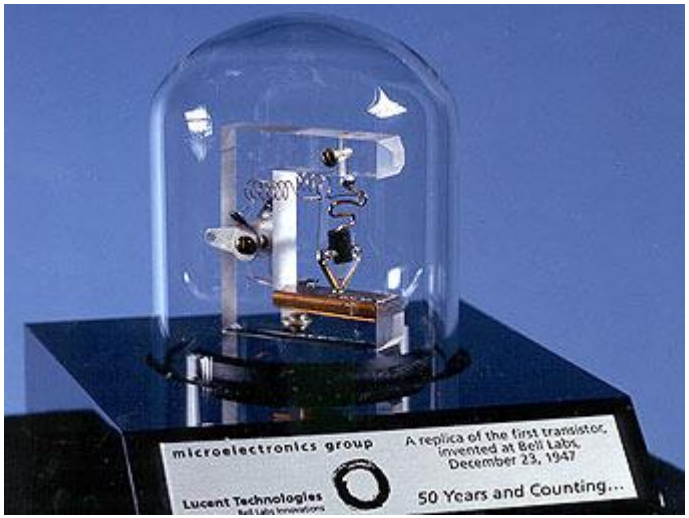
Field-Effect Superconductivity : the history and the status quo

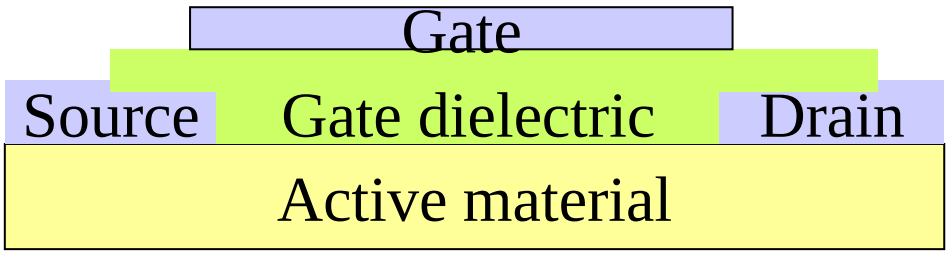
S. Brazovskii and N. Kirova
LPTMS&LPS, CNRS,Université Paris-Sud, Orsay, France.



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'.



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

2002	Darkness in the Murray Hills tunnel
2002 +	Side light at the Alpine tunnel section - Geneva.
2003 +	Light at the Pacific end of the tunnel - Tsukuba, Japan.
2010	Explosions of studies on oxides and organic conductors.
25 years ago	Theorists calling – Chernogolovka, Russia.

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.**

Metallization of polyacethylene by doping *1979* →Nobel prise 2000.

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**

b. S.B. N.K. and V. Yakovenko , Solid State Commun. 1985

"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_2CuO_4

S. B. and V. Yakovenko, JETP Let. & Phys. Let. 1988

"... ***induce excess charge on the surface of the dielectric La_2CuO_4 by the field effect transistor or in the Schottky junction.***

... Superconductivity can be observed in this two dimentional 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.

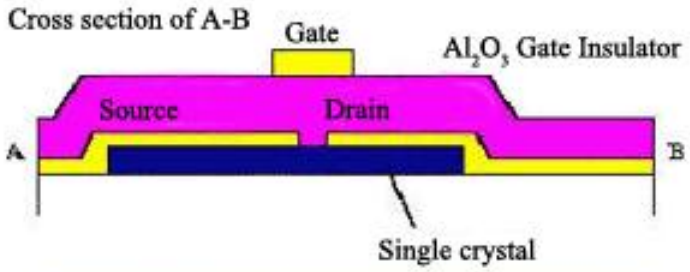
Dielectrics	**E_D 10^6V/cm**	**ε_D**	**$\varepsilon_D E_D$ 10^7V/cm**	**$n=\varepsilon_D E_D/4\pi e$ 10^{13} cm^{-2}**	**$x=n(3.8A)^2$ in % - 10^{-2}**
SiO_2	**6**	**4- 10**	**2.4 - 6**	**1.3 – 3.3**	**1.9 – 4.8**
Al_2O_3	**5**	**8 - 9**	**4 – 4.5**	**2.2 - 2.5**	**3.2 – 3.6**
Y_2O_3	**5**	**9 - 13**	**4.5 – 6.5**	**2.5 – 3.6**	**3.6 – 5.2**
HfO_2	**50**	**15**	**75**	**41.4**	**60**
$PbTiO_3$	**0.5**	**30 - 200**	**1.5 – 10**	**0.83 – 5.5**	**1.2 – 7.9**

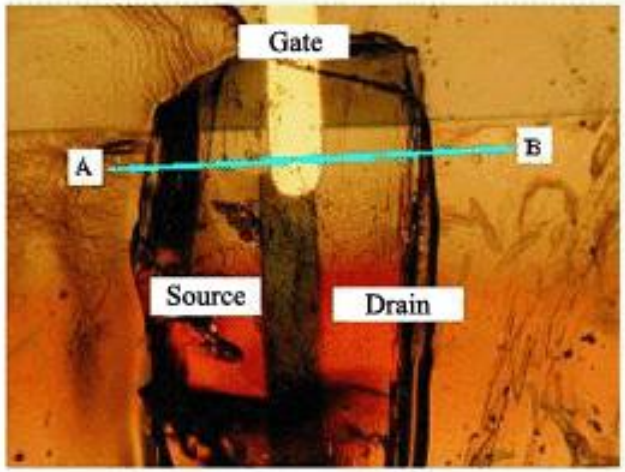
Notice the promising case of HfO_2 gate. Exotic in mid-80's, it became a working material today, in epoch of high-K and 32 nm.

