The Abdus Salam International Centre for Theoretical Physics

2157-18

**Workshop on Principles and Design of Strongly Correlated Electronic Systems**

*2 - 13 August 2010*

# Electric Field Induced Superconductivity with Electric Double Layer Transistors

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# Electric field induced superconductivity with electric double layer transistors (EDLT)

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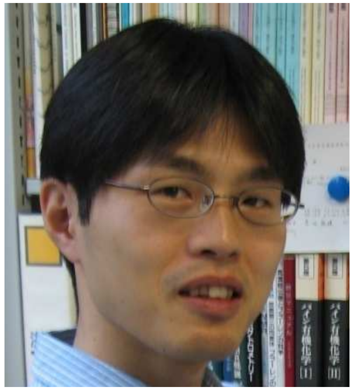
# OUTLINE

- Introduction :
  - Electric-field induced superconductivity
  - Electric double layer transistor (EDLT)
- Oxide semiconductors
  - ZnO and $SrTiO_3$
- For further increase of carrier density
- Layered material ZrNCl
  - Bulk properties and E-induced SC
- Summary

# Acknowledgements (In-house collaboration at IMR, Tohoku)

## Development of EDLTs (IMR)

**H. Shimotani**



**H. T. Yuan**

**J. T. Ye**

**Y. Kasahara**

## Oxides (WPI-AIMR)

**M. Kawasaki**

**K. Ueno**

## Low-T physics (IMR)

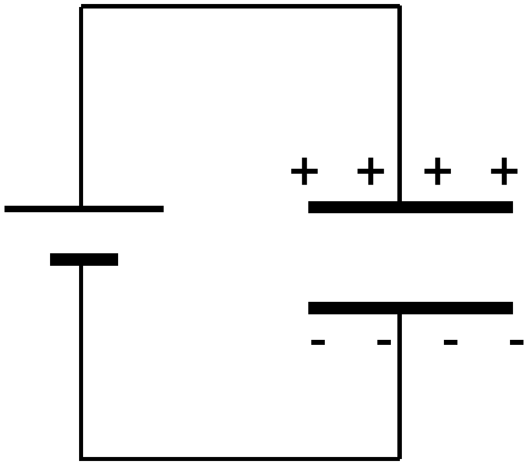
**T. Nojima**

**S. Nakamura**

# History 1

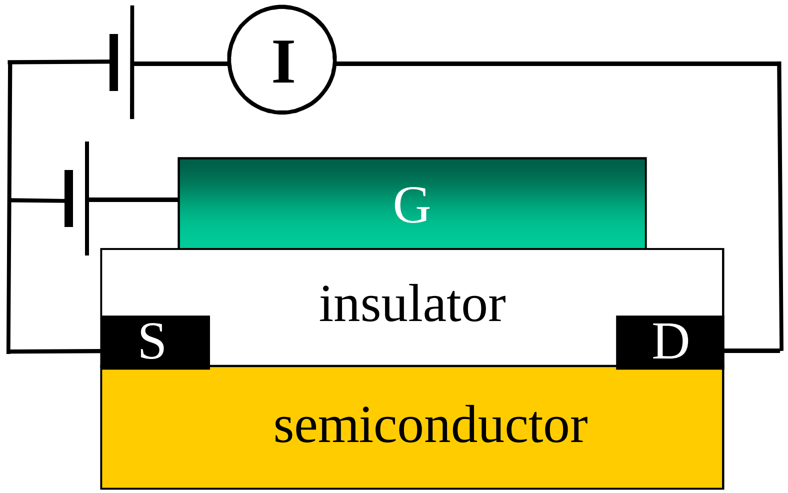
## Measuring resistance of capacitor electrodes

### Capacitor
**Charge accumulation device**




Resistance measurement
of capacitor electrodes (1906)

### Field Effect Transistor (FET)
**Current switching device**




Patent of MOS-FET (1930s)

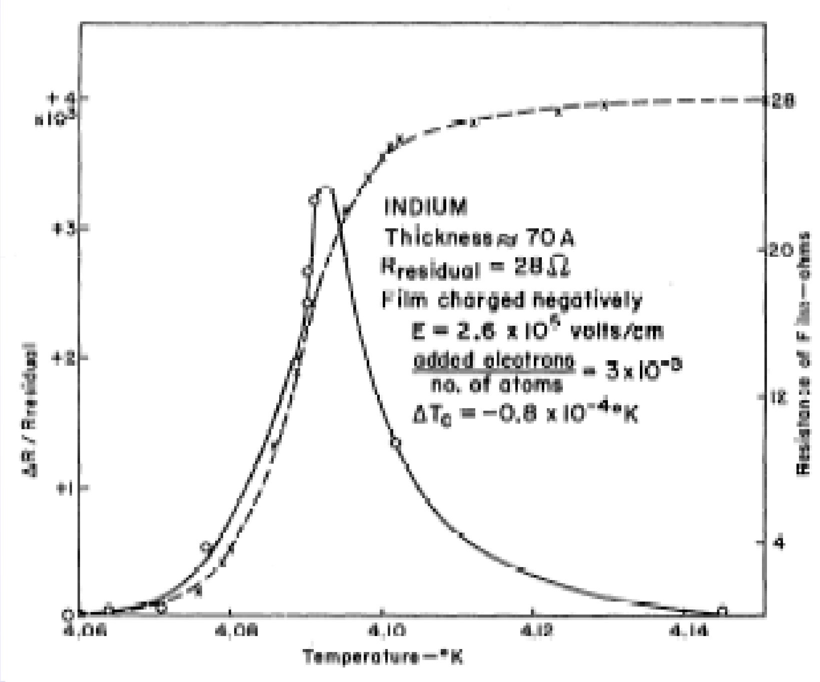
Electric field control of
superconductor
R. E. Glover, III & M. D. Sherrill (1960)

Invention of Si-MOSFET
D. Kahng & M. M. Atalla（1960）

# History 2

## Electric Field Control of Tc in superconductors

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




Indium

$T_c$ = 4.1 K, $\Delta T_c$ = - 0.8 x $10^{-4}$ K

**Challenge:**

**Can you increase Tc from zero to finite?**

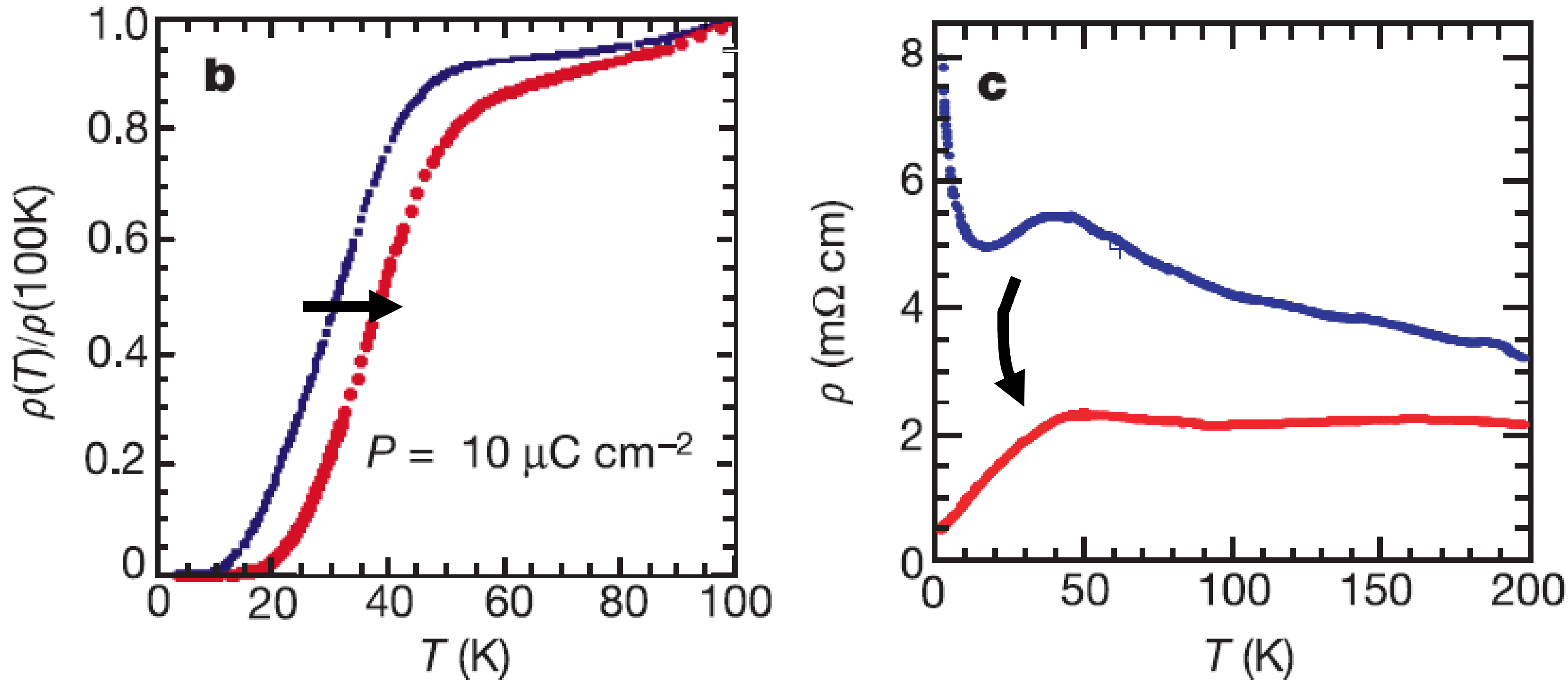
# History 3

## Field effects of High Tc cuprates

- Chemical doping to insulators yields high Tc (1986)
- Field-effect in high Tc with chemical doping (1991)

