

Electrostatic Tuning of the Superconductor- Insulator Transition*

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Introduction

There are several types of systems that exhibit superconductor-insulator transitions.

These include:

- Single Josephson Junctions

- Arrays of Josephson Junctions

- Uniform (microscopically homogeneous) disordered ultrathin films

- Granular ultrathin films

These transitions are believed to be quantum phase transitions with control parameters such as perpendicular or parallel magnetic field, disorder, film thickness, and magnetic impurity doping.

Outline of Topics Covered

1. Some Past History
2. Electrostatic Charging
3. New Results on Electrostatic Charging of Ultrathin Films

Experimental Approach: Films

Ultrathin Quench-deposited Films

Shal'nikov (1940s) - quench-condensed Hg (substrates held at liquid helium temperatures).

Buckel, Hilsch, Glover, (1950s and 60s) physical characterization and study of superconducting fluctuations.

Strongin and collaborators: quench-condensation in ultra-high vacuum environment

Dynes and co-workers, Goldman and co-workers, Valles and coworkers, Xiong and co-workers, Wu and co-workers: elaboration on quench-condensation, study of localization and SI transitions

Sputtered films of MoGe and In_2O_3

Beasley, Hebard, Ovadyahu, Kapitulnik, Gantmakher and others.

High Temperature Superconducting Films

Many Groups

Disorder and Superconductivity

The early theories of dirty superconductors due to Anderson and Abrikosov and Gor'kov are applicable only in the low-disorder regime.

In this regime the superconducting transition temperature does not depend on the concentration of non-magnetic impurities. This is what is known as **Anderson's Theorem**.

However, with a high enough level of disorder, **Anderson localization** occurs. This changes the game.

The effect of strong disorder on superconductivity is a challenging problem as it involves both interactions and disorder.

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

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

Films Grown on a - Ge Substrates- Nominally Homogeneous

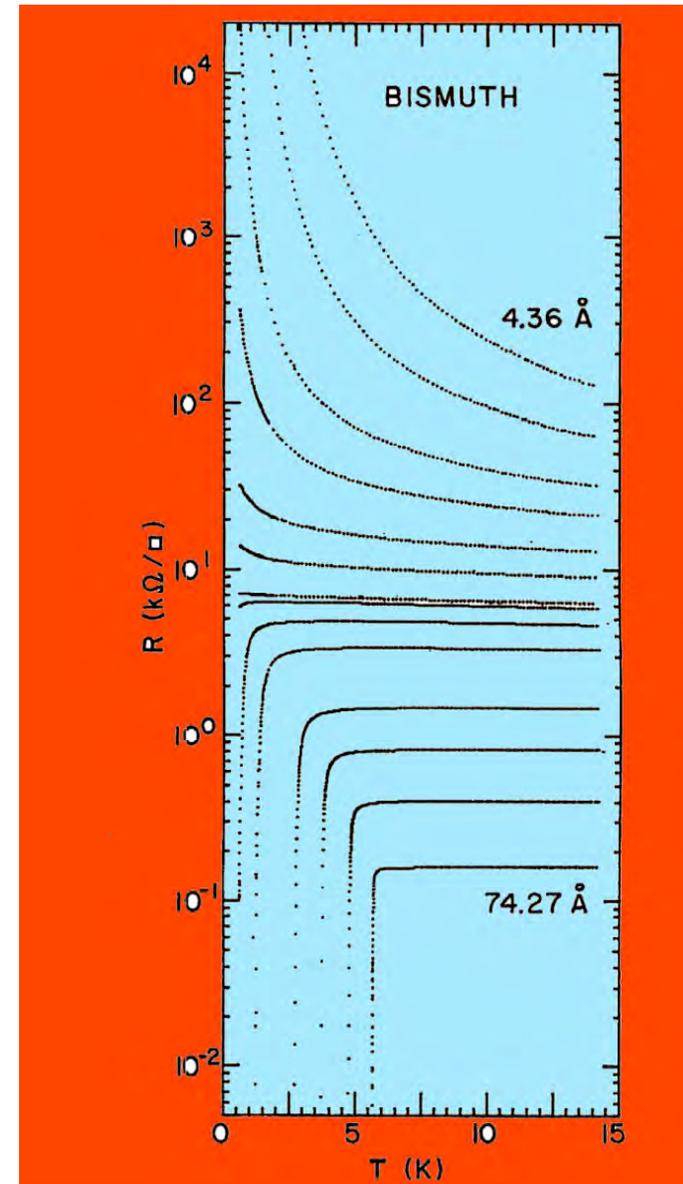
Cyclic evaporation leads to evolution of superconductivity with thickness.

Apparent separation between superconducting and insulating behavior.

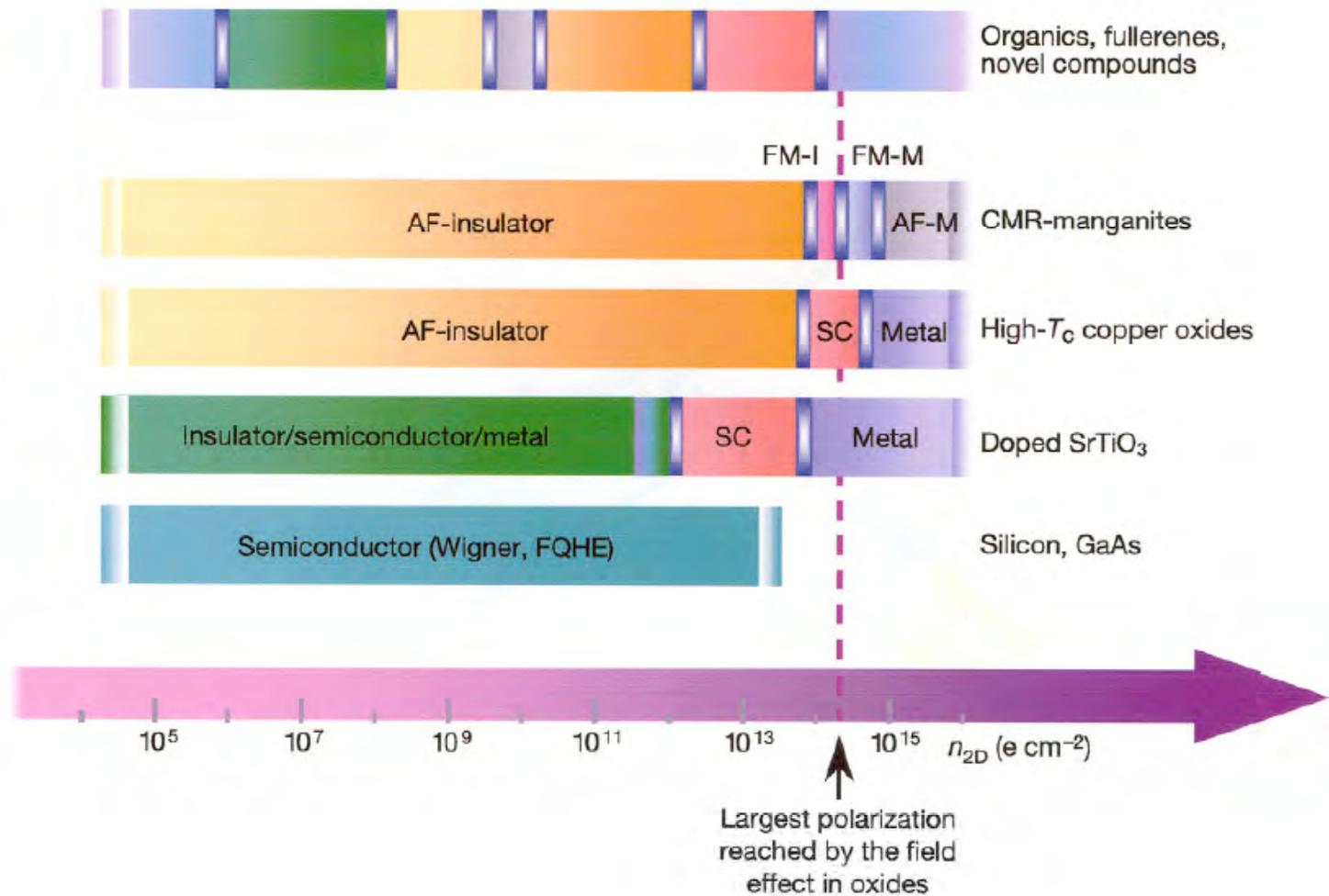
Critical resistance close to $h/4e^2 = 6450 \Omega$

