Electrostatic Tuning of Superconductivity

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Introduction

Goal

Carry out fundamental modifications of the properties of superconductors through controlled and reversible changes in carrier concentration *without altering the level of disorder*

Materials

Cuprate **superconductors**

Two-dimensional and interfacial superconductors

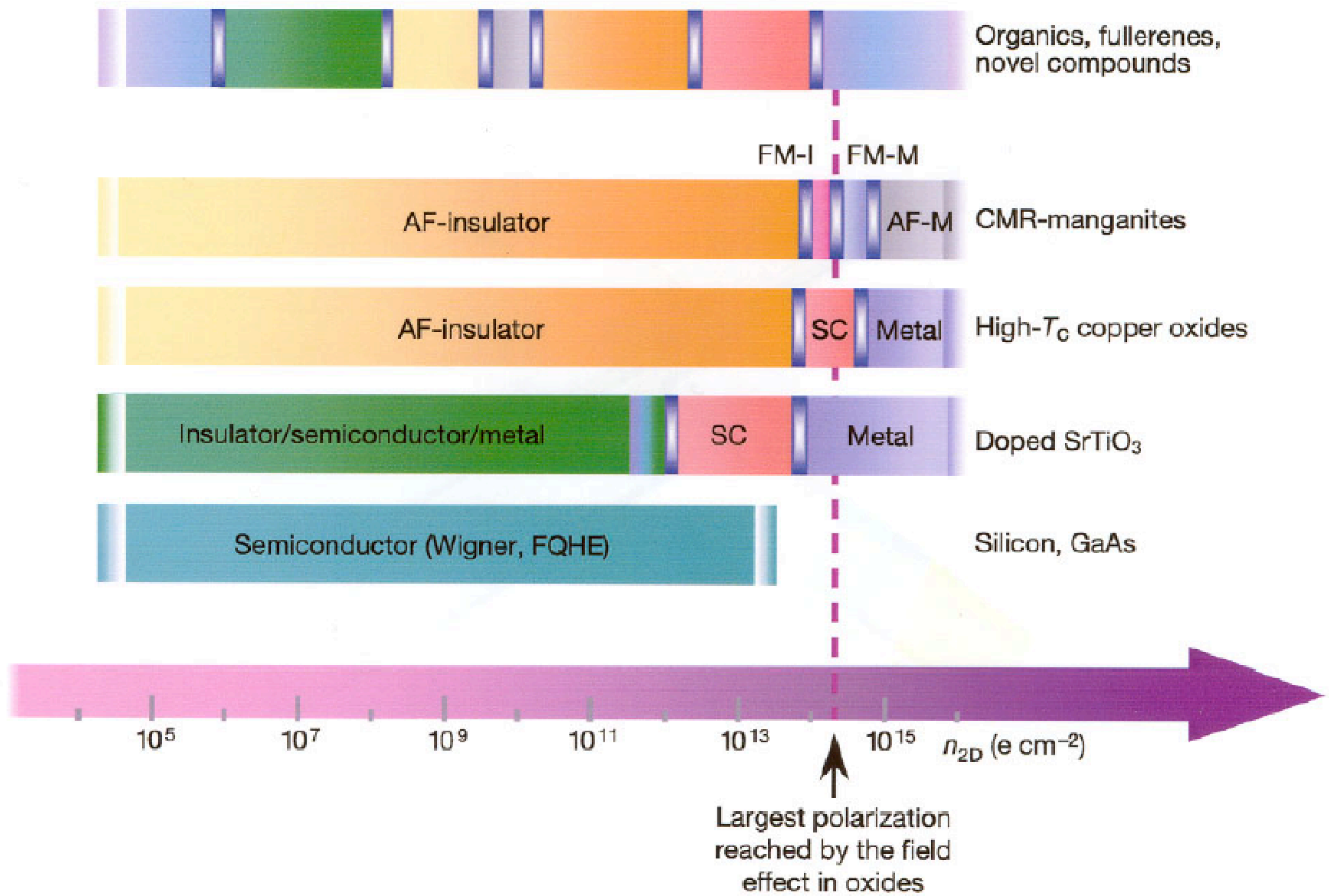
Can provide a tool for studying
quantum critical behavior

Can be the source of new devices

Development can in principle draw on the extensive
experience with Si-field effect transistors

With the current level of technology, significant
levels of charge transfer have already been
achieved.

Properties of Materials as a Function of Sheet Charge Density



From: C.H. Ahn, J.-M. Triscone, J. Mannhart, Nature August 28 (2003).

Requirements for Experiments

close competition between two or more electronic phases in which

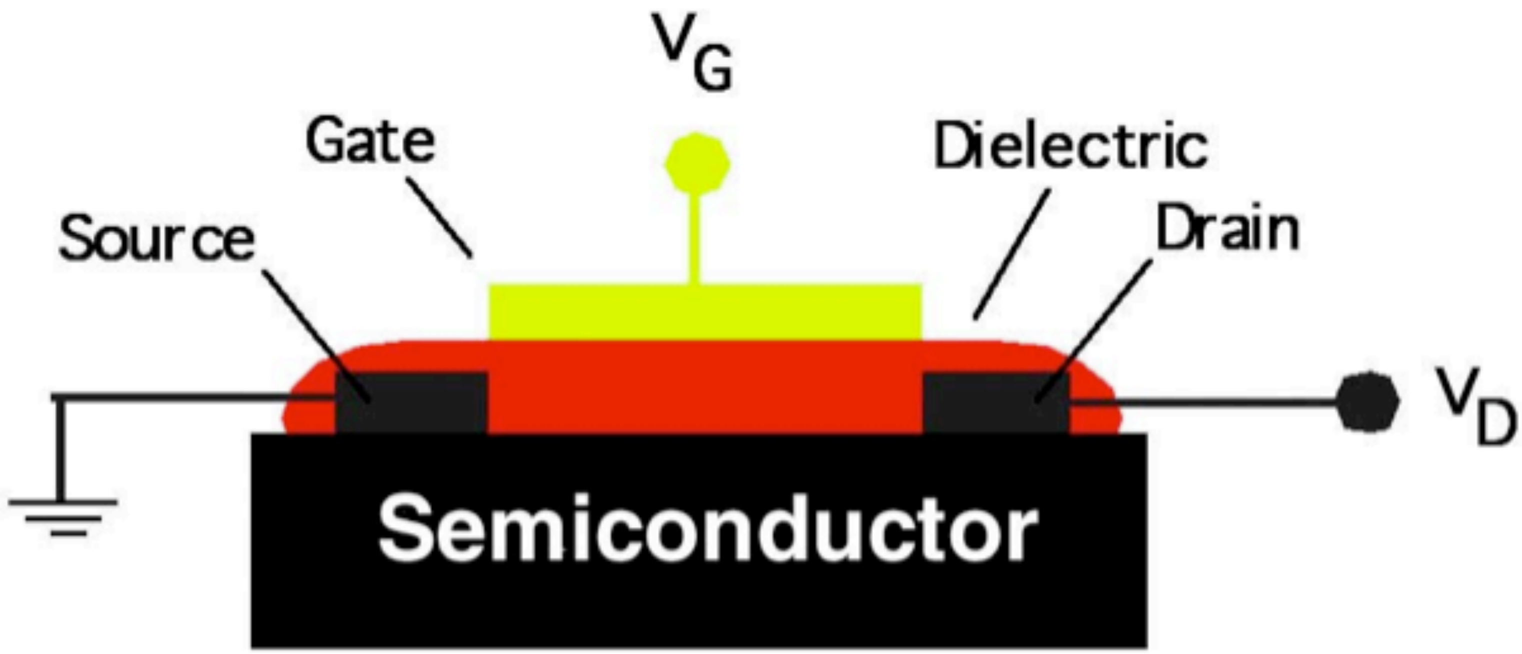
small changes in chemical composition, strain or external fields bring about transitions between phases

Configurations

FETs

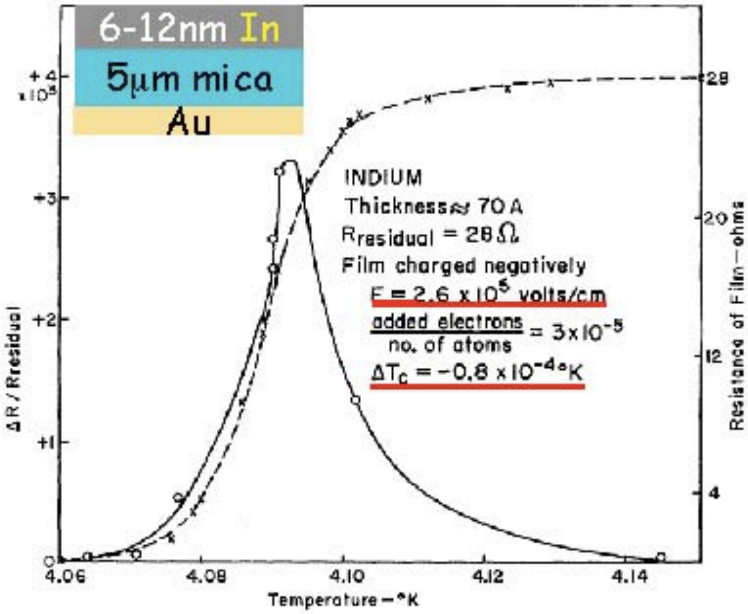
use of a polarizable ferroelectric layer such as PZT.

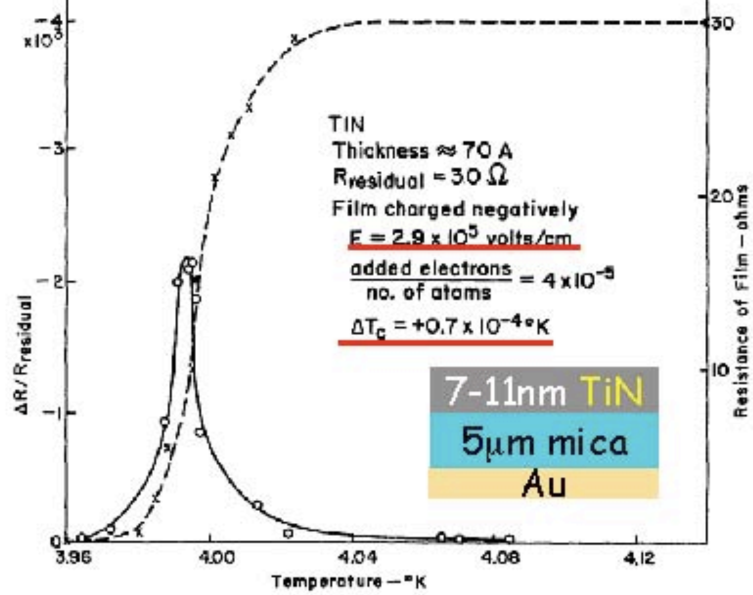
Cartoon of a Simple Field Effect Transistor



The Beginning:

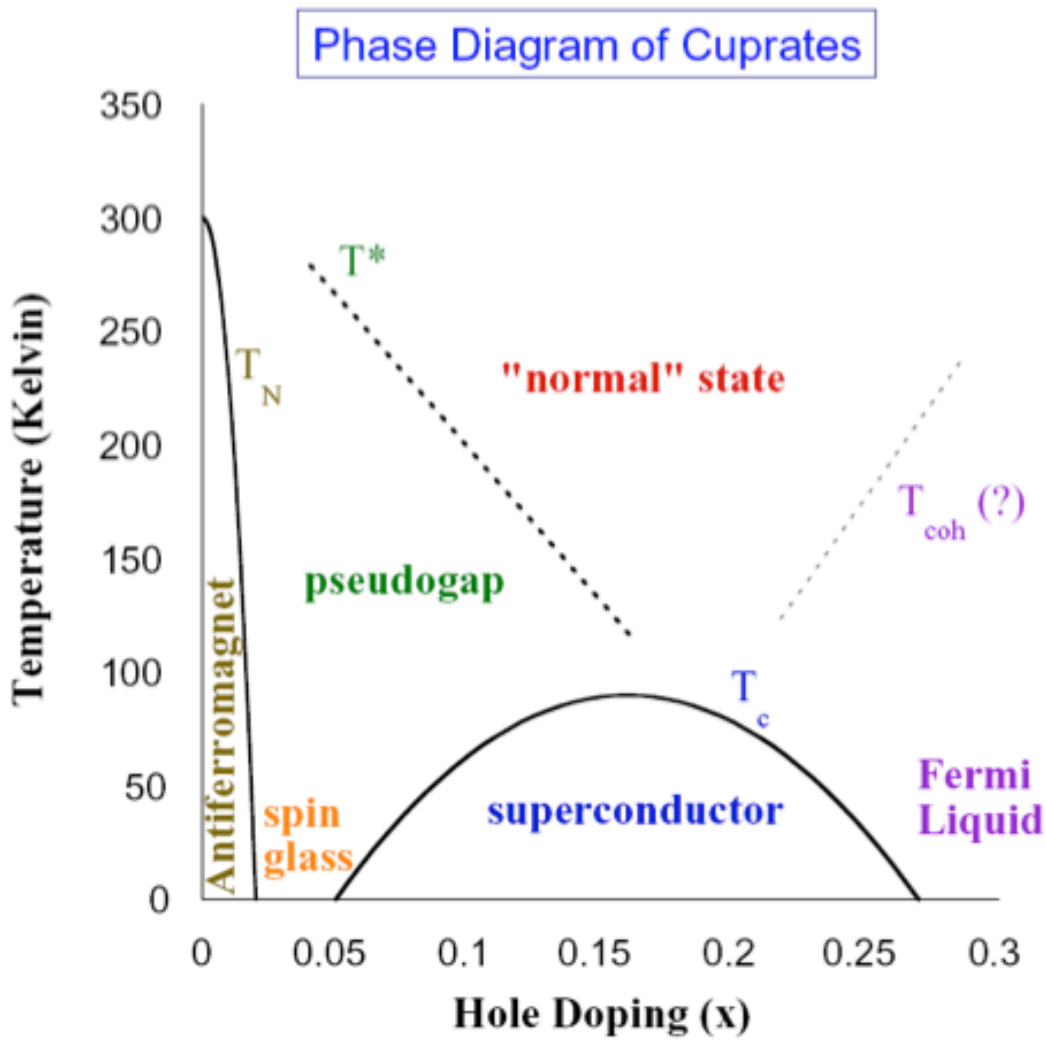
CHANGES IN SUPERCONDUCTING CRITICAL TEMPERATURE PRODUCED BY ELECTROSTATIC CHARGING*





R. E. Glover III and M. D. Sherrill, Phys. Rev. Lett. **5**, 248 (1960)

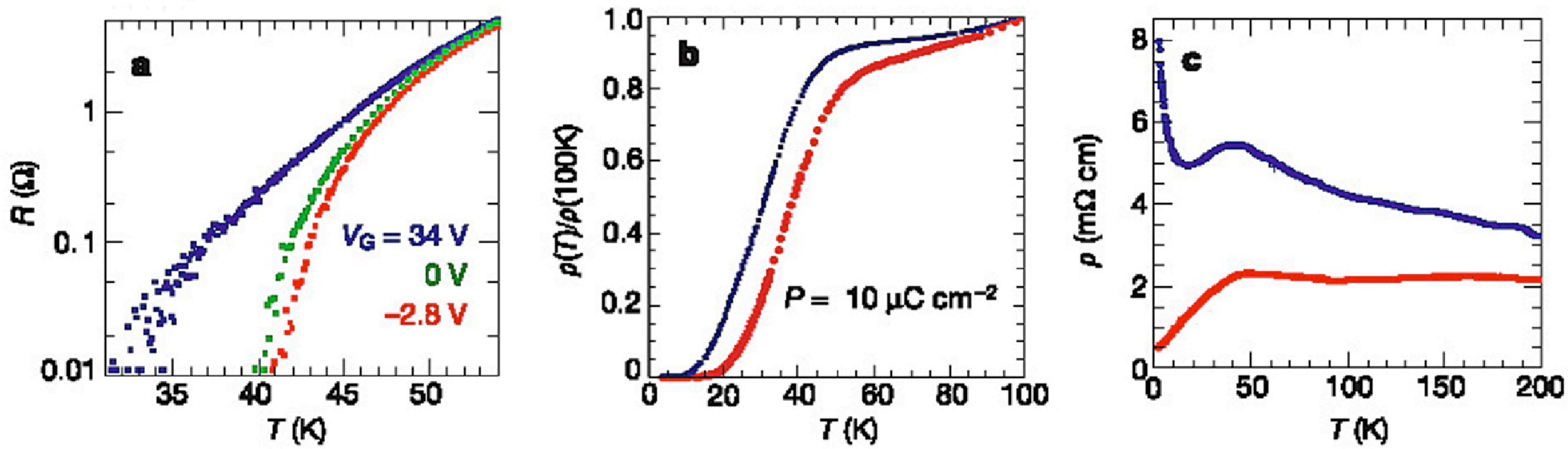
$$\frac{|\Delta T_c|}{T_c} \cong 0.002\%$$



From: M. Norman

Superconductivity starts at x ~ 0.03,corresponding to 3.5 x 10^{13} per plane.

Tuning Superconductivity by Ferroelectric Polarization and by Electrostatic Charging



a. 8nm thick $YBa_2Cu_3O_{7-\delta}$ channel with a ~300 nm thick $Ba_{0.15}Sr_{0.85}TiO_3$ gate insulator

b. 2nm thick $GdBa_2Cu_3O_{7-\delta}$ film induced by a 300 nm thick PZT layer acting as ferroelectric gate. Curves are normalized in the normal state.

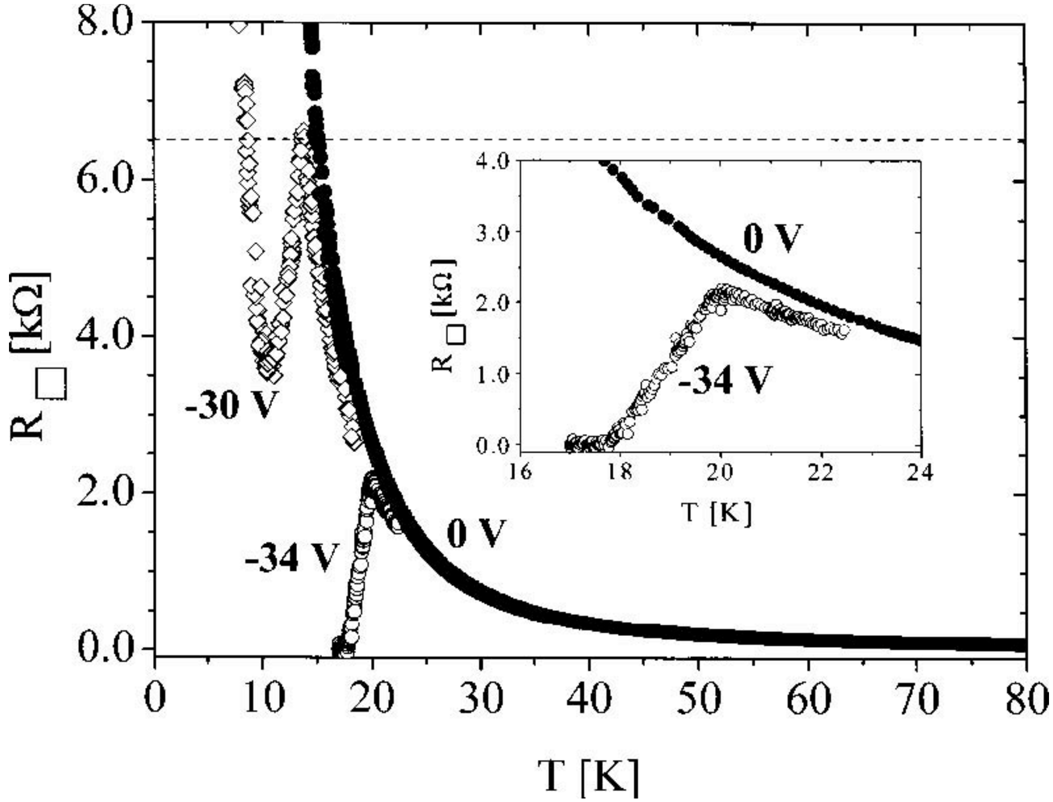
c. 2 nm thick $GdBa_2Cu_3O_{7-\delta}$ film whose doping level has been chosen to be close to the S-I transition.

a. Mannhart, J., 1996, Supercond. Sci. Technol. **9**, 49.

b and c. Ahn, C. H., J.-M. Triscone, and J. Mannhart, 2003, Nature London **424**, 1015.

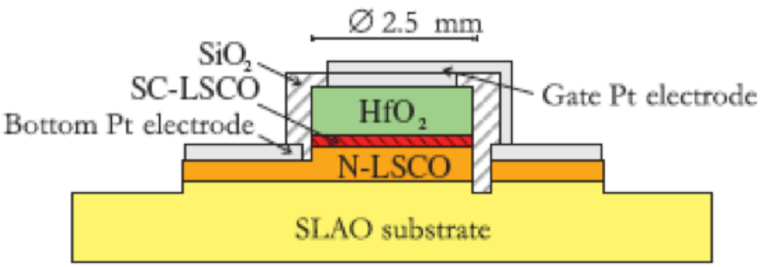
FET device consisting of a $Nd_{1.2}Ba_{1.8}Cu_3O_x$ film grown on a (100) $SrTiO_3$ substrate, overlayed with an Al_2O_3 insulator and an Au gate.

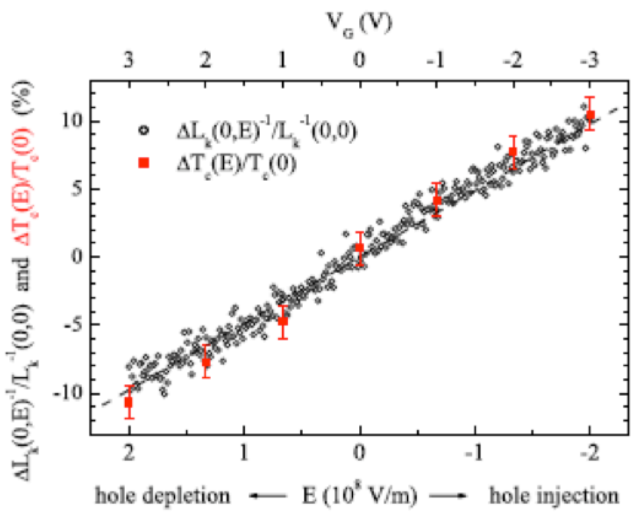
Reversible changes of the hole density were found.

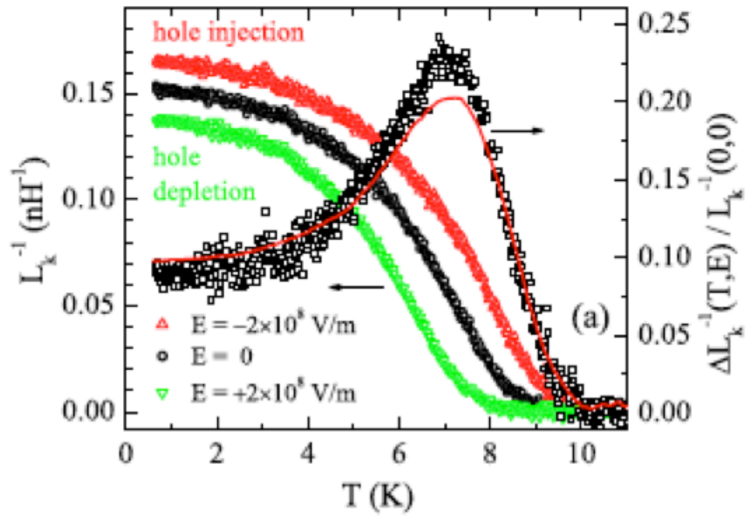


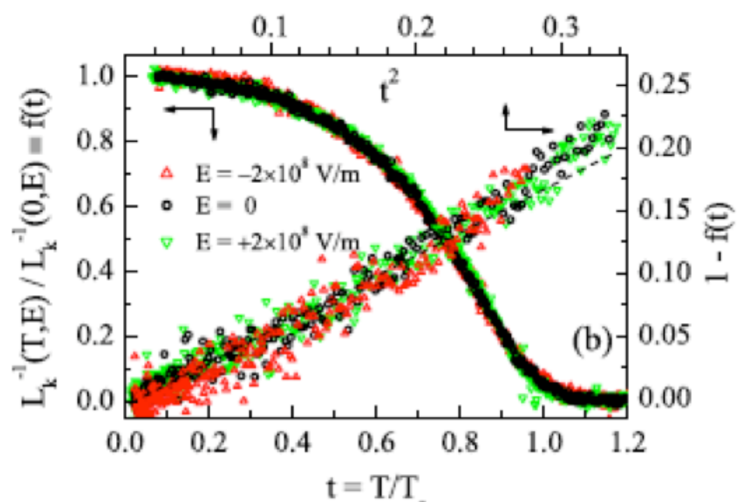
A. Cassinese *et al.*, 2004, Appl. Phys. Lett. **84**, 3933.