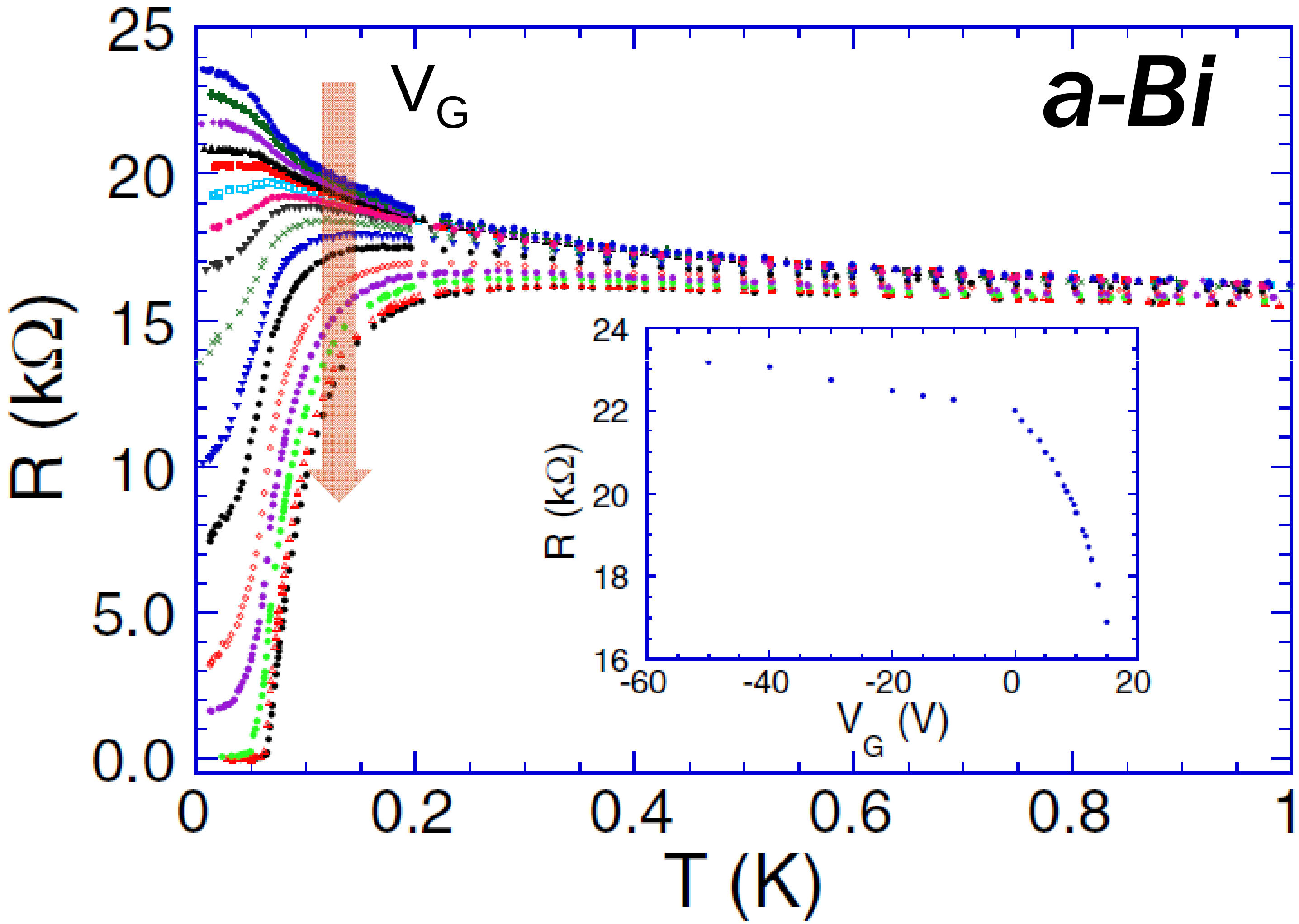
$YBa_2Cu_3O_{7-\delta}$

C. H. Ahn, J.-M. Triscone, and J. Mannhart Nature 423, 1015 (2003).



# History 3'

## Gate control of Localization-Superconductivity Transition




IMR

K. L. Parendo, A. G. Goldman et al., PRL 94, 197004 (2005)

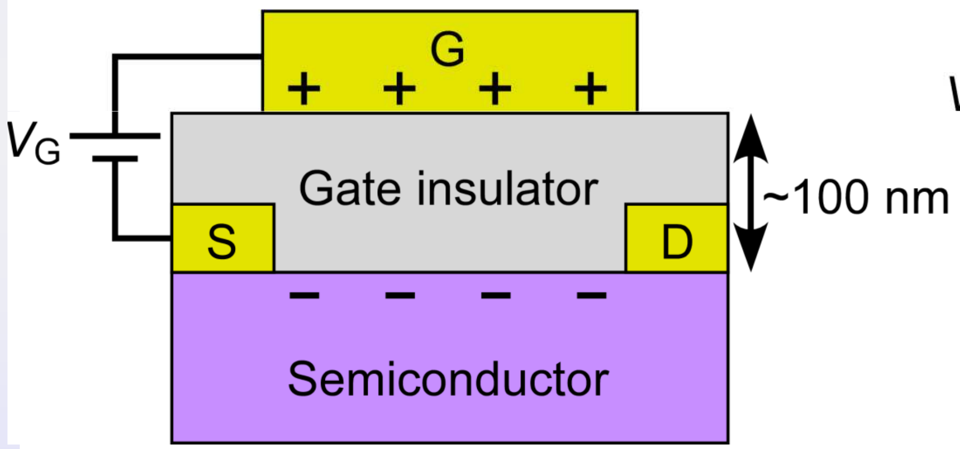
## Conventional FET

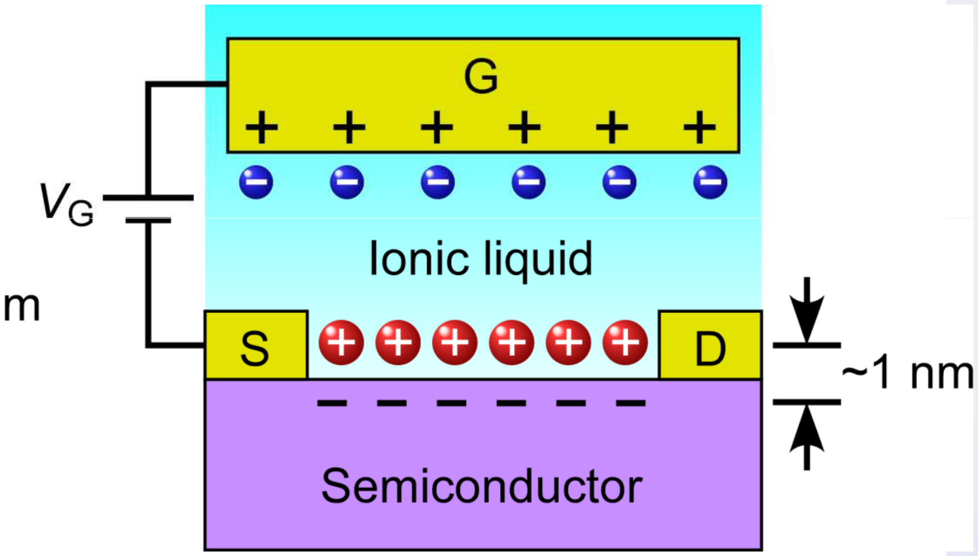
## Our approach

# Solid Gate

# Liquid gate

(electric double layer transistor)




