Electrostatic Tuning of Superconductivity

Allen M. Goldman
School of Physics and Astronomy
University of Minnesota
Paarticipating Graduate Students

Yen-Hsiang Lin
Kevin Parendo (US Patent Office)
Sarwa Tan (Schlumberger)
Melissa Eblen-Zayas (Carleton College)
Anand Bhattacharya (Argonne National Laboratory)
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

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


\[
\frac{\Delta T_c}{T_c} \approx 0.002\%
\]
Superconductivity starts at $x \approx 0.03$, corresponding to $3.5 \times 10^{13}$ per plane.
Tuning Superconductivity by Ferroelectric Polarization and by Electrostatic Charging

- a. 8nm thick YBa$_2$Cu$_3$O$_{7-\delta}$ channel with a ~300 nm thick Ba$_{0.15}$Sr$_{0.85}$TiO$_3$ gate insulator
- b. 2nm thick GdBa$_2$Cu$_3$O$_{7-\delta}$ 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$_2$Cu$_3$O$_{7-\delta}$ film whose doping level has been chosen to be close to the S-I transition.

FET device consisting of a Nd$_{1.2}$Ba$_{1.8}$Cu$_3$O$_x$ film grown on a (100) SrTiO$_3$ substrate, overlayed with an Al$_2$O$_3$ 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 $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$

$T_c \sim n_s (T=0)$—appears to Satisfy Uemura relation

Two-coil Method for Measuring Kinetic Inductance

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

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

\[ \lambda_0^2 = mc^2 / 4\pi ne^2 \]
Modulation of the Properties of Nd$_{1+x}$Ba$_{2-x}$Cu$_3$O$_{7-y}$
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.
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 \( \Theta \) shall be explained, that the mean free path of an electron shall vary as \( \Theta^{-2} \).

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 \( 2\lambda \), where \( \lambda \) is the mean free path in a large mass of the metal, \( \lambda' \) the mean free path in the film is given by

\[
\lambda' = \lambda \left( 1 - \frac{\lambda}{4t} \right), \quad \ldots \ldots \ldots \quad (1)
\]

and if \( t < \lambda \)

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

from which it follows that \( \lambda' \) does not begin to diminish rapidly as \( t \) decreases, until \( t \) becomes less than \( \lambda \). The thickness at which \( \lambda' \), and consequently the conductivity, starts to diminish rapidly gives, on this theory, an approximate measure of the mean free path. Now if \( \lambda \) 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 \( \Theta^{-1} \) (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 \( \Theta^{-3} \) as above.

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

Kelvinox 400 dilution-refrigerator (Bottom loading)


< 1K

< 10 K

UHV

a-Ge or a-Sb underlayer of 6Å thickness is deposited in-situ.
0.05-0.1Å increments of metal.
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.
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 transition.

Haviland, Liu, and Goldman
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 10 µm to 100 µm. Surface roughness of approximately 1 µm.

Diameter of the thinned region is typically 4 mm.

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.

Why Strontium Titanate?
SrTiO$_3$ as a Dielectric for Electrostatic Doping

$\kappa_e > 19,000$ below 10 K
Electrostatic “doping” at various film thicknesses

50 volts is about $3 \times 10^{13}$ carriers/cm$^2$

**a-Bi Film with Thickness 9.91 Å**

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

\[ d = 10.22 \text{Å} \]
\[ \Delta n = 0 \]
\[ \Delta n = 3.4 \times 10^{13}/\text{cm}^2 \]
\[ \Delta n_c = 1.4 \times 10^{13}/\text{cm}^2 \]
\[ n_0 = 10^{15}/\text{cm}^2 \] (W. Buckel)
Systematics of the Insulating State

*Mott* Hopping Conduction:

\[ R(T) = R_0 \exp \left[ \left( \frac{T_0}{T} \right)^{\frac{1}{3}} \right] \]

*Strong Screening* due to high dielectric constant may suppress the Coulomb Gap.
The insulator becomes “weakly localized” precisely when superconductivity appears!

\[ y = 9.5355 + 0.16717x \quad R^2 = 0.98957 \]

\[ y = 6.1901 + 0.49543x \quad R^2 = 0.99834 \]
write: \( G(T) = G_0 + k \ln(T/T_0) \)

The effect “saturates”
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)
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)

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

Pair breaking parameter tuning

Data for resistance must be multiplied by 0.55.
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 $\text{Nd}_{1+x}\text{Ba}_{2-x}\text{Cu}_3\text{O}_{7-y}$

M. Salluzzo et al., PRB 78, 054524 (2008)
Superconductivity at the LAO/STO Interface

Electric Double-Layer FET

Electrolyte: polyethylene oxide, containing $\text{KClO}_4$

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 Universality 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.