Field-Effect Superconductivity: the history and the status quo

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John Bardeen
Nobel Prizes in Physics
1956 and 1972

The personal synergy of inventions in semi- and superconductivity now is materialized through experimental achievements of 2000’.

Active material
Source
Gate dielectric
Gate
Drain
Field effect transistor, FET
Field effect dream to transform any material to any electronic state. Anticipating a tunable superconductivity in oxides and beyond

Bell Labs, G. Shoen affair – its very negative and well stimulating impact

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>2002</td>
<td>Darkness in the Murray Hills tunnel</td>
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<td>2002</td>
<td>Side light at the Alpine tunnel section - Geneva.</td>
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<tr>
<td>2003</td>
<td>Light at the Pacific end of the tunnel - Tsukuba, Japan.</td>
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<tr>
<td>2010</td>
<td>Explosions of studies on oxides and organic conductors.</td>
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<tr>
<td>25 years ago</td>
<td>Theorists calling – Chernogolovka, Russia.</td>
</tr>
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Goal: create a field effect injection up to ~10% per surface unit cell.

Ingredients of modern research:
Active material, accepting either electrons or holes, and possessing different, tunable – insulating, metallic, superconducting – ground states:
High-Tc superconductors - cuprates and pnictides - in antiferromagnetic states,
transition metals oxides with charge- and orbital-ordering,
transition metals halcogenides with charge density waves,
organic conductors with the charge ordering,
polyacethelene family of conducting polymers.
Untimely theories

1. Early 80’s, rise of conducting polymers.
Dissatisfaction about effects of charged disorder.
Additional intrigue:
Firm theoretical and experimental grounds for formation of bipolarons – 2-electronic particles, prone to superconductivity.
Desire: to obtain them in a pristine state. Hence two suggestions:
   a. S. Brazovskii and N. Kirova 1981  Call for optical pumping of solitons
"On the possible superfluidity of bipolarons at the junction surface
“... A dense system of bypolarons can be produced by the equilibrium charge injection at the surface of Schottky or MIS junctions. ...Possible superconductivity due to Bose condensation of bypolarons is studied.
... (unlike conventional heterojunctions), here traps due to dangling bonds must be small since the interlayer bonds are saturated ... "
The last practical comment was proved later (R. Friend) by easiness of "painting" the polymeric LED
2. Late 80’s, Epoch of high-Tc superconductivity.  
Dissatisfaction about effects of charged, substitutional and oxygen disorders.  
Intrigue: Intrinsic relation of the superconductivity in the doped state and the pristine antiferromagnetic Mott insulator  
Desire: to obtain the superconductivity without doping. Hence the suggestion:  

Possible superconductivity on the junction surface of dielectric La$_2$CuO$_4$  
S. B. and V. Yakovenko, JETP Let. & Phys. Let. 1988  
“... induce excess charge on the surface of the dielectric La$_2$CuO$_4$ by the field effect transistor or in the Schottky junction.  
... Superconductivity can be observed in this two dimensional system ... to manufacture superconducting devices controlled by electric field ...”  

Recall also J. Mannhart and A. Baratoff, "Superconducting p-n junctions" 1993  
Possibility to explore existence of both n- and p- doped cuprates.
Feasibility of the extreme Field Effect as seen 2 decades ago, V. Yakovenko 1988, unpublished. Achievable concentrations of electrons at the surface of the CuO$_2$ plane for different gate dielectrics. x=15% was most wanted.

<table>
<thead>
<tr>
<th>Dielectrics</th>
<th>$E_D$ $10^6$V/cm</th>
<th>$\varepsilon_D$</th>
<th>$\varepsilon_D E_D$ $10^7$V/cm</th>
<th>$n=\varepsilon_D E_D/4\pi e$ $10^{13}$ cm$^{-2}$</th>
<th>$x=n(3.8\text{A})^2$ in % - $10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>6</td>
<td>4- 10</td>
<td>2.4 - 6</td>
<td>1.3 – 3.3</td>
<td>1.9 – 4.8</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>5</td>
<td>8 - 9</td>
<td>4 – 4.5</td>
<td>2.2 - 2.5</td>
<td>3.2 – 3.6</td>
</tr>
<tr>
<td>Y$_2$O$_3$</td>
<td>5</td>
<td>9 - 13</td>
<td>4.5 – 6.5</td>
<td>2.5 – 3.6</td>
<td>3.6 – 5.2</td>
</tr>
<tr>
<td>HfO$_2$</td>
<td>50</td>
<td>15</td>
<td>75</td>
<td>41.4</td>
<td>60</td>
</tr>
<tr>
<td>PbTiO$_3$</td>
<td>0.5</td>
<td>30 - 200</td>
<td>1.5 – 10</td>
<td>0.83 – 5.5</td>
<td>1.2 – 7.9</td>
</tr>
</tbody>
</table>

