = \frac{\hbar I_c}{2e}(1-\cos\varphi)$$

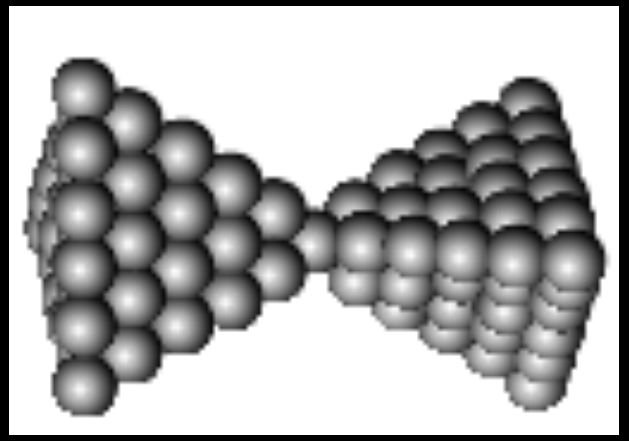


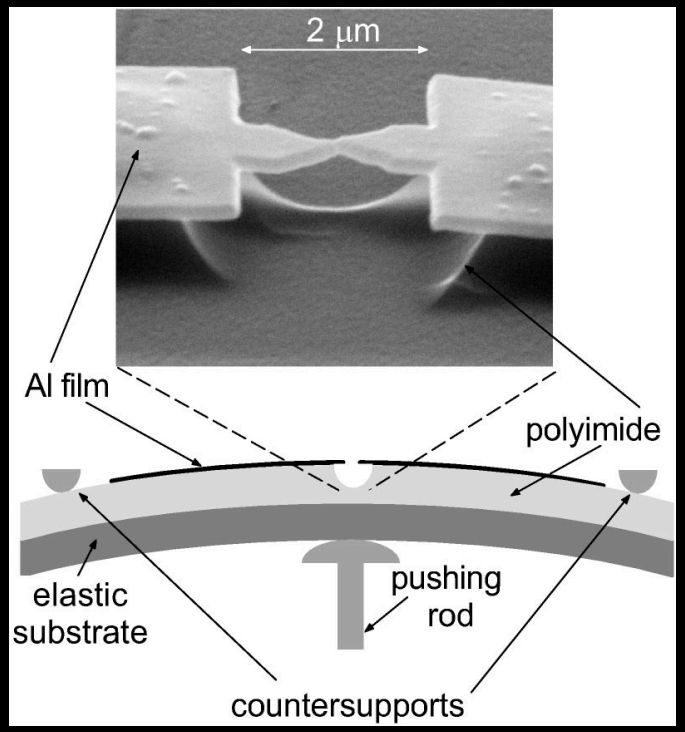


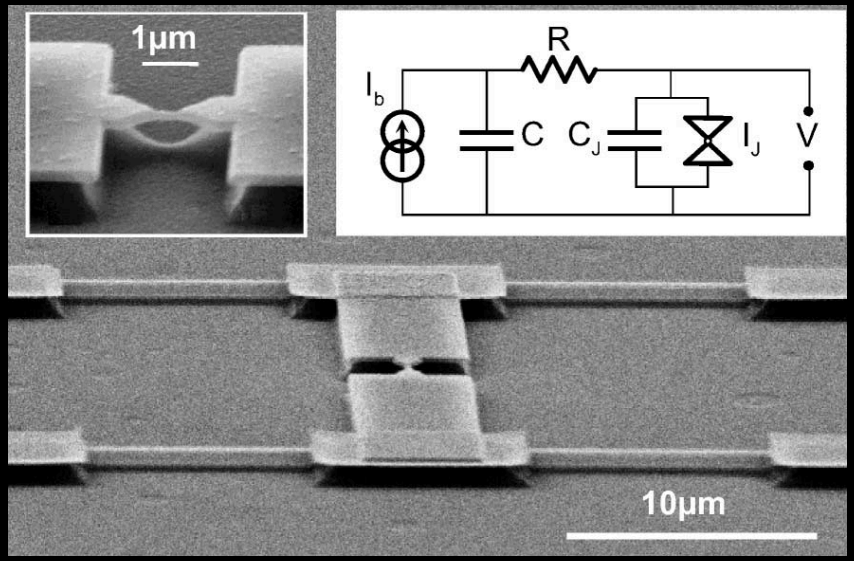
Mechanically controllable break junctions