Experimental Strategy	Achievements	
Pure FET	IMT transition in SrTiO3	2003 AIST, Tsukuba
Pure optical pumping, no gate.	$R_{1-x}A_xMnO_3$ Transformation : charge-orbital ordered insulator --> ferromagnetic metal	Miyano 2005 (Tokyo U.)
MBE+ ferroelectric MBE – Molecular Beam Epitaxy	Electrostatic Modulation of Superconductivity in $GdBa_2Cu_3O_{7-x}$ Superlattices SC at interface of LaAlO/SrTiO3	Triscone 1999 Geneva) Bozovic (BNL, USA) Reyren 2007, Triscone 2008
Gate voltage + optical pumping across the gate	Photoinduced IMT VO2, TiO2, LaSrMnO3 CaCuO2	Hiroi 2002 (ISSP, Japan)
Double-Layer Transistor by electrolyte gating	Surface carrier density reached 10^{15} /cm^2 Superconductor–insulator transition in $La_{2-x}Sr_xCuO_4$	Iwasa 2008 (Tokyo) Bozovic 2011 (BNL, USA)

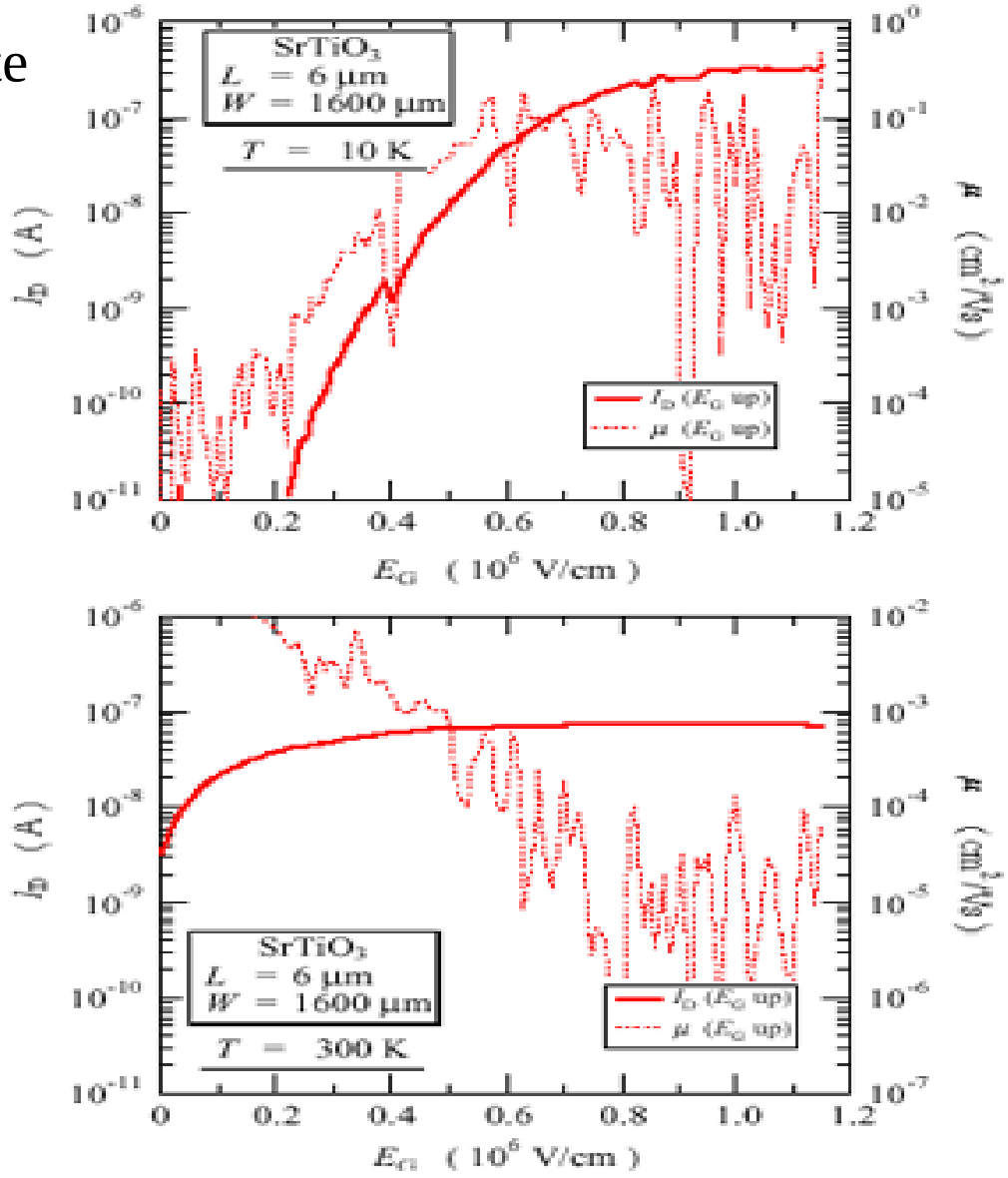
Strategy 1. Direct assault at a minimal possible frontier. Micro gate area may have no leakage defects. *Inoue et al*

Field effect doping of $SrTiO_3$
CERC-AIST, Tsukuba, Japan





FET constructed on single crystal



Drain current $\mathbf{I_D}$ and the mobility $\boldsymbol{\mu}$ plotted against the gate electric field $\mathbf{E_G}$

Strategy 2. Direct assault, pure optical pumping, no gate.