Notice the promising case of HfO$_2$ gate. Exotic in mid-80's, it became a working material today, in epoch of high-K and 32 nm.
<table>
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<tr>
<th>Experimental Strategy</th>
<th>Achievements</th>
<th>Year/Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure FET</td>
<td>IMT transition in SrTiO3</td>
<td>2003 AIST, Tsukuba</td>
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<tr>
<td>Pure optical pumping, no gate.</td>
<td>R$_{1-x}$A$_x$MnO$_3$ Transformation: charge-orbital ordered insulator $\rightarrow$ ferromagnetic metal</td>
<td>Miyano 2005 (Tokyo U.)</td>
</tr>
<tr>
<td>MBE+ ferroelectric</td>
<td>Electrostatic Modulation of Superconductivity in GdBa$_2$Cu$<em>3$O$</em>{7-x}$</td>
<td>Triscone 1999 Geneva)</td>
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<td></td>
<td>Superlattices</td>
<td>Bozovic (BNL, USA)</td>
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<td></td>
<td>SC at interface of LaAlO/SrTiO3</td>
<td>Reyren 2007, Triscone 2008</td>
</tr>
<tr>
<td>Gate voltage + optical pumping across the gate</td>
<td>Photoinduced IMT VO$_2$, TiO$_2$, LaSrMnO$_3$ CaCuO$_2$</td>
<td>Hiroi 2002 (ISSP, Japan)</td>
</tr>
<tr>
<td>Double-Layer Transistor by electrolyte gating</td>
<td>Surface carrier density reached $10^{15}$/cm$^2$ Superconductor–insulator transition in La$_{2-x}$Sr$_x$CuO$_4$</td>
<td>Iwasa 2008 (Tokyo) Bozovic 2011 (BNL, USA)</td>
</tr>
</tbody>
</table>
Strategy 1. Direct assault at a minimal possible frontier. Micro gate area may have no leakage defects.

Inoue et al

Field effect doping of SrTiO$_3$
CERC-AIST, Tsukuba, Japan

Drain current $I_D$ and the mobility $\mu$ plotted against the gate electric field $E_G$

FET constructed on single crystal
**Strategy 2.** Direct assault, pure optical pumping, no gate.

Photoinduced insulator-to-metal transition

K. Miyano & N. Takubo, *University of Tokyo.* 2005

Perovskite manganites, $R_{1-x}A_xMnO_3$

(compounds of the colossal magnetoresistance)

Transformation: charge- and orbital-ordered insulating (COOI) state $\rightarrow$ ferromagnetic metallic (FMM) phase

$Pr_{0.55}(Ca_{1-y}S_{y})_{0.45}MnO_3$ film on $(LaAlO_3)_{0.3}(SrAl_{0.5}TaO_3)_{0.7}$ (110) substrate, $y = 0.25$

Laser pulses transform COOI $\rightarrow$ FMM

Photon energy is 2.3 eV
Strategy 3. Combination of the gate voltage with the optical pumping across the gate

Photocarrier Injection to Transition Metal Oxides
Y. Muraoka and Z. Hiroi -- ISSP, Japan

Estimated photo-doping: \( \sim 10^{20}/\text{cm}^3 \), i.e. 1% per TM
Strategy 4 – Gigantic amplification of the gate voltage in the field effect by adding the ferroelectric layer.

Electrostatic Tuning of the Hole Density in NdBa2Cu3O7 Films and its Effect on the Hall Response

FIG. 1. Side view: Schematic view of the device; on a (100) SrTiO₃ substrate, a thin (001) NBCO layer and (001) PZT layer have been deposited. Top view: The path used to measure the resistivity and Hall effect. The dimensions of the patterned resistivity paths are 20 µm (width) by 80 µm (length). The light gray area is where the polarization is switched.

FIG. 2. Resistivity versus temperature for the two polarization states. P⁺ is the polarization direction that adds holes to the superconducting layer. The change in resistivity is about 9% at room temperature. The shift in $T_c$ is about 1 K. Inset: Normalized resistivities as a function of temperature.

260 A: SrTiO$_{3-x}$, SrTi$_{1-x}$Nb$_x$O$_3$, Sr$_{1-x}$La$_x$TiO$_3$  
500 A: Pb(Zr,Ti)O$_3$

The P+ state - removing electrons from the Nb-STO layer.
The P- state - adding electrons to the Nb-STO layer (increasing the doping level).
Electrostatic Modulation of Superconductivity in Ultrathin GdBa$_2$Cu$_3$O$_{7-x}$ Films
J.-M. Triscone group SCIENCE 1999

PZT/20 Å GBCO/72Å PBCO heterostructure for the two polarizations.
Upper curve - removal of holes.

Achieved: switching off of the superconductivity in a pre-doped material.
Still necessary: turn the SC on from the pristine undoped insulator
**Strategy 5 – interdiscplinary**
Method of electrolitic condensor – from polymeric FET.