**Weak electric field**

**～1 MV/cm**

**< 1 x $10^{13}$ cm$^{-2}$**

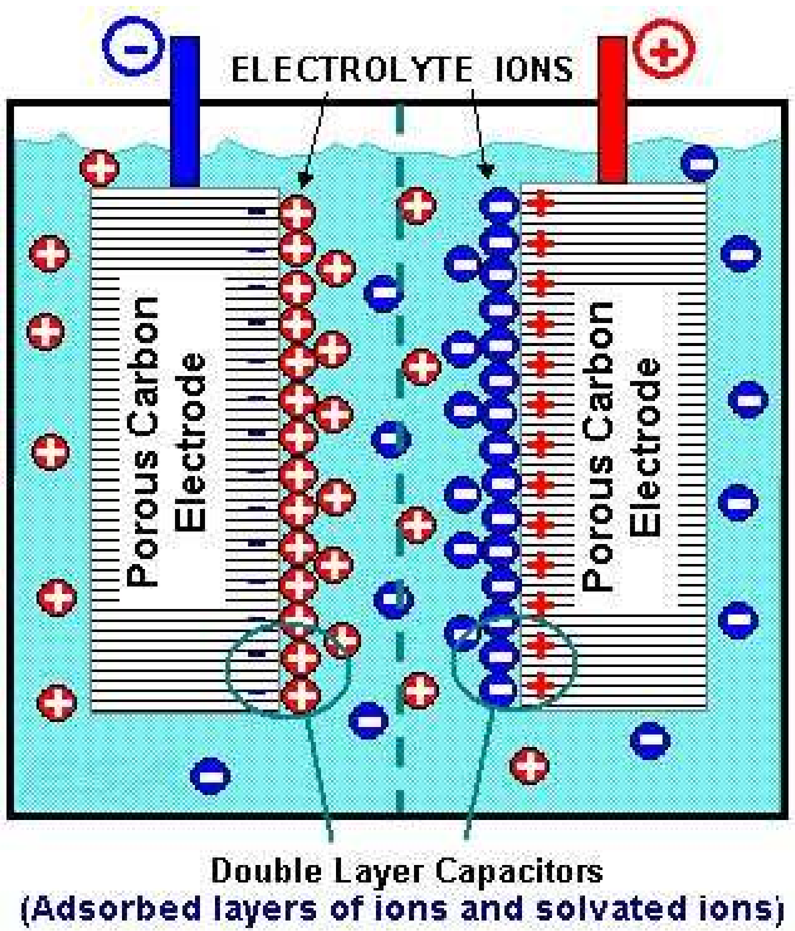
**Strong electric field**

**＞10MV/cm**

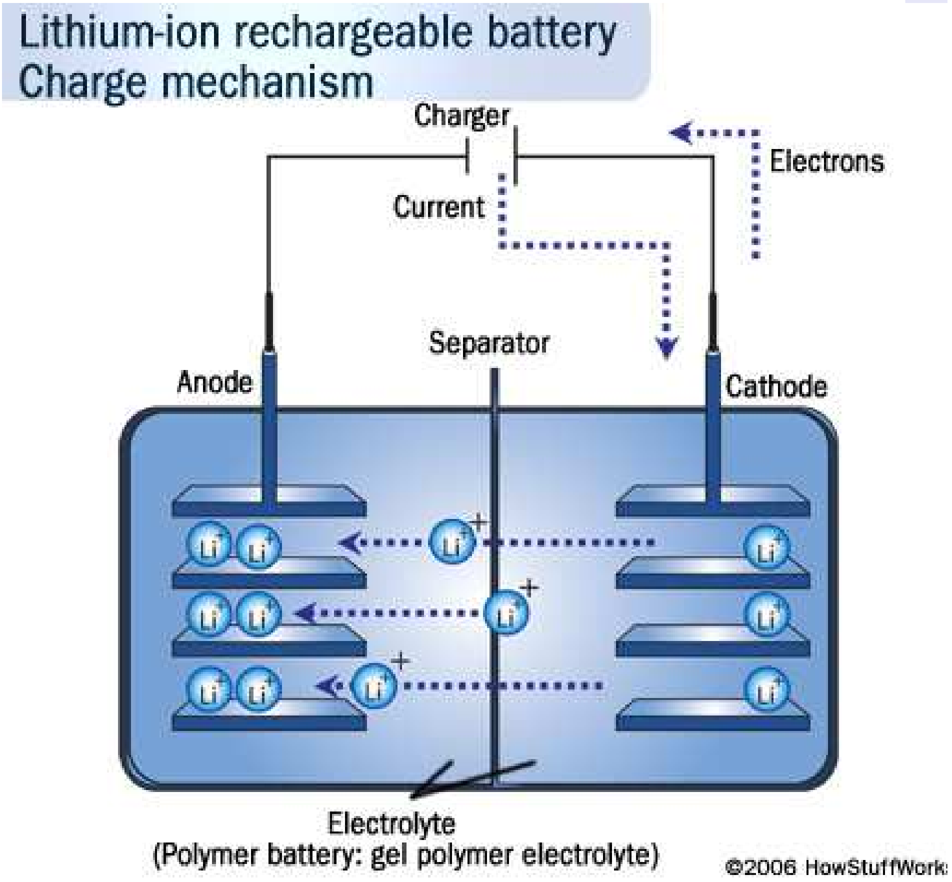
**＞ 5 x $10^{14}$ cm$^{-2}$**

# Charge accumulation devices

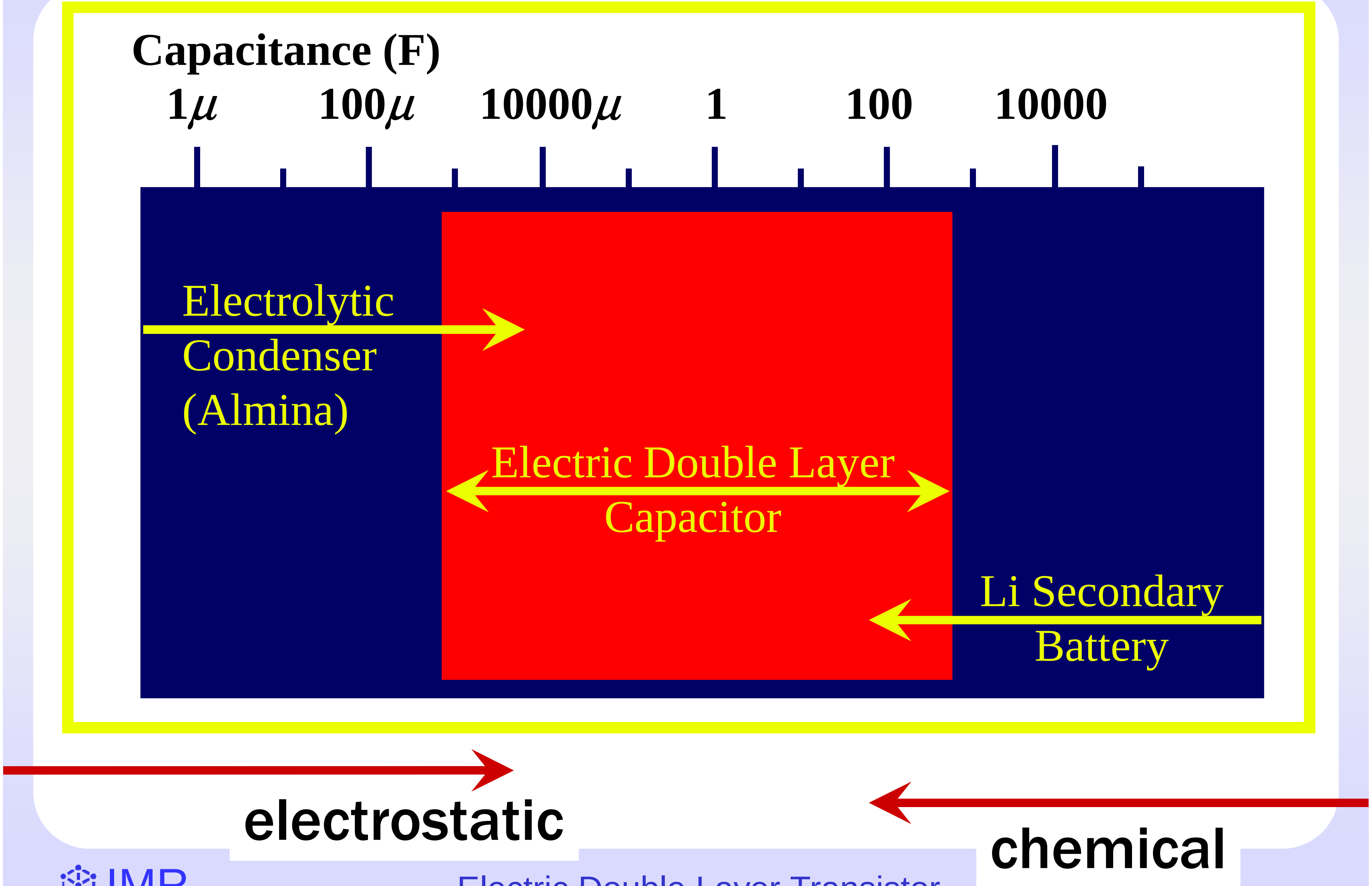
Electric Double Layer Capacitor




Lithium Ion Secondary Battery

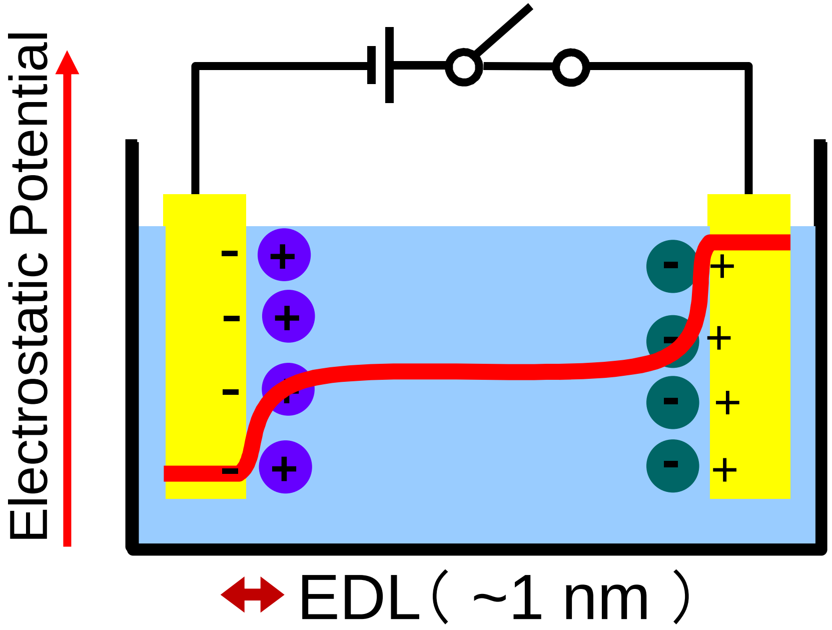


# Charge Accumulation Devices

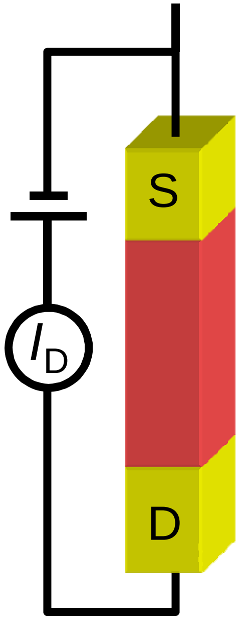


# Electric Double Layer (EDL)

## Electric Double Layer Capacitor (EDLC)




Replace one of the electrodes by



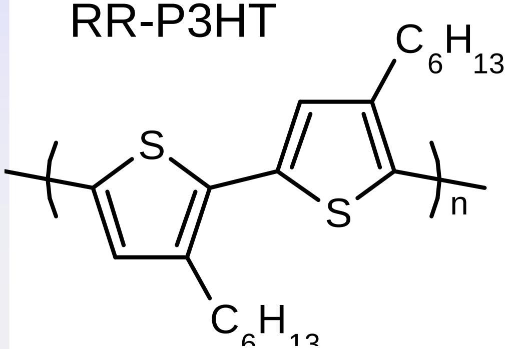

EDLC on market (Japan Chemicon Inc.)

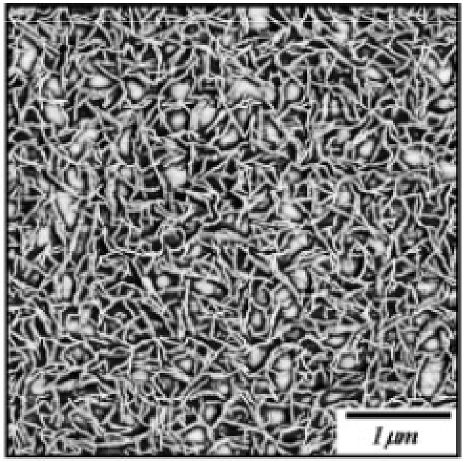
EDL-transistor (EDLT)

{ large capacitance
large charge density }

# Application of EDLTs to organic transistors with low voltage operation

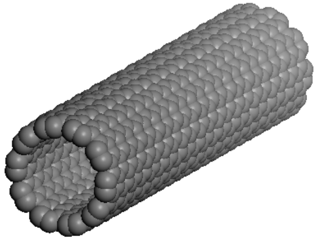
polythiophene
RR-P3HT

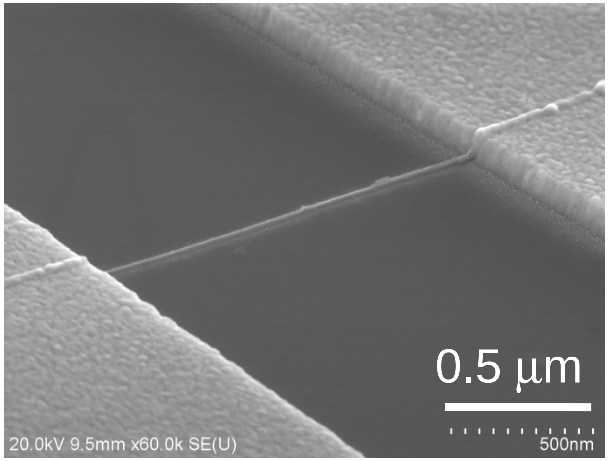



H. Shimotani *et al.*,
*APL* (2005)

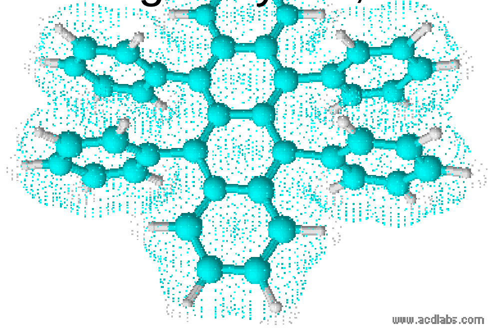
Single walled carbon nanotubes
SWNT

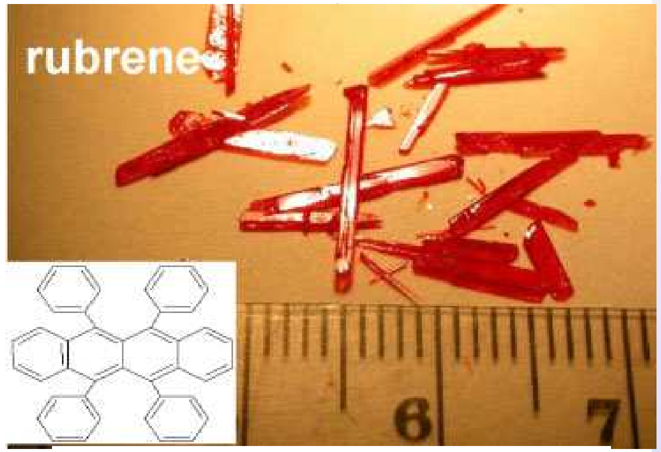





H. Shimotani *et al.*,
*APL* (2006)

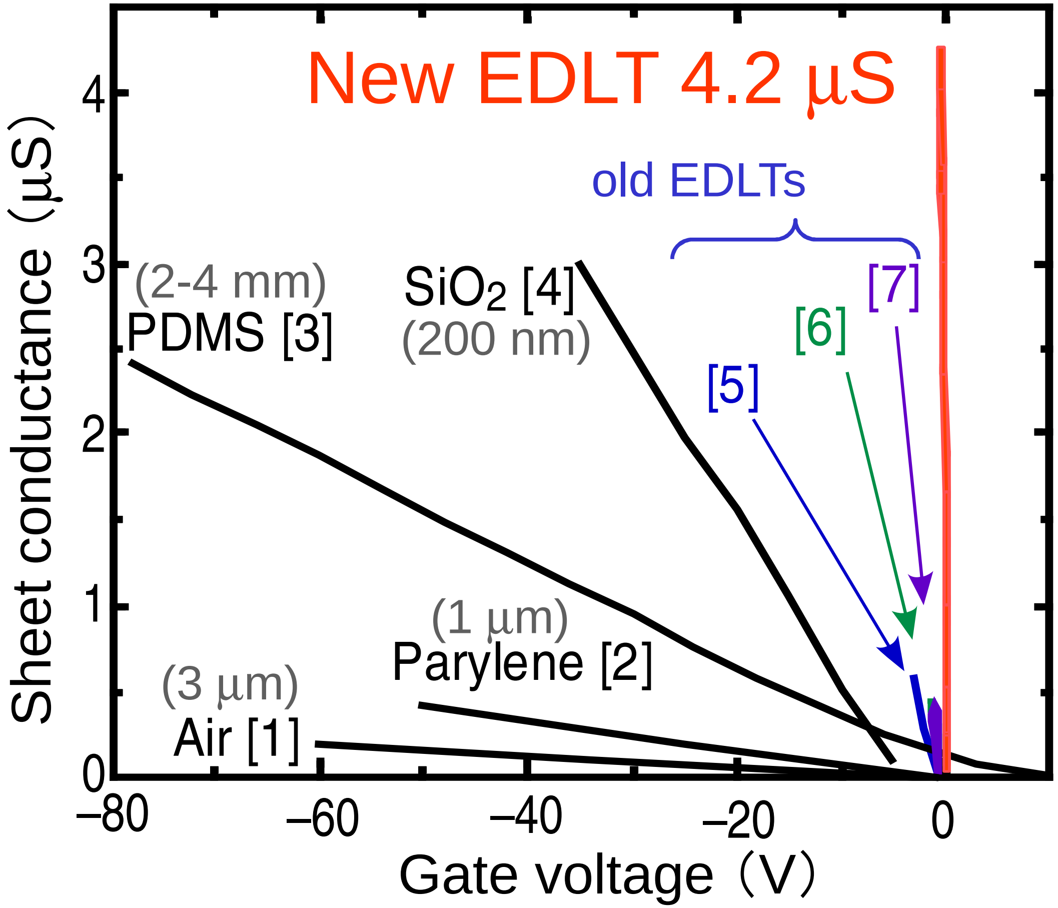
Organic semiconductor
Single crystal, Rubrene

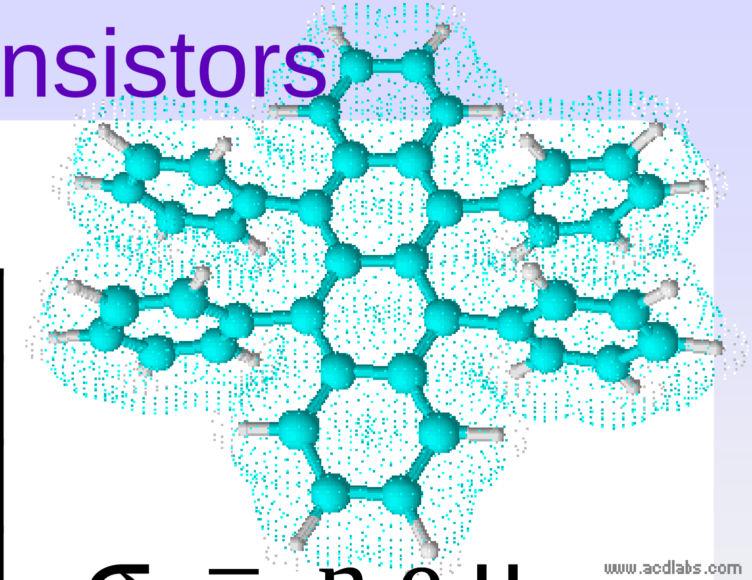



H. Shimotani *et al.*,
*APL* (2006),*JJAP* (2007)

# Rubrene single crystal transistors
## : solid gate vs. liquid gate




$$\sigma = n e \mu$$


[1] Menard *et al.*, Adv. Mat. (2004)
[2] Podzorov *et al.*, APL (2003)
[3] Sundar *et al.*, Science (2004)
[4] Stassen *et al.*, APL (2004)
[5] Panzer *et al.*, APL (2006)
[6] Takeya *et al.*, APL (2006)
[7] Shimotani *et al.*, APL (2006)


- Low voltage operation and highest conductance

H. Shimotani et al. JJAP 46 3613 (2007)

# EDLT for sensor applications (since 1980s)

## Application of EDLTs to high density charge accumulation and electric-field induced superconductivity

| | |
|---|---|
| Polymer | H. Shimotani *et al.*, *APL* 86, 022104 (2005) |
| Nanotube | H. Shimotani *et al. APL* 88, 073104 (2006) |
| Rubrene Xtal | H. Shimotani *et al.*, *APL* 89, 203501 (2006) |
| Rubrene Xtal | H. Shimotani *et al.*, *JJAP* 46, 3613 (2007) |
| ZnO Xtal | H. Shimotani et al. *APL* 91, 082106 (2007) |
| NiO Xtal | H. Shimotani et al. *APL* 92, 242107 (2008) |
| $SrTiO_3$ Xtal | K. Ueno et al., *Nat. Mater*. 7, 855 (2008) |
| Ionic Liquid | H. T. Yuan et al., *Adv. Funct. Mater.* ONLINE (2009) |

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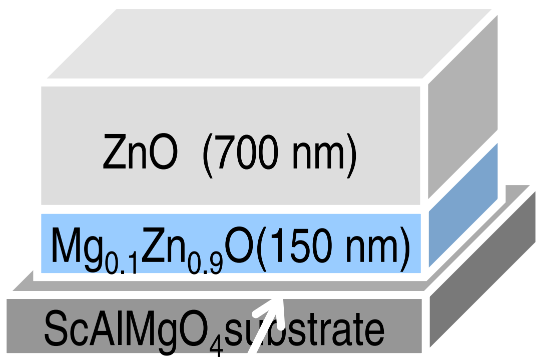
# Device fabrication