photoinduced insulator-to-metal transition

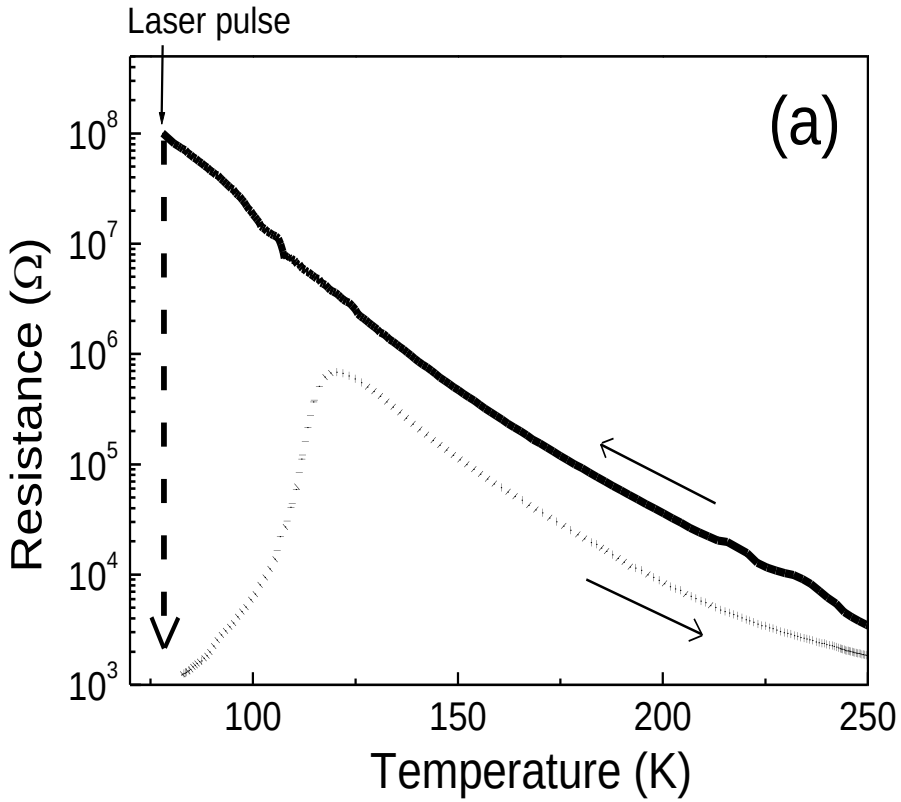
K. Miyano & N. Takubo, *University of Tokyo.* *2005*

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

(compounds of the colossal magnetoresistance)

Transformation : charge- and orbital-ordered insulating (COOI) state

➔ 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, $y = 0.25$

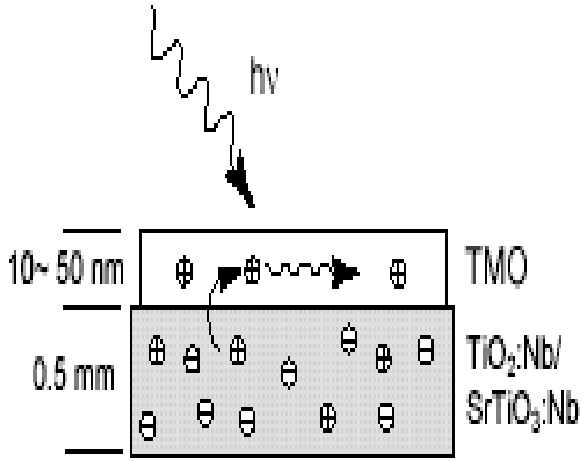
Laser pulses transform COOI ➔FMM

Photon energy is 2.3 eV

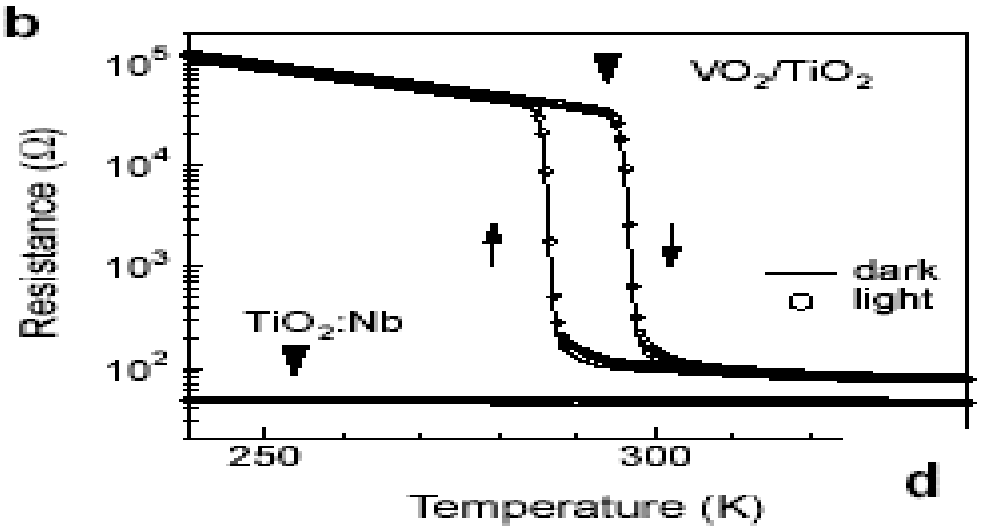
Strategy 3. Combination of the gate voltage with the optical pumping across the gate

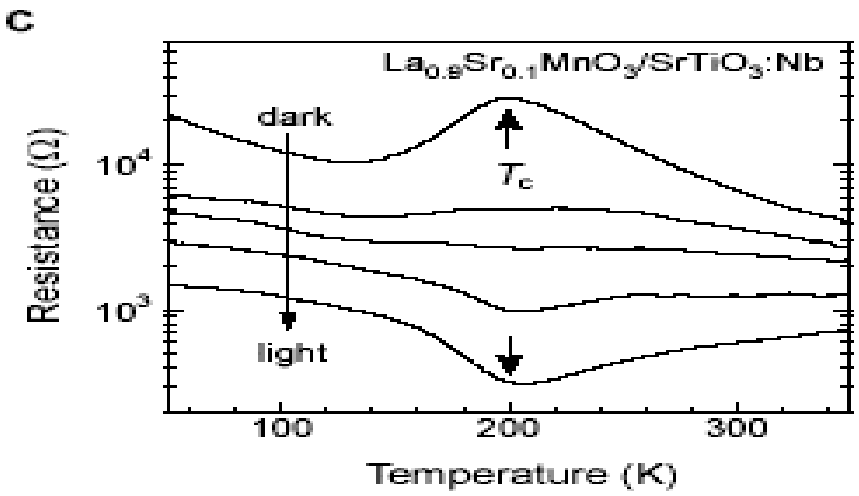
Photocarrier Injection to Transition Metal Oxides