**Electric-field-induced superconductivity in an insulator**

liquid – solid electrolite – as gate dielectric (K+) are electrostatically adsorbed on the SrTiO$_3$

\[ V_G = 3.5 \text{ V}, \quad n_{2D} > 1 \times 10^{14} \text{ cm}^{-2}, \quad \text{usually } n_{2D} \sim 1 \times 10^{13} \text{cm}^{-2} \]
Superconductor–insulator transition in La$_{2-x}$Sr$_x$CuO$_4$ at the pair quantum resistance, Nature, 472 (2011) 458 I.Bozovic group

synthesis of epitaxial films of La$_{2-x}$Sr$_x$CuO$_4$ ($x=0.06 – 0.20$) 1, 1.5, 2 unit cell thick, and fabrication of double-layer transistors (NaF+polyethylene glicole)

At low concentration SC disappears via Bose glass phase without pair breaking

Achieved: switching off of the superconductivity in a pre-doped material.
Still necessary: turn the SC on from the pristine undoped insulator
Recall J. Mannhart and A. Baratoff, "Superconducting p-n junctions" 1993
Possibility to explore existence of both n- and p- doped cuprates.
In order to eliminate a side effect of the disorder, we suggest studying the superconductivity in a two-dimensional system of electrons which is induced at the surface of an insulating La$_2$CuO$_4$ single crystal or a crystal of a similar compound, by means of an external electric field at a low temperature. This effect might be implemented in structures such as a field-effect transistor or a Schottky contact. The surface of the contact should be parallel to the CuO$_2$ layers.

We wish to discuss those effects which do not depend on the nature of the high-temperature superconductivity and which are related exclusively to the two-dimensional nature of the copper oxides. We assume that the CuO$_2$ layers are coupled only weakly to each other and that the superconductivity, like antiferromagnetism, can occur independently in each layer.

\[ \epsilon_L (\varphi_{m+1} - 2\varphi_m + \varphi_{m-1}) = -4\pi edn_m, m = 1, 2, \ldots; \]

\[ \epsilon_L (\varphi_0 - \varphi_1) = -\epsilon_D E_D d + 4\pi edn_0; \varphi_\infty = 0. \]

If bulk LCO is not SC, but metallic:

\[ \varphi_m = \varphi_0 \exp (-mk), \quad k = \arccosh (\eta + 1), \]

\[ \varphi_0 = -\epsilon_D E_D d / \left[ \eta + (\eta (\eta + 2))^{1/2} \right] \epsilon_L, \quad \eta = 2\pi d v e^2 / \epsilon_L. \]

With \( v = 2 \text{ (eV \cdot molecule)}^{-1}, \ d = 13 \text{ A}, \) and \( \epsilon_L = 10, \) we find \( \eta = 17 \) and \( k = 3.5. \)

The electric field is thus screened by essentially a single CuO$_2$ layer, with the index
Polymers

Doped

- Bipolarons: volume concentration depends on the doping level
- But: dopant induced disorder suppresses the possibility Bose condensation also in homogeneous material
- Little chance for Bose condensation

Undoped

- FET MIS junction allows to introduce charge, hence to create bipolarons on the junction surface
- Advantages: no additional disorder
- Problems: Wigner crystallization, dipole formation, High electric field
Superconductivity from the Bose-condensation of bipolarons or of prefabricated Cooper pairs at the junction surface:


Some theory problems to be solved:

- In “conventional” Bose condensation the number of particle is fixed. In FET the electrochemical potential is monitored by external electric field – no ideal BEC.
- 2D ideal gas: Condensation is not allowed in any sense
- 2D non ideal gas: Bose condensation is possible in a sense of Beresinski-Kosterlitz-Touless

*Specific questions:*

- effects of Coulomb forces
- values of the required electric field
Model

\[ L = \int_0^\infty dz \int d^2r \left\{ \psi^* \left[ E + \frac{1}{2M_\|} \frac{\partial^2}{\partial r^2} + \frac{1}{2M_\perp} \frac{\partial^2}{\partial z^2} \right] \psi + \Phi(R)[2en(R) + 2e'n(R')] \right\} \]

\[ \Phi(R)[2en(R) + 2e'n(R')] - \frac{1}{8\pi} \left[ \varepsilon_\perp \left( \frac{\partial \Phi}{\partial z} \right)^2 + \varepsilon_\| \left( \frac{\partial \Phi}{\partial r} \right)^2 \right] \]

\[ \frac{1}{2M_\perp} \frac{d^2\psi_0(z)}{dz^2} + V(z)\psi_0(z) = 0 \]

\[ \varepsilon_\perp \frac{d^2V(z)}{dz^2} + 4e^2\psi_0^2(z) = 0 \]

Formation of the self-consistent potential wall with the single localized eigenstate at the given eigenvalue of \( \mu \).

Screening by the single wave function.

Electric field \( E \sim 10^7 \) eV

Cold atoms: trap is fixed
Conclusions and perspectives

• Field effect – electrostatic switching of electronic states at the surface is well confirmed by divers experimental methods

• The 2D, even monolayer superconductivity does exist

• Methodic progress raised the scale of manipulation from milli K to 30 K

• Non realized or unattended issues:
  
  Realisation of semi – super devices.
  
  Superconducting p-n junction
  
  time-resolved optical pumping and detection
  
  Extension to organic materials