## ■ ZnO single crystalline thin film

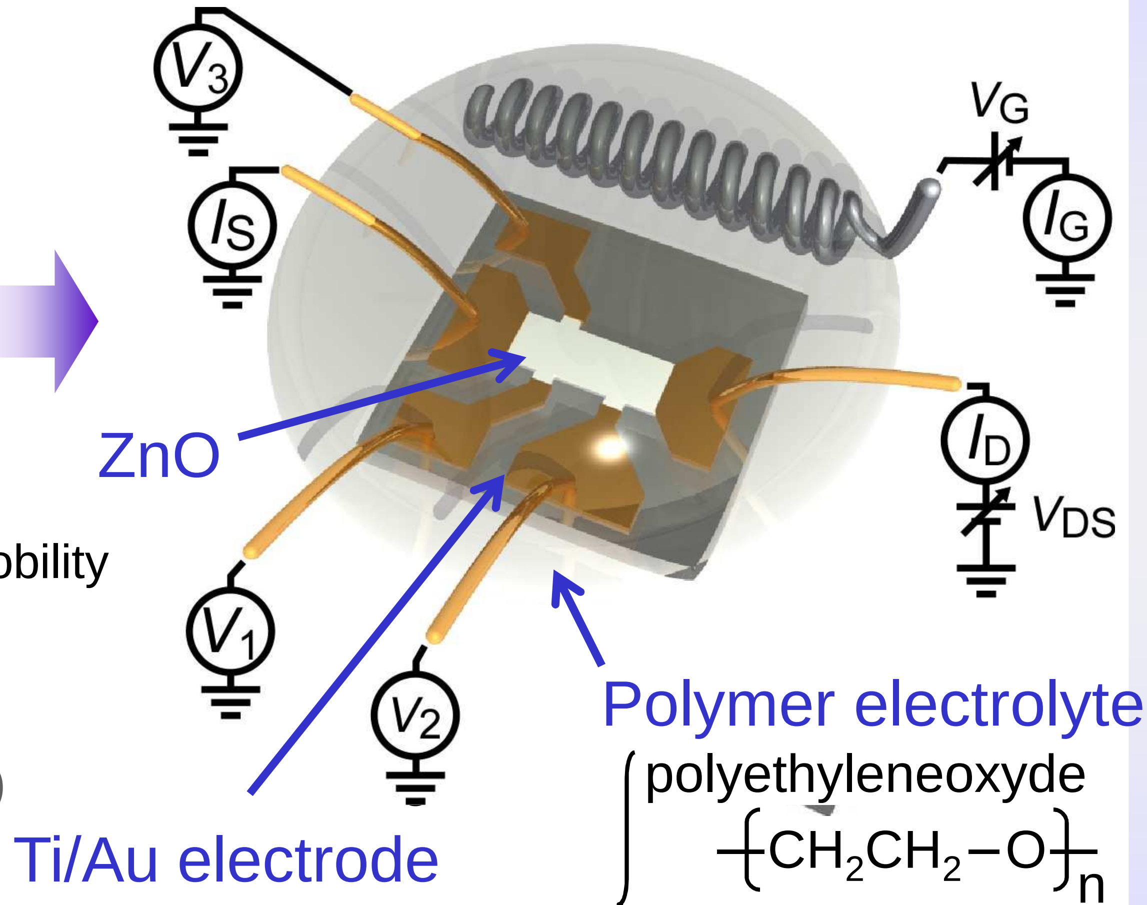



Low carrier density and high mobility

$$\begin{pmatrix} \mu = 100\ \mathrm{cm^2V^{-1}s^{-1}} \\ n = 7.7 \times 10^{15}\ \mathrm{cm^{-3}} \end{pmatrix}$$

Tsukazaki et al., APL 88, 152106 (2006)

## ■ EDL-FET



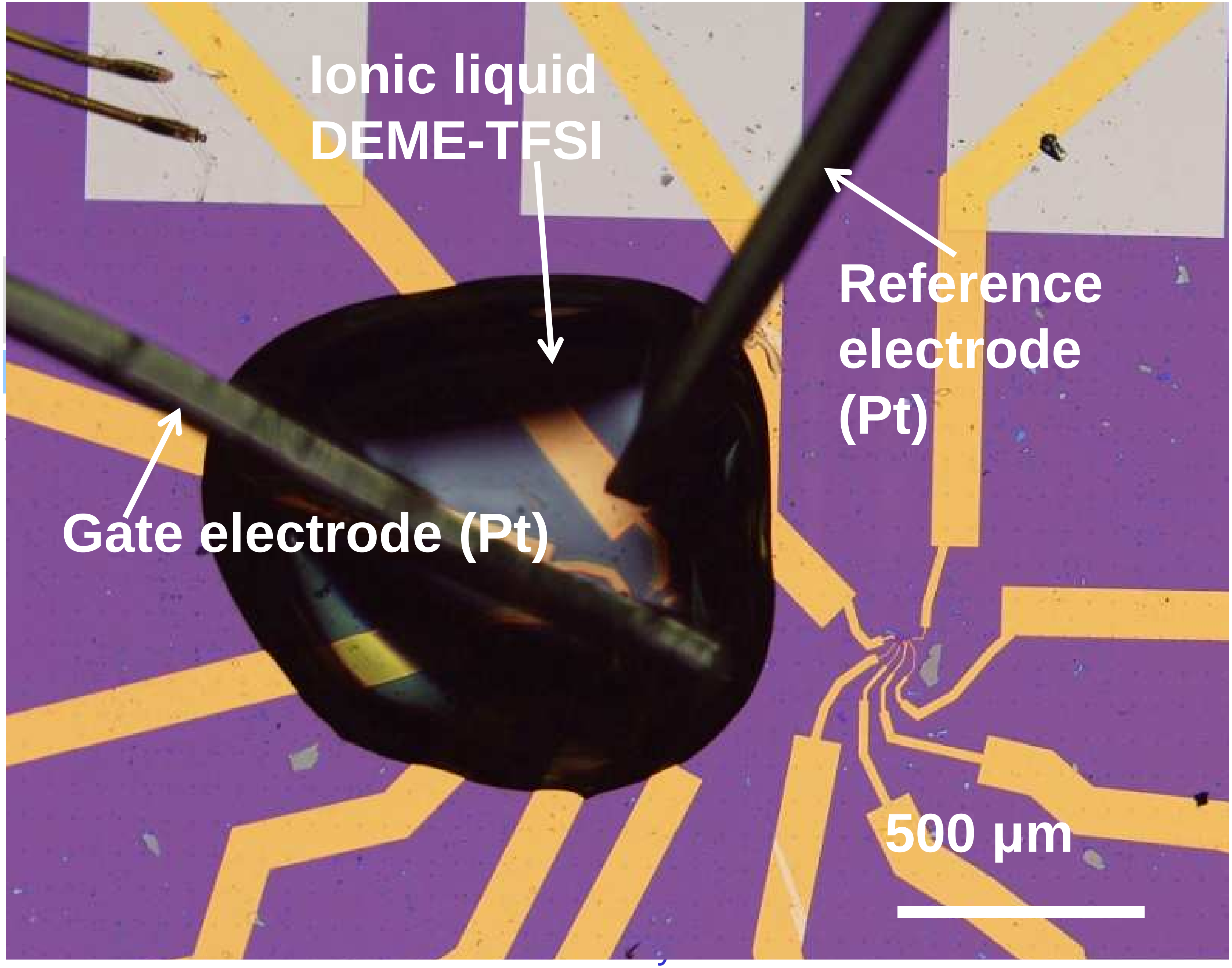

- polyethyleneoxyde
  $-\!\left[CH_2CH_2-O\right]\!-_n$
- $KClO_4$
  ([O]/[K] = 20/1)