Tuning T_c of $La_{2-x}Sr_xCuO_4$





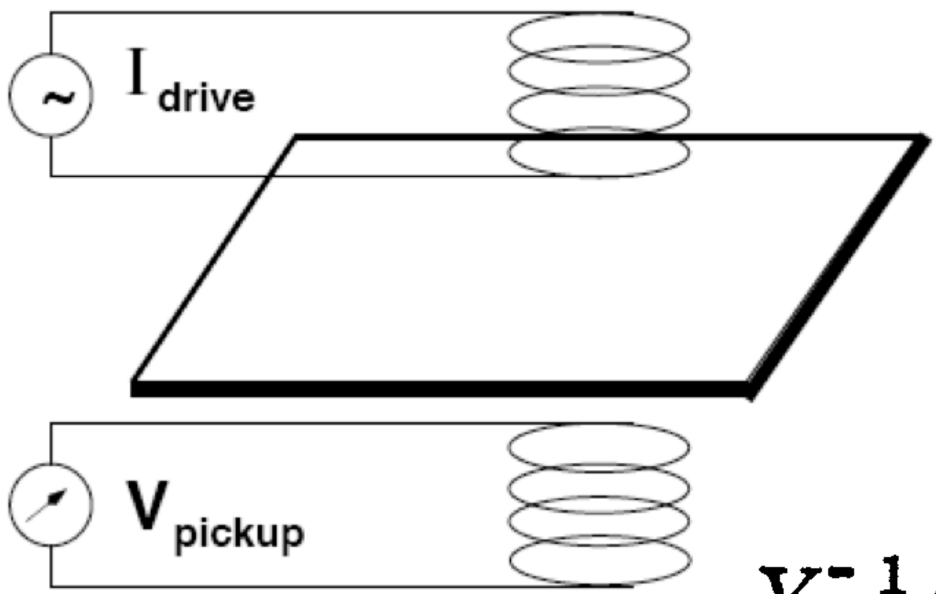




T_c ~ n_s (T=0)—appears to Satisfy Uemura relation

A. Rufenacht, J.-P. Locquet, J. Fompeyrine, D. Caimi, and P. Martinoli,PRL **96, 227002 (2006)**

Two-coil Method for Measuring Kinetic Inductance

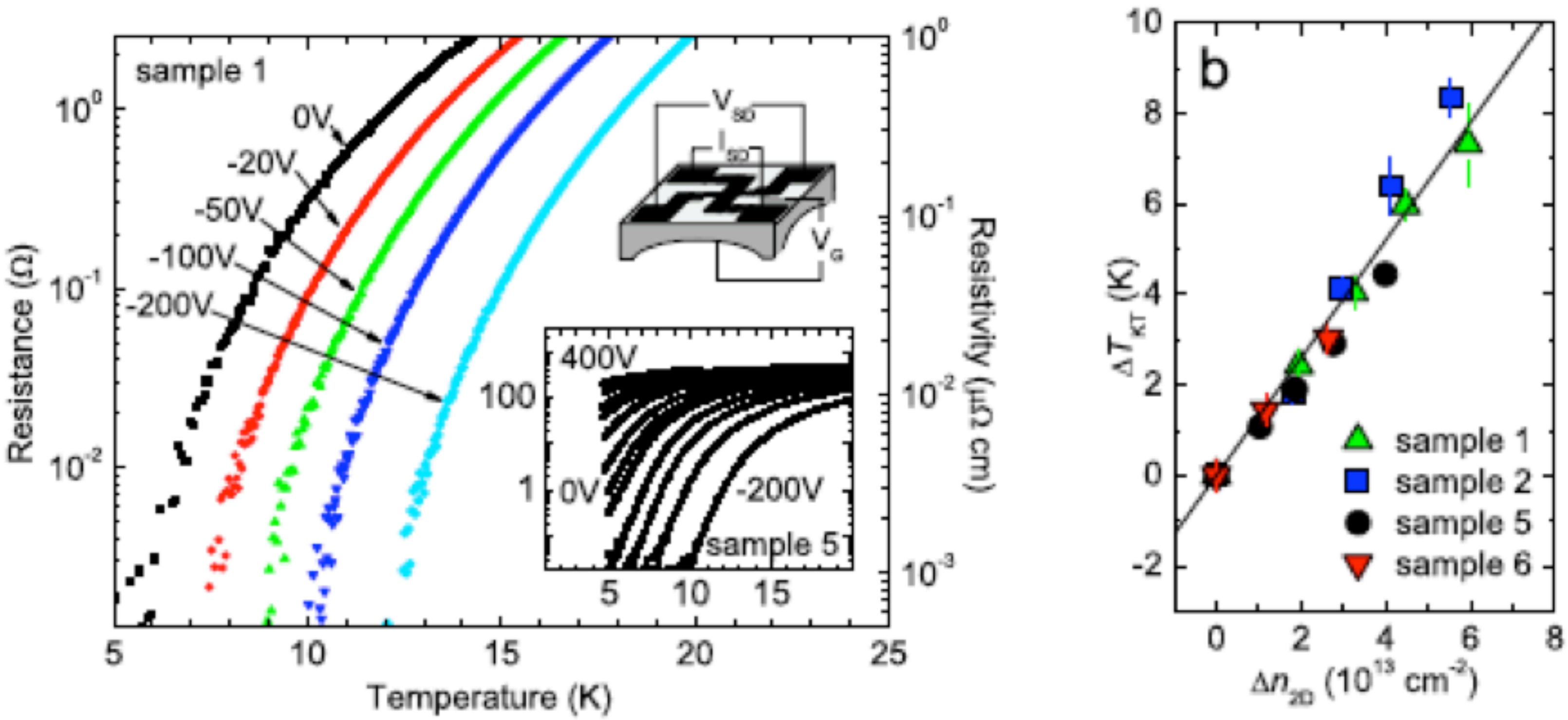


$$Y^{-1} = R + i\omega L$$

$$L_K = m_e / n_s e^2 = 2\pi\Lambda / c^2$$

$$\lambda_0^2 = mc^2 / 4\pi n e^2$$

Modulation of the Properties of $Nd_{1+x}Ba_{2-x}Cu_3O_{7-y}$



D. Matthey, N. Reyren, J.-M. Triscone, and T. Schneider, PRL **98, 057002 (2007)**

$T_{KT} \sim n_{2D}^{\nu z}$

Can one gate across the nonsuperconductor-superconductor boundary?

Brings up the issue of Quantum Critical Points!

Classical critical point-- thermal fluctuations--scale invariance, divergent correlation length. The free energy is a non-analytic function at $T = T_c$.

Quantum critical point--quantum fluctuations at $T = 0$ -- scale invariance, divergent correlation lengths. The ground state energy is a non-analytic function of a tuning parameter at $g = g_c$.

The tuning parameter may be pressure, **charge**, magnetic field, doping, or disorder, depending upon the system.

Disorder and Superconductivity

Early theories of dirty superconductors are applicable only in the low-disorder regime (Anderson's Theorem)

With a high enough level of disorder, Anderson localization occurs.

The effect of strong disorder on superconductivity involves both interactions and disorder.

Under strong conditions of electron localization, superconductivity should disappear, even with an attractive interaction.

Superconductivity in two dimensions is special -- transition is topological and there is no true long-range order.

Investigate the "thickness-dependence" of superconductivity

Phil Mag 28 467 (1914)

Thickness dependence of Resistance

LII. *The Electrical Resistance of Thin Metallic Films, and a Theory of the Mechanism of Conduction in such Films.* *By* W. F. G. SWANN, *D.Sc., A.R.C.S.**

THE theory which attributes electrical conduction to the presence of free electrons requires, in order that the variation of the resistance of a metal with the temperature θ shall be explained, that the mean free path of an electron shall vary as θ^{-2} †.

The original object of the present work was to test this fact by direct experiment. Patterson ‡ has shown that the specific resistance of a very thin film is abnormally high, and moreover, that it increases enormously rapidly as the thickness diminishes below a certain critical value. Sir J. J. Thomson has shown that a rapid increase of this kind can be explained as due to the fact that when the dimensions of the film get comparable with the mean free path of an electron, those electrons which at any instant are moving in a direction inclined to the plane of the film do not get a chance of travelling for their complete mean free path, so that the electric field does not produce in them the full velocity which it would produce if the true mean free paths were described. Sir J. J. Thomson shows that if t, the thickness of the film, is greater than 2λ, where λ is the mean free path in a large mass of the metal, λ' the mean free path in the film is given by

$$\lambda' = \lambda\left(1 - \frac{\lambda}{4t}\right), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and if $t < \lambda$

$$\lambda' = t\left\{\frac{3}{4} + \frac{1}{2}\log\frac{\lambda}{t}\right\}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

from which it follows that λ' does not begin to diminish rapidly as t decreases, until t becomes less than λ. The thickness at which λ', and consequently the conductivity, starts to diminish rapidly gives, on this theory, an approximate measure of the mean free path. Now if λ varies as

* Communicated by the Author. Experiments performed at the University of Sheffield. Paper read at the Meeting of the British Association, 1913.

† Formerly it was supposed that the mean free path should vary as θ^{-1} (see Sir J. J. Thomson, 'Corpuscular Theory of Matter,' p. 80), but O. W. Richardson (Phil. Mag. [6] xxiii. p. 275) points out that in the theory of the Thomson effect (which plays an important part in the subject) a term has been omitted by all previous workers. The inclusion of this term leads to θ^{-2} as above.

‡ Patterson, Phil. Mag. [6] iv. 1902.

Fig. 1.

