Ivane Javakhishvili Tbilisi State University

Elevter Andronikashvili Institute of Physics

Superconductivity in nanostructures

Part II

Alexander Shengelaya

Batumi, ISCFMMT 2022, October 2022

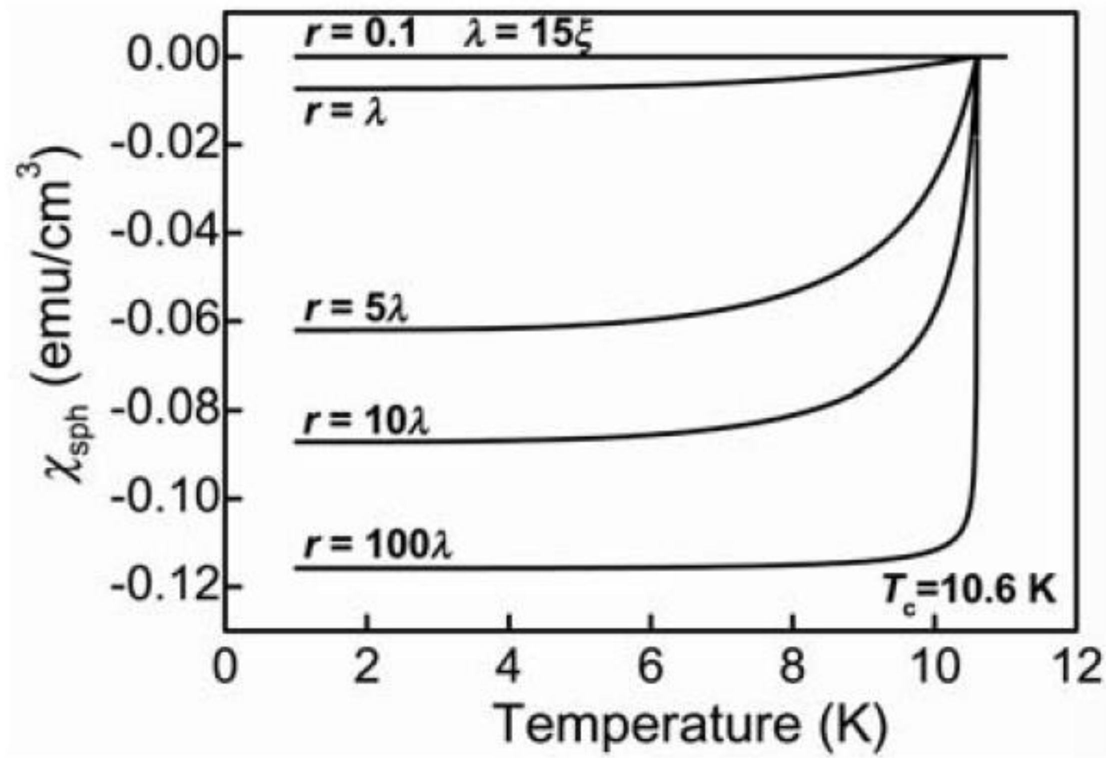
Diamagnetism of superconducting nanoparticles

First, the magnetic susceptibility is much reduced from the bulk value of $\chi_{\text{bulk}}^{\text{SC}} = -1/(4\pi)$ to

$$\chi_{\text{grain}}^{\text{SC}} = -\frac{3}{2}\frac{1}{40\pi}\frac{r^2}{\lambda_L{}^2}\frac{r}{\xi_0} \qquad (1)$$

where r is the radius of the particle, ξ_0 is the coherence length, and λ_L is the London penetration depth.[35,36] For lead particles of 11.4 nm diameter this leads to the reduction in the signal amplitude by 5.3×10^4 times. Combin-

$$\chi'(T) = -\frac{3}{2\rho}\left\{1 - \frac{6\lambda_L(T)}{d}\coth\left(\frac{d}{2\lambda_L(T)}\right) + \frac{12\lambda_L^2(T)}{d^2}\right\},$$



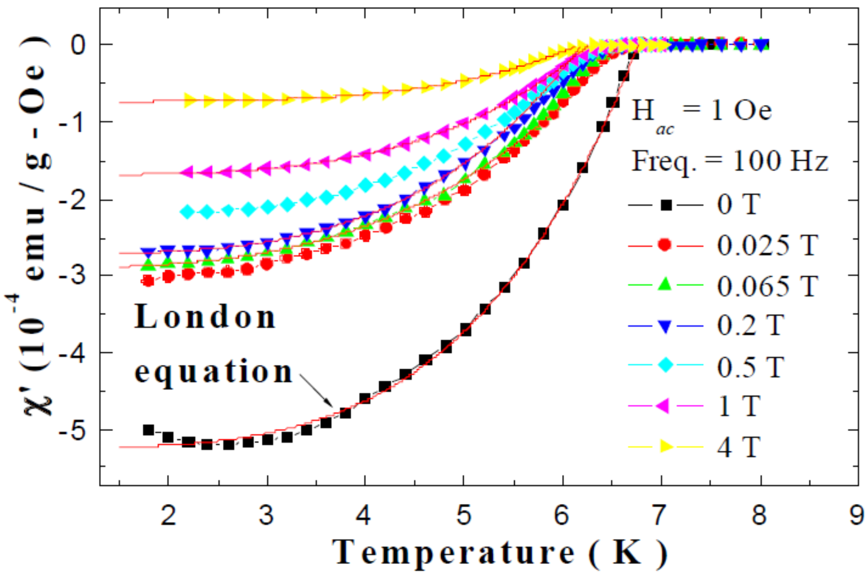
phys. stat. sol. (c) **3**, No. 9, 2947 – 2952 (2006) / **DOI** 10.1002/pssc.200567141

Granular-percolative superconductivity in organic materials: comparison with HTSC ceramics