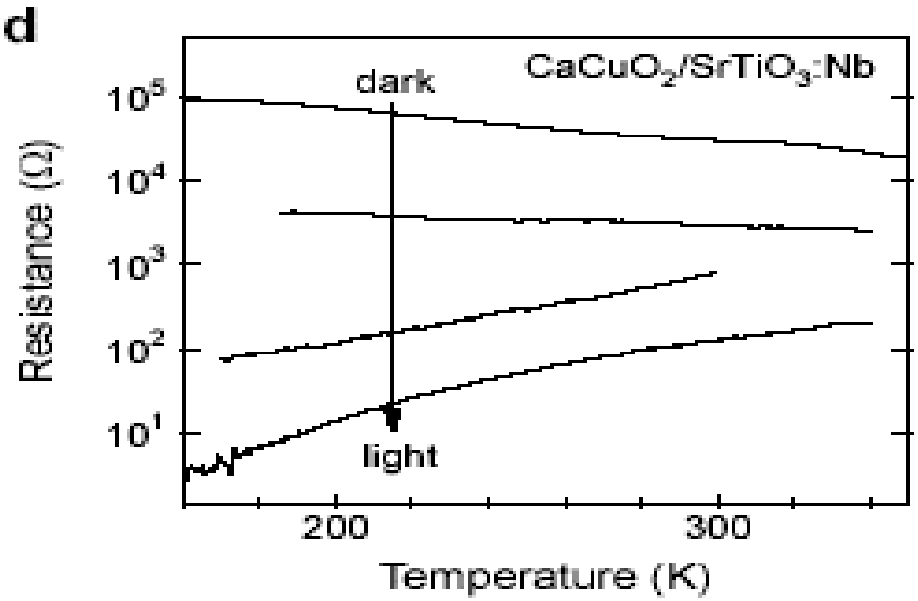
Y. Muraoka and Z. Hiroi -- ISSP, Japan



Estimated photo-doping:
~10^{20}/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

J.-M. Triscone group, Geneve. Phys. Rev. Let. 2002

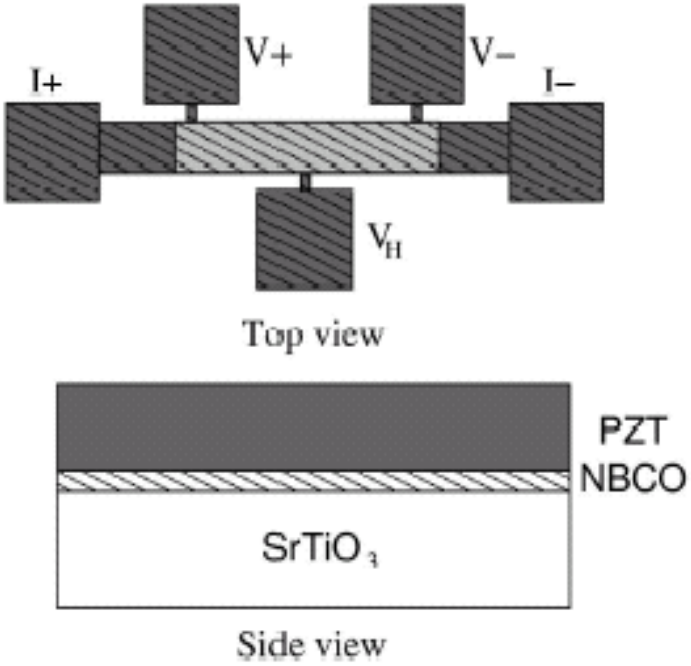


FIG. 1. Side view: Schematic view of the device; on a (100) $SrTiO_3$ substrate, a thin (001) NBCO layer and (001) PZT layer have been deposited. Top view: The path used to measure the resistivity and Hall effect. The dimensions of the patterned resistivity paths are 20 μm (width) by 80 μm (length). The light gray area is where the polarization is switched.

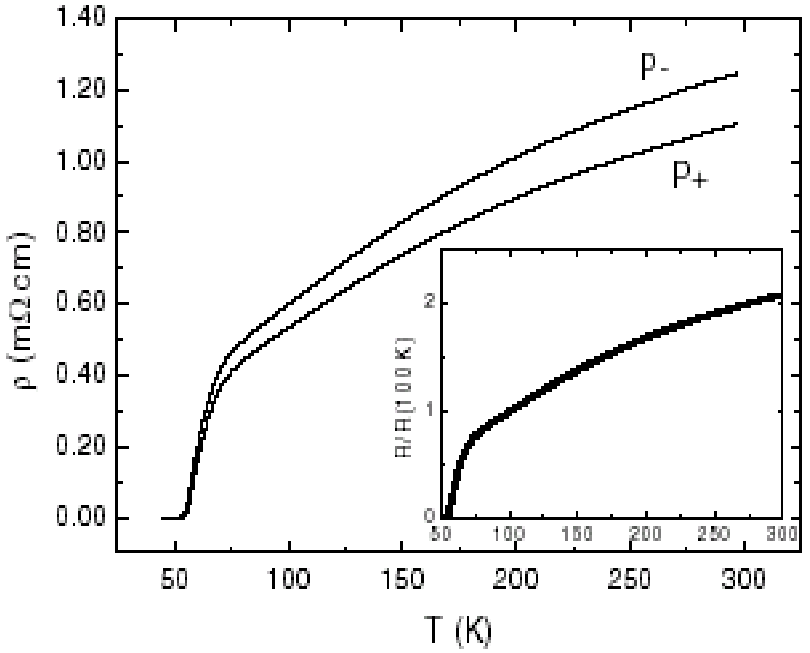
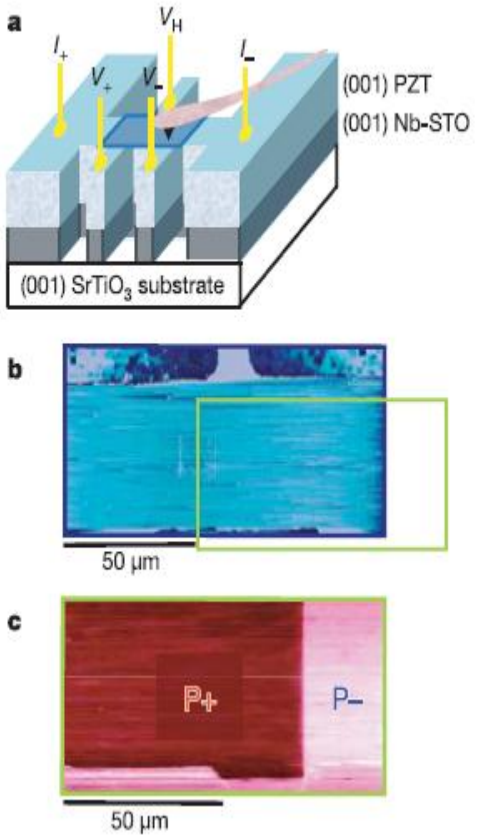