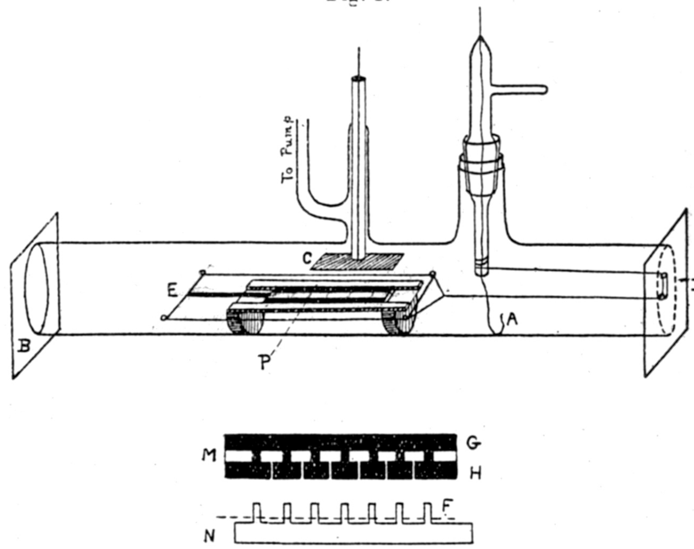
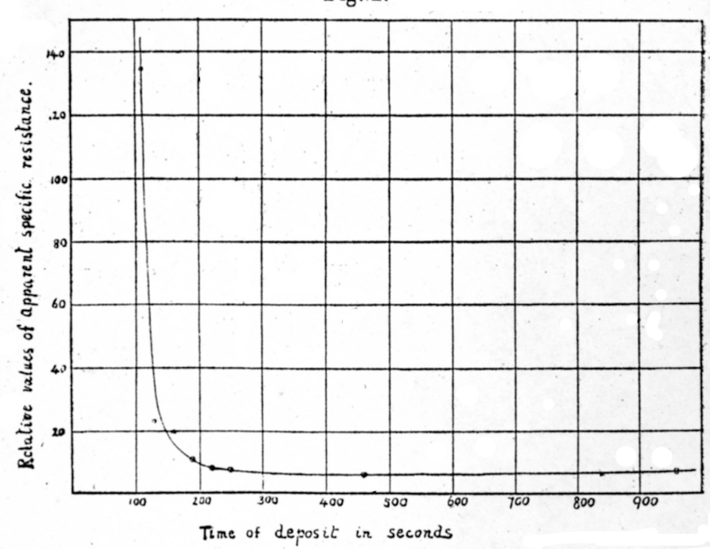
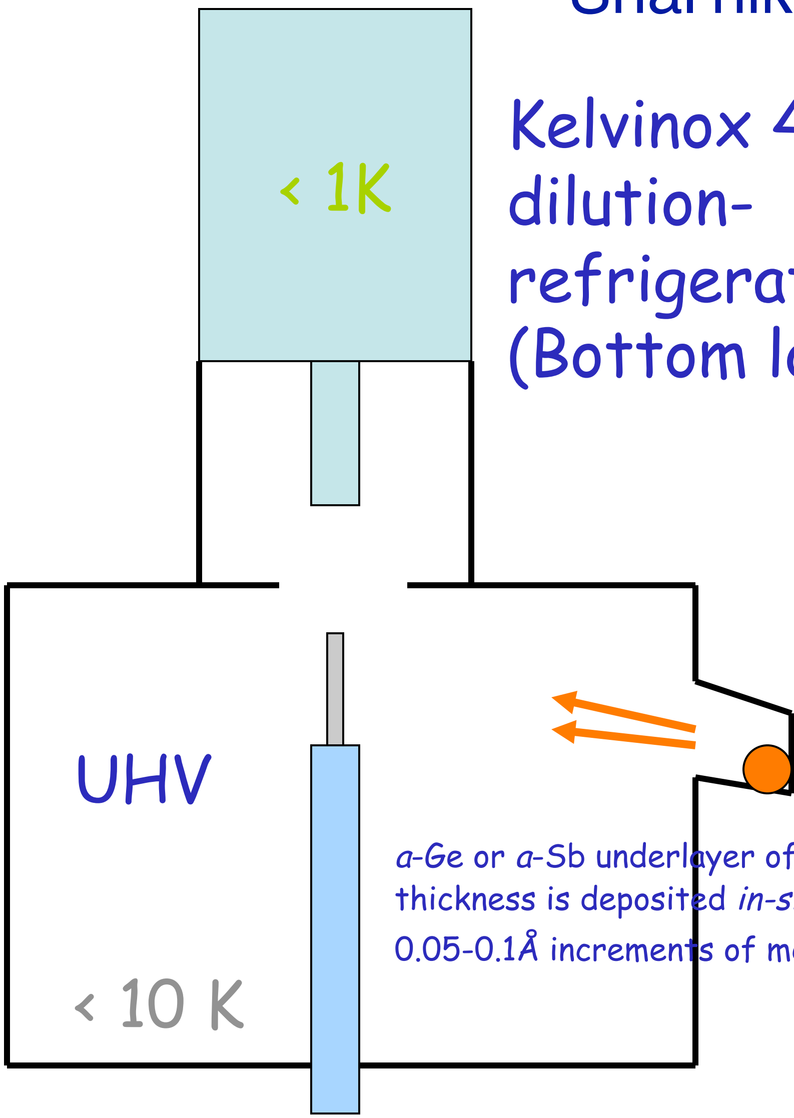


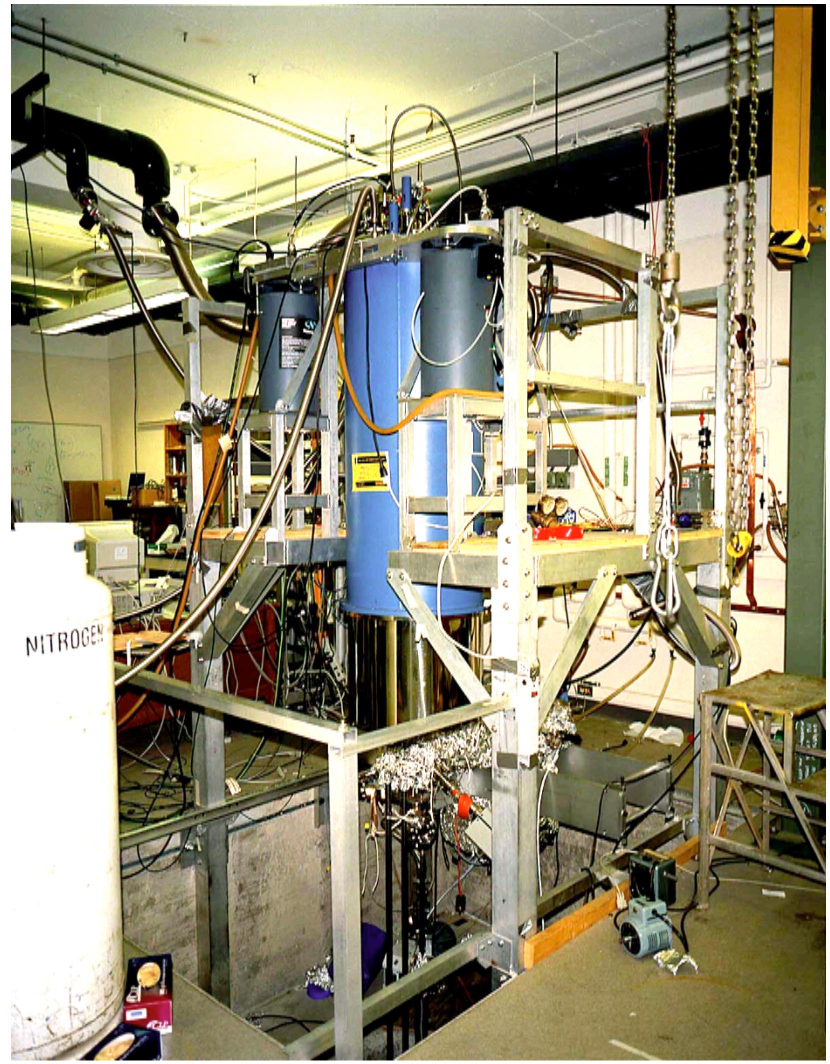
Fig. 2.



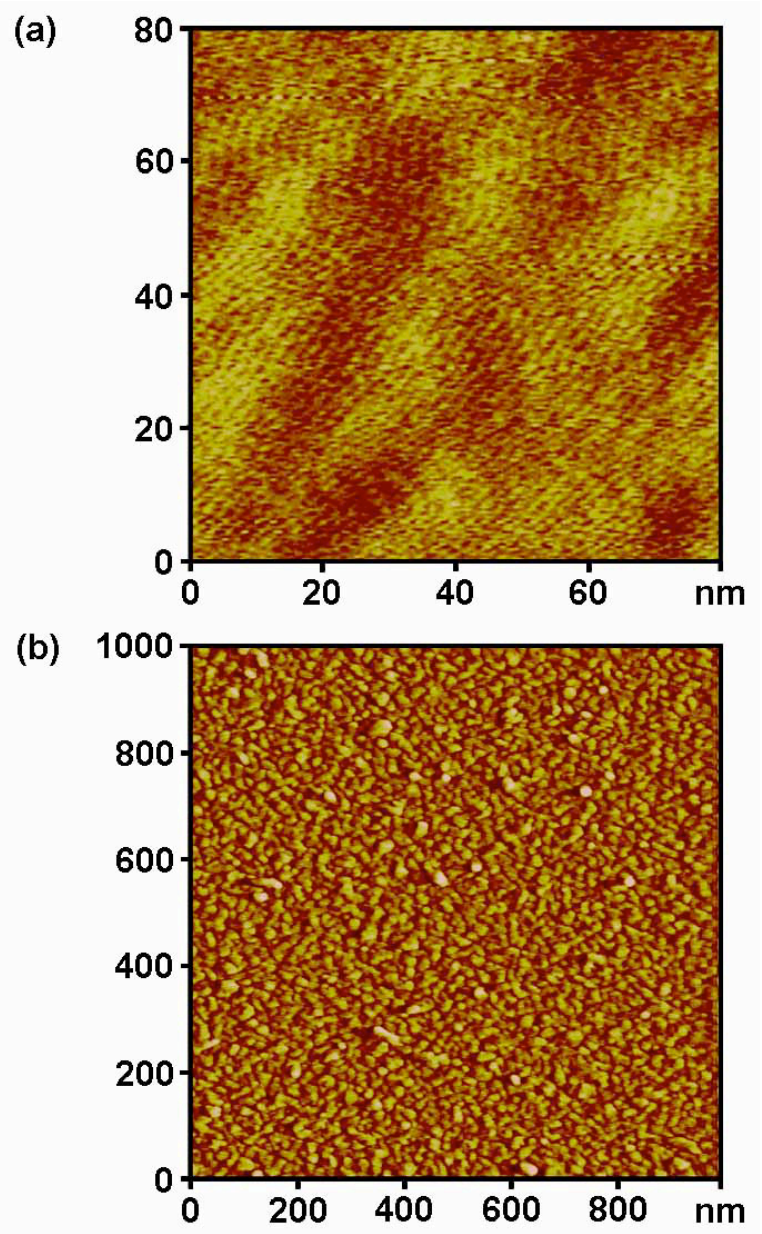
Apparatus for Quench-Condensation (Pioneered by Shal'nikov and Strongin)



Kelvinox 400 dilution-refrigerator (Bottom loading)



L.M. Hernandez and A.M. Goldman, Rev. Sci. Instrum. 73, 162 (2002)



Atomic Force Microscope Images of amorphous (a) and granular (b) films produced by quench evaporation. The amorphous film is grown on top of an a-Sb underlayer. The granular film is grown directly on the substrate.

The height variations of (a) are the order of 0.3 nm, whereas those of (b) are the order of the grain size. The rms roughness of (a) is about 0.03 nm.

Films Grown on *a*-Ge Substrates - Homogeneous

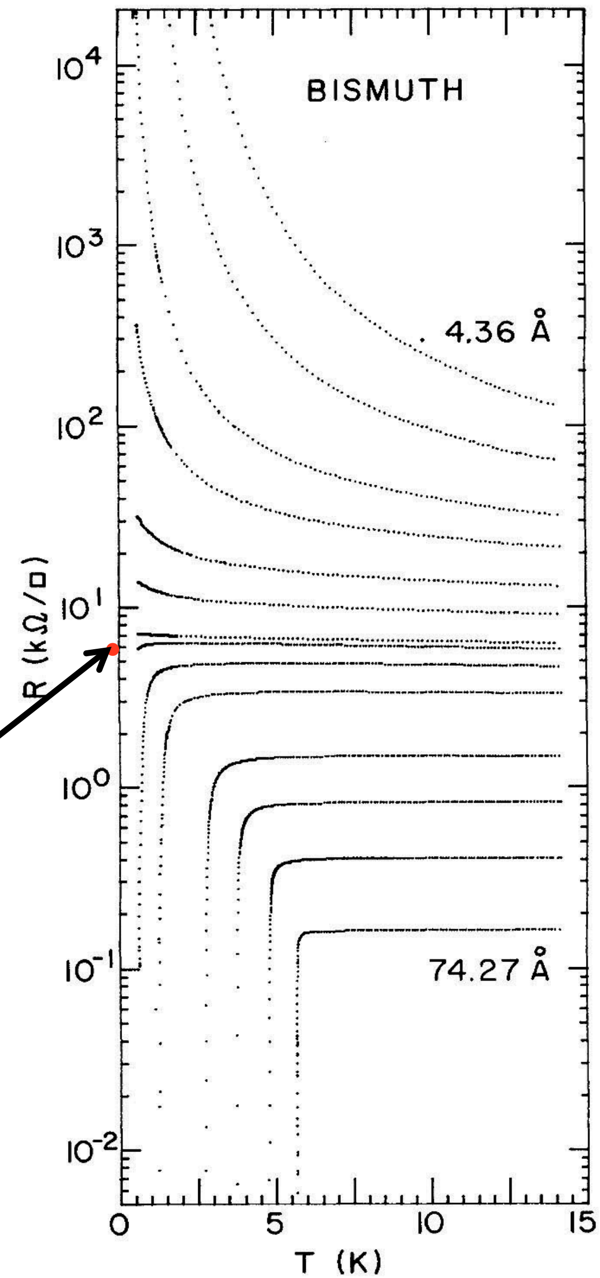
Cyclic evaporation leads to evolution of superconductivity with thickness.