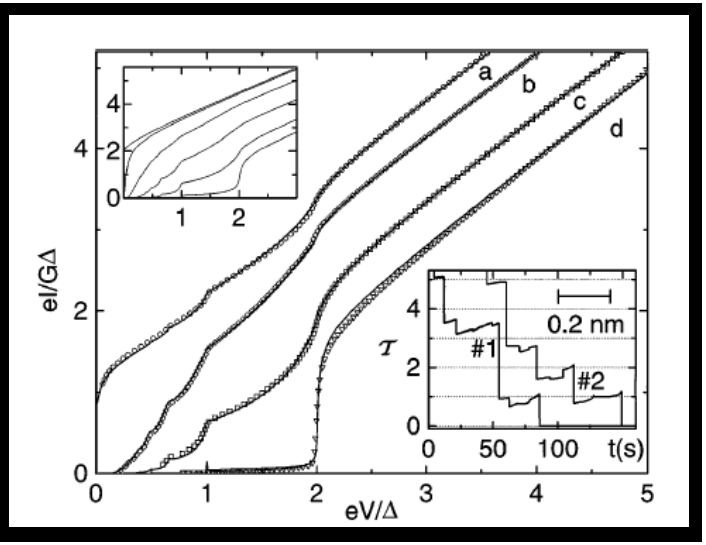




VOLUME 78, NUMBER 18 PHYSICAL REVIEW LETTERS 5 MAY 1997

Conduction Channel Transmissions of Atomic-Size Aluminum Contacts

E. Scheer, P. Joyez, D. Esteve, C. Urbina,* and M. H. Devoret
Service de Physique de l'Etat Condensé, Commissariat à l'Energie Atomique, Saclay, F-91191 Gif-sur-Yvette Cedex, France
(Received 4 February 1997)



VOLUME 85, NUMBER 1 PHYSICAL REVIEW LETTERS 3 JULY 2000

Supercurrent in Atomic Point Contacts and Andreev States

M. F. Goffman,[1] R. Cron,[1] A. Levy Yeyati,[2] P. Joyez,[1] M. H. Devoret,[1] D. Esteve,[1] and C. Urbina[1]
[1]*Service de Physique de l'Etat Condensé, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France*

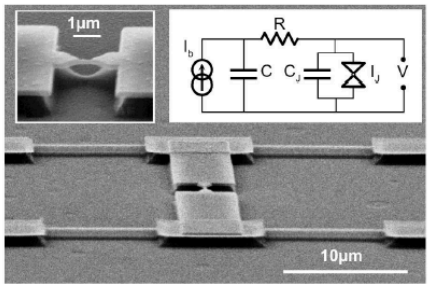


FIG. 2. Micrograph of Al microbridge in a dissipative environment. Each *IV* probe contains a AuCu (weight ratio 3:1) resistor (10 μm-long, 500 nm wide, and 30 or 50 nm thick) and a large (2.5 mm)^2, 180 nm thick AuCu/Al pad (not shown) that forms with the metallic substrate a large capacitor. Substrate is phosphor-bronze covered by a 2 μm thick layer of polyimide. Left inset: side view of bridge (150 nm thick Al layer with 100 nm wide constriction in the middle) suspended by selective

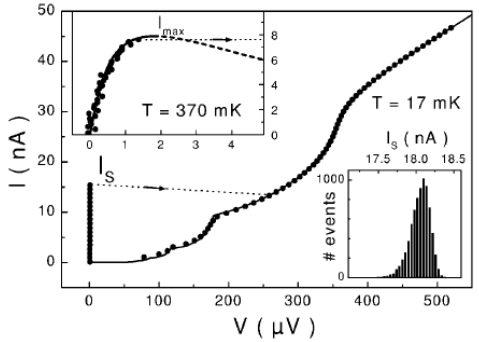
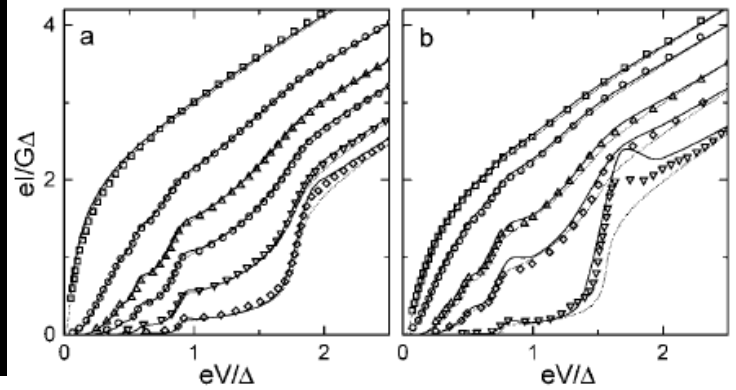