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

Data Suggests: Quantum Phase Transition (QPT)



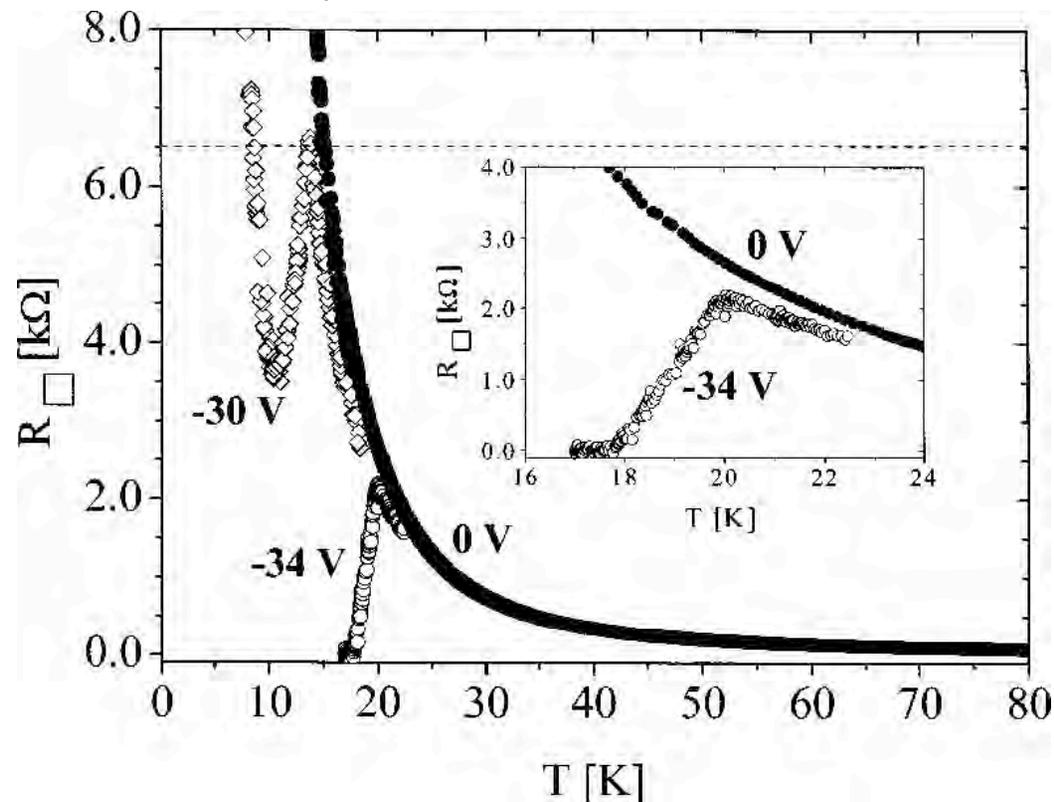
Electrostatic Gating



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

Recent Work

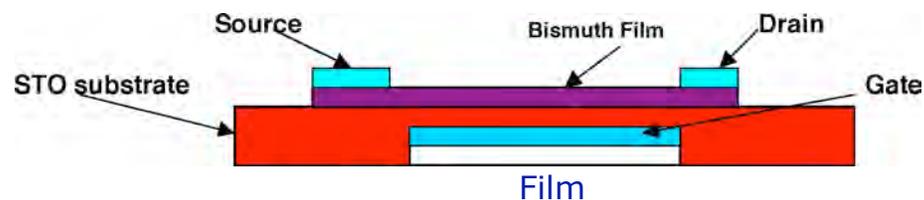
Cassinese *et al*, (2004) described an FET device consisting of a $\text{Nd}_{1.2}\text{Ba}_{1.8}\text{Cu}_3\text{O}_x$ film grown on a (100) SrTiO_3 substrate, overlaid with an Al_2O_3 insulator and an Au gate. They demonstrated reversible changes of the hole density.



Combined Substrate and Gate Insulator

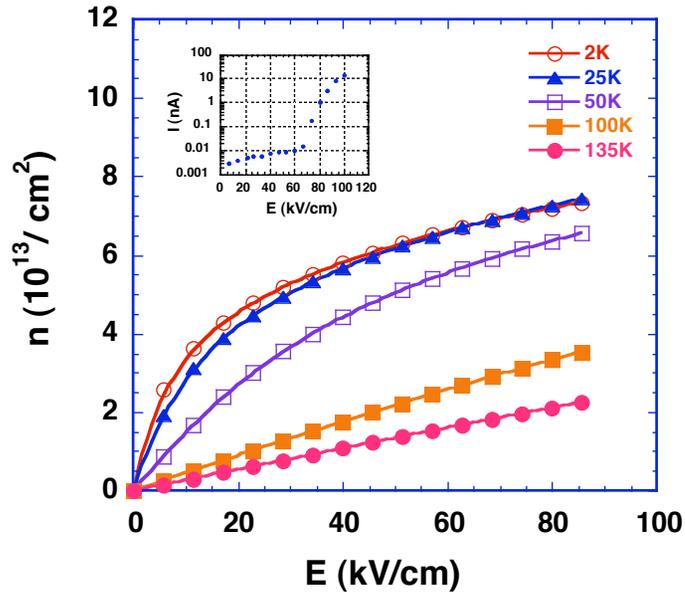
Strategy: Use Strontium Titanate as both a substrate and a gate insulator.
high dielectric constant below 10K,, $\kappa_e > 10,000$
available with epi-polished surface can be made atomically
smooth.
can be thinned mechanically

The back of a micro-machined substrate.
A typical height profile is superimposed on the picture.
Thickness in the middle can range from $10\mu\text{m}$ to $100\mu\text{m}$, with surface roughness of approximately $1\mu\text{m}$. The diameter of the thinned region is typically 4mm.



Cartoon of parallel plate capacitor geometry, with insulating substrate separating a bismuth film from the gate electrode. The thickness of the film is about 10 \AA , the source and drain are about 100 \AA , and the thickness of the substrate between the gate and the film is approximately $50 \mu\text{m}$.