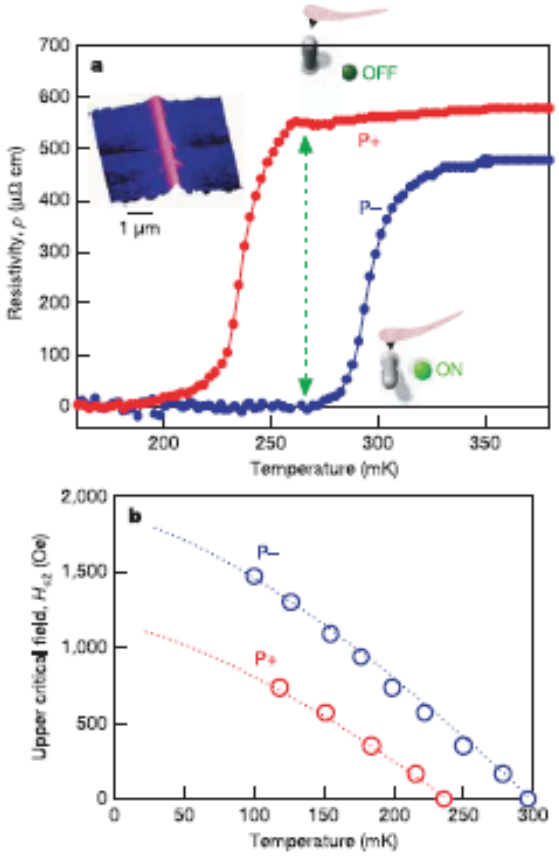
FIG. 2. Resistivity versus temperature for the two polarization states. P^+ is the polarization direction that adds holes to the superconducting layer. The change in resistivity is about 9% at room temperature. The shift in T_c is about 1 K. Inset: Normalized resistivities as a function of temperature.

Local switching of two-dimensional superconductivity using the ferroelectric field effect *J.-M. Triscone, et al* Nature **441** (2006) 195

260 A : $SrTiO_{3-x}$, $SrTi_{1-x}Nb_xO_3$, $Sr_{1-x}La_xTiO_3$

500 A : $Pb(Zr,Ti)O_3$



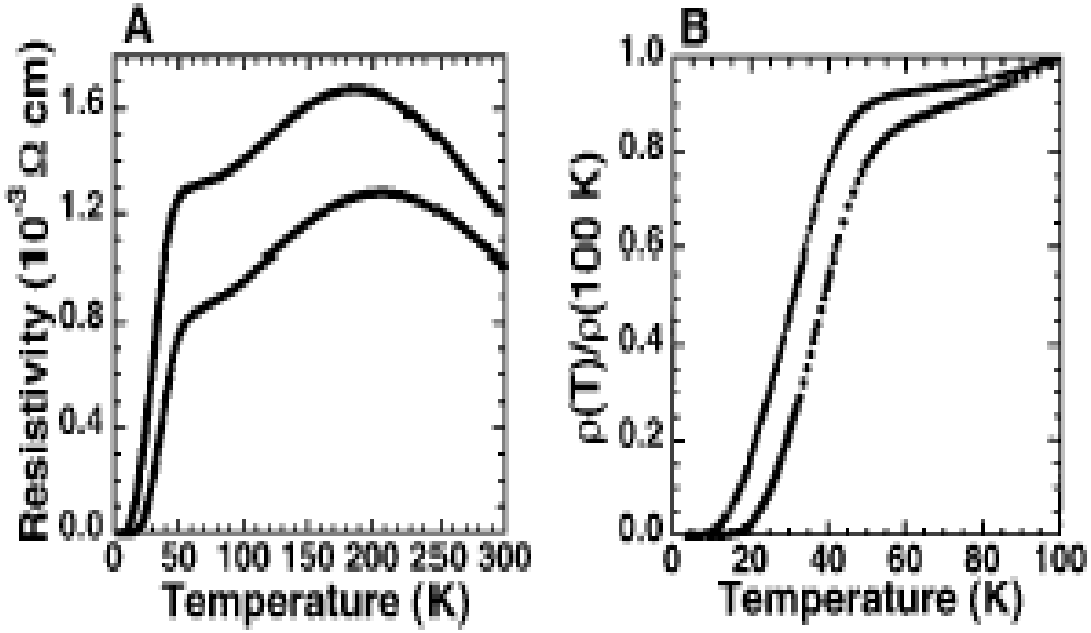


The P+ state - removing electrons from the Nb-STO layer.