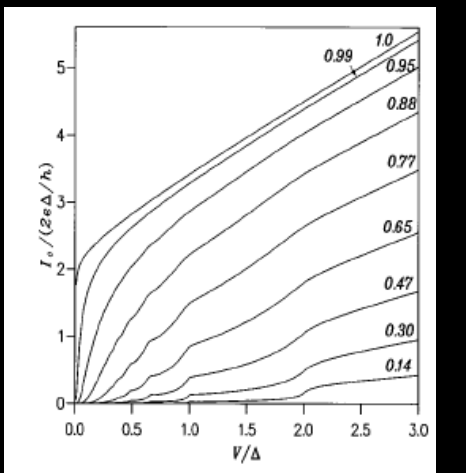
FIG. 3. Large scale *IV* characteristic of atomic contact, measured at 17 mK (dots). Switching at current I_s from super-



VOLUME 86, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JANUARY 2001

Proximity Effect and Multiple Andreev Reflections in Gold Atomic Contacts

E. Scheer,[1,*] W. Belzig,[2] Y. Naveh,[3,†] M. H. Devoret,[4] D. Esteve,[4] and C. Urbina[4]

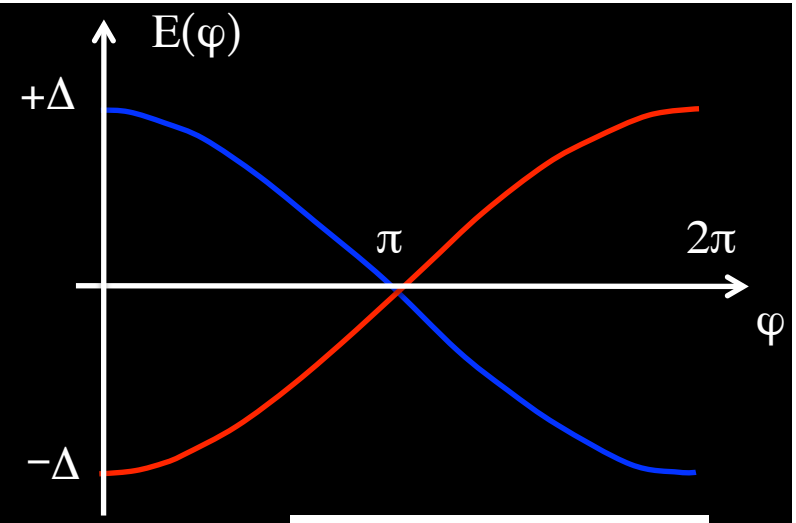


PHYSICAL REVIEW B VOLUME 54, NUMBER 10 1 SEPTEMBER 1996-II

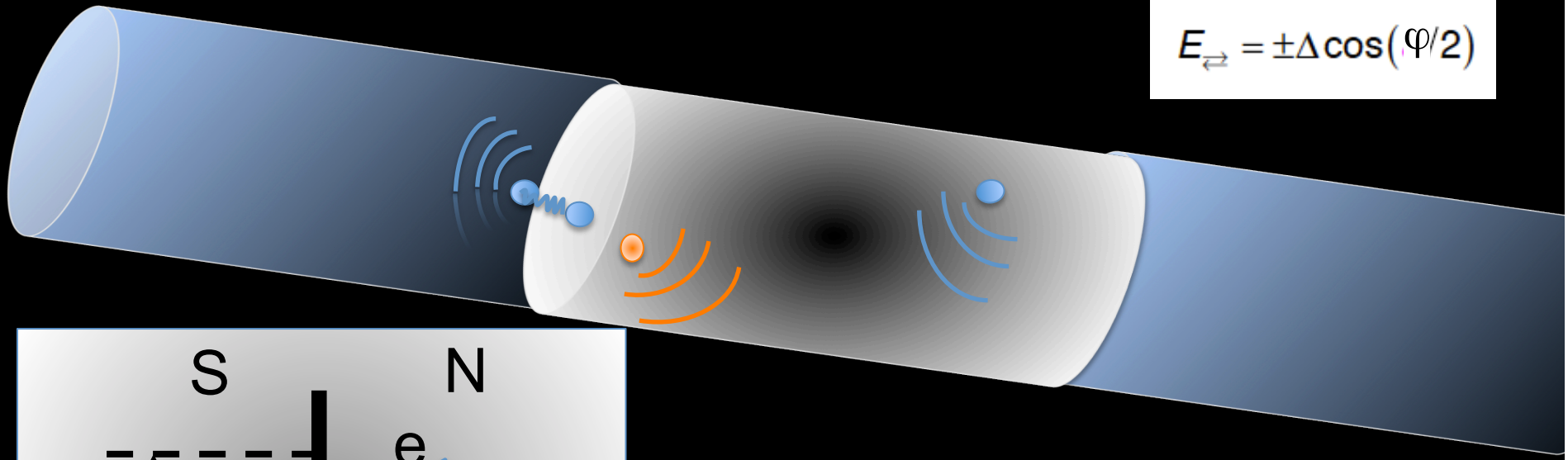
Hamiltonian approach to the transport properties of superconducting quantum point contacts