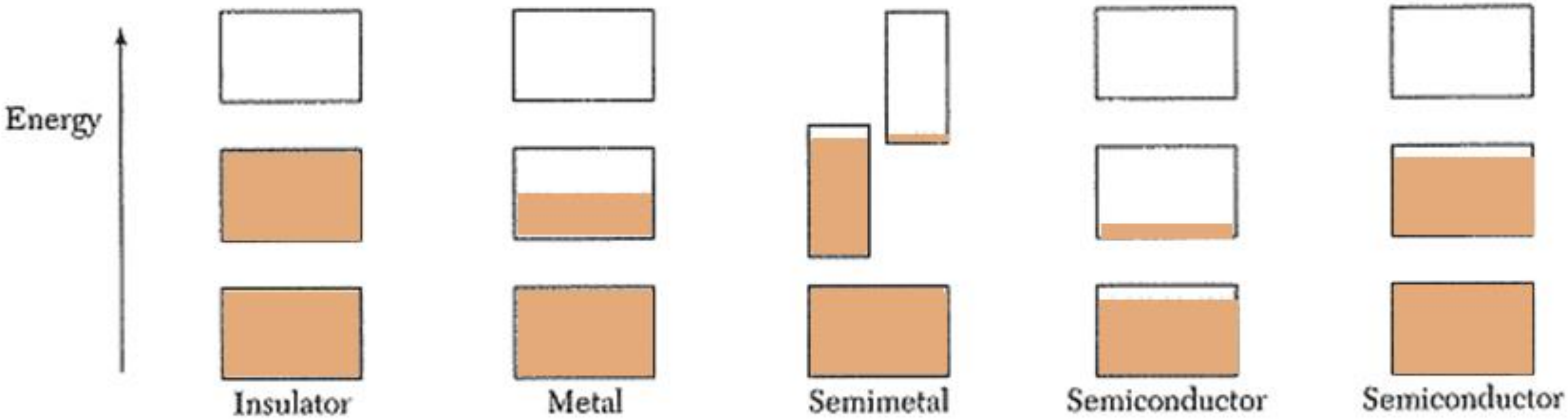
S. Senoussi[*,1], **F. Pesty**[1], **A. Ramzi**[2], **A. Tirbiyine**[2], **A. Haouam**[3], **A. Taoufik**[2], and **C. R. Pasquier**[1]

$$\chi'(T) = -\frac{3}{2\rho}\left\{1 - \frac{6\lambda_L(T)}{d}\coth\left(\frac{d}{2\lambda_L(T)}\right) + \frac{12\lambda_L^2(T)}{d^2}\right\},$$

$$\lambda_L(T) = \lambda_L(0)\left[1 - \left(\frac{T}{T_C}\right)^4\right]^{-1/2}.$$

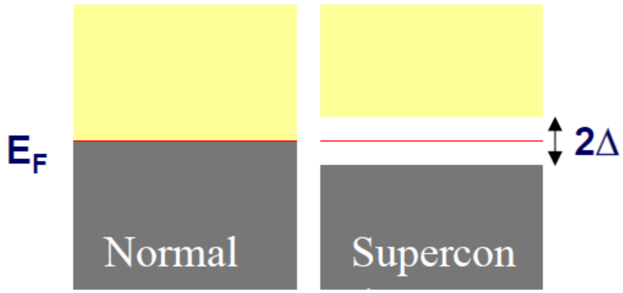


Bands of energy levels in solids



finite T impurities

In its simplest form BCS theory leads to the following quantitative formula;