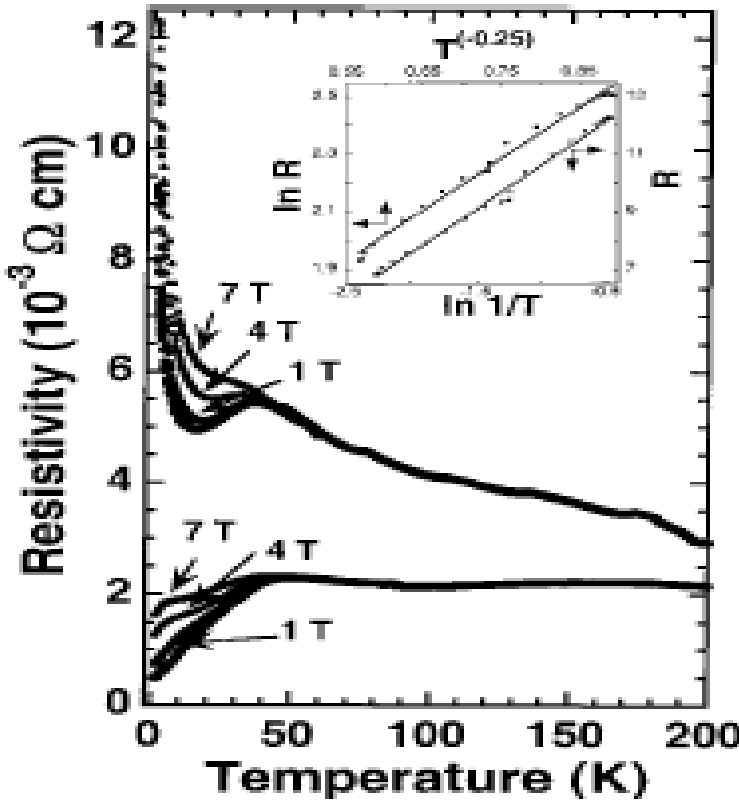
The P- state - adding electrons to the Nb-STO layer (increasing the doping level)

Electrostatic Modulation of Superconductivity in Ultrathin $GdBa_2Cu_3O_{7-x}$ Films

J.-M. Triscone group SCIENCE 1999



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



R(T) in magnetic field.
Upper curves: depletion to the insulating state

Achieved: switching off of the superconductivity in a pre-doped material.

Still necessary: turn the SC on from the pristine undoped insulator

Strategy 5 – interdiscuplinary

Method of electrolitic condensor – from polymeric FET.

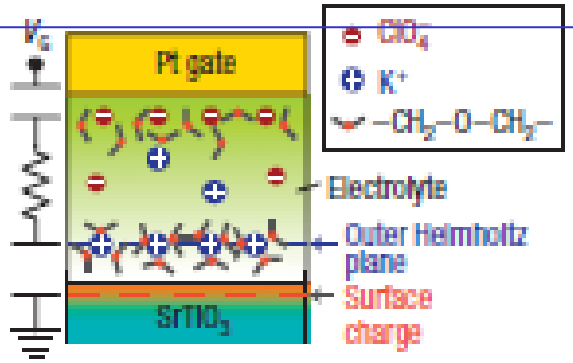
Electric-field-induced superconductivity in an insulator

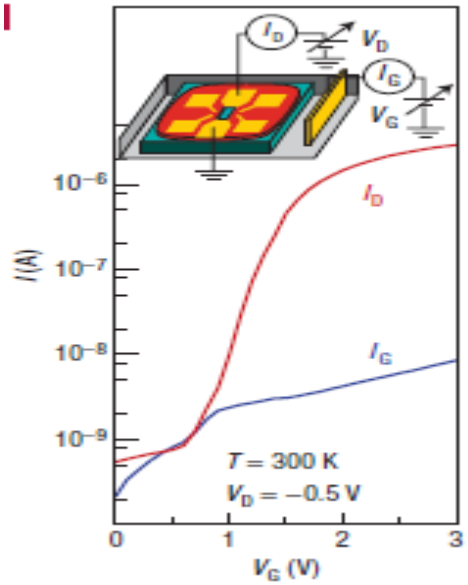
Iwasa group, Nature Materials **7** (2008) 855; **9**, 125 (2010).

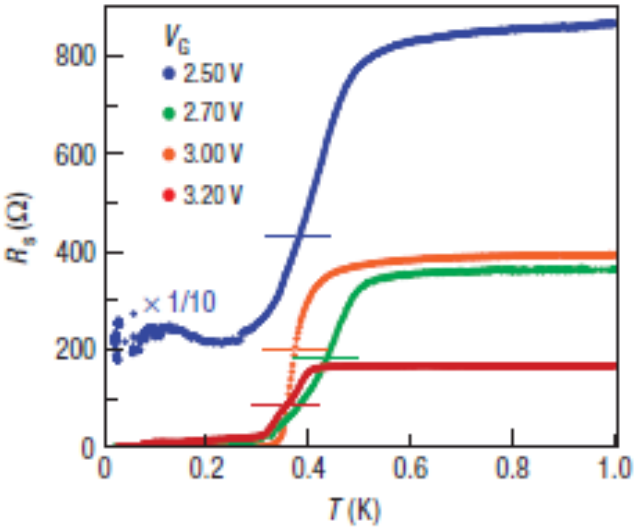
R.H. Friend group: Adv. Mater. ***22***, *2529 (2010).*

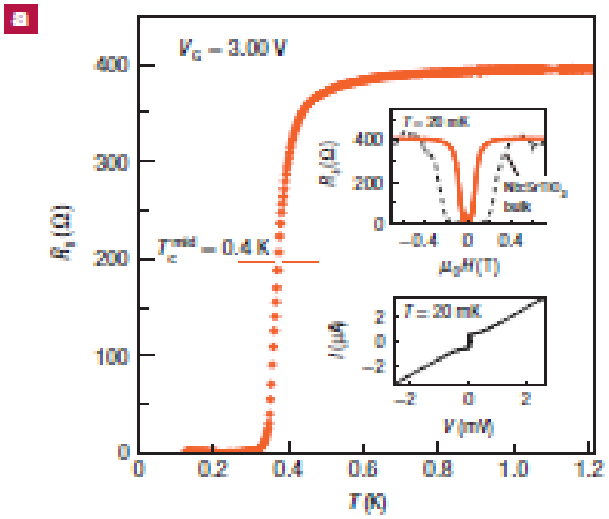
liquid – solid electrolite – as gate dielectric