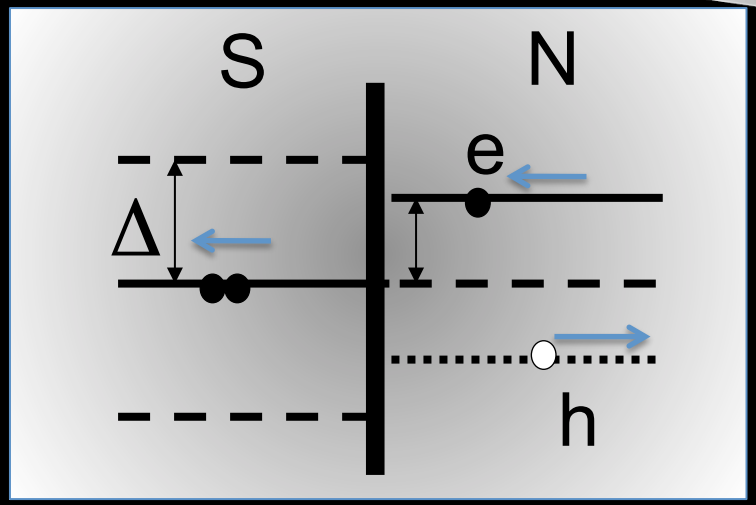
J. C. Cuevas, A. Martín-Rodero, and A. Levy Yeyati
Departamento de Física Teórica de la Materia Condensada C-V, Facultad de Ciencias, Universidad Autónoma de Madrid,

Andreev bound states
in a short (L<ξ) ballistic channel



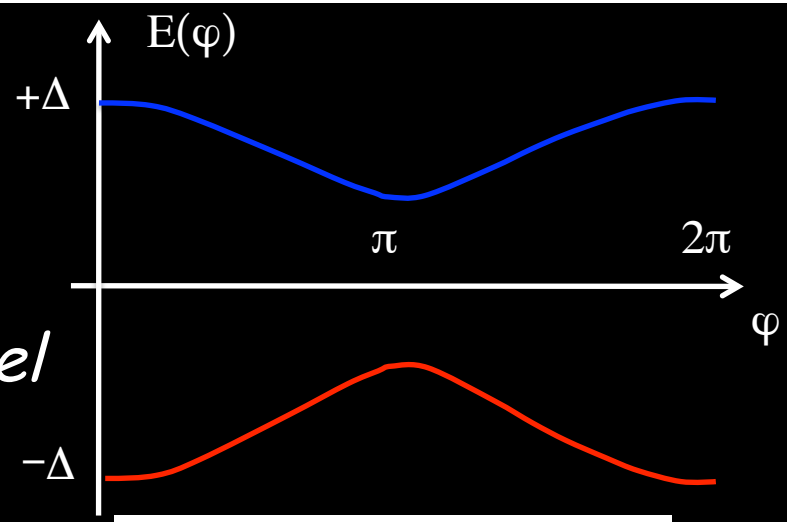
$$E_{\rightleftarrows} = \pm\Delta\cos(\varphi/2)$$





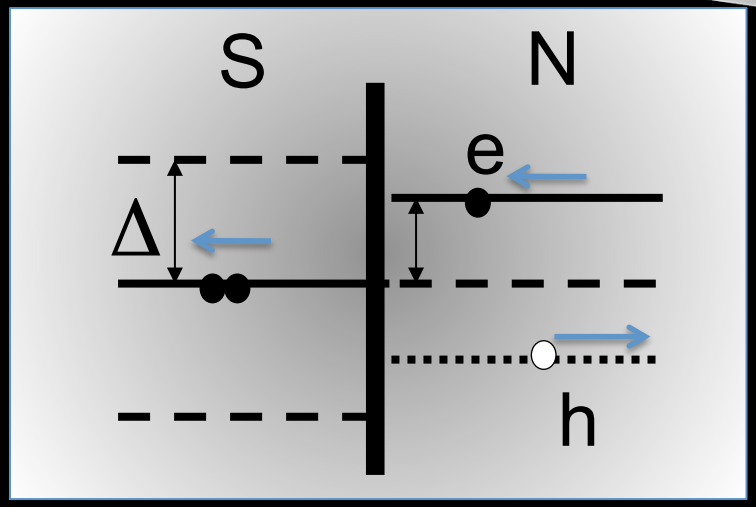
The Josephson effect in terms of Andreev reflection