$$2\Delta = 3.53 k_B T$$ **for T=0**

$$T_c = \theta_D \exp\left[\frac{-1}{VN(E_F)}\right]$$

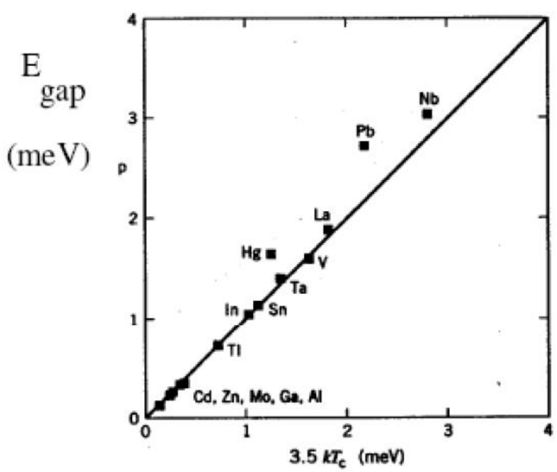
V = electron-phonon interaction

θ_D = **Debye temperature**

$N(E_F)$ = Density of states of a given spin at the Fermi level

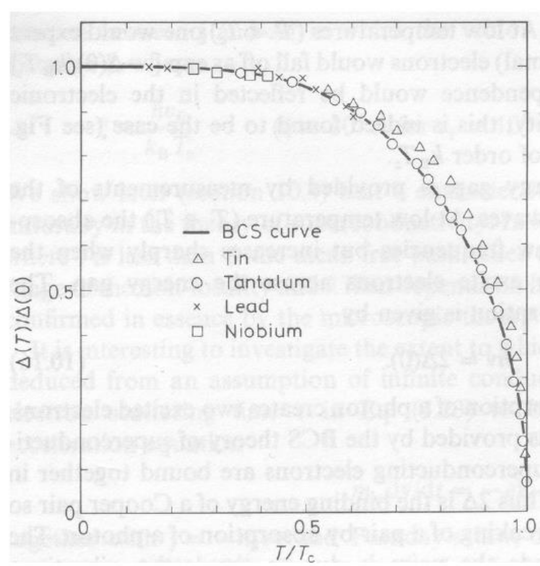
Note that $VN(E_F) << 1$

$$E_{gap} \sim 10^{-4} E_F$$

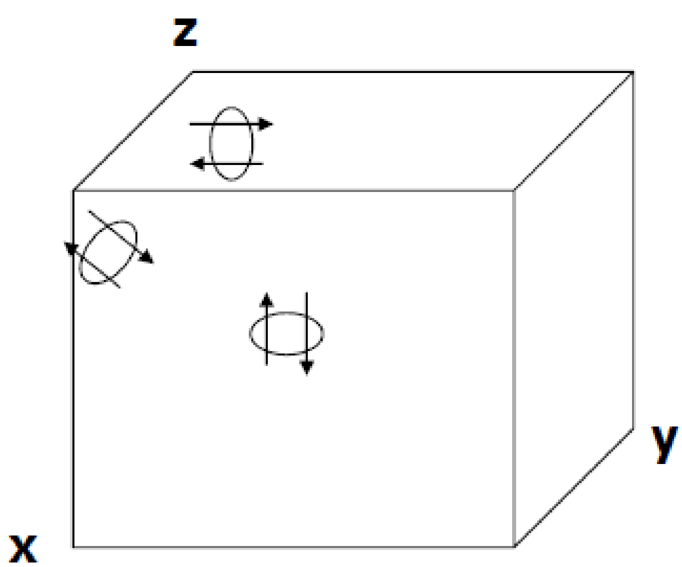


BCS calculated gap

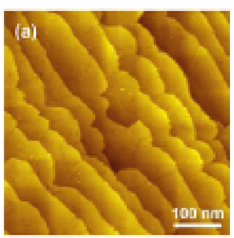
Temperature dependence of energy gap



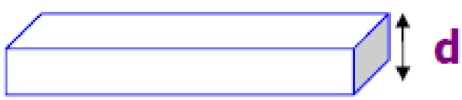
Dimensionality



3 D bulk Superconductor

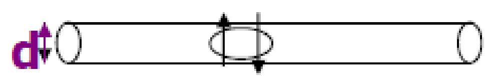


Pb thin film

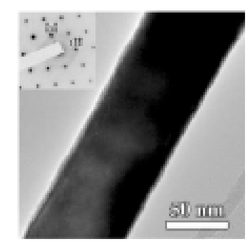


2 D Superconductivity

If d< ξ



1 D Superconductivity



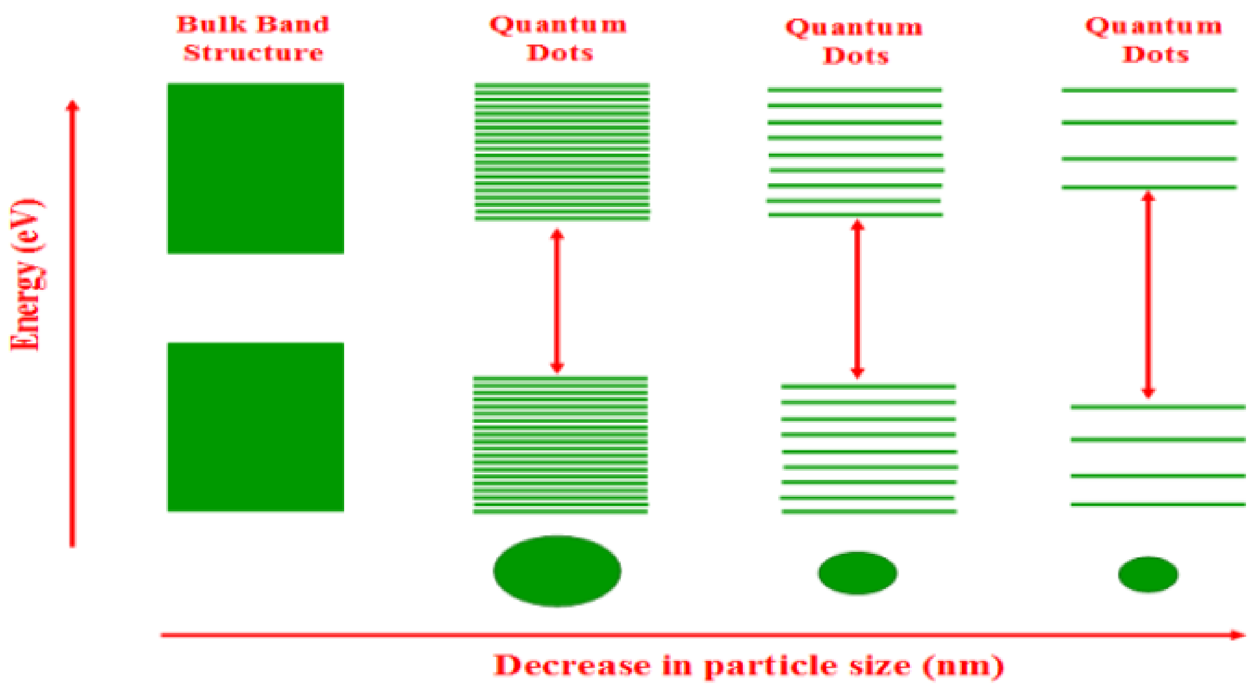
Pb nanowire

Jian Wang (王健)
International Center for Quantum Materials, School of Physics, Peking University

Energy level quantization in nanoparticles

Distance between energy levels: $d \sim E_F/N \qquad N \sim \dfrac{V}{\lambda_F^3}$