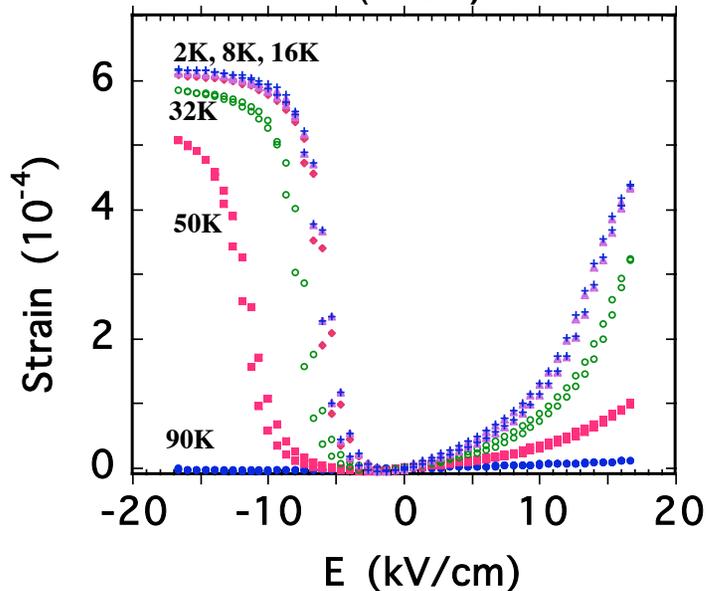
SrTiO₃ in an Electric Field



Nonlinear $\epsilon(E)$

thickness = 35 μm

Induced charge at 2K, 85kV/cm = $7.5 \times 10^{13} \text{ cm}^{-2}$

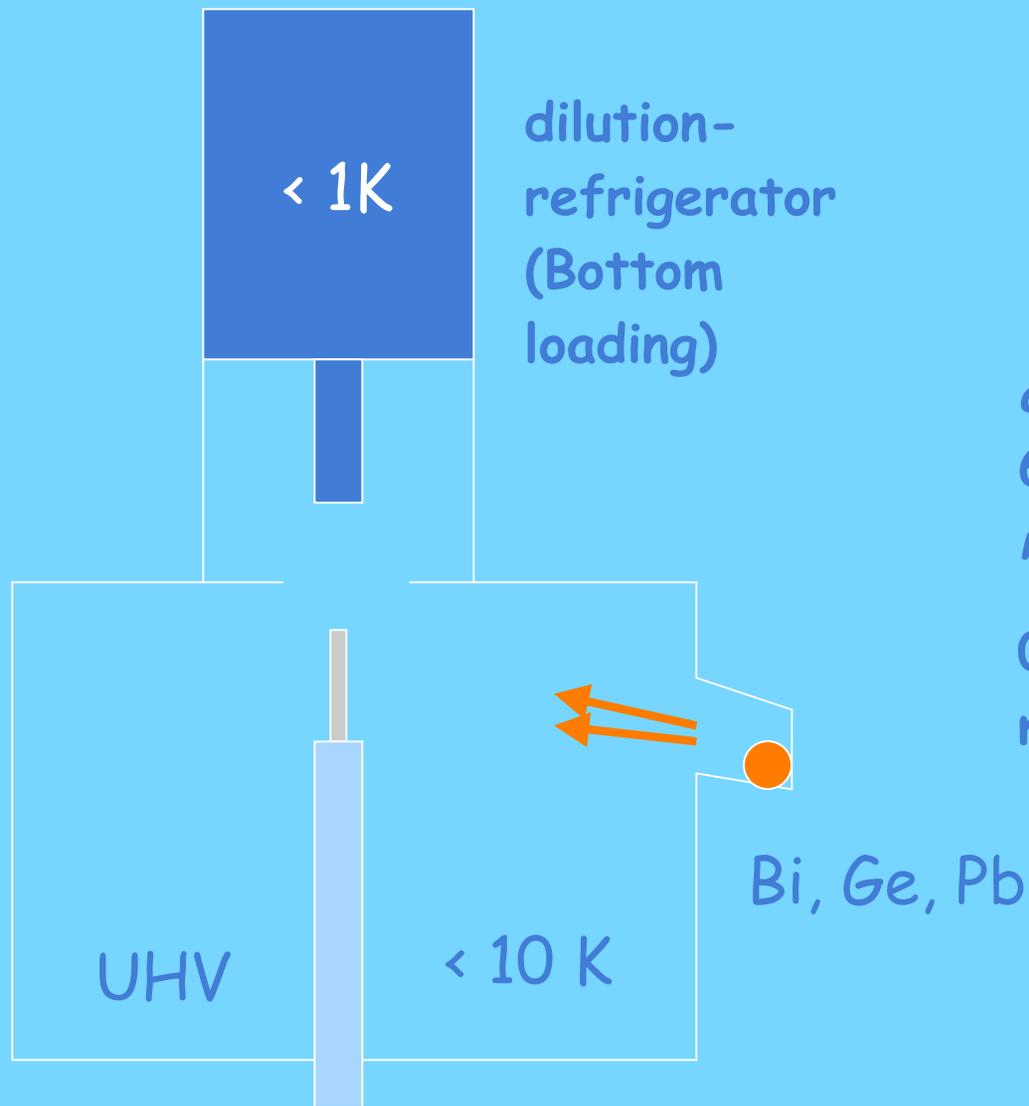


Electrostriction

Strain due to Electrostriction = $+ 6 \times 10^{-4}$
 $3.905\text{\AA} + 0.0024\text{\AA}$ (LCMO 3.87\AA)

E strain = (lattice mismatch of LCMO on STO)/15

Apparatus for Quench-Condensation



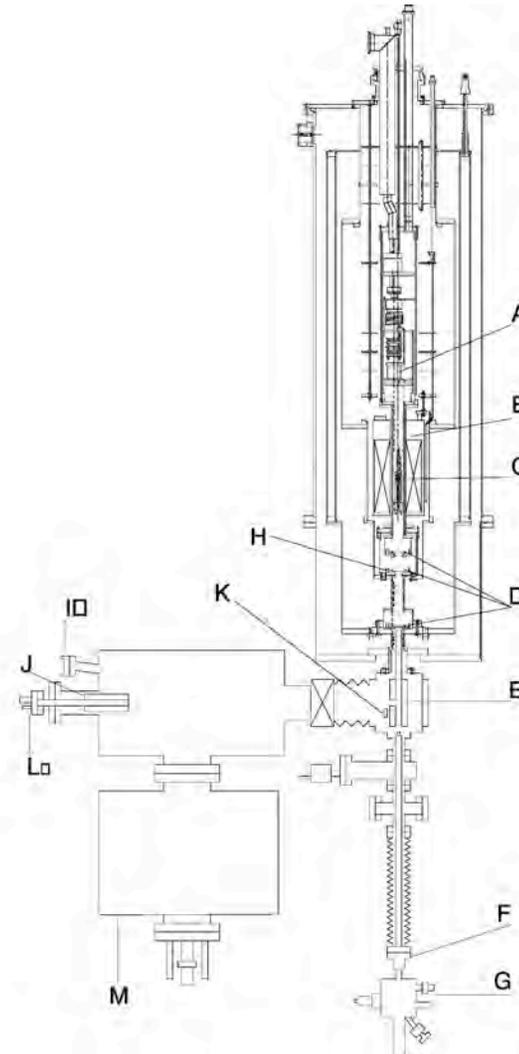
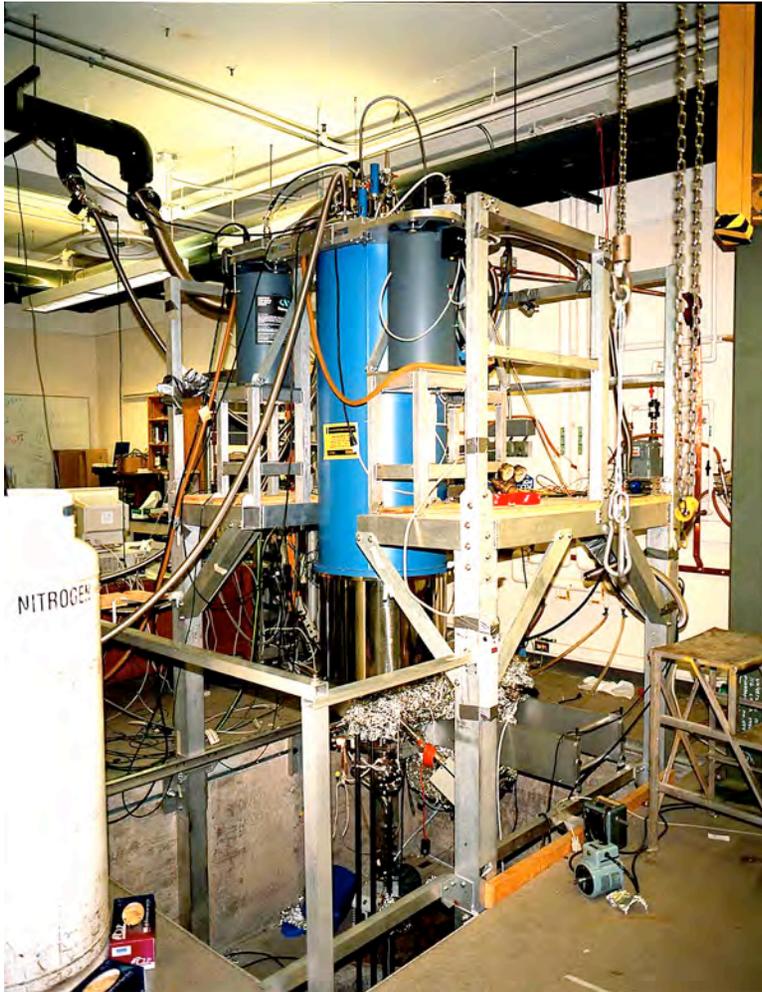
a-Ge or *a-Sb* underlayer of 6\AA thickness is deposited *in-situ*.