Electric Double Layer Transistor

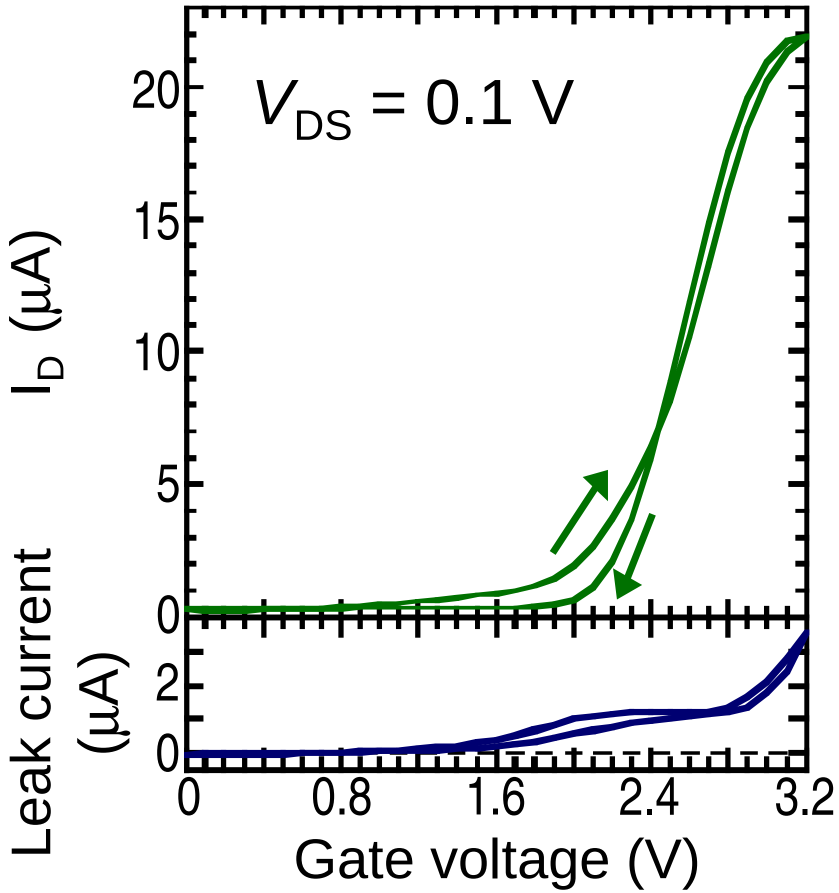
# Device fabrication

# Device fabrication

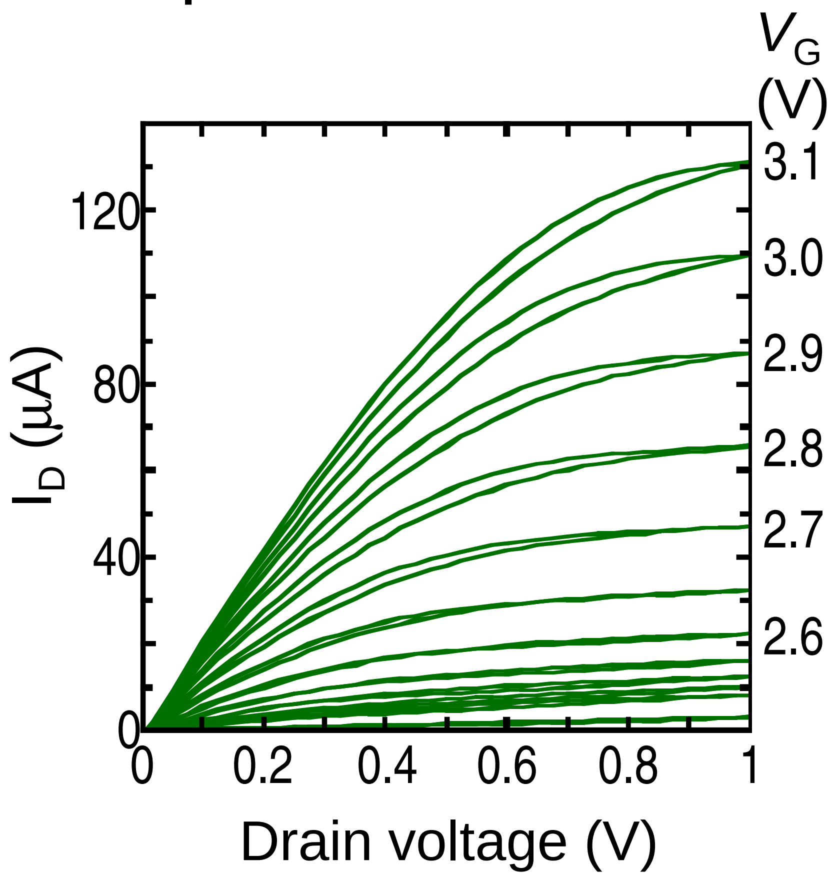


# Characteristics of ZnO-EDLT

- Transfer curve

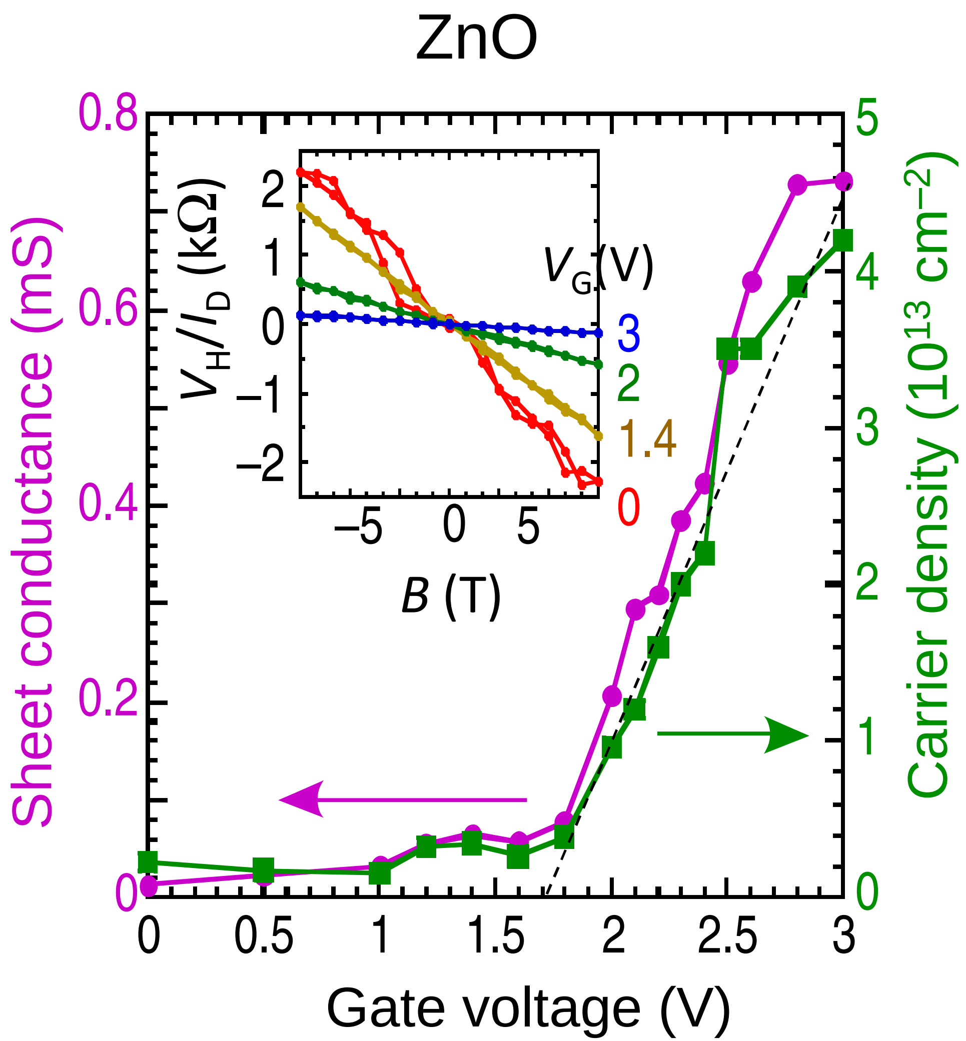



- Output curve




n-type operation

# Direct measurement of carrier density (Hall effect )



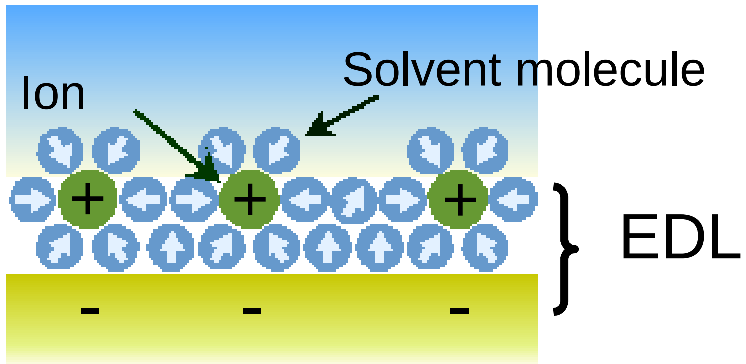

$$ne = Q = CV$$

C ~ 7.8 μF/cm$^2$

(cf. 15 μF/cm$^2$ on Au)

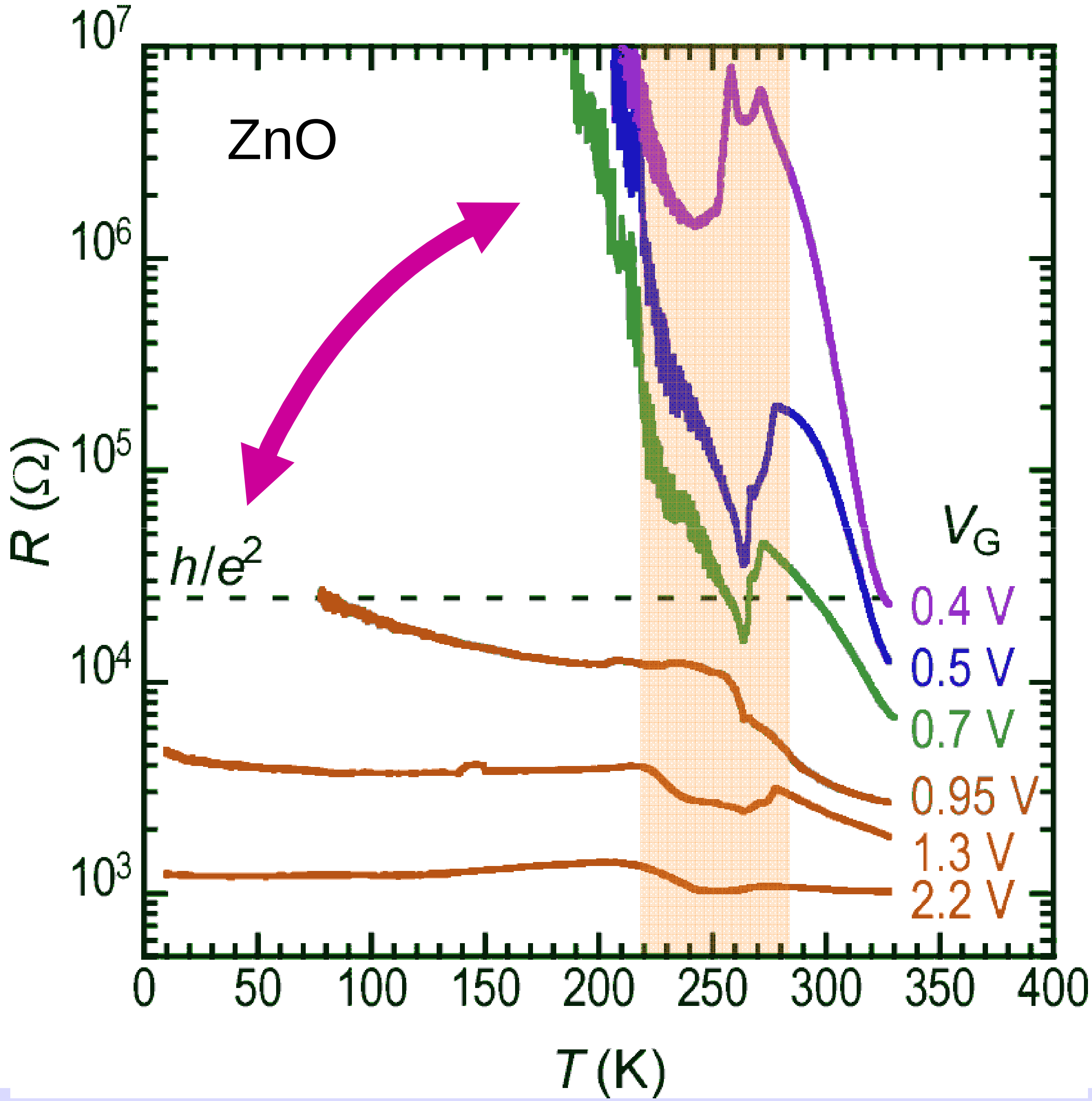
(ε = 10 $\varepsilon_0$ for PEO solvent)