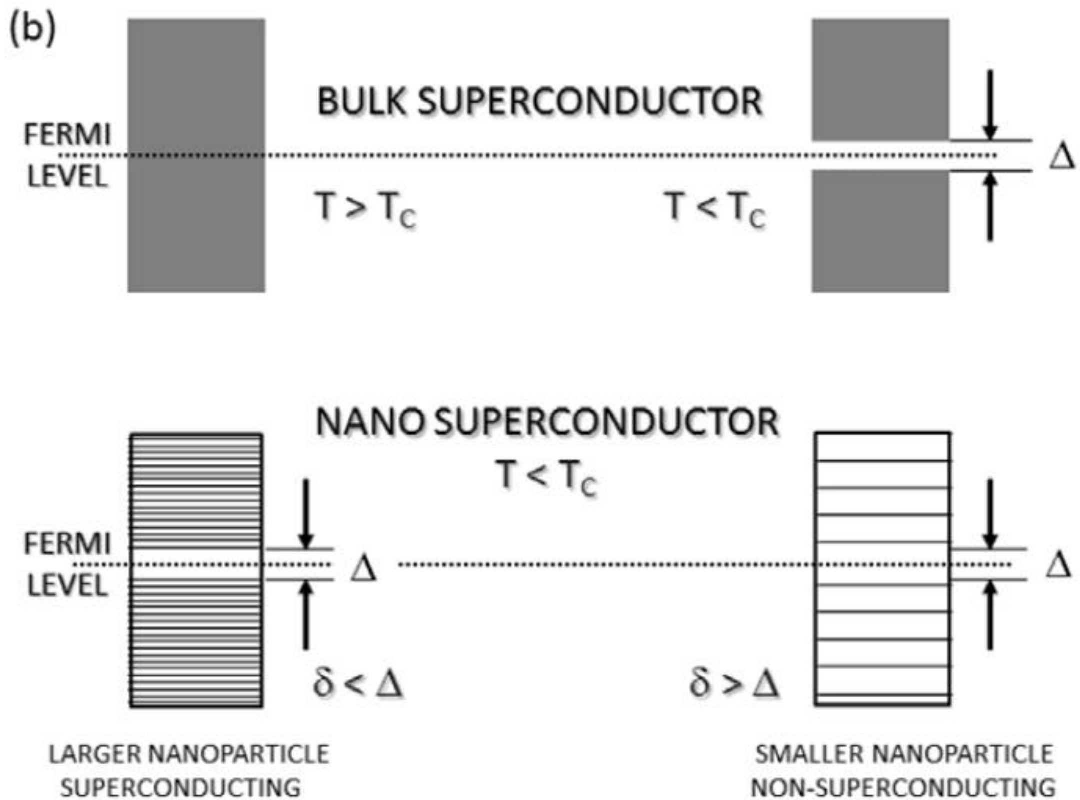
$$d \sim 1/V$$



H. I. Ikeri, A. I. Onyia, V. C. Onuabuchi

International Journal of Engineering and Applied Sciences (IJEAS)
ISSN: 2394-3661, Volume-8, Issue-7, July 2021

Superconductivity in nanoparticles

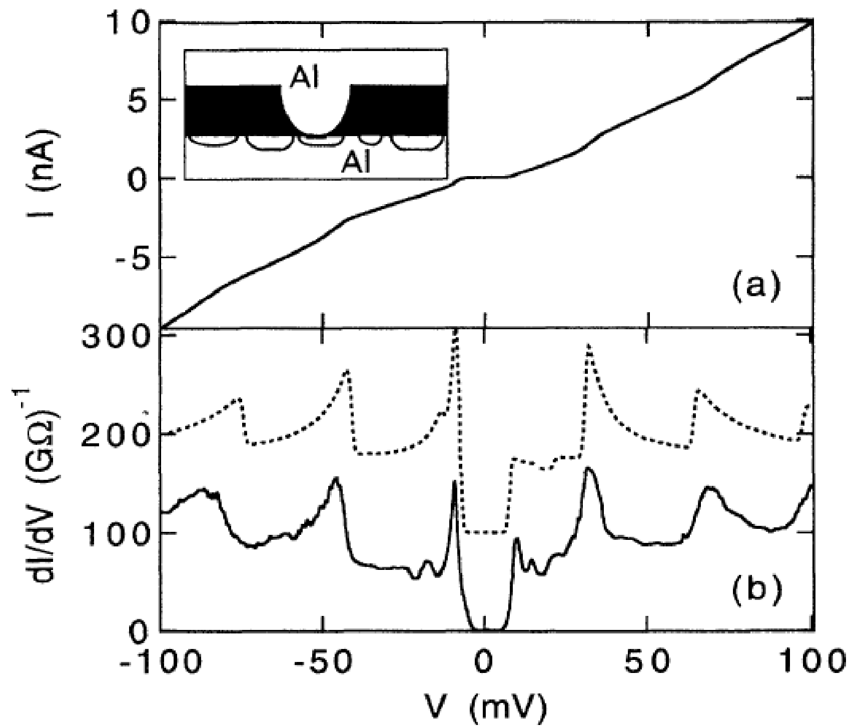


P. W. Anderson (1959): when $d > \Delta$ no superconductivity !

Spectroscopic Measurements of Discrete Electronic States in Single Metal Particles

D. C. Ralph, C. T. Black, and M. Tinkham
Department of Physics and Division of Applied Sciences, Harvard University, Cambridge, Massachusetts 02138
(Received 21 November 1994)

We have made tunnel junctions containing one Al particle of diameter <10 nm. Tunneling via discrete electronic states in the particle produces steps in the current-voltage (I-V) curve, providing, for the first time, a spectroscopic measurement of the electronic energy levels in a metal particle. With superconducting leads, the I-V contribution from each discrete state has the form of the BCS density of states. We can determine the parity of the electron number in the particle's ground state through the effects of an applied magnetic field on the I-V curve.



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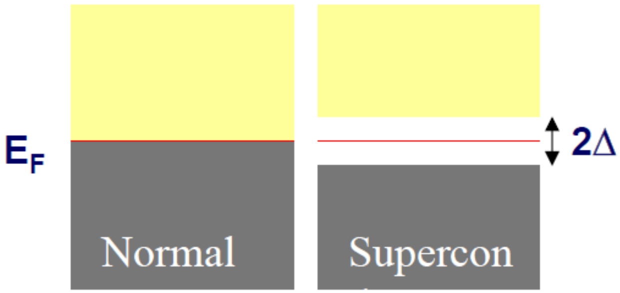

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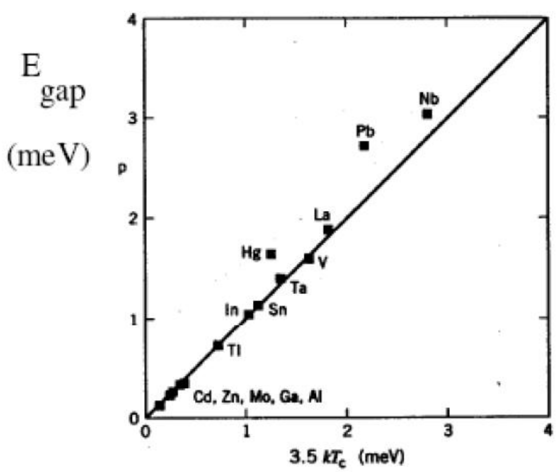