Andreev bound states
in a short (L<ξ) reflective channel

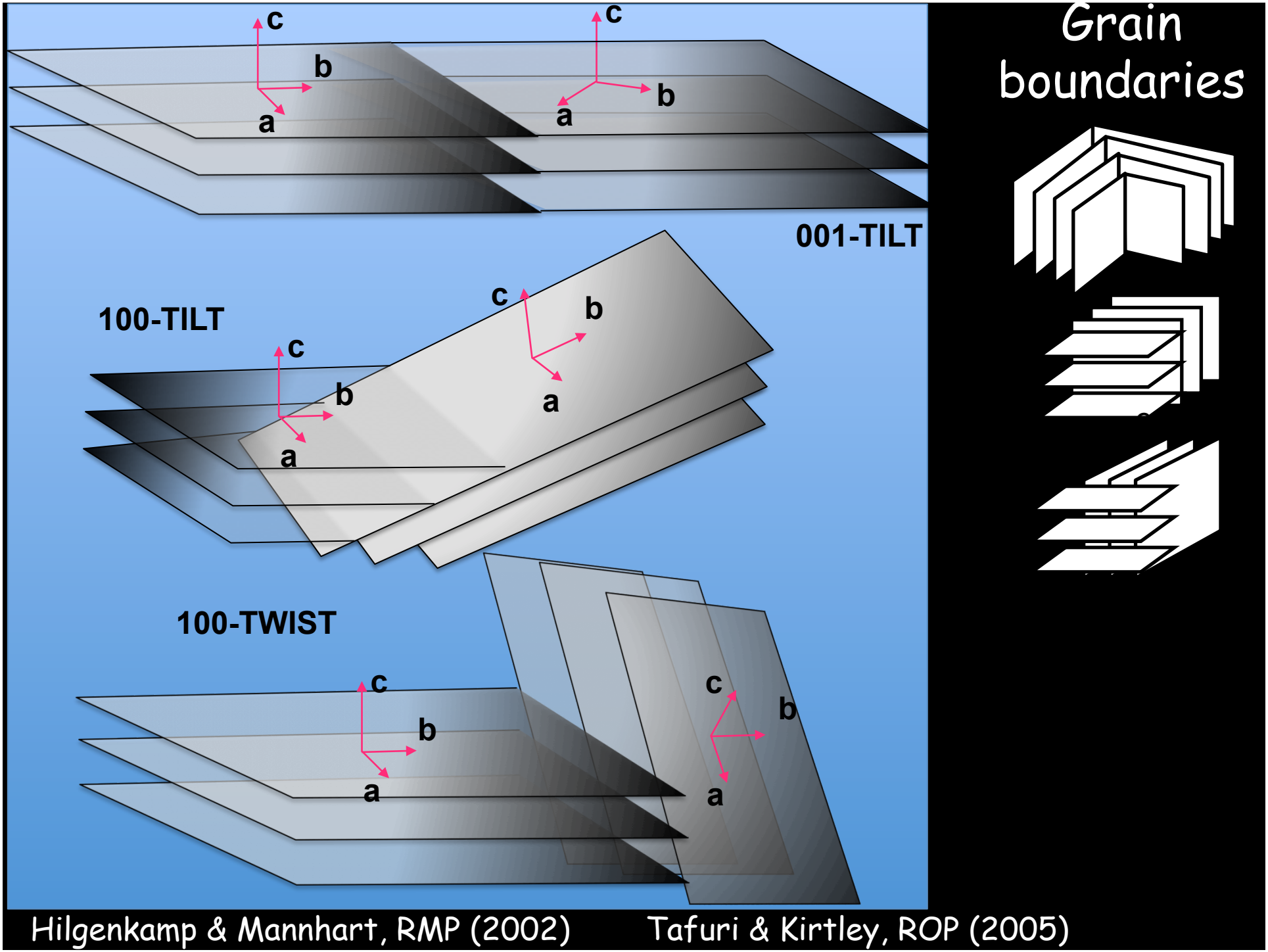


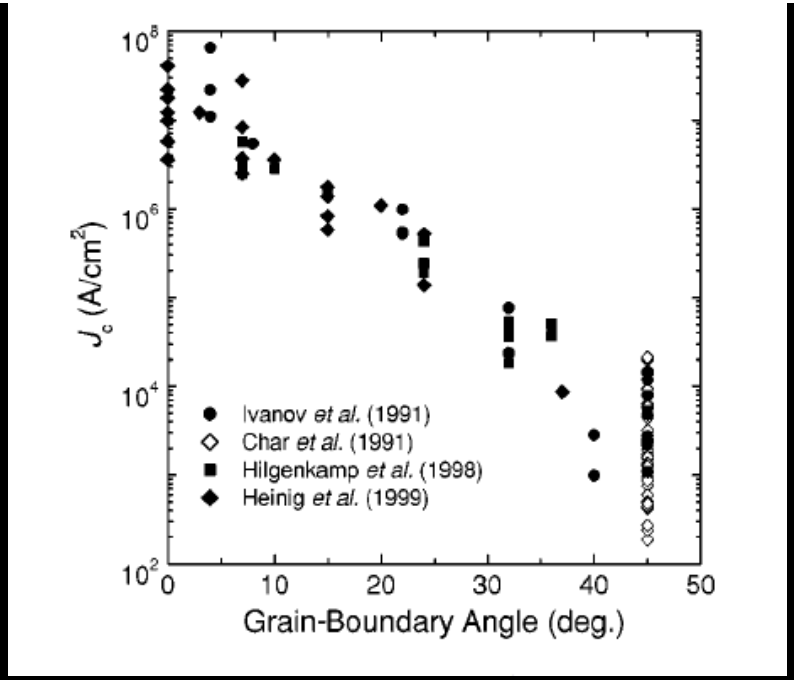
$$E_{\pm} = \pm\Delta\sqrt{1-\tau\sin^2(\varphi/2)}$$

Furusaki, Tsukada, Beenakker (1991)