thickness of EDL ~ 1 nm



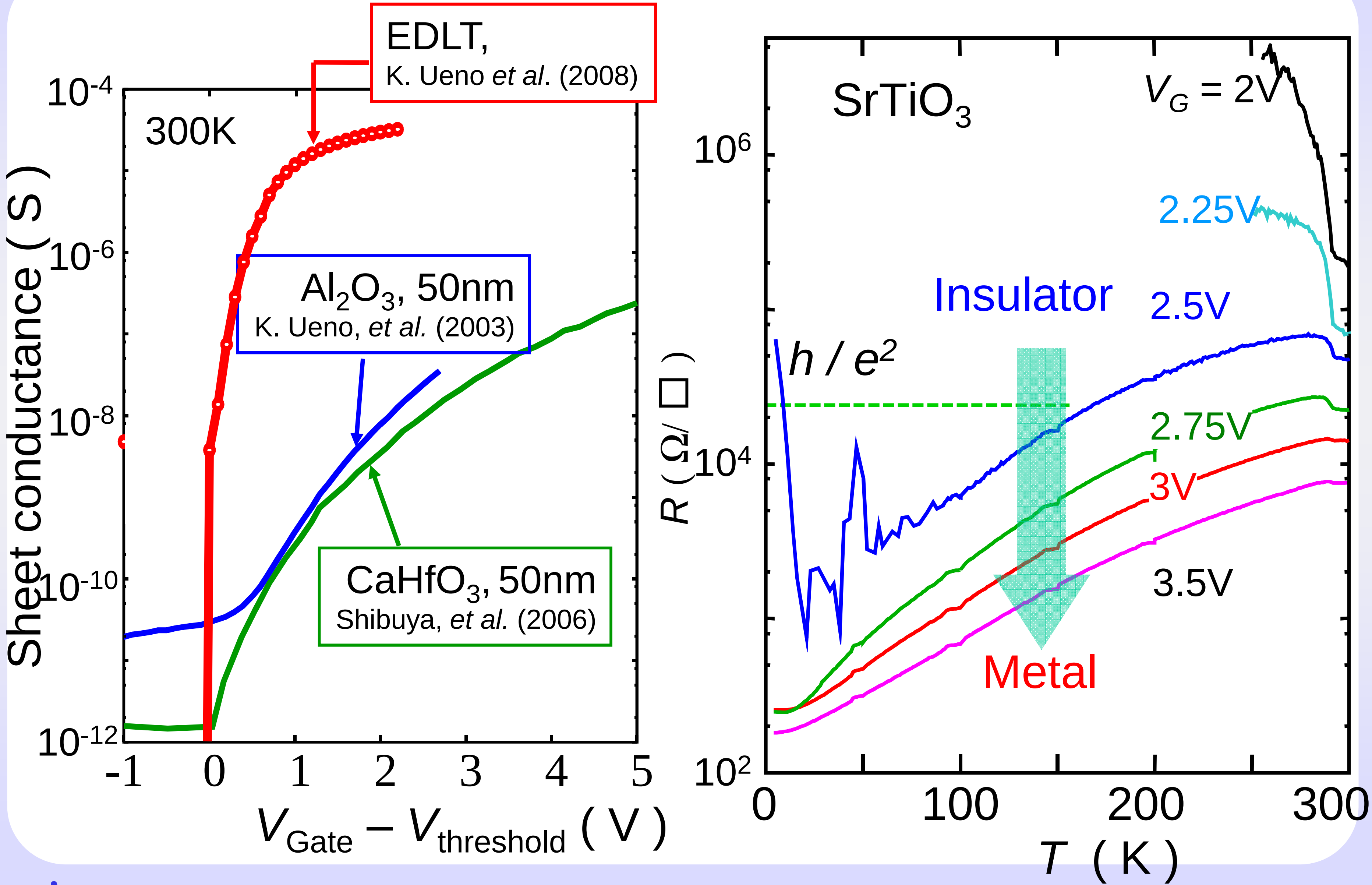

H. Shimotani et al. *APL* 91, 082106 (2007)

# Gate-induced Insulator-metal transition in ZnO

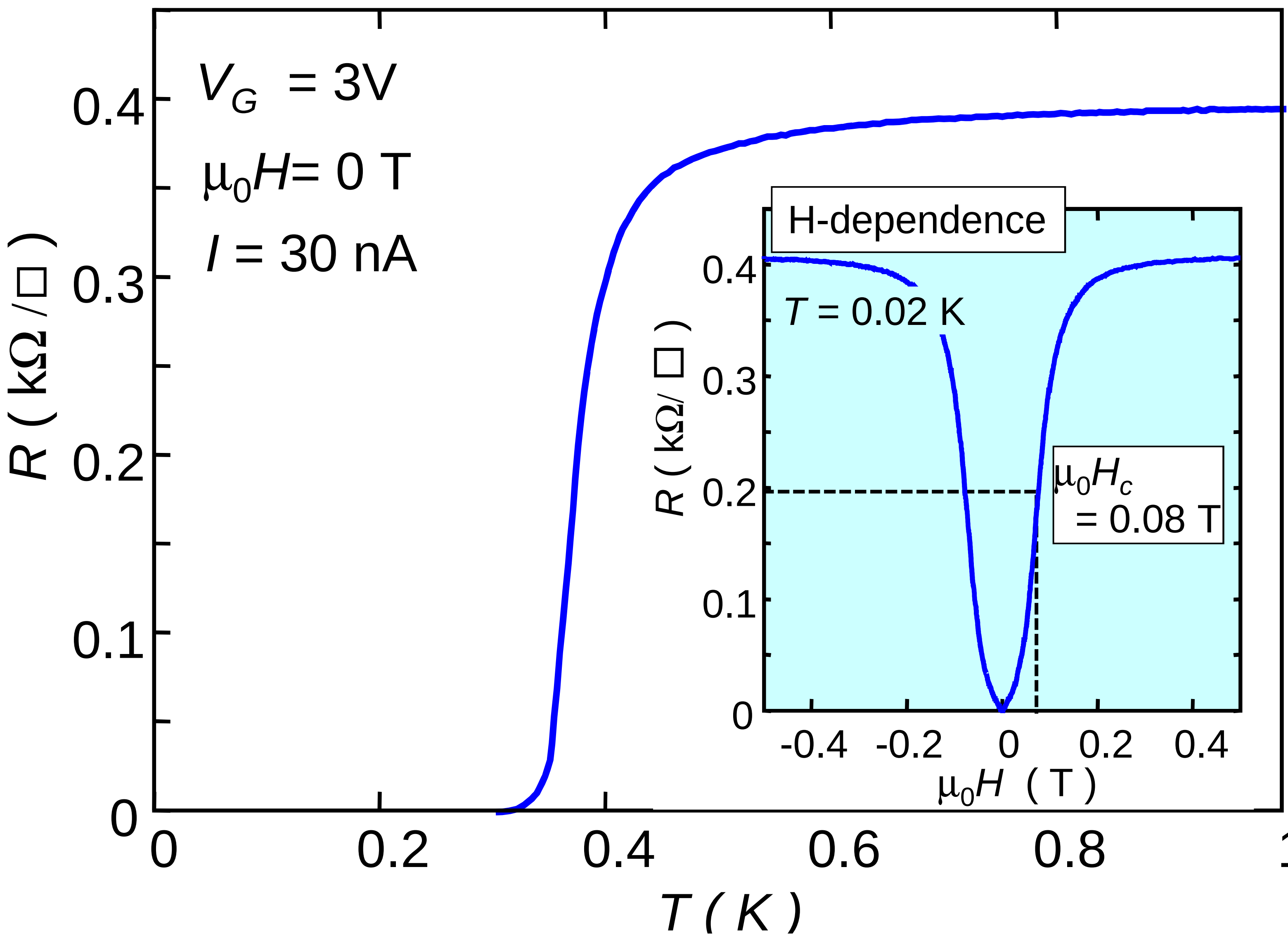



H. Shimotani et al.
Appl. Phys. Lett.
**91**, 082106 (2007)

# $SrTiO_3$ / PEO($KClO_4$)-EDLT

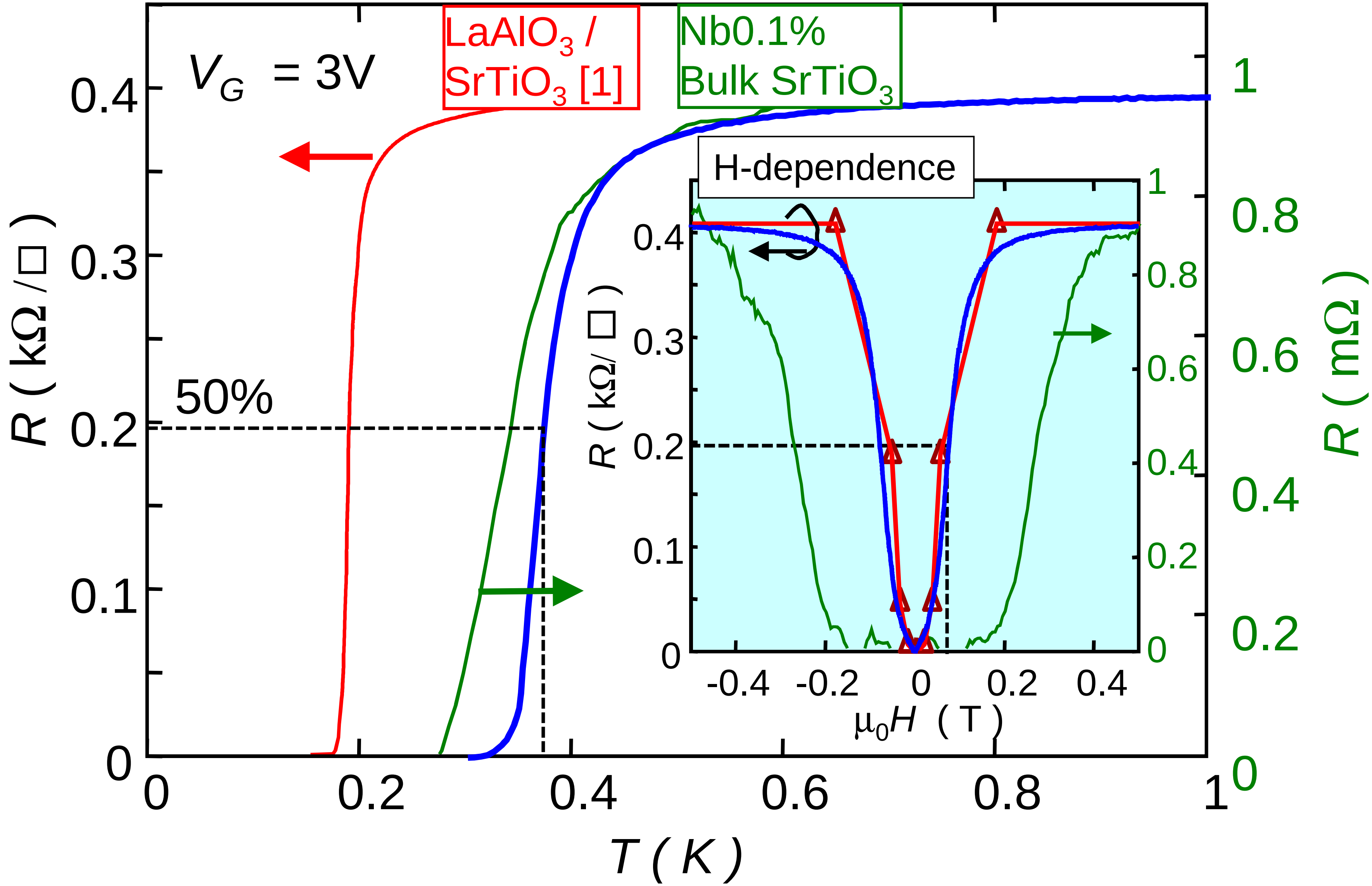


# Electric field-induced superconductivity in $SrTiO_3$




K. Ueno et al., Nat. Mater. 7, 855 (2008)

# Comparison with other systems




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

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# Go beyond $SrTiO_3$

**Uniqueness of $SrTiO_3$**

1. Nb:$SrTiO_3$,$SrTiO_{3-\delta}$
   The lowest carrier density superconductor

2. Established know-how to make atomically-flat surfaces (Kawasaki, 1994)

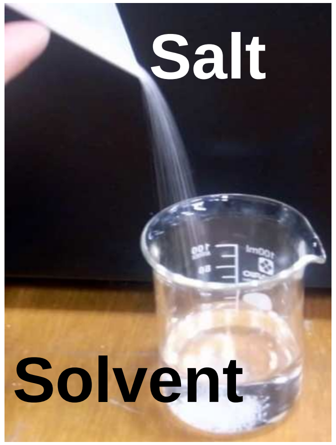
3. $SrTiO_3$-FET with solid gate was already fabricated (Ueno, Takagi, Kawasaki, Tokura, 2003)

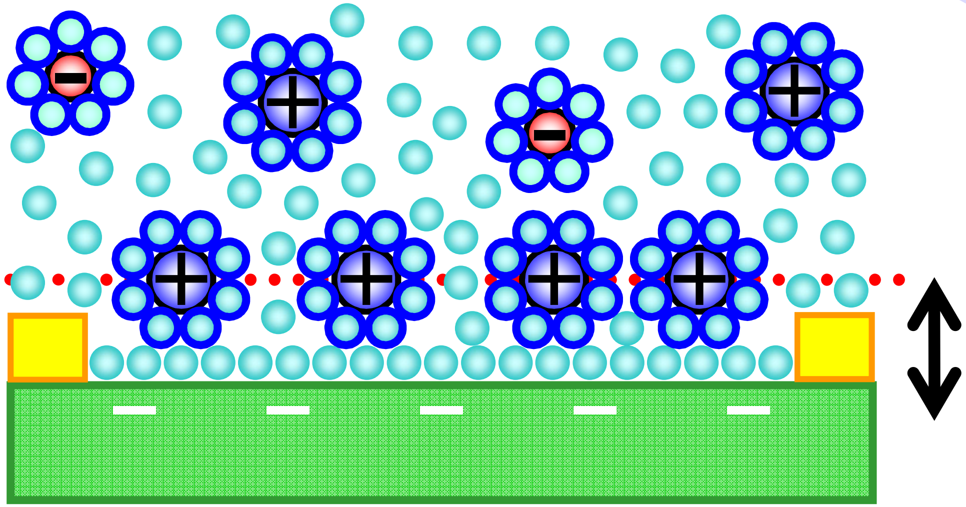
4. $SrTiO_3$ is a quantum paraelectric.