(K+) are electrostatically adsorbed on the $SrTiO_3$







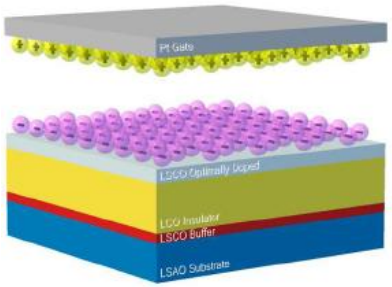


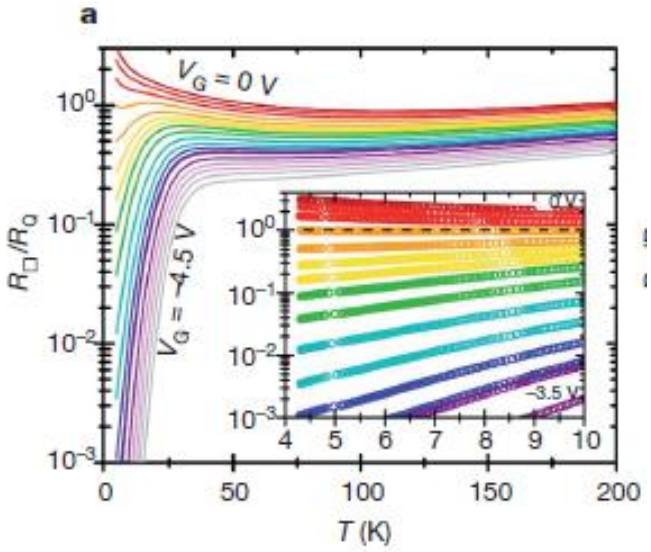
V_G = 3.5 V, $n_{2D} > 1\times10^{14}$ cm^{-2}, usually $n_{2D} \sim 1\times10^{13}cm^{-2}$

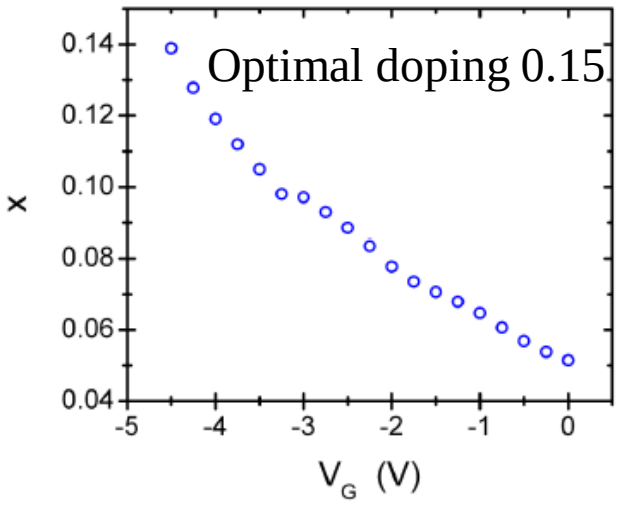
Strategy 6: hybrid of 4 and 5 Electrolyte upon the MBE

Superconductor–insulator transition in $La_{2-x}Sr_xCuO_4$ at the pair quantum resistance, Nature, **472** (2011) 458 *I.Bozovic group*

synthesis of epitaxial films of $La_{2-x}Sr_xCuO_4$ (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

APPLIED PHYSICS LETTERS 95, 062510 (2009)

Josephson effect between electron-doped and hole-doped iron pnictide single crystals

Xiaohang Zhang,[1,a)] Shanta R. Saha,[1] Nicholas P. Butch,[1] Kevin Kirshenbaum,[1] Johnpierre Paglione,[1] Richard L. Greene,[1] Yong Liu,[2] Liqin Yan,[2] Yoon Seok Oh,[2] Kee Hoon Kim,[2] and Ichiro Takeuchi[3]

[1]*Department of Physics and CNAM, University of Maryland, College Park, Maryland 20742, USA*

[2]*Department of Physics and Astronomy, CSCMR & FPRD, Seoul National University, Seoul 151-747, Republic of Korea*

[3]*Department of Materials Science and Engineering, University of Maryland, College Park, Maryland 20742, USA*

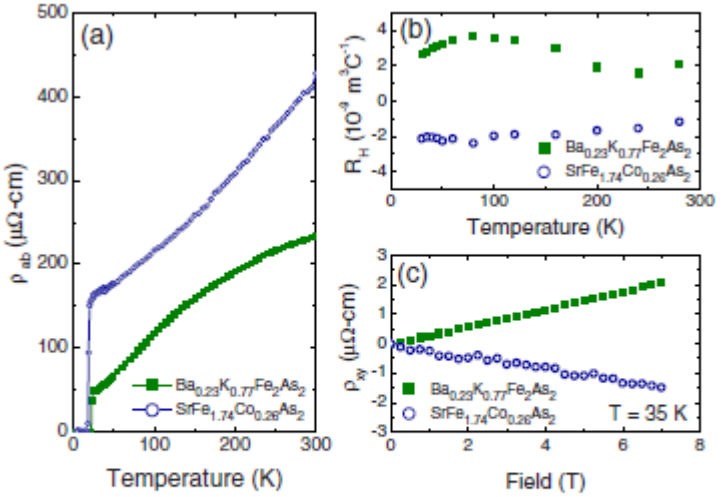
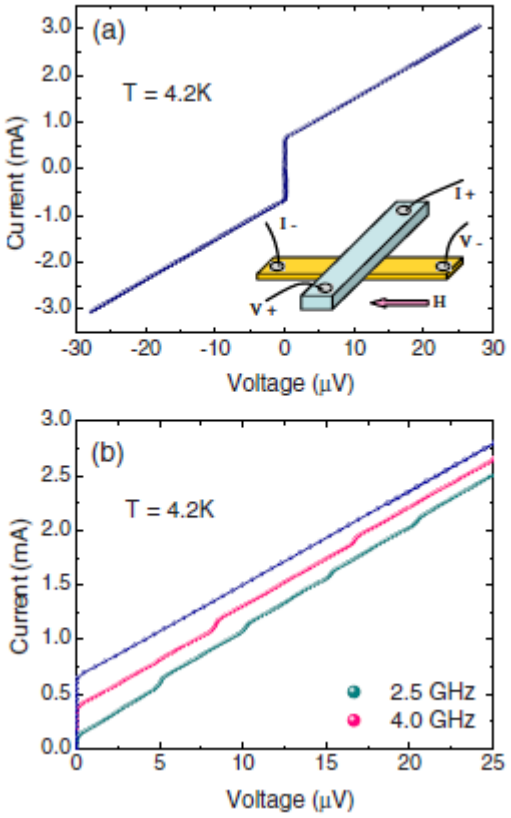