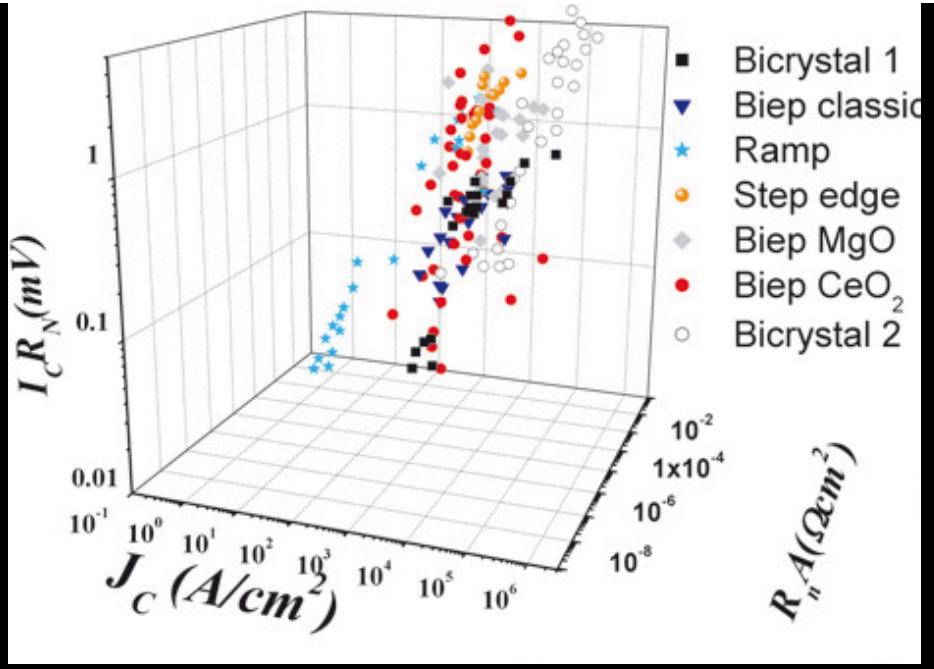


The Josephson effect in terms of Andreev reflection

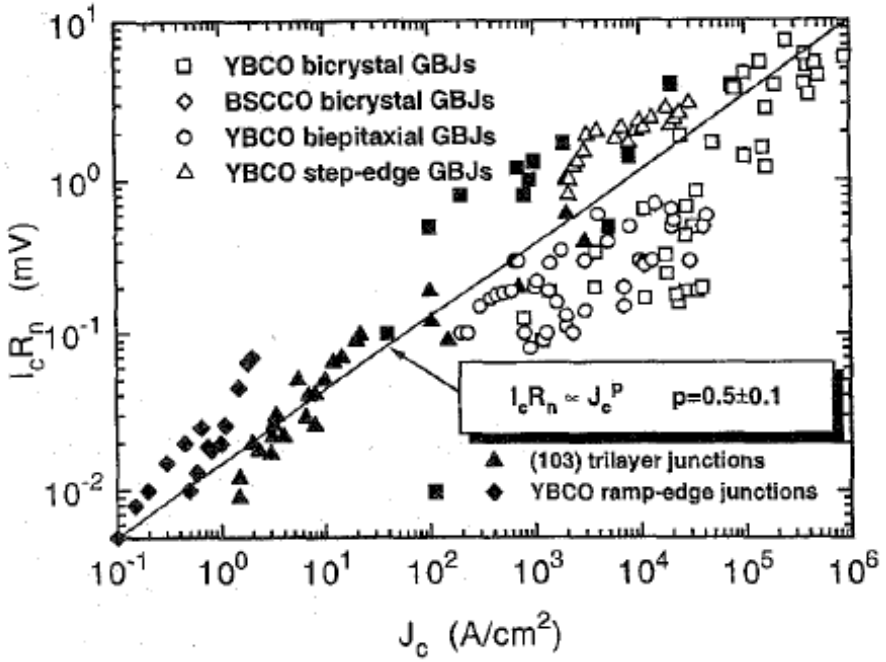

c
b
a
001-TILT
100-TILT
100-TWIST
Grain boundaries
Hilgenkamp & Mannhart, RMP (2002)
Tafuri & Kirtley, ROP (2005)



Hilgenkamp & Mannhart, RMP (2002)



Tafuri & Kirtley, ROP (2005)