Apparent separation between superconducting and insulating behavior.

Critical resistance close to $h/4e^2 = 6450\ \Omega$

Curves of R(T) at different thicknesses look like renormalization flows.

Data Suggests: Quantum Critical Point (QCP) or zero-temperature quantum phase transiton

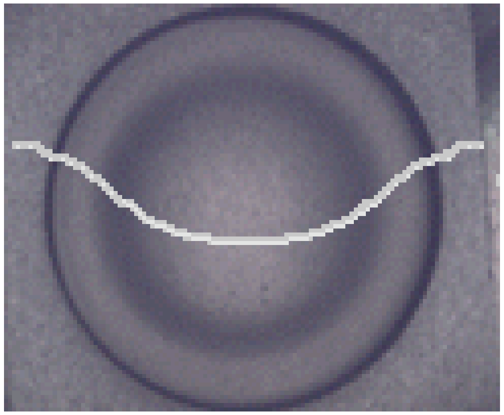


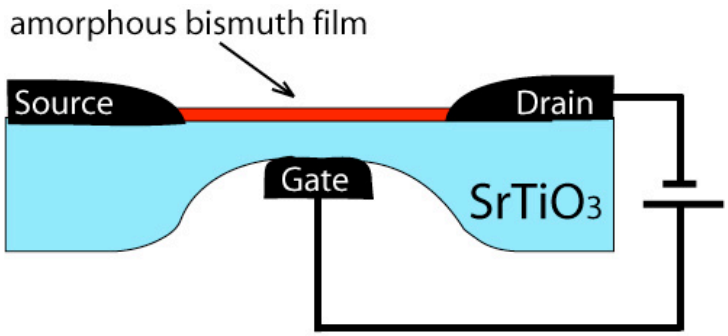
Haviland, Liu, and Goldman
Phys. Rev. Lett. 62, 2180 (1989)

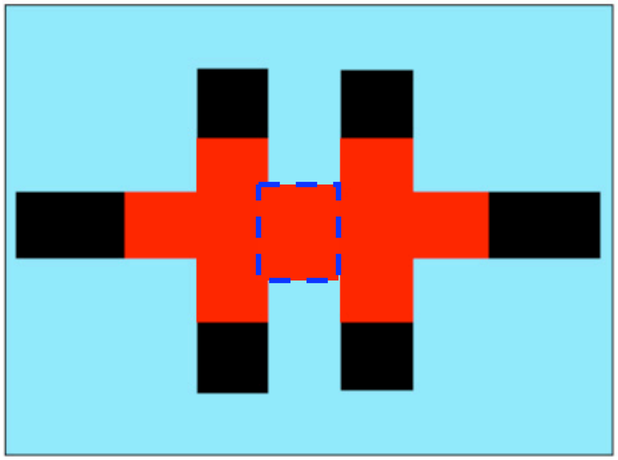
FET Structure: Combined Substrate and Gate Insulator

Back of a micro-machined substrate.
Height profile is superimposed on the picture.
Thickness in middle can range from 10μm to 100μm
Surface roughness of approximately 1μm.

Diameter of the thinned region is typically 4mm.





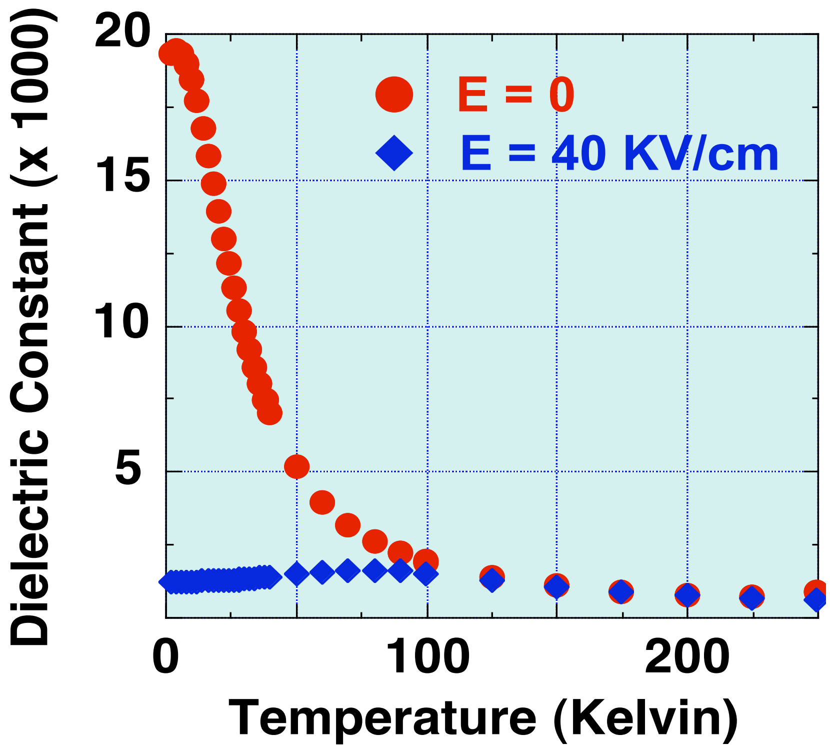


Cartoon of insulating substrate separating a Bi film from the gate Thickness of the film is about 10 Å, and that of the source and drain about 100 Å. Separation between the gate and the film is approximately 50 μm.

A. Bhattacharya, *et al.*, APL **85**, 997 (2004)

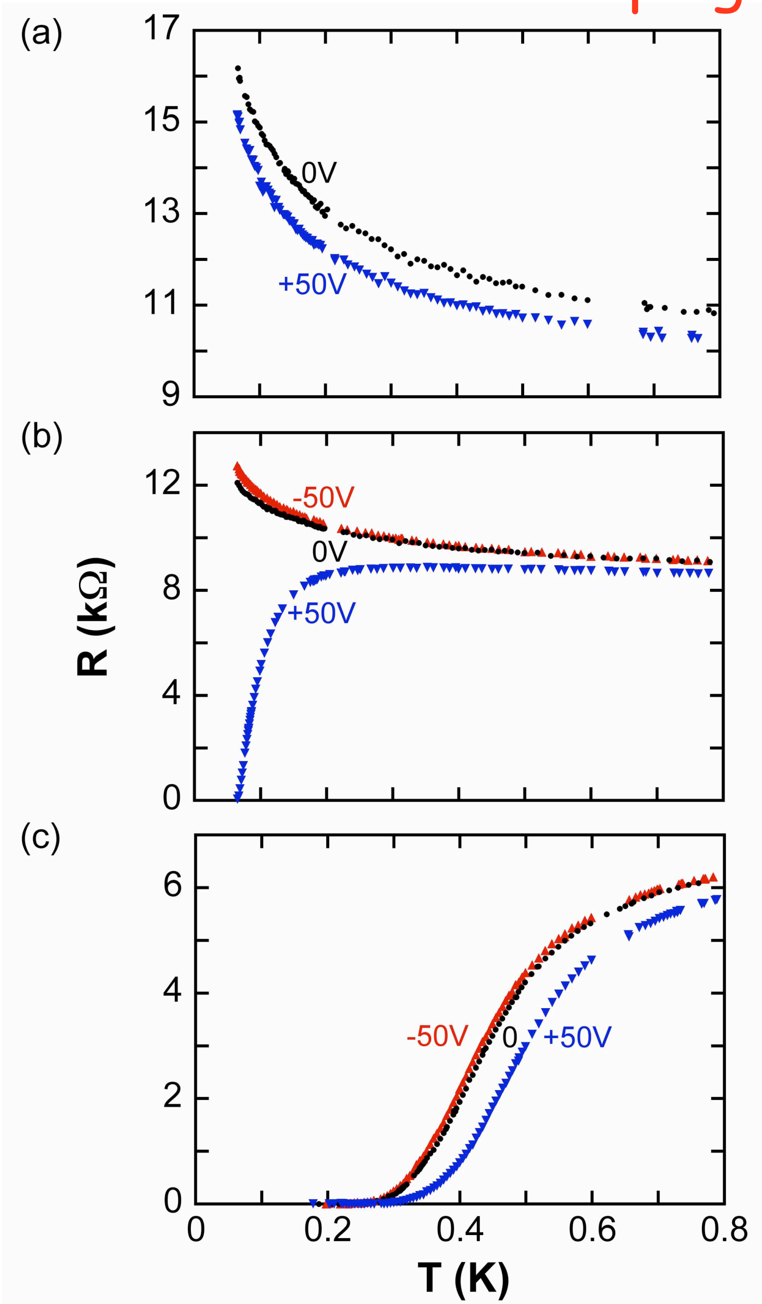
Why Strontium Titanate?