FIG. 1. (Color online) Temperature dependence of the in-plane resistivity (a) and the Hall coefficient (b) for $SrFe_{1.74}Co_{0.26}As_2$ and $Ba_{0.23}K_{0.77}Fe_2As_2$ single crystals; (c) field dependence of Hall resistivities obtained at 35 K for the two single crystals.



Recall J. Mannhart and A. Baratoff, "Superconducting p-n junctions" 1993

Possibility to explore existence of both n- and p- doped cuprates.

Possible superconductivity at the surface of a contact of insulating La_2CuO_4

S. A. Brazovskiĭ and V. M. Yakovenko
L. D. Landau Institute of Theoretical Physics, Academy of Sciences of the USSR

(Submitted 21 June 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 3, 159–161 (10 August 1988)

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_2CuO_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.

$$\epsilon_L(\varphi_{m+1}-2\varphi_m+\varphi_{m-1}) = -4\pi e d n_m,\ m = 1,2,\ldots;$$

$$\epsilon_L(\varphi_0-\varphi_1) = -\epsilon_D E_D d + 4\pi e d n_0;\ \varphi_\infty = 0.$$

If bulk LCO is not SC, but metallic:

$$\varphi_m = \varphi_0 \exp(-mk),\ k = \operatorname{arcch}(\eta+1),$$

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

with $\nu = 2$ (eV·molecule)$^{-1}$, $d = 13$ 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 supresses 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:

after S.B. N.K. and V. Yakovenko , Solid State Commun. 1985

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

$$L=\int_0^\infty dz\int d^2r\left\{\psi^*\left[E+\frac{1}{2M_\parallel}\frac{\partial^2}{\partial r^2}+\frac{1}{2M_\perp}\frac{\partial^2}{\partial z^2}\right]\right\}\psi+$$

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

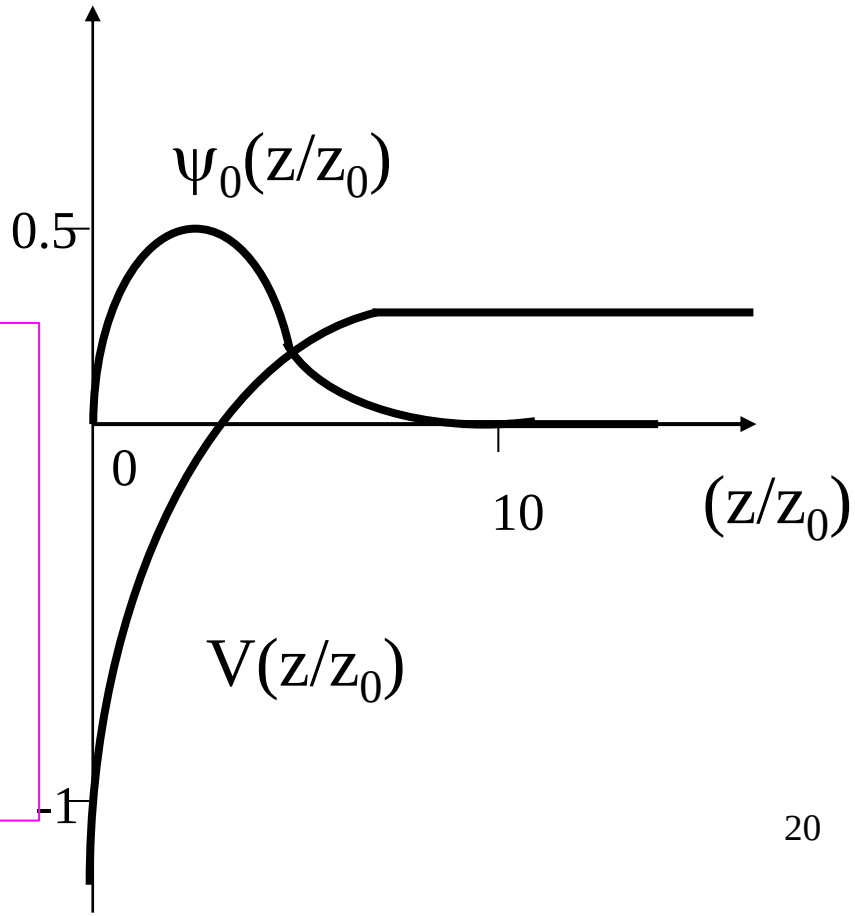
$$\frac{1}{2M_\perp}\frac{d^2\psi_0(z)}{dz^2}+V(z)\psi_0(z)=0$$

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

Formation of the self-consistent potential wall with the single localized eigenstate at the given eigenvalue of μ. Screening by the single wave function.

Electric field E~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 30K**

- **Non realized or unattended issues:**

  Realisation of semi – super devices.

  Superconducting p-n junction

  time-resolved optical pumping and detection

  Extension to organic materials