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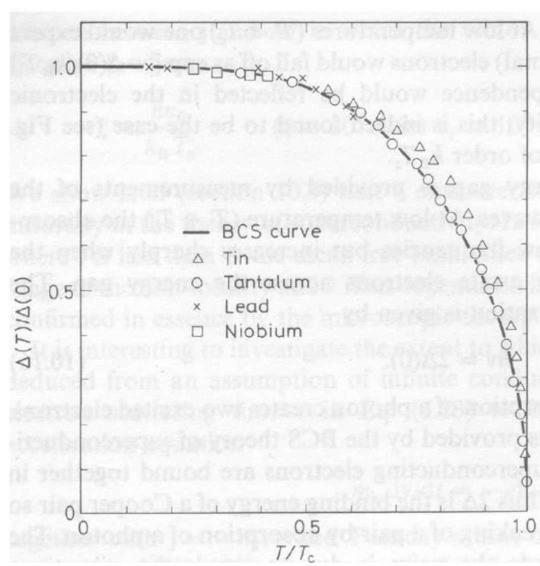
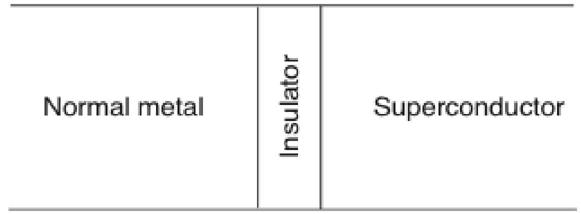
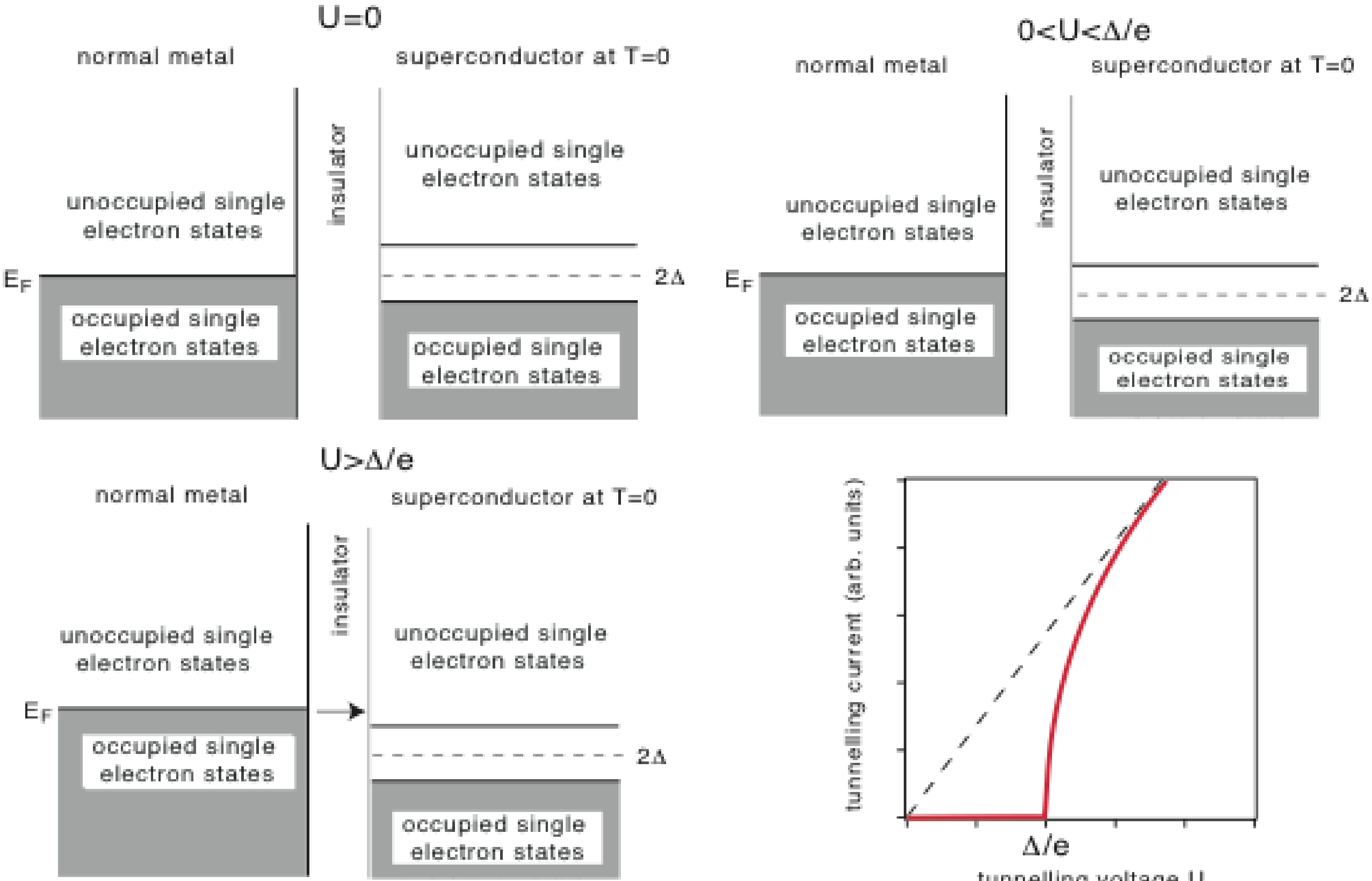
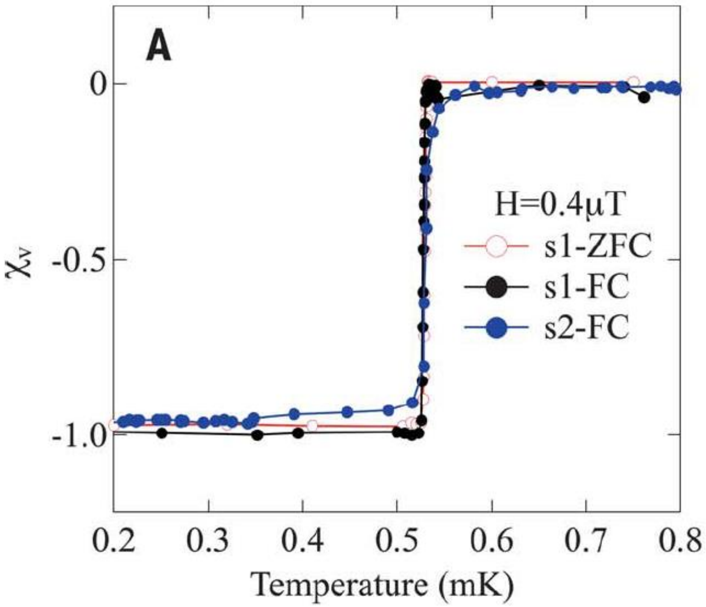