$SrTiO_3$ as a Dielectric for Electrostatic Doping



K_e > 19,000 below 10 K

Electrostatic "doping" at various film thicknesses



50 volts is about 3 x 10^{13} carriers/cm^2

a-Bi Film with Thickness 9.91 Å

a-Bi Film with Thickness 10.22 Å

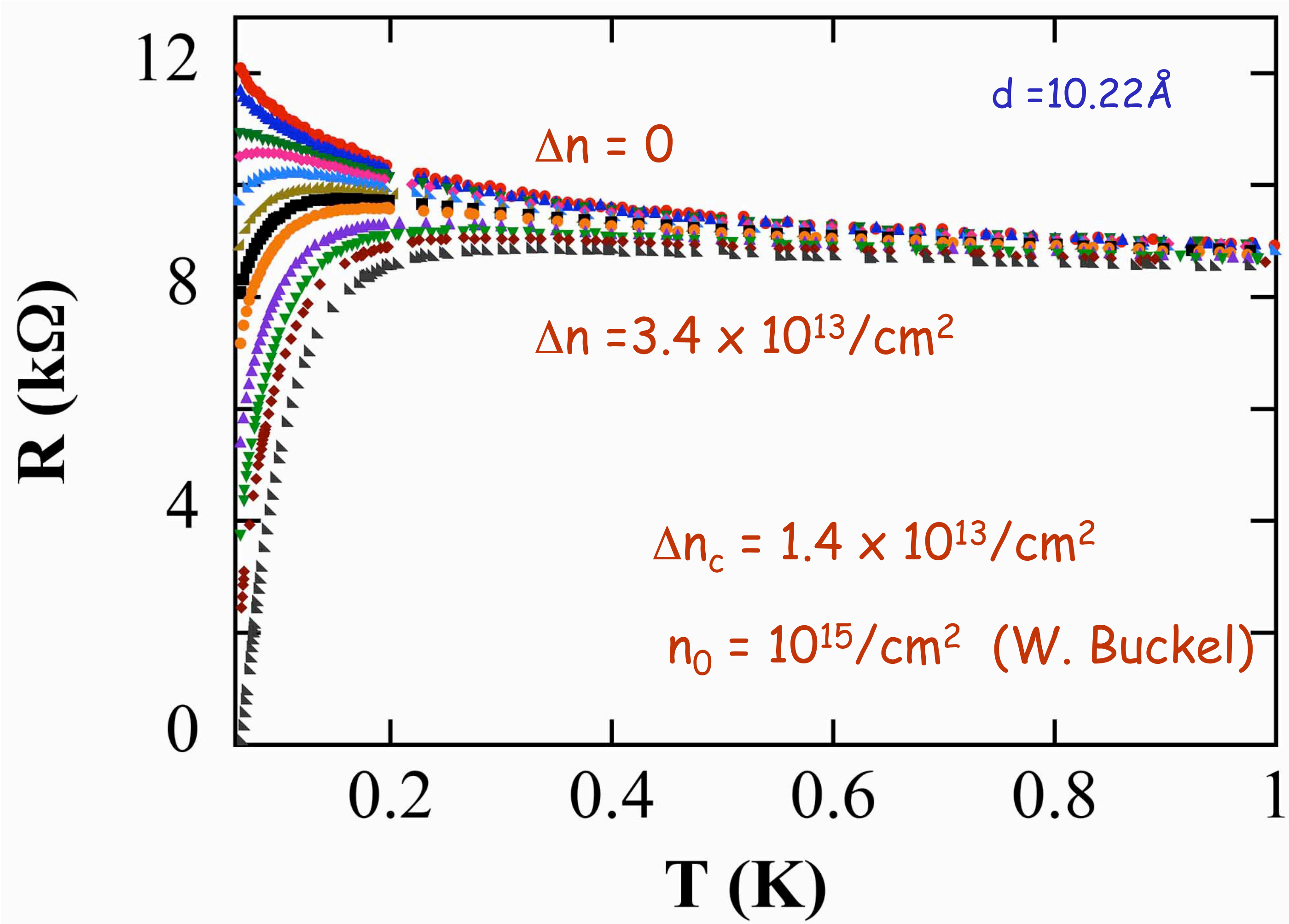
a-Bi Film with Thickness 10.59 Å

T_{co} (T_c at V_g = 0 volt) = 446 mK

V_g = 50 volts increases T_c by 56 mK

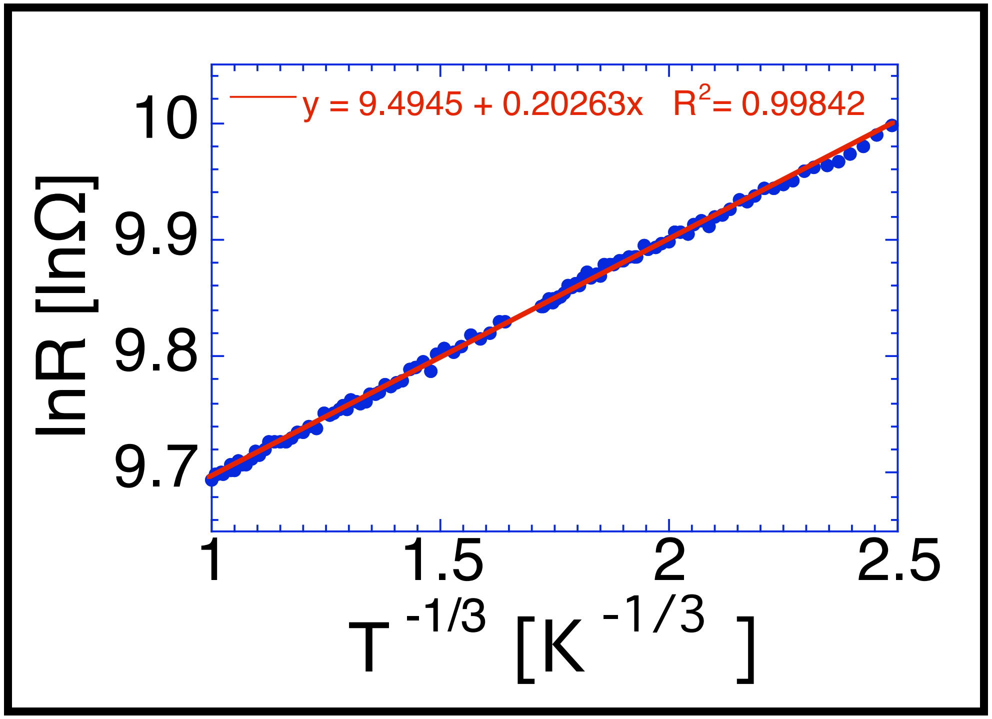
V_g = - 50 volts decreases T_c by 10 mK

Electrostatically Tuned S-I Transition



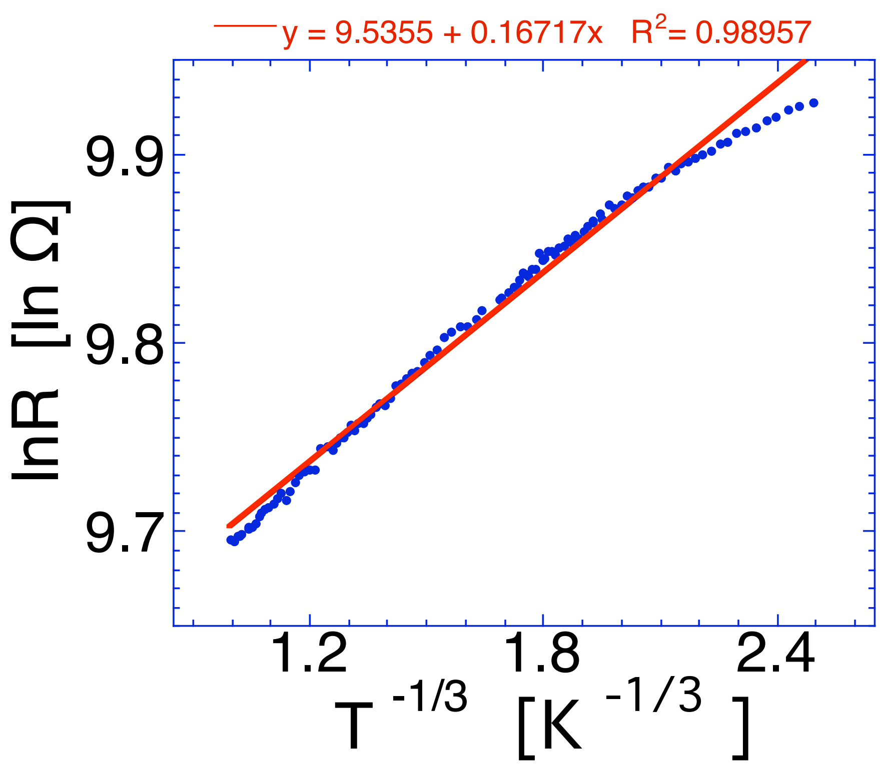
Systematics of the Insulating State

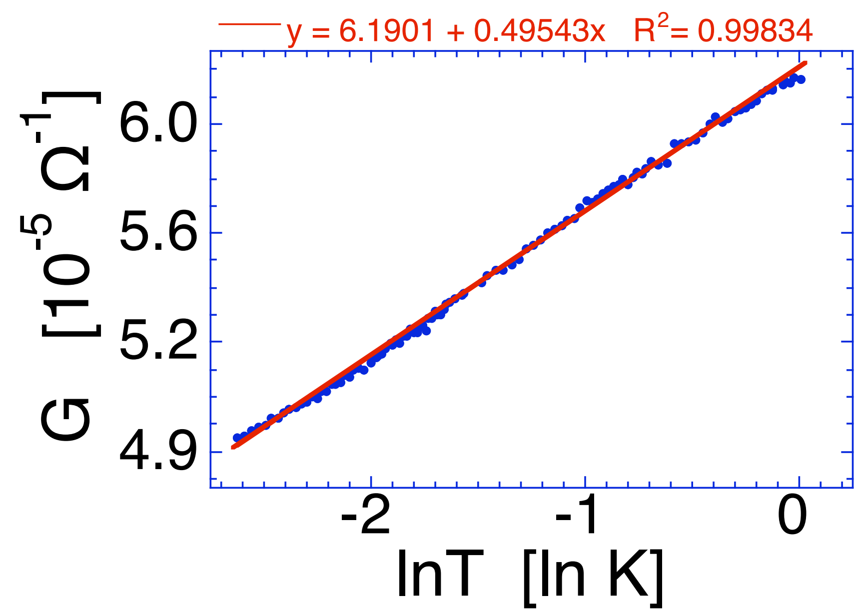
Mott Hopping Conduction: $$R(T) = R_0 \, Exp\,[(\frac{T_0}{T})^{\frac{1}{3}}]$$



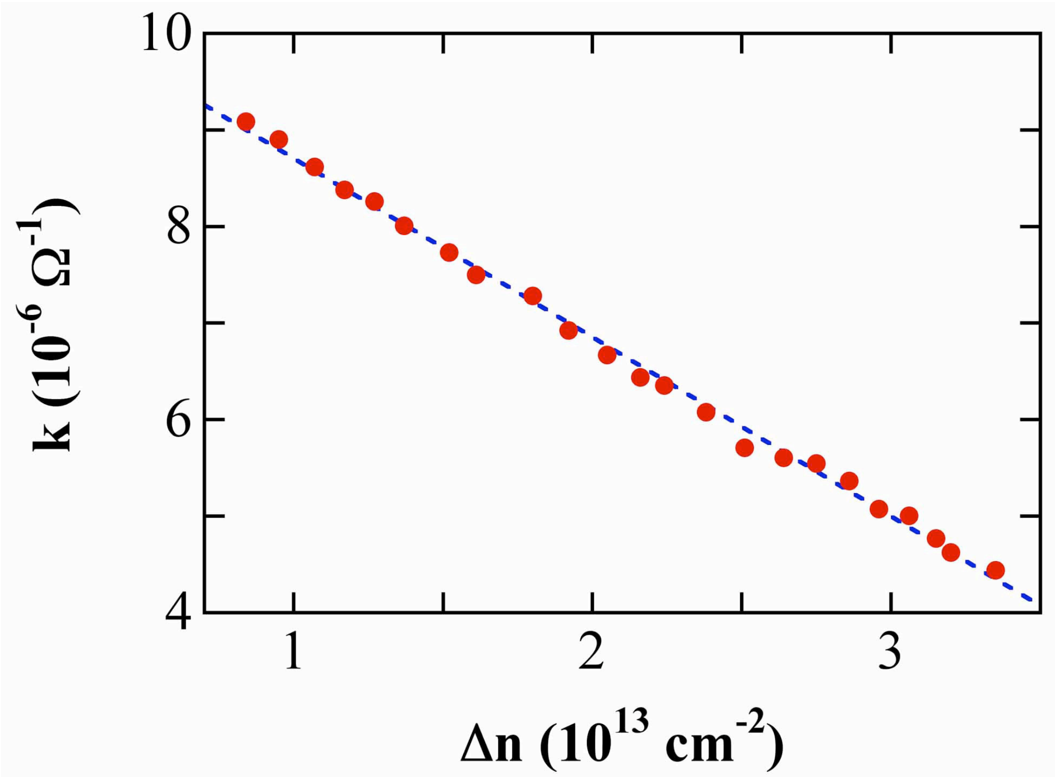
Strong Screening due to high dielectric constant
may suppress the Coulomb Gap

The insulator becomes "*weakly localized*" precisely when superconductivity appears!