# Ionic Liquids

## Polymer Electrolyte

**Solvent + Salt**

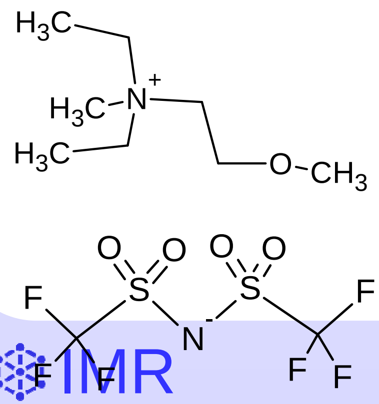


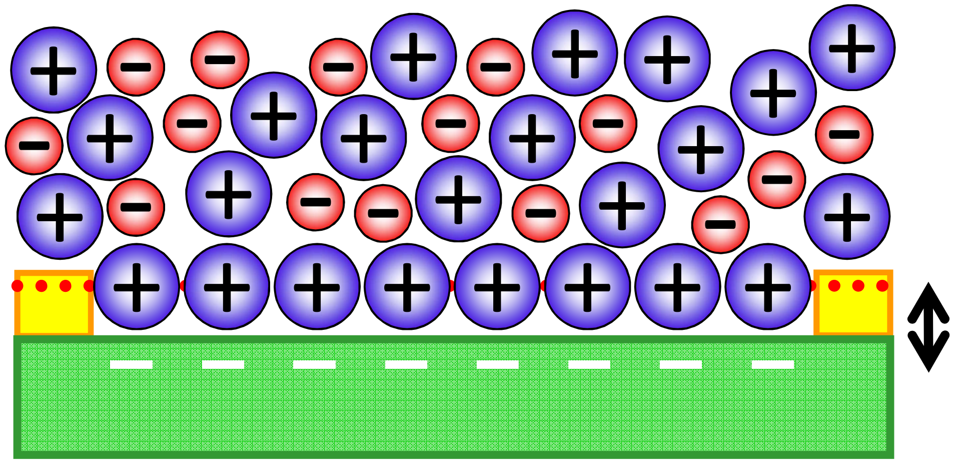



**d ~ size of solvent molecule**

## Ionic Liquid

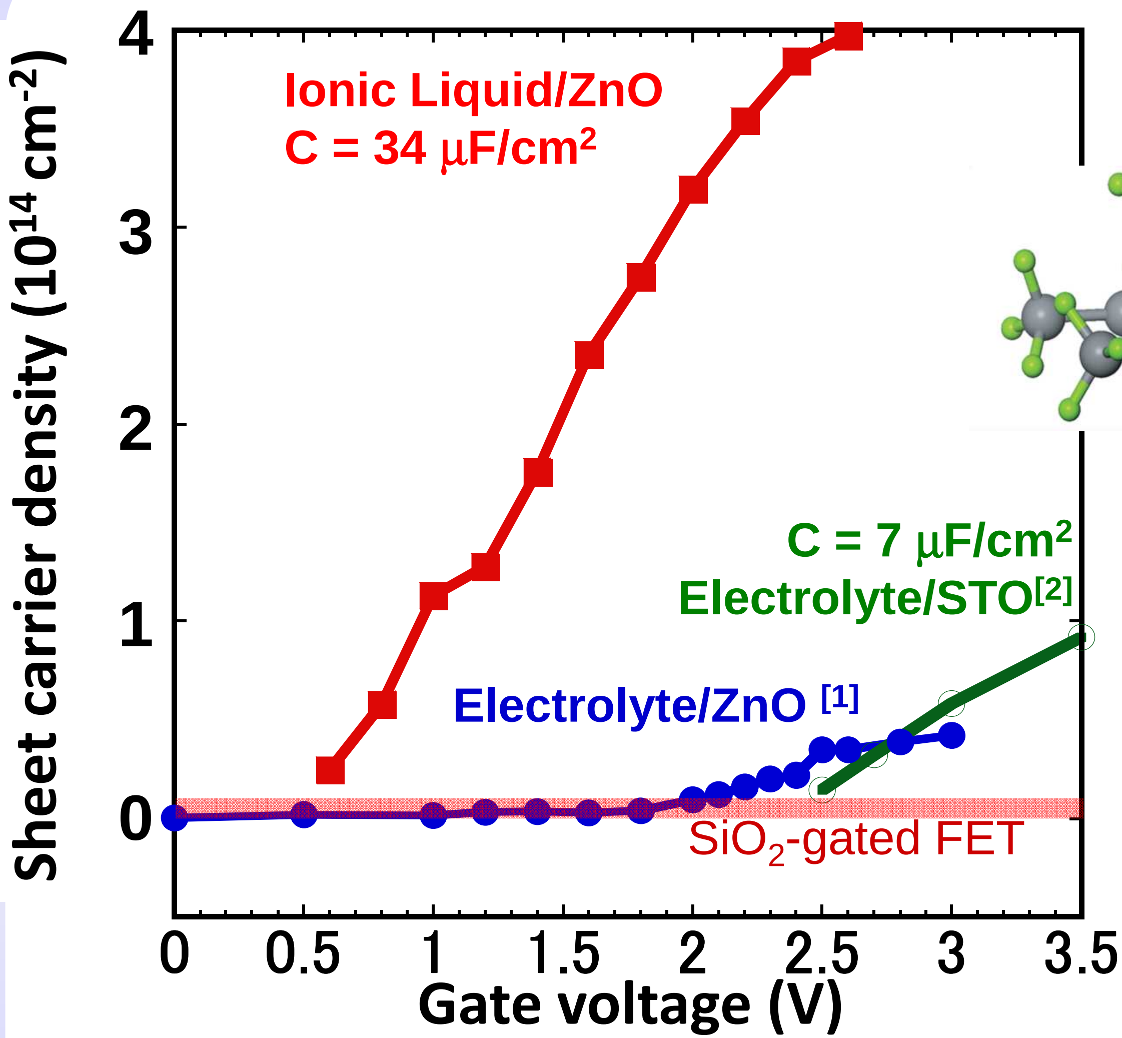
**Melt at RT**



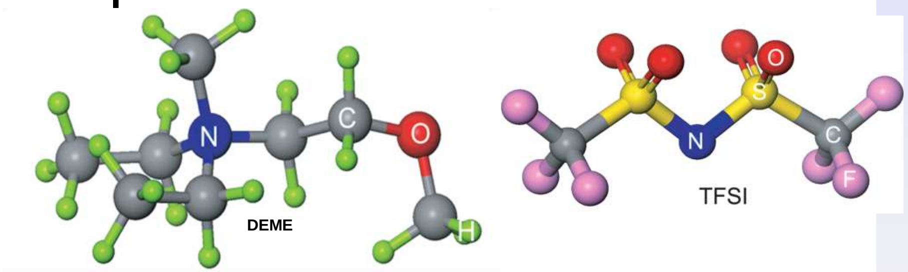


**d ~ size of cation molecule smaller than electrolyte**

# Ionic liquid vs. Electrolyte for ZnO




**Ionic liquid**: ***DEME-TFSI***

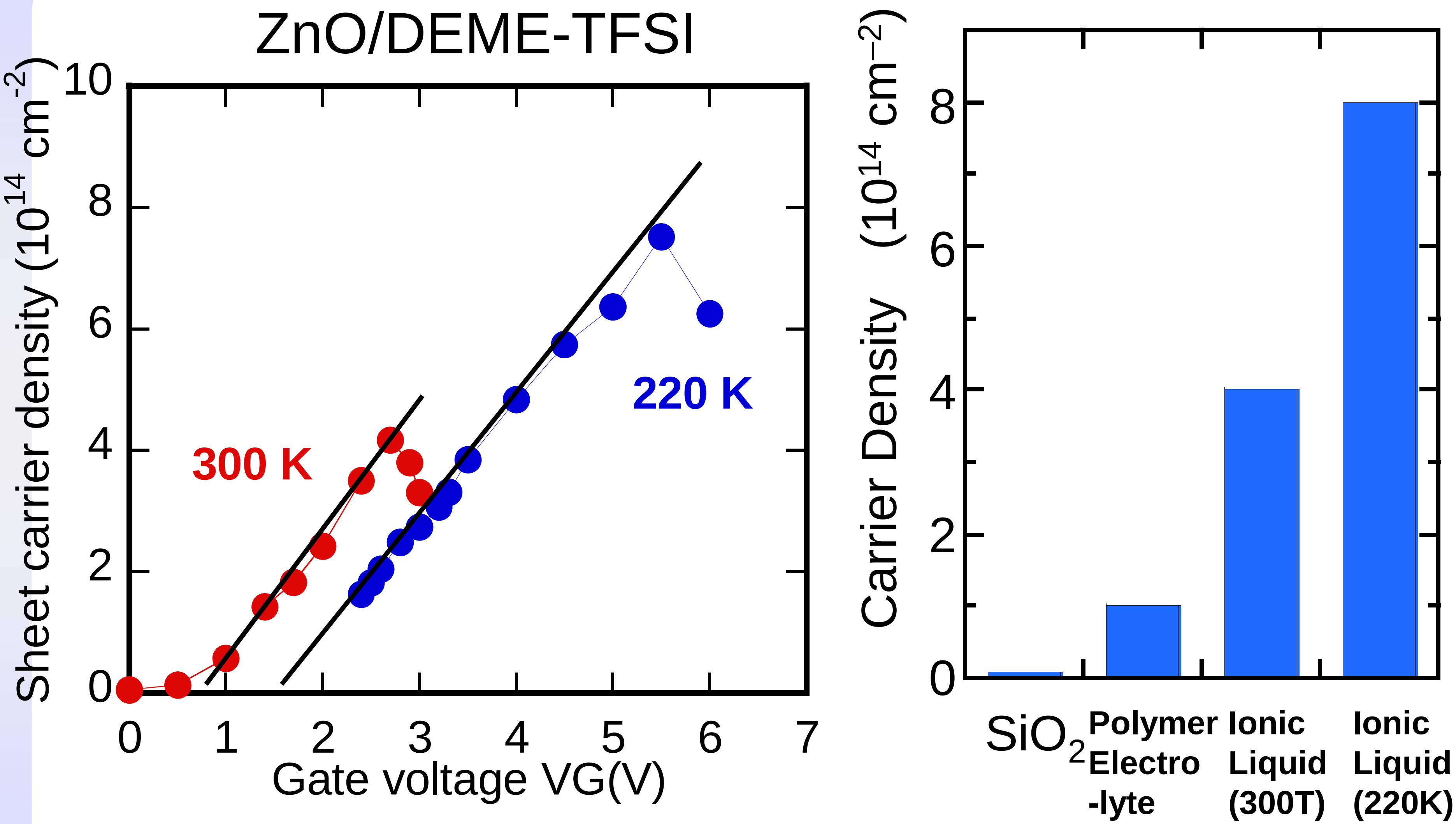



H. T. Yuan *et al*., *Adv. Funct. Mater.* 19, 1046 (2009)

[1] H. Shimotani *et.al., APL.* ***91***,082106 (2007)

[2] K. Ueno *et al*., *Nat. Mater.* **7**, 855 (2008)

# Enhanced Electrostatic Charging at Low T




$4 \times 10^{14}$ cm$^{-2}$ ≥ $n_{2D}$ required for superconductivity
in cuprates, fullerides, organics, ･･･

IMR

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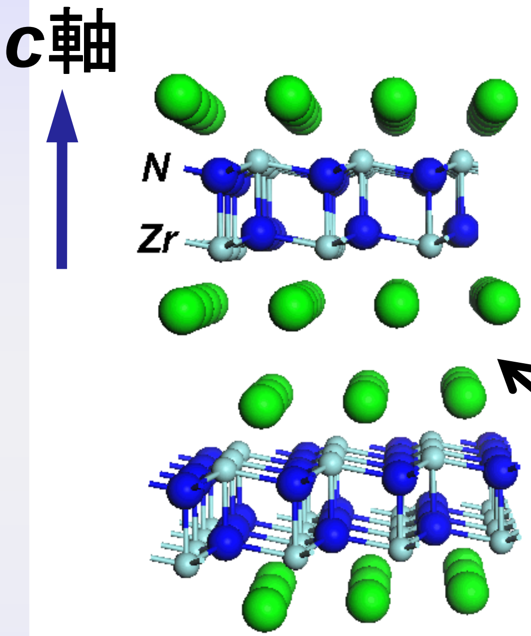
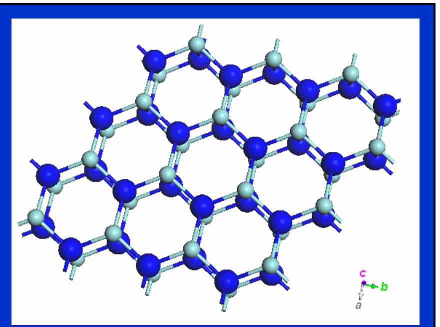
# Electron doped β-ZrNCl (Yamanaka et al. (1996, 1998))