$0.05\text{-}0.1\text{\AA}$ increments of metal.

Bi, Ge, Pb

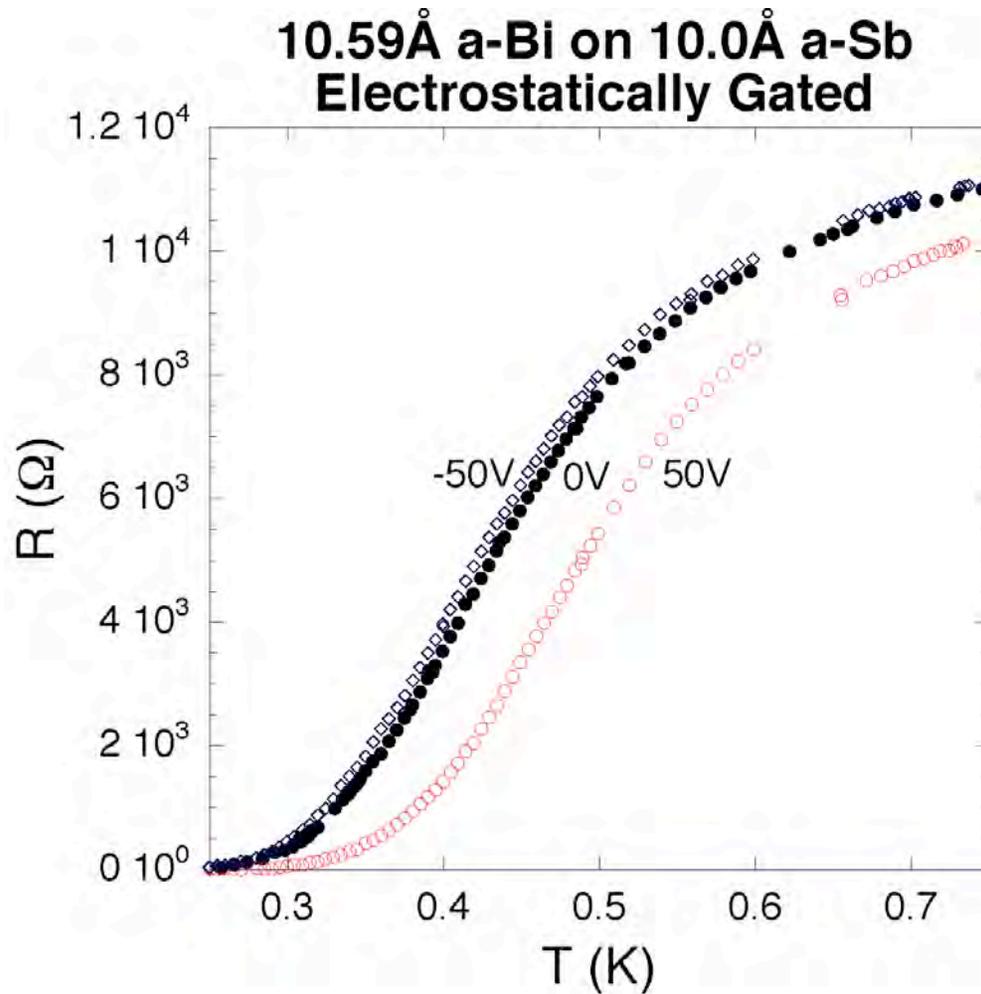
L.M. Hernandez and A.M. Goldman, Rev. Sci. Instrum. 73, 162 (2002)

System for Quench-Deposited Films



0.004K limiting
temperature
15T field
Sample rotator

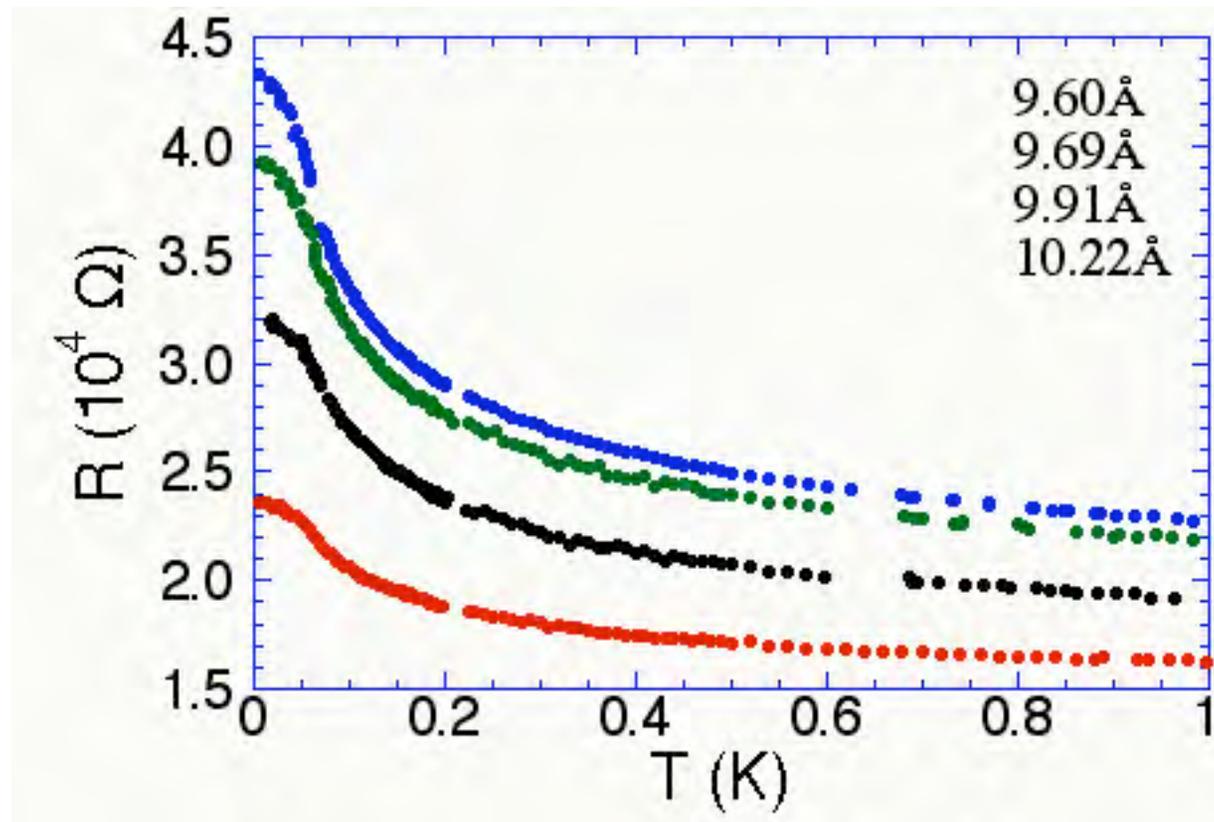
Tuning the Superconducting Transition Electrostatically