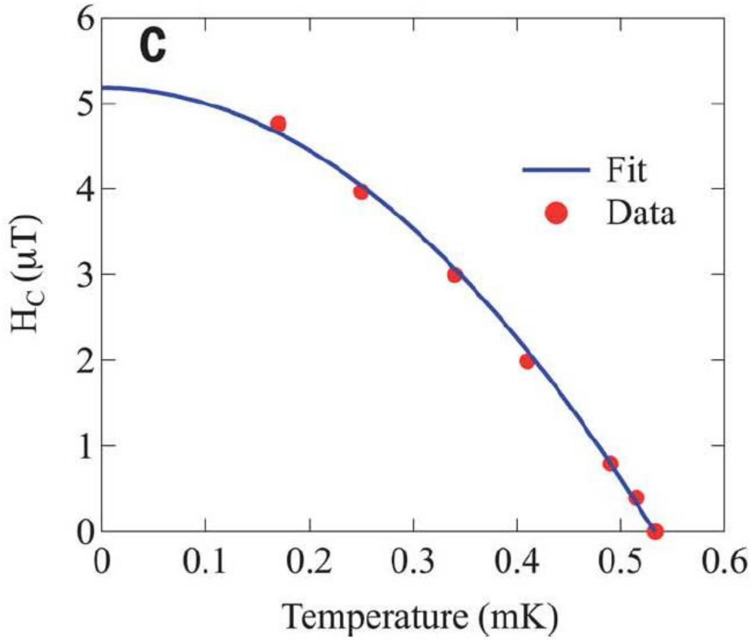
Detection of the gap: tunnelling





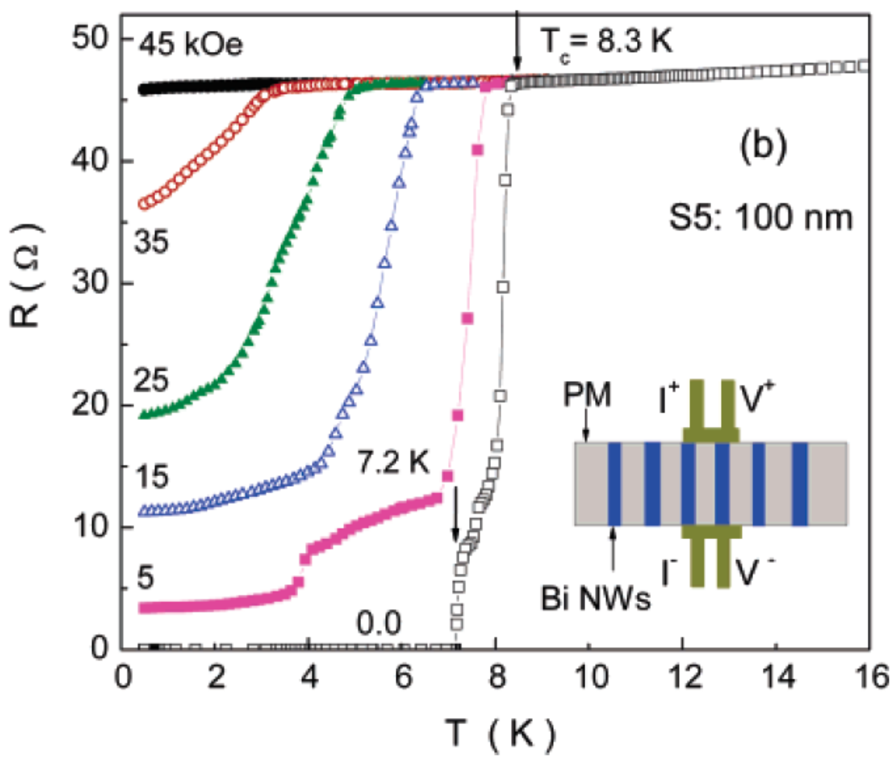
Superconductivity in pure Bi at ambient pressure

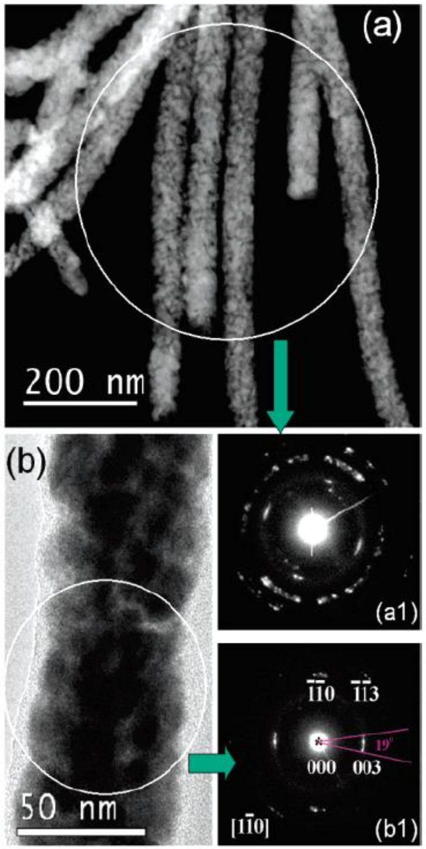




Prakash *et al.*, *Science* **355**, 52–55 (2017)

Superconductivity in granular bismuth nanowires





Tian *et al*., *Nano Lett*. **6**, 2773 (2006)