## β-ZrNCl

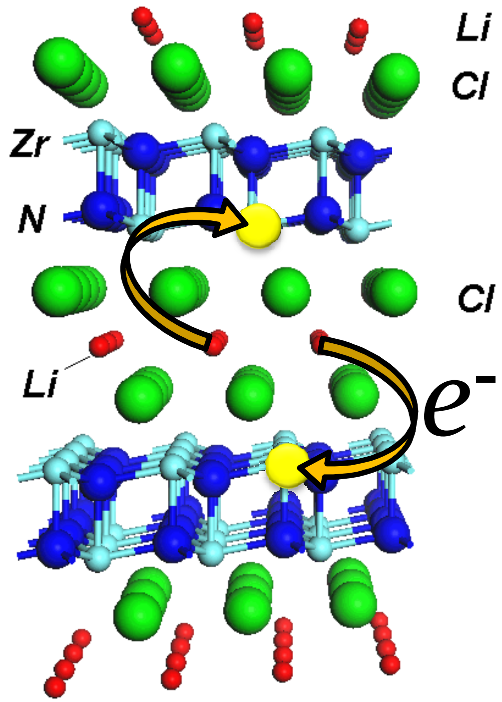


Double honeycomb lattice of Zr & N

Van der Waals gap

## $Li_xZrNCl$




$4d^0$

Intercalation of Alkali metals

Electron doping in Zr–N layer

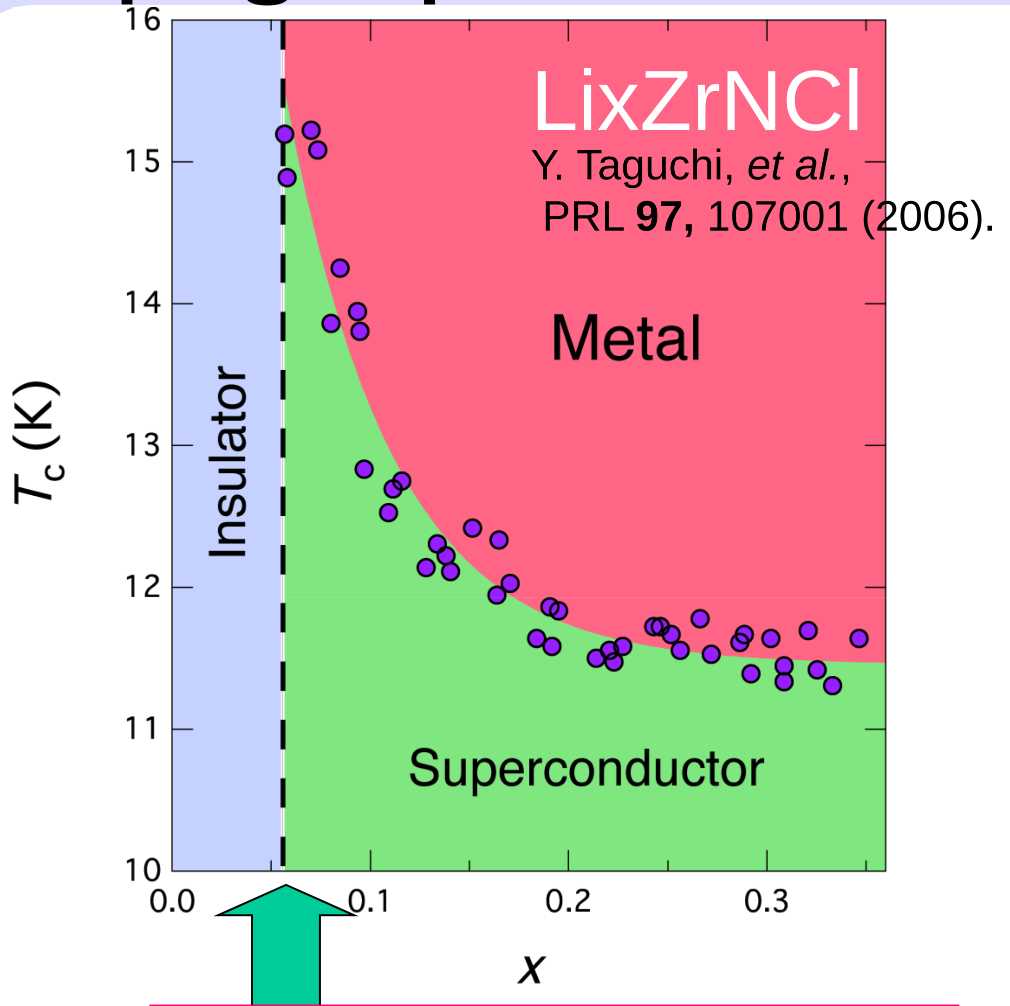
$4d^{x}$

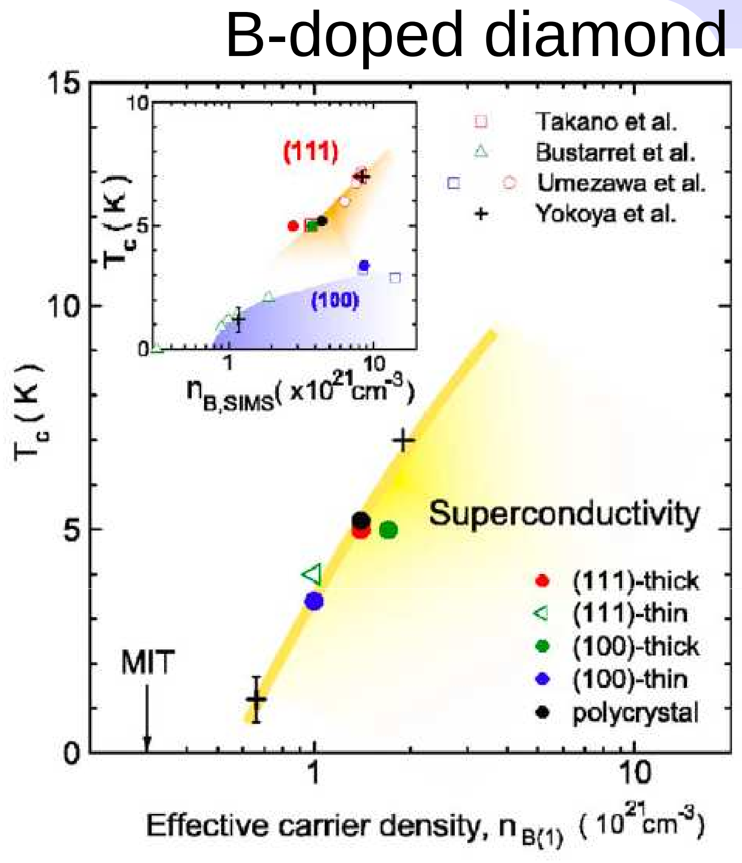
**Band Insulator**

**Superconductor**

**Zr; 15K, Hf; 25K**

# Doping dependence of Tc

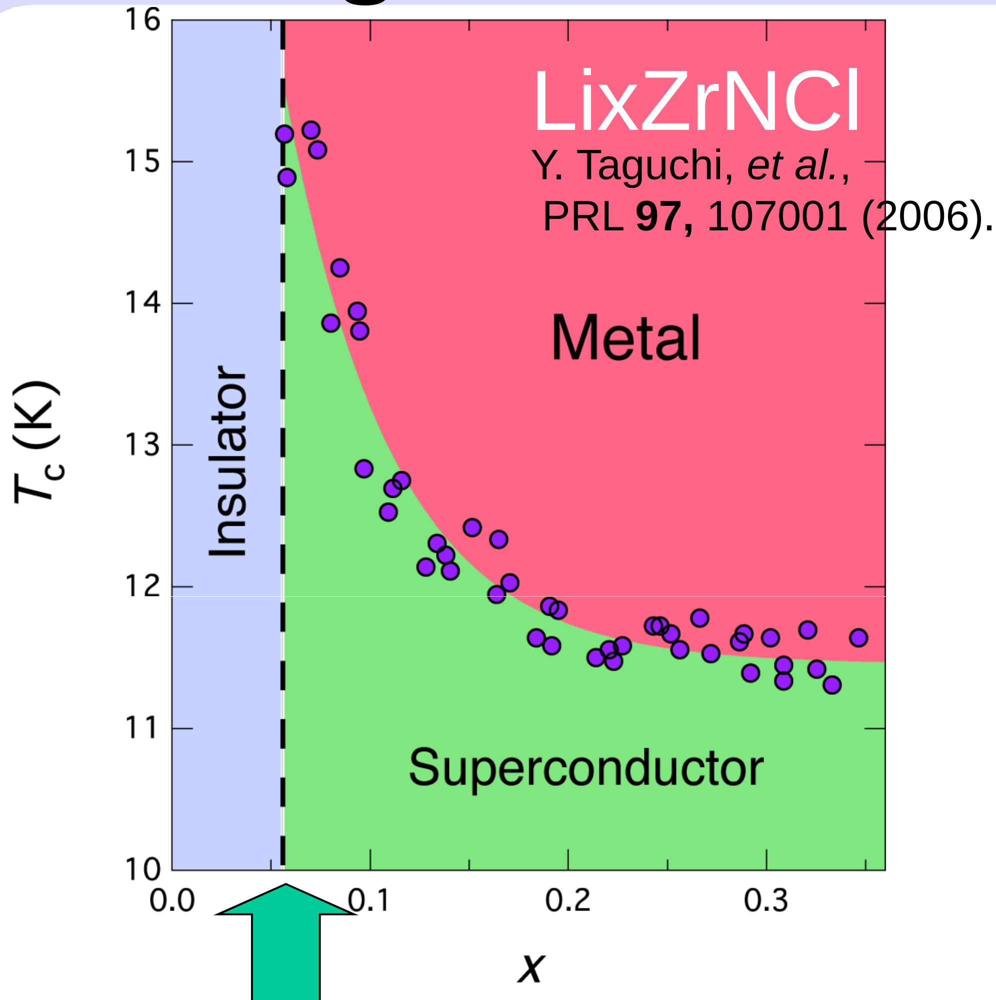


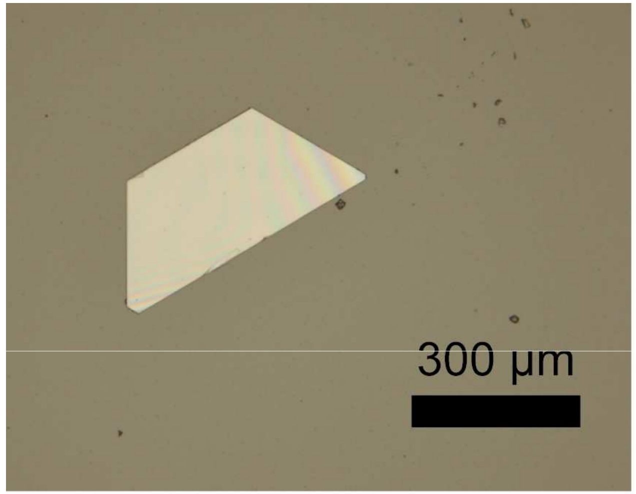




K. Mukuda *et al.*, PRB 75, 033301 (2007)

1. 0.8 x $10^{14}$ cm$^{-2}$/layer reachable with IL

# Advantage of ZrNCl for EDLT




1. 0.8 x $10^{14}$ $cm^{-2}$/layer reachable with IL
2. Cleavable; atomically flat surface available

# Characteristic features of superconductivity in $Li_xZrNCl$ : **Small γ**

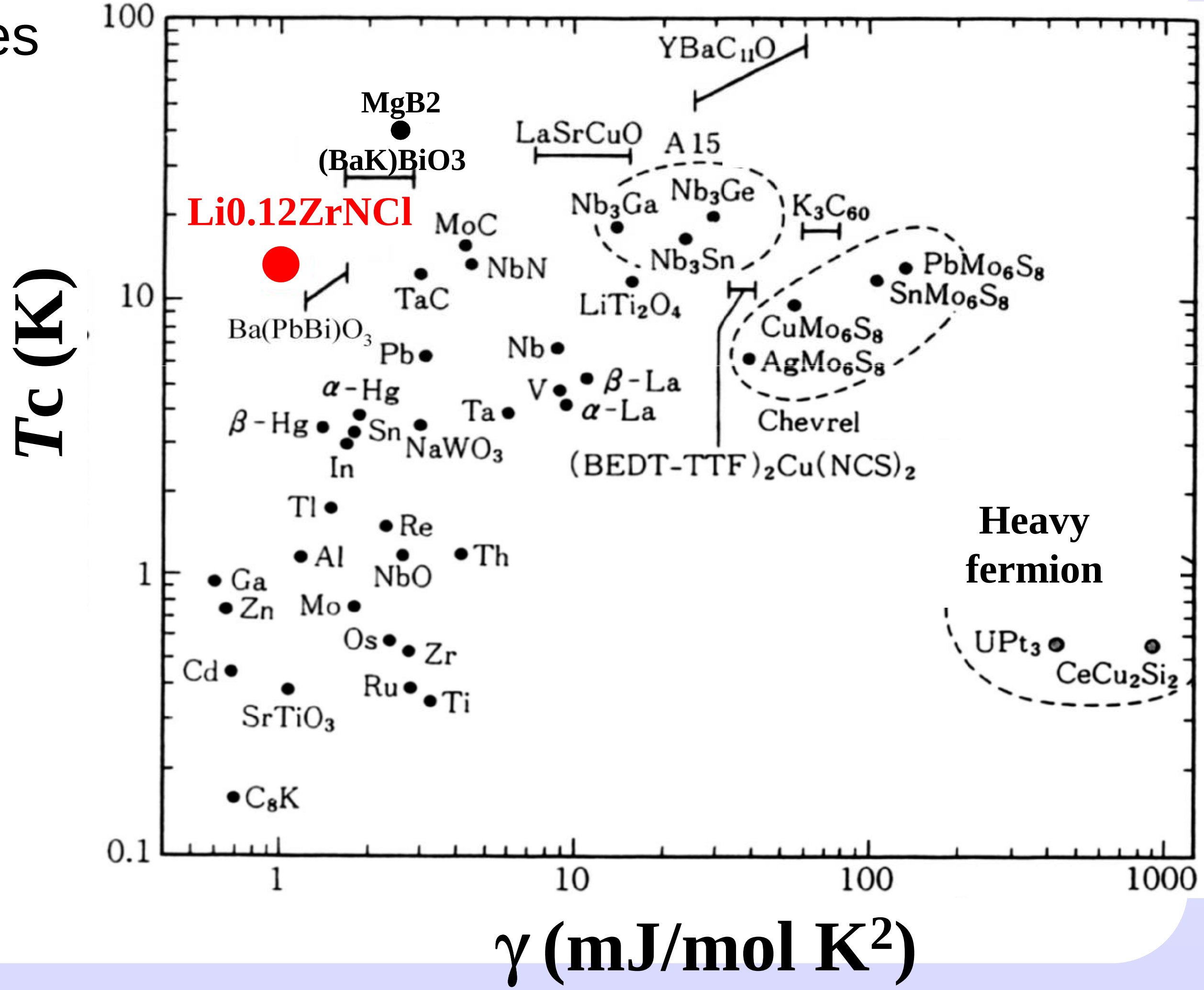
Y. Taguchi, *et al.*, PRL 94, 217002 (2005).

- Small density of states

  $\gamma_n$ = 1.1 mJ/mol K$^2$

  $$\gamma_n = \frac{2}{3}\pi^2 k_B^2 (1+\lambda) N(0)$$

- Very weak electron-phonon coupling
  - Raman scattering
  - Isotope effect



# Specific heat & magnetic susceptibility in Li doped ZrNCl

With reducing *x*,

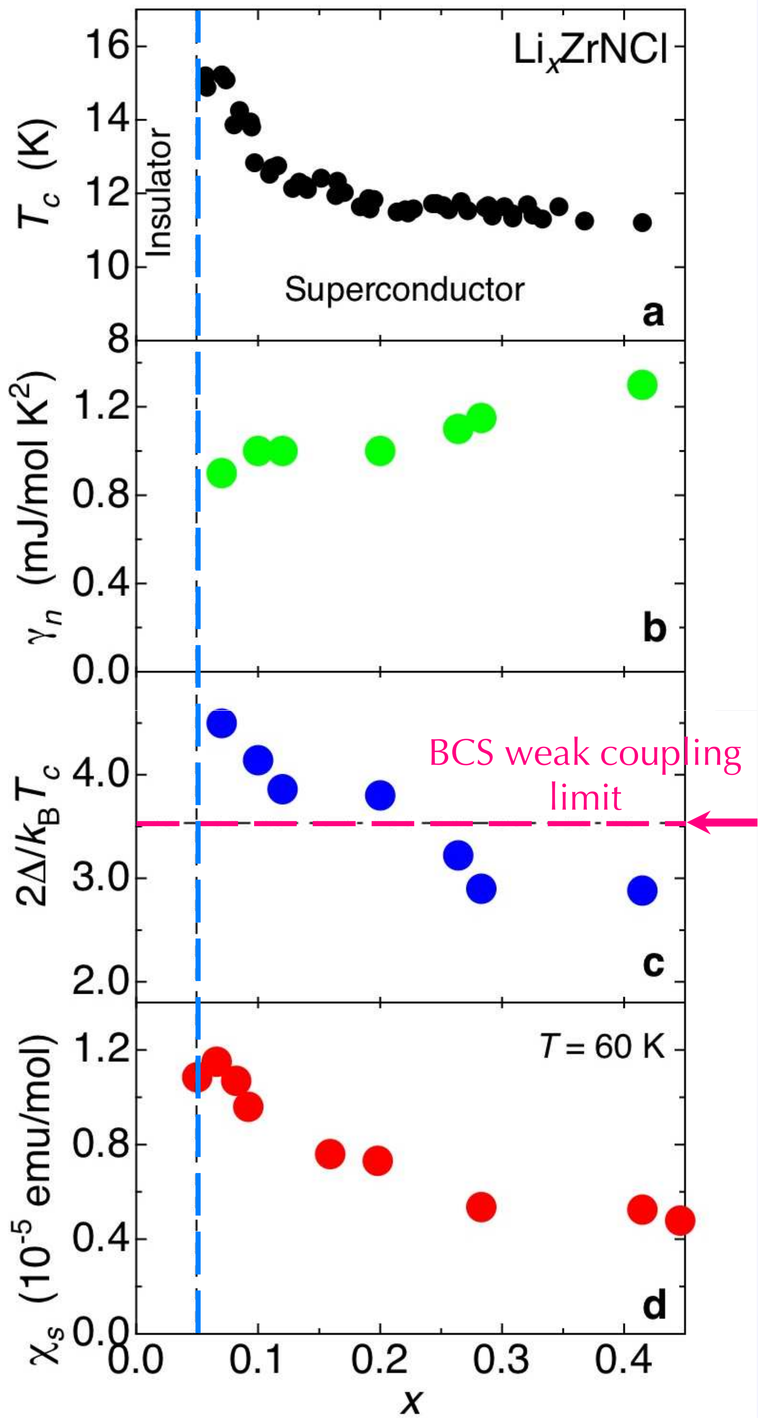
- $T_c$ **INCREASES**
- $\gamma_n$ : **Density of states DECREASES**