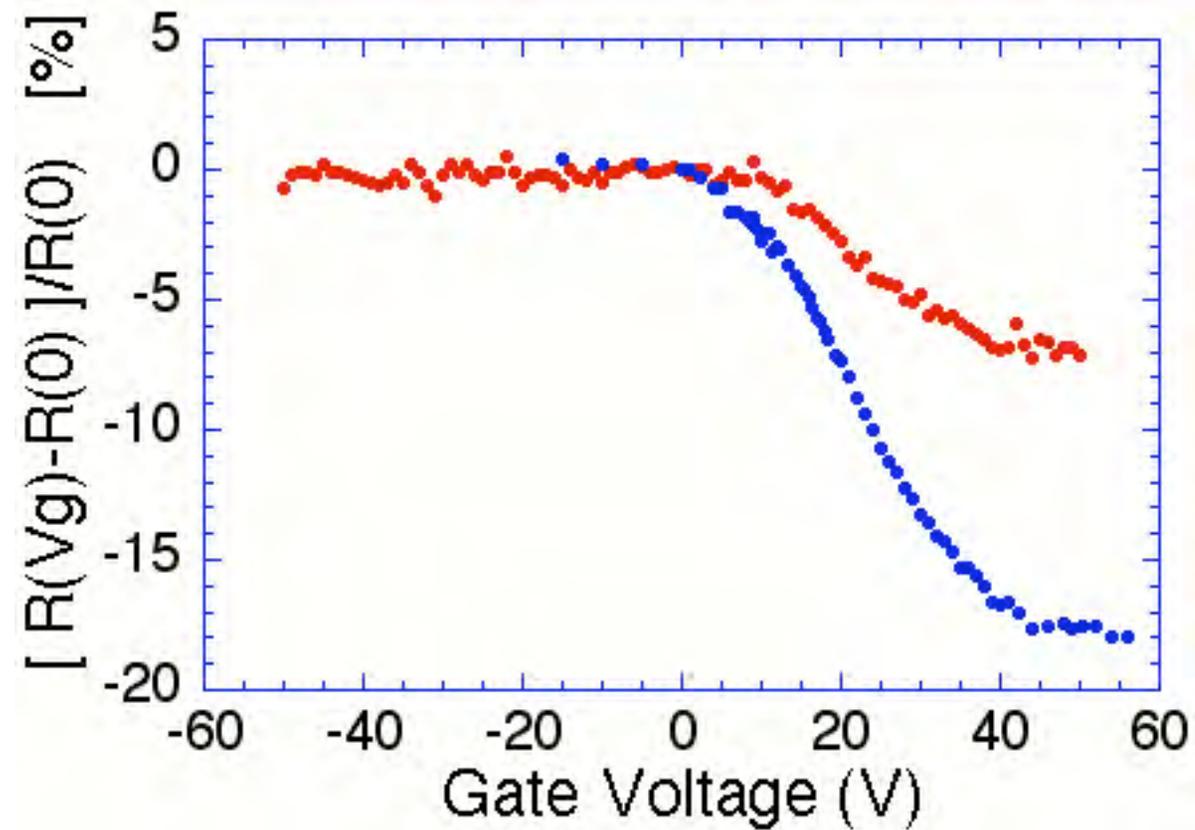
Serious asymmetry in the response to gate voltage is found.

Negative voltage produces a small effect. Positive yields major response. This suggests that electrons are the carriers consistent with Buchel.