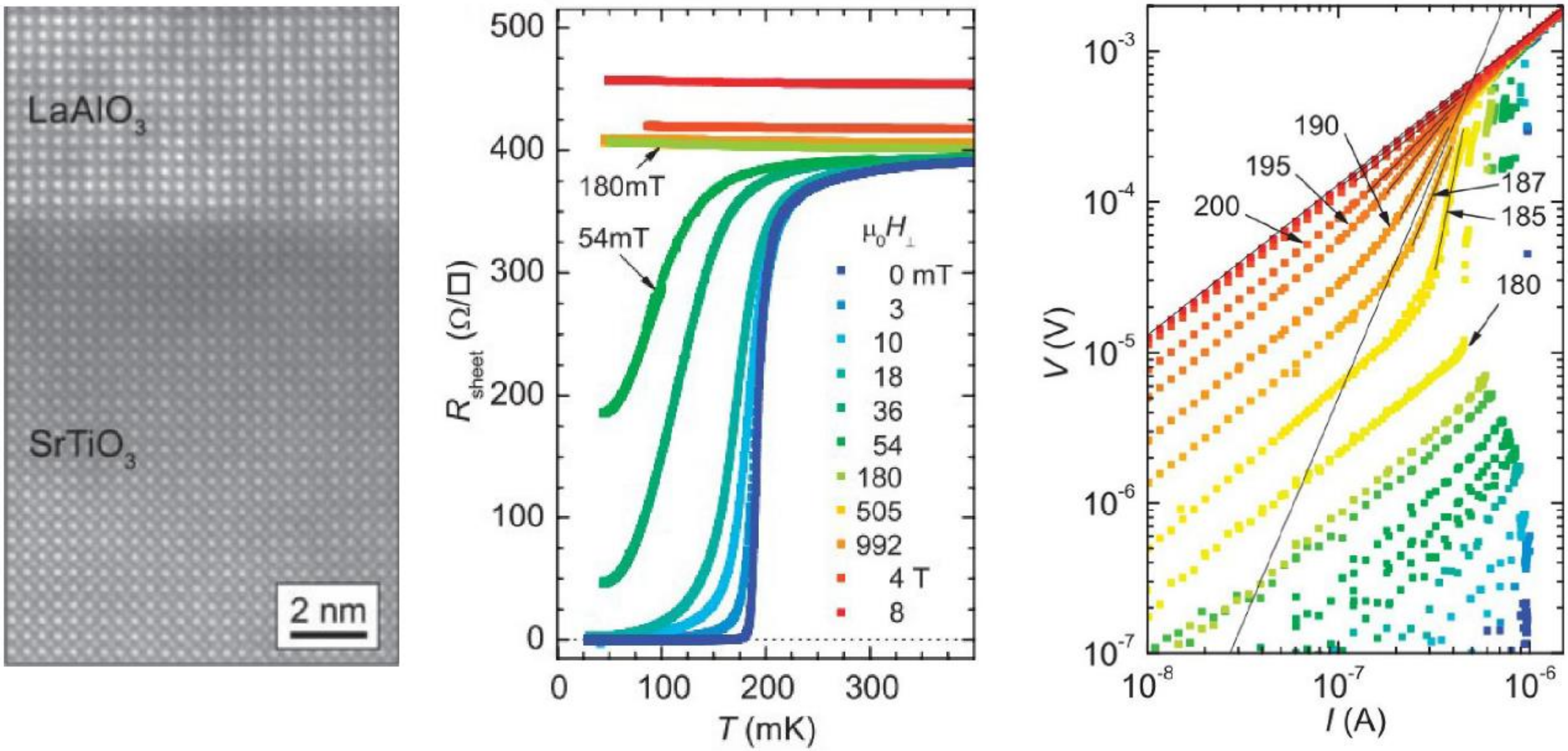
Interface Superconductivity

1. Superconductivity occurs at or near the interface between two different materials (metals, insulators, semiconductors) neither of which is superconducting.

2. Interface-enhanced superconductivity (Tc is significantly higher than either constituents .)

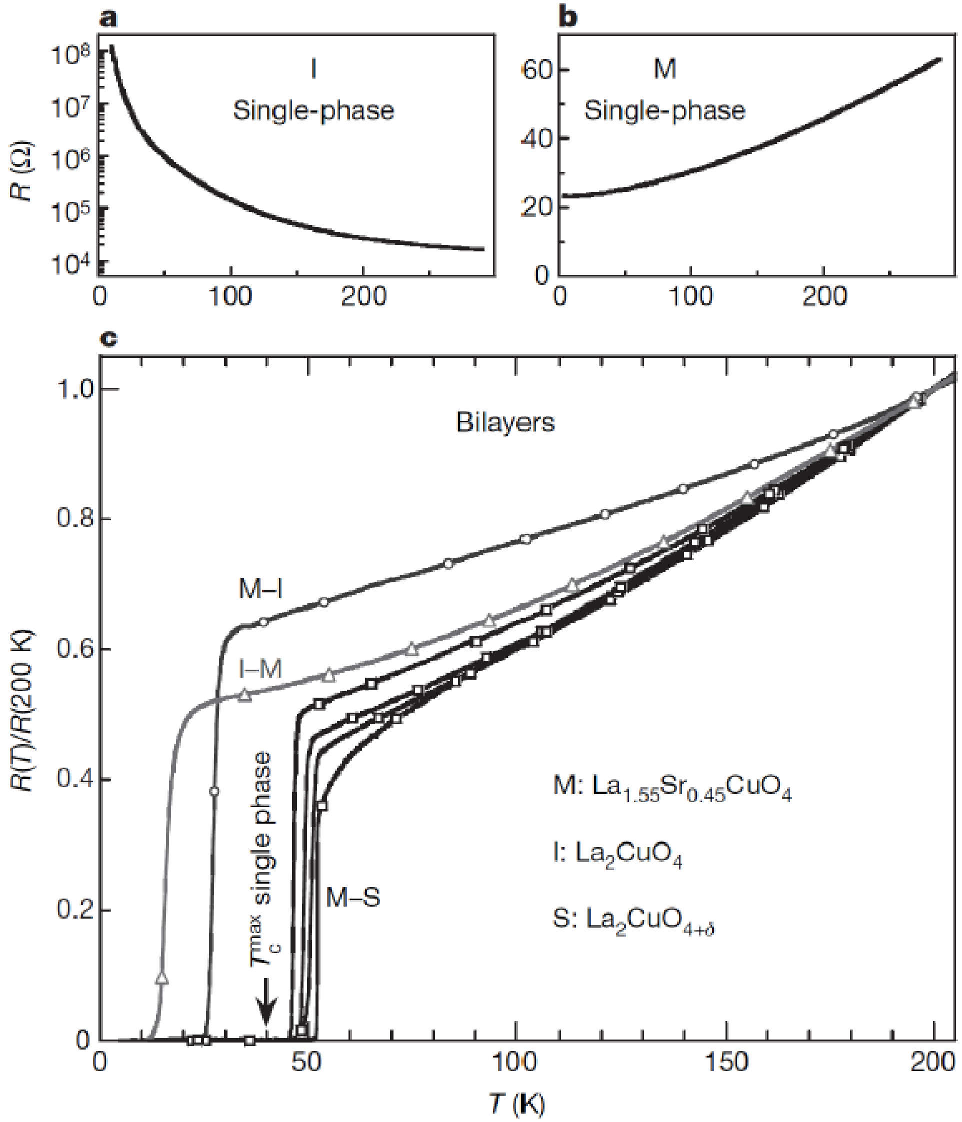
- Interface superconductivity can be considered as 2D if the thickness of the layer where superconductivity occurs is comparable to or smaller than the superconducting coherence length ξ.