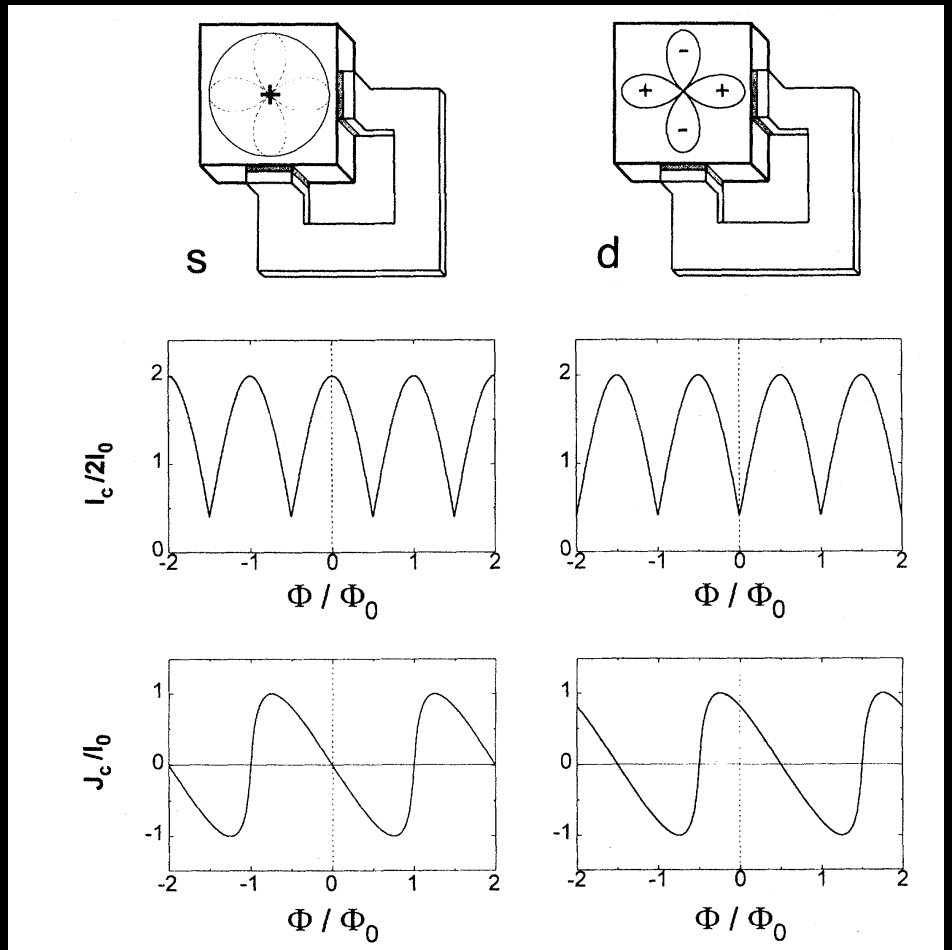
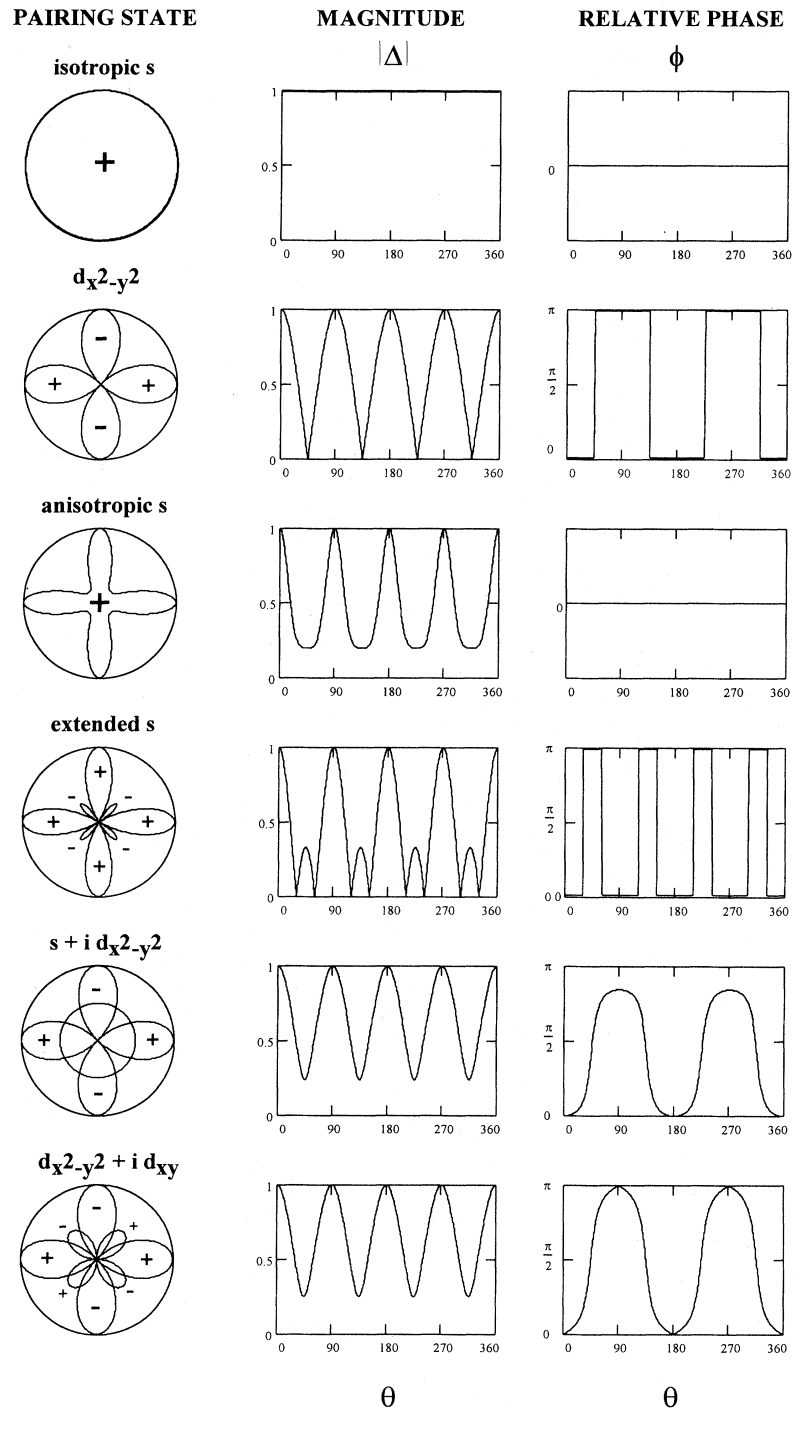


About I_cR_n

Gross, Koelle et al. IEEE Appl. Supercond. (1997)

Phase-sensitive tests of the symmetry of the pairing state in the high-temperature superconductors—Evidence for $d_{x^2-y^2}$ symmetry

D. J. Van Harlingen

Department of Physics and Materials Research Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

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