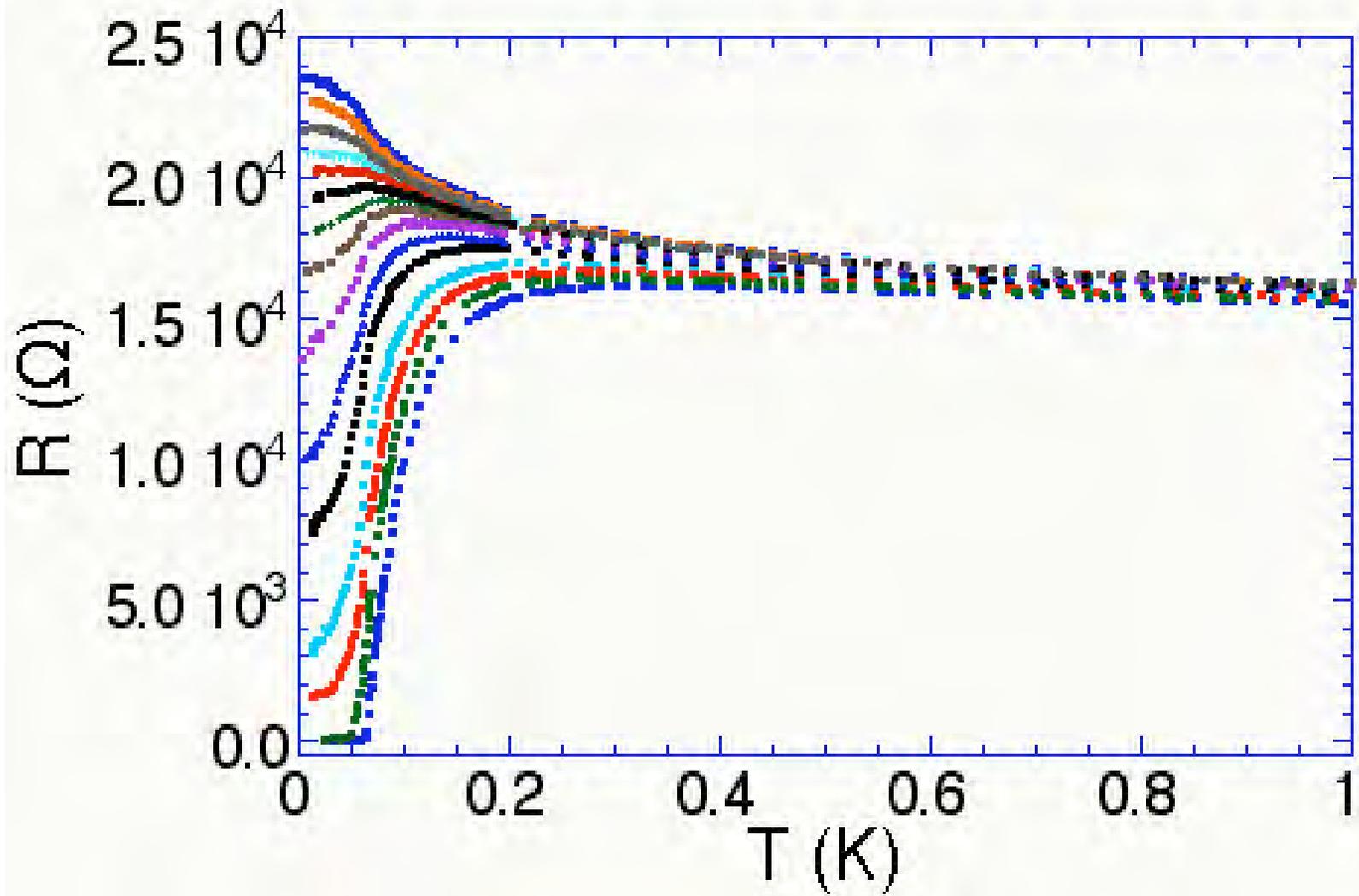
R(T) at Different Thicknesses



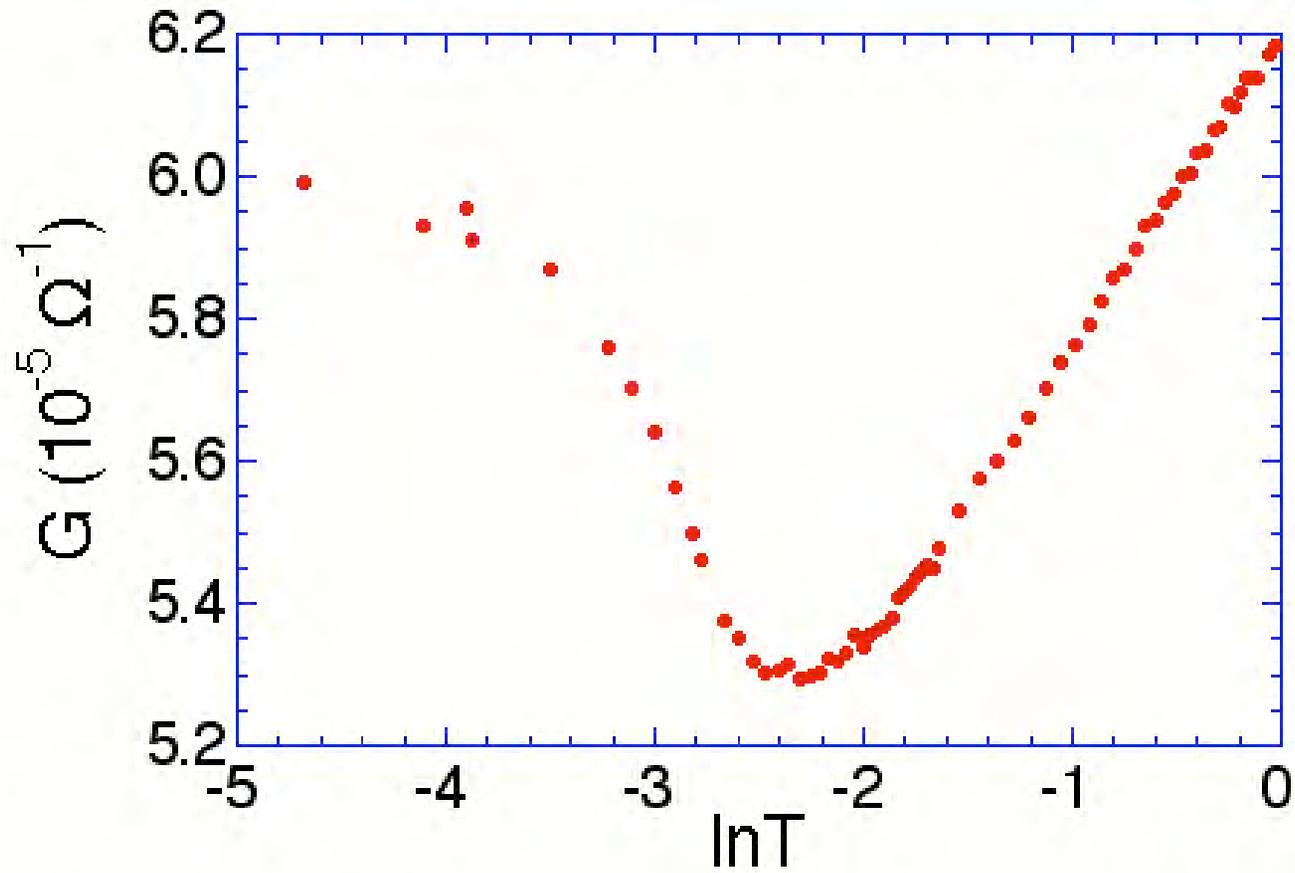
Resistance vs. Gate Voltage at 200 mK



$R(T)$ vs. V_G



G vs. lnT



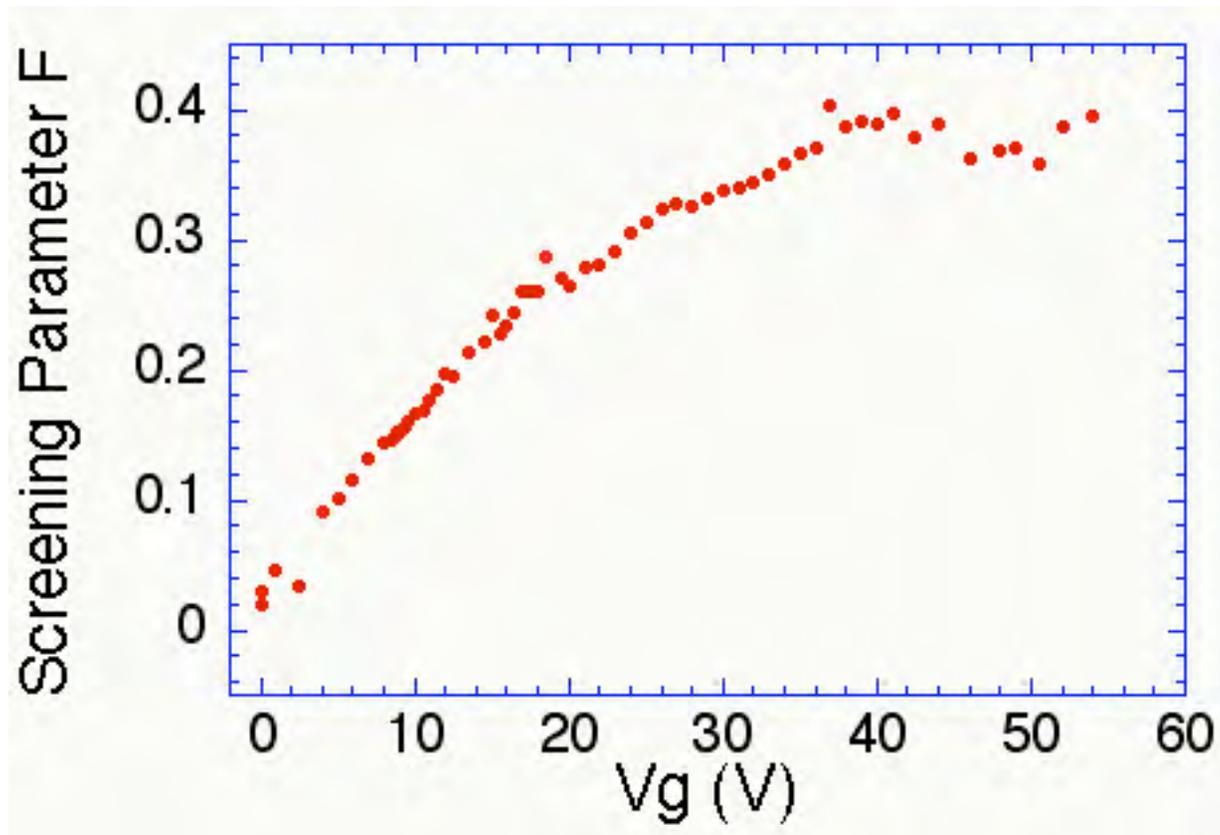
Weak Localization/Electron-Electron Interaction Effects