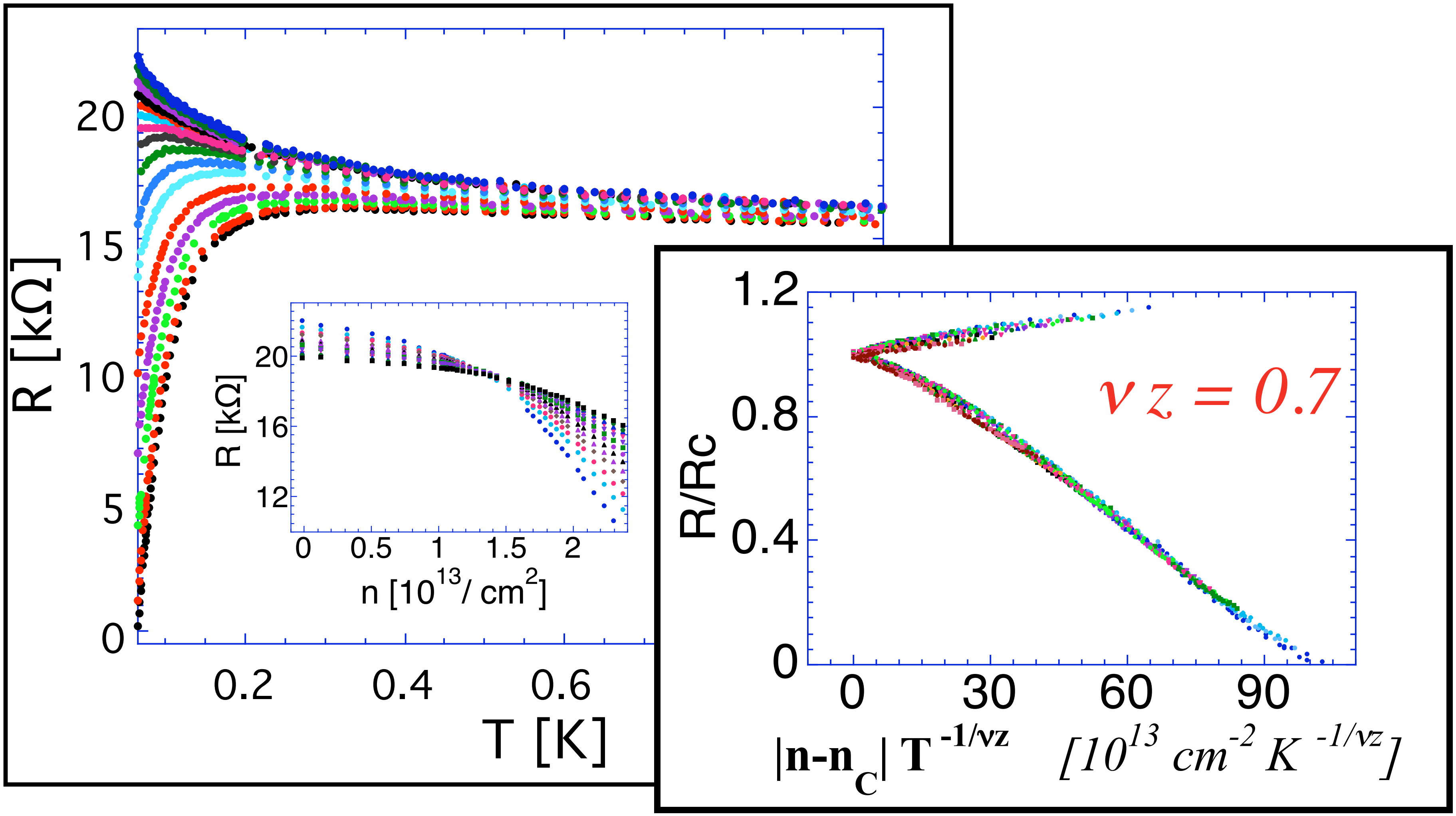


write: $G(T) = G_0 + k \ln(T/T_0)$



The effect "saturates"

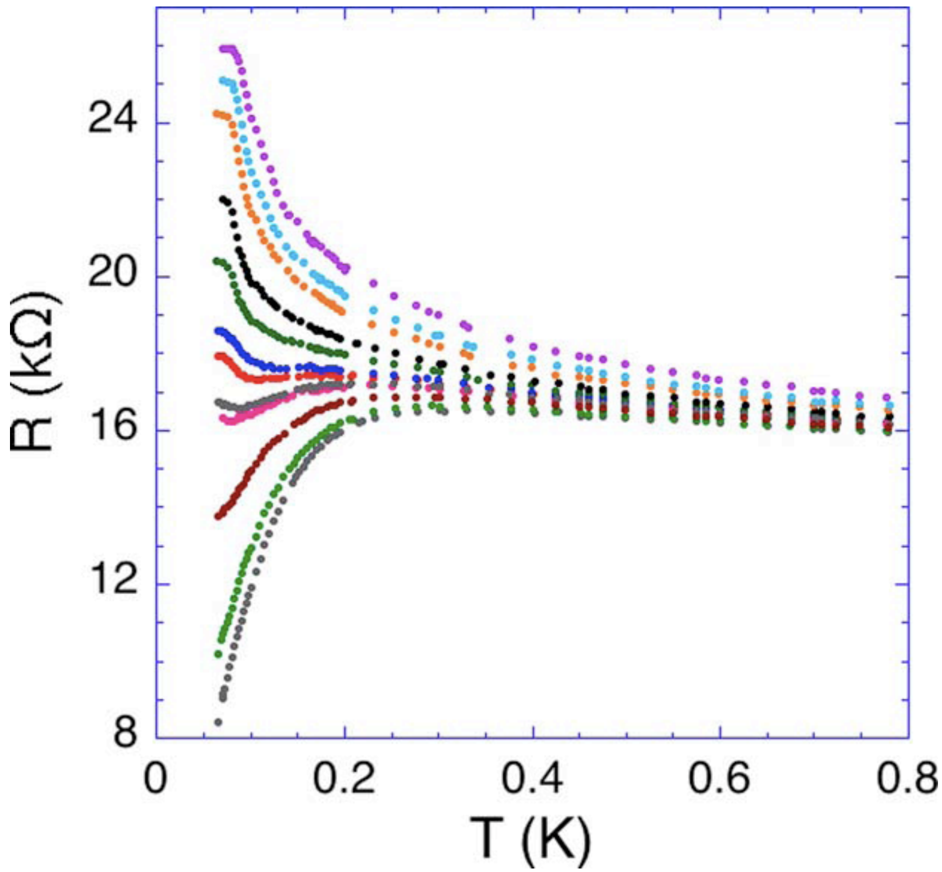
Scaling



If z =1 this is universality class of the 2D+1 XY model or Boson Hubbard model without disorder

K. Parendo *et al.*, PRL 95, 049902 (2005)

Parallel Field Tuned Transition



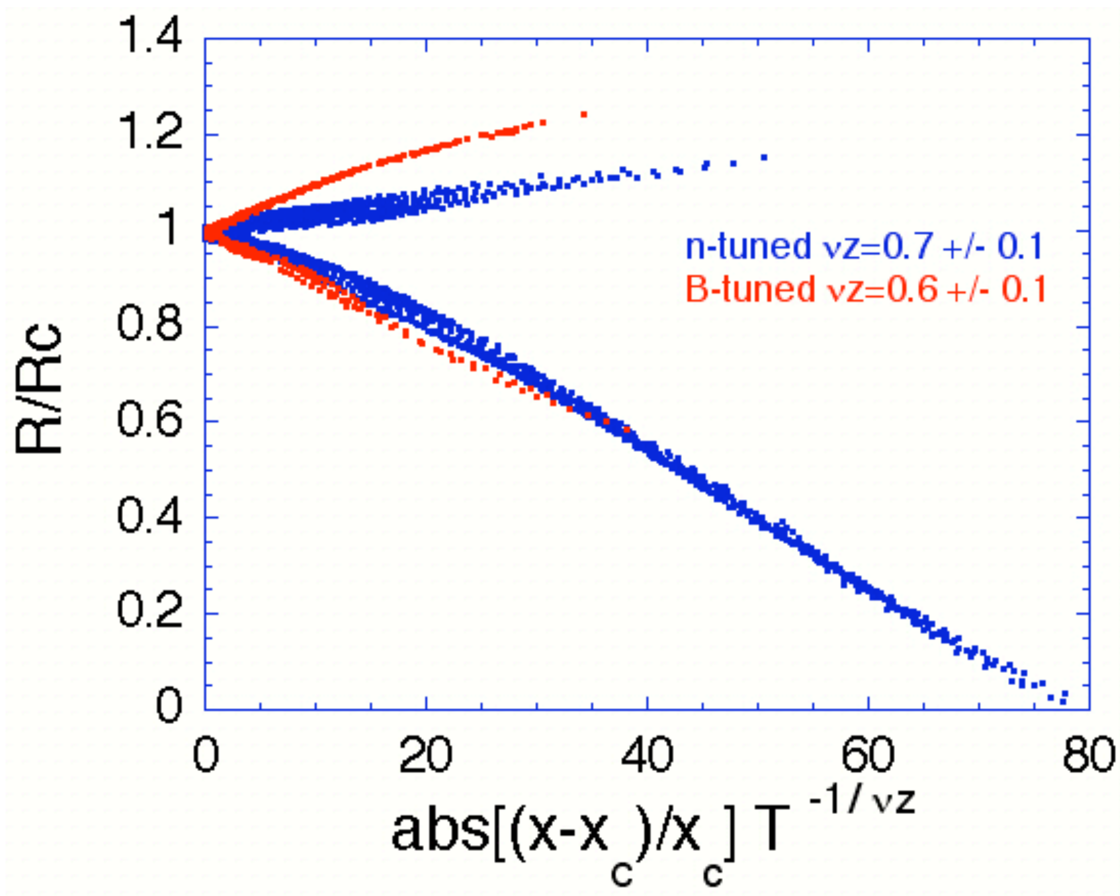
$\Delta n = 3.35 \times 10^{13}$ /cm^2

Pair breaking parameter tuning

Data for resistance must be multiplied by 0.55.

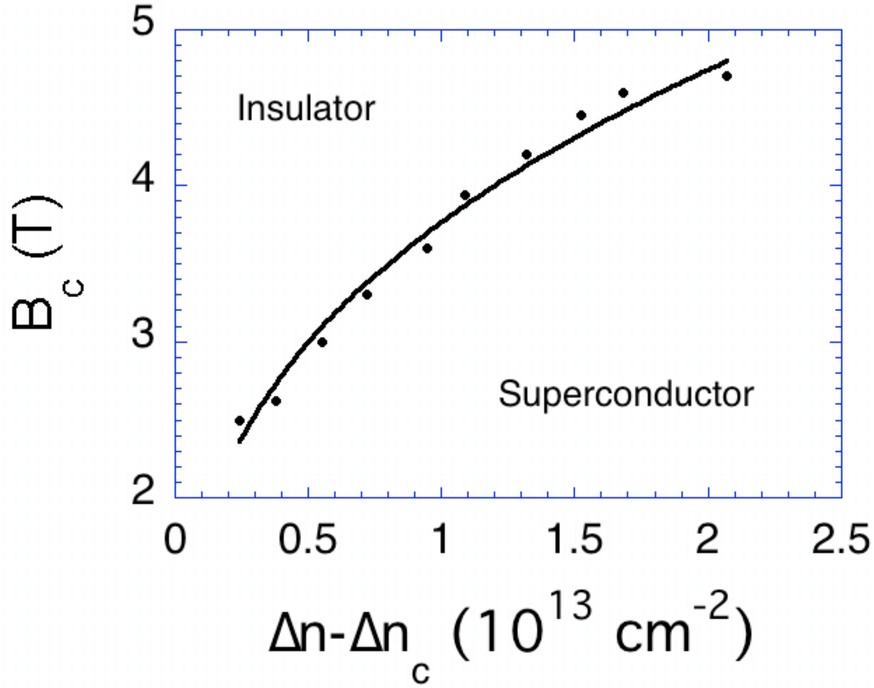
Resistance vs. Temperature at Various Parallel Magnetic Fields (B = 2, 2.5, 4.25, 4.375, 4.75, 5, 5.75, 6.5, 8, 9, 11 T bottom to top)

Scaling plot for n-Tuned and $B_{||}$-Tuned Transitions



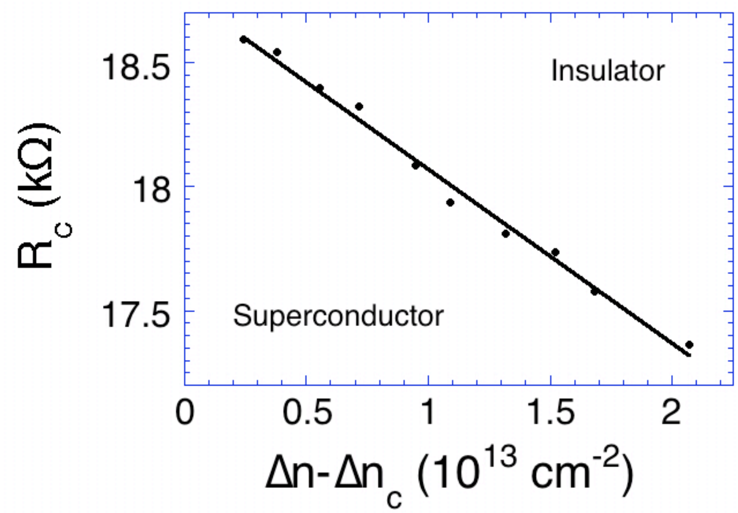
K. Parendo *et al.*, PRB 73, 174527 (2006).