Superconductivity at $LaAlO_3/SrTiO_3$ interface



- The thickness of the superconducting sheet is estimated to be ~ 4 nm.
- Clear signature of the BKT transition was found in V-I curves.

N. Reyren et al. Science 317, 1196 (2007)



Gozar *et al.*, *Nature* **455**, 782 (2008)

Theoretical concepts

"On surface superconductivity"
V. L. Ginzburg, Phys. Lett. **13** (1964) 101.

two different situations:

(i) the electrons in surface states fill partially the surface bands, and hence in an otherwise insulating material a near-surface layer can acquire metallic character and becomes superconducting

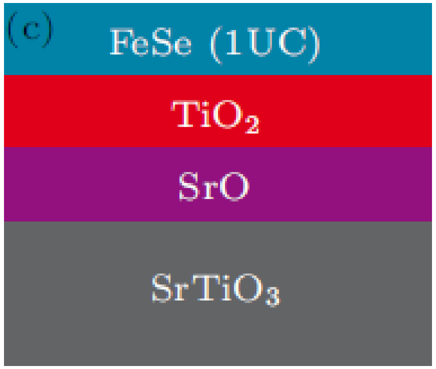
(ii) attraction between carriers occurs only near the surface due to surface phonons, variation in screening, etc., while in the bulk the interaction is repulsive.

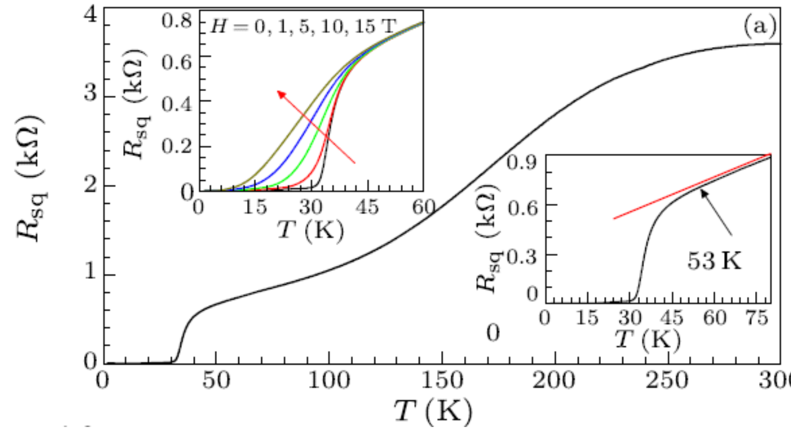
Later he even envisioned that the electron interaction may be modified and controlled by depositing "dielectric or monomolecular layers on the surface"

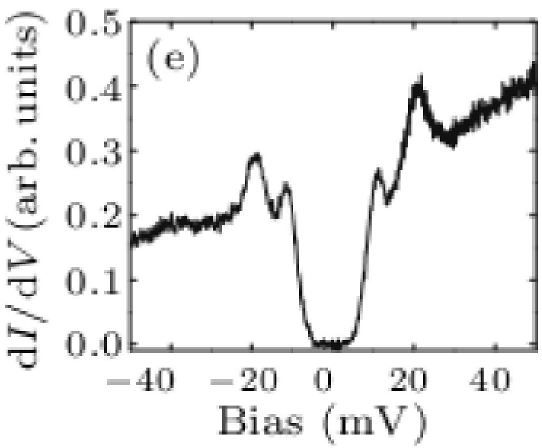
"Model for an Exciton Mechanism of -Superconductivity"
D. Allender, J. Bray, and J. Bardeen, Phys. Rev. B **7**, 1020 (1973).

Proposed a thin metal layer on a semiconductor surface.
They found an impressive T_c enhancement effect when the stringent conditions on the Interfaces are met.

Single layer FeSe on STO



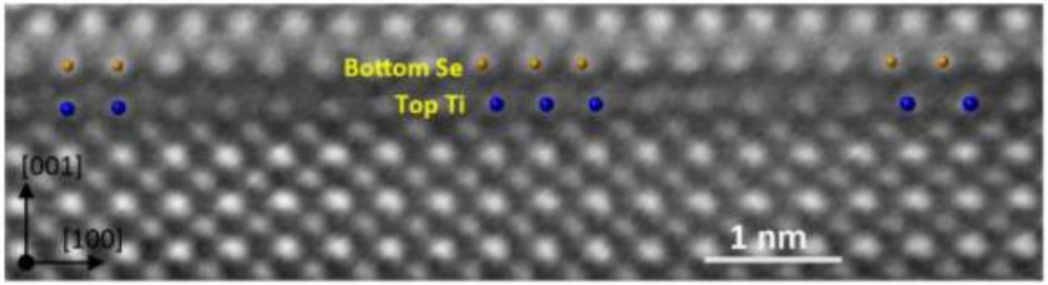


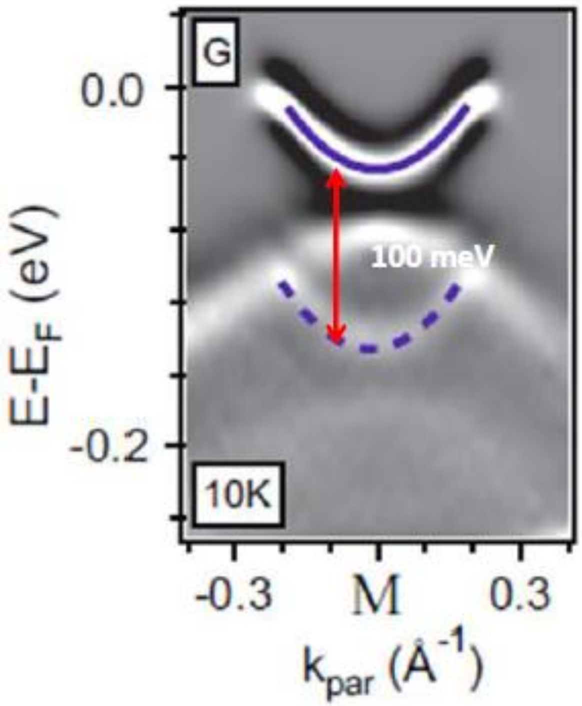


1UC-FeSe film on Nb-doped STO substrate

The large superconducting-like gap Δ=20.1 meV by STM

FeSe on STO: Interface Effect (2)





Lee *et al.*, *Nature* **515**, 782 (2014)