$$G = G_B + G_{WL} + G_{EE}$$

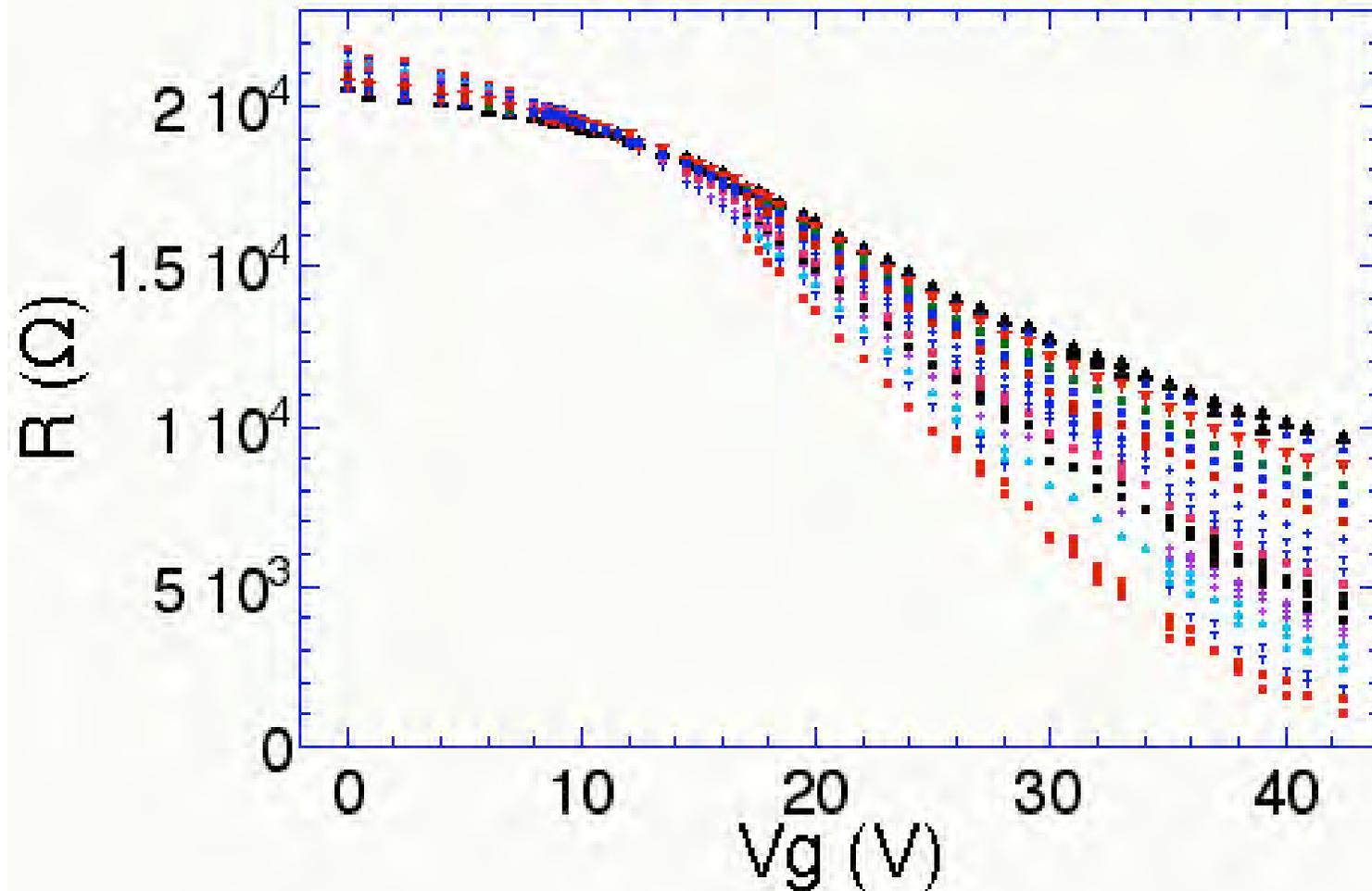
$$G_{WL} = \alpha p \frac{e^2}{2\pi^2 \hbar} \ln(T)$$