"Phase Diagram" at T = 0

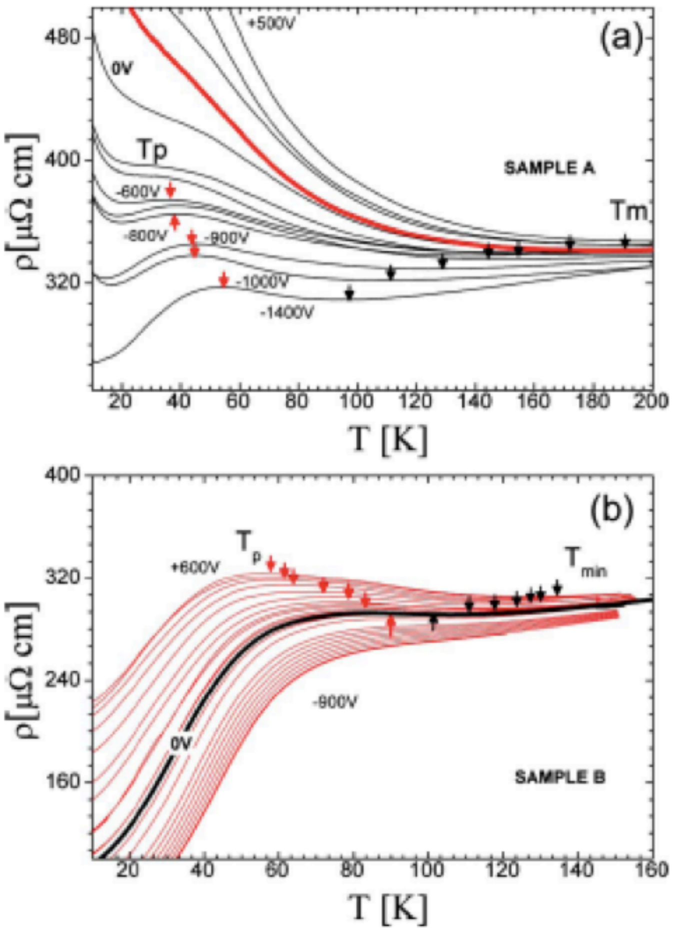


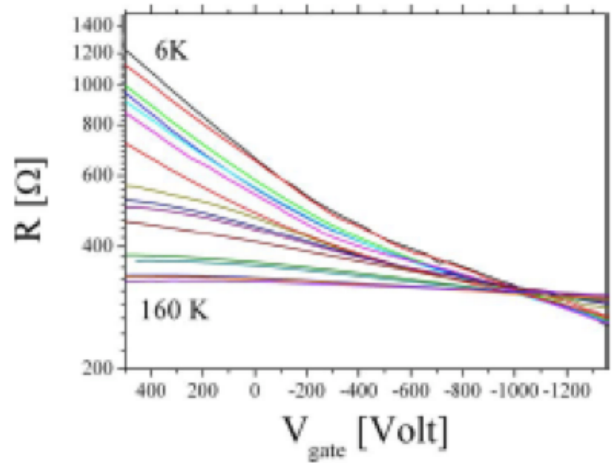
Perpendicular critical field scale was 0 to 1 Tesla.

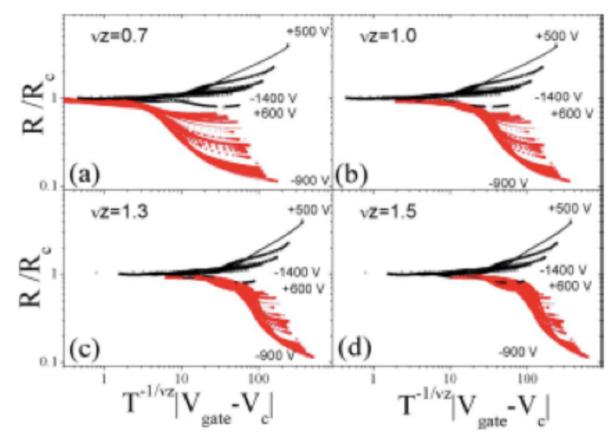
Critical Resistance



Tuning Superconductivity in $Nd_{1+x}Ba_{2-x}Cu_3O_{7-y}$

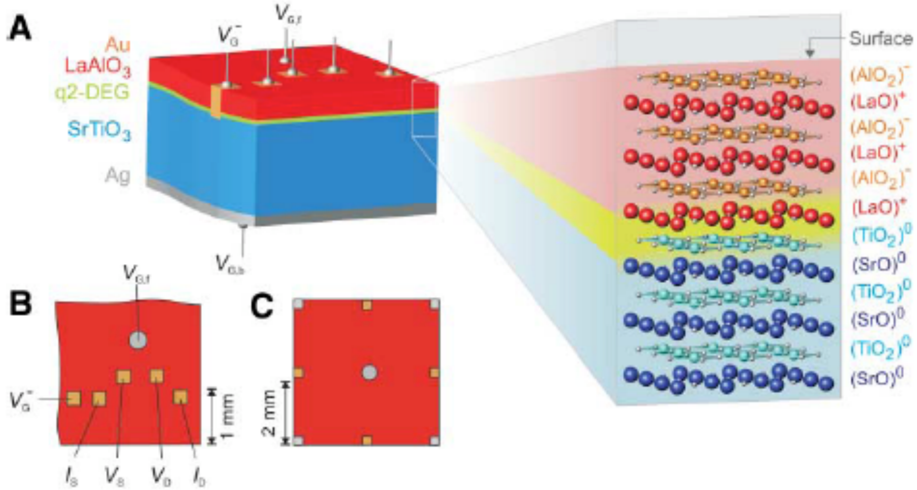


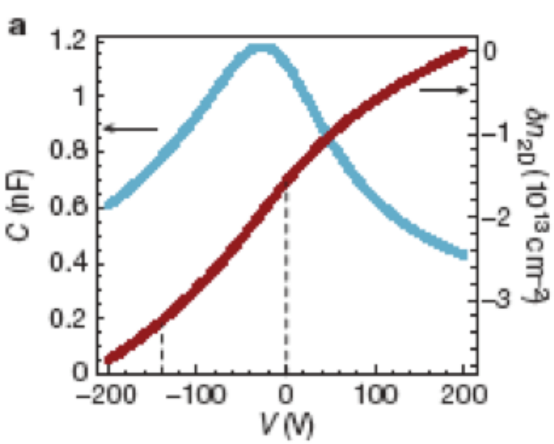


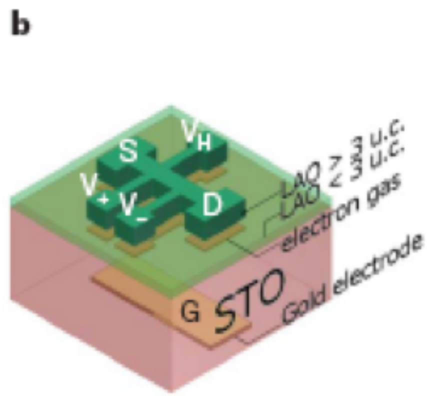


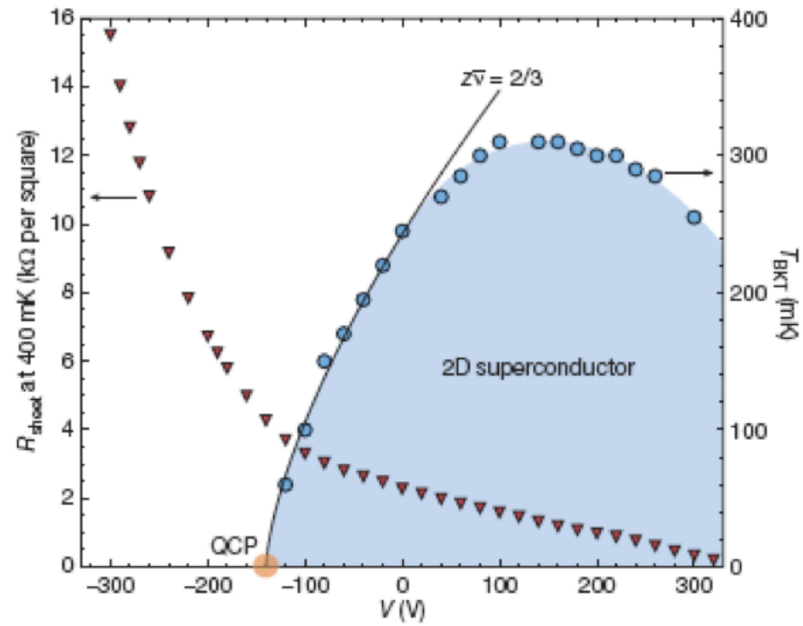
M. Salluzzo *et al.*, PRB **78**, 054524 **(2008)**

Superconductivity at the LAO/STO Interface







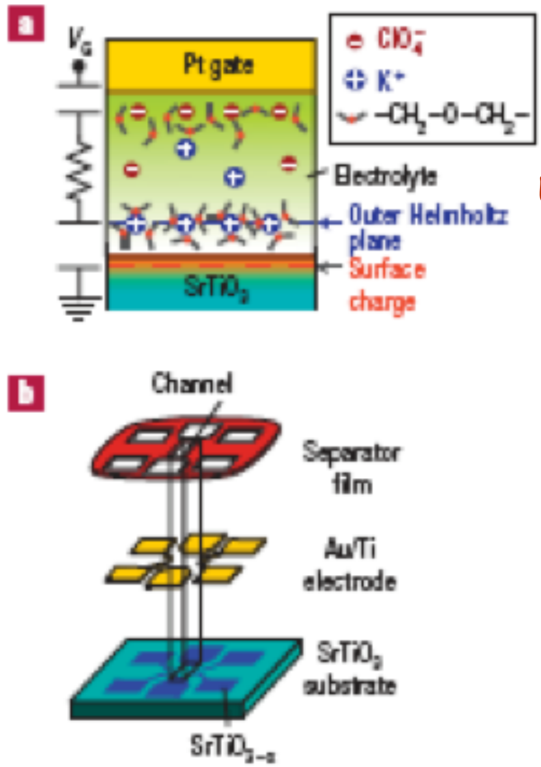


S. Thiel, *et al.*, Science **313**, 1942 (2006)

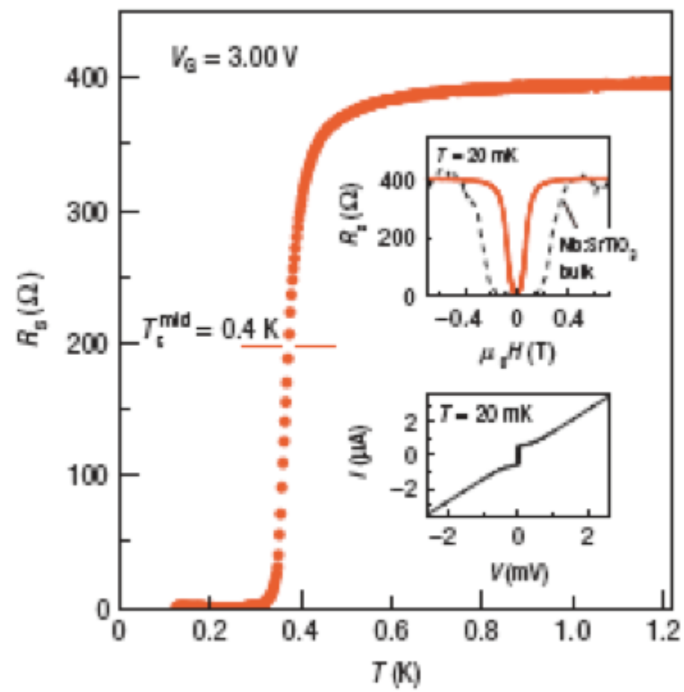
N. Reyren, *et al.*, Science **317**, 1196 (2007)

A. D. Caviglia, *et al.*, Nature **456**, 624 (2008)

Electric Double-Layer FET



Electrolyte: polyethylene oxide, containing $KClO_4$



K. Ueno *et al.*, Nature Materials **7**, 855 (2008)

Summary

It is possible to electrostatically tune superconductivity- in simple metals in 2D, in cuprates, in 2D interface systems and in STO

In metals the quantum phase transition appears to belong to the 3D XY Universiality class and is accompanied by an insulator metal transition

The same appears to happen in STO/LAO interfaces-which may be nothing more than doping STO with electrons

Approach appears to have general applicability to many strongly correlated electron systems.

Issues such as charge ordering and electronic phase separation may be amenable to study using the electric field effect.

Major issue may be the interfaces between source and drain electrodes and the material of interest as well as charge trapping in the high dielectric constant gate insulator.