$$G_{EE} = \left(1 - \frac{3F}{4}\right) \frac{e^2}{2\pi^2 \hbar} \ln(T)$$

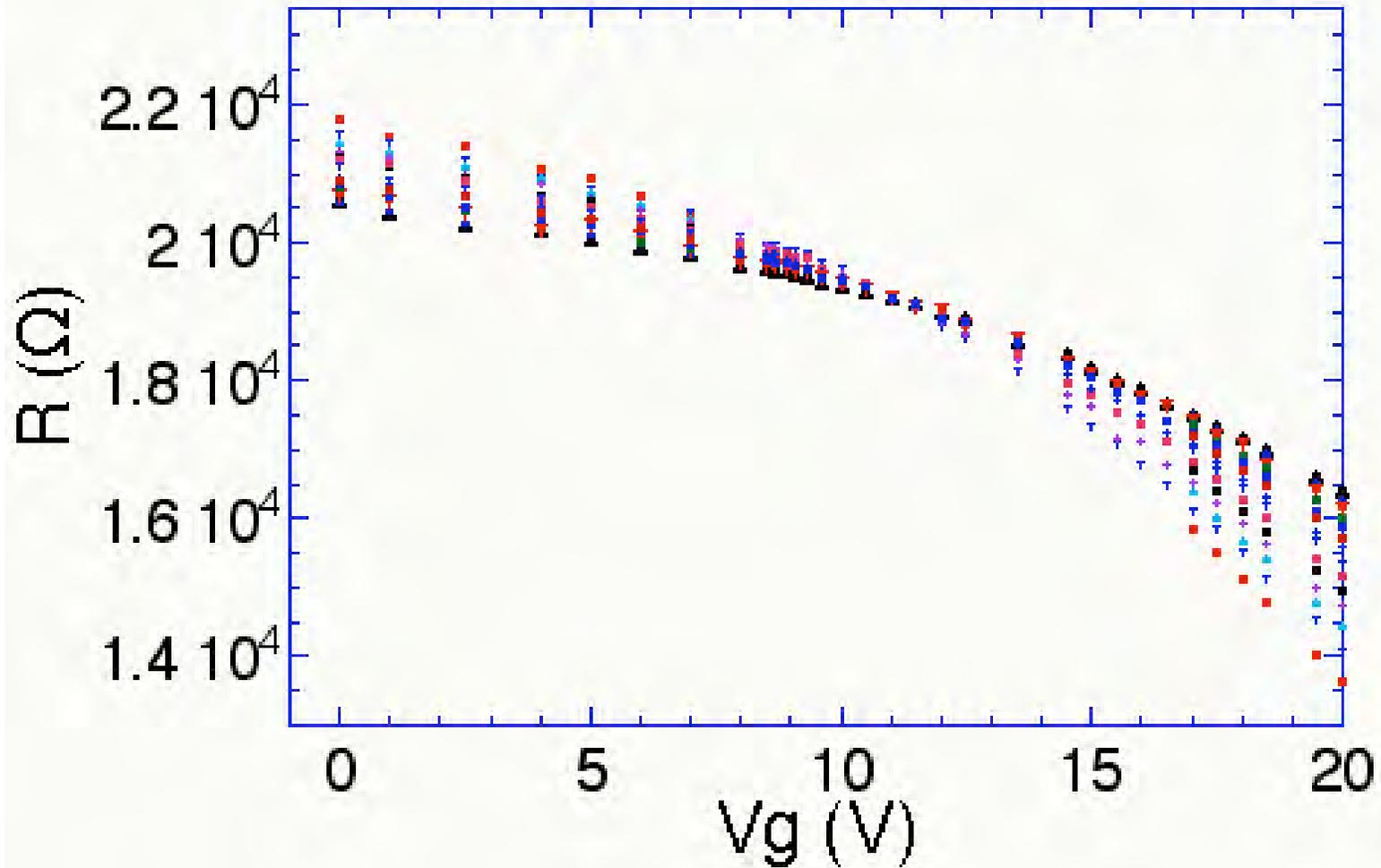
F vs. V_g



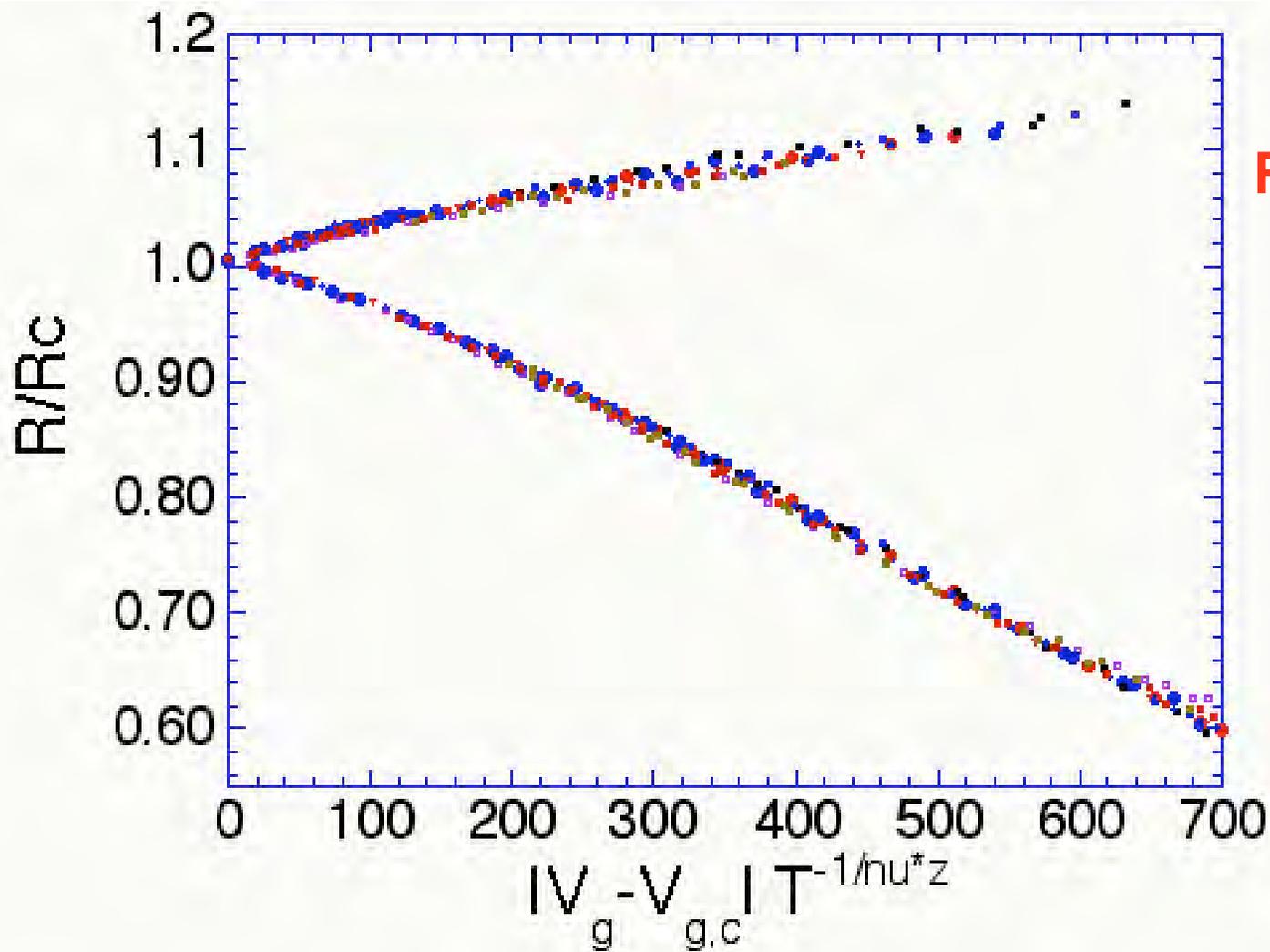
Crossing Point



Crossing Point Detail



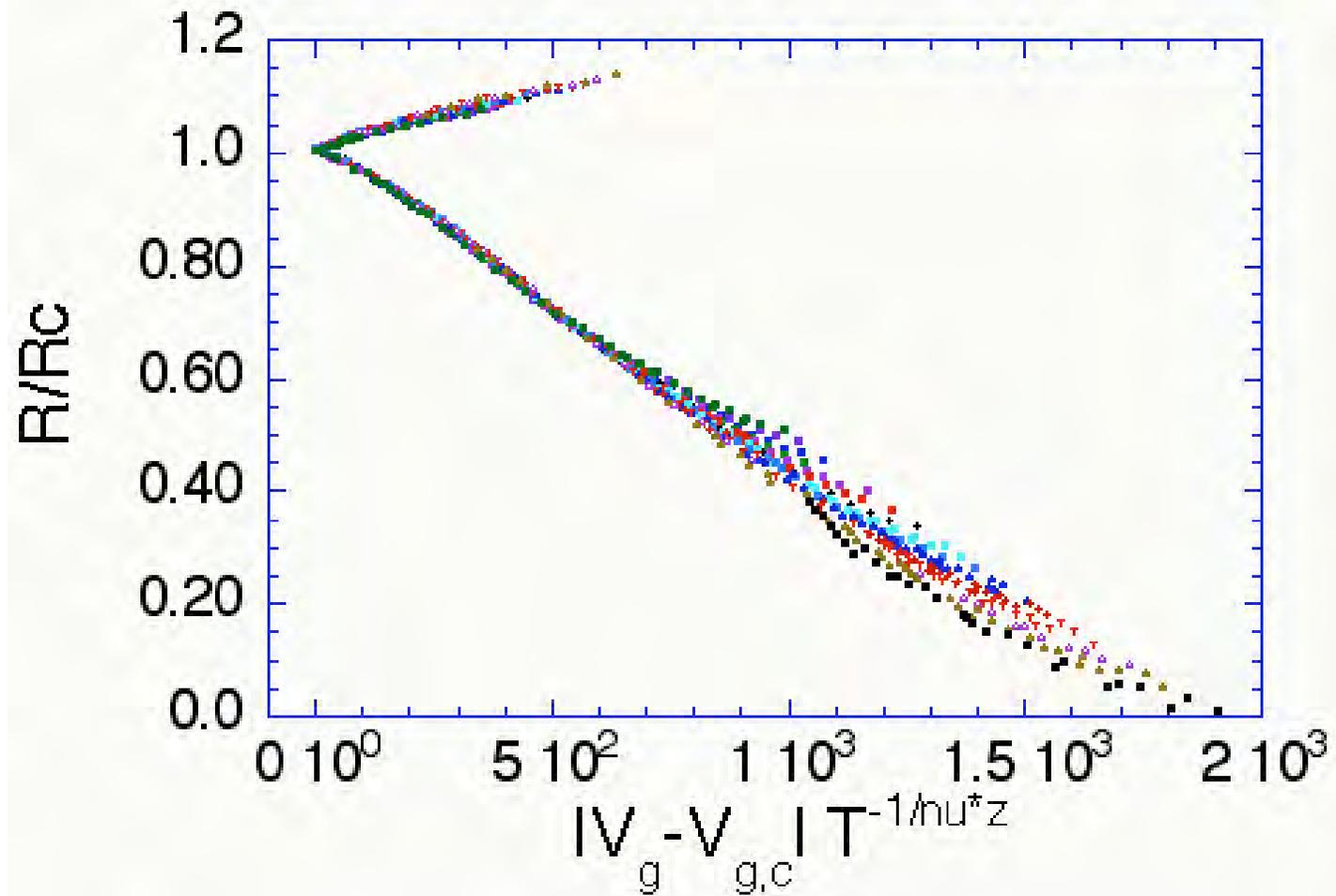
Scaling



$$R_{\square} = R_c F(\delta/T^{1/\nu z})$$

$$\nu z = 2/3$$

Broader Look at Scaling



Comments

Known

1. Have induced superconductivity electrostatically in an FET configuration.
2. Electrostatic charging seems to transform 2D *Mott* hopping to $\ln T$ dependence.
3. The Hartree screening parameter changes systematically with V_g .
4. Scaling works within limits down to $R = 0$. The metallic regime we see appears to be an artifact of not cooling the electrons despite our efforts at shielding and grounding.
5. Critical exponent product $\nu z \sim 3/2$, which is the value for the 3D XY model.

Comments, ctd.

Unknown

1. Saturation of response to V_g not understood.
2. Asymmetry of response to V_g not understood.
3. Is the entire effect a consequence of a charge layer and screening or is it a consequence of uniform doping?
4. Why does it work at all as actual carrier change is maximally $3.3 \times 10^{13}/\text{cm}^2$ at $V_g = 50\text{V}$?
5. Critical resistance very high.

Relationship to other SI transitions? Is this a screening-controlled transition? Relevance to experiments with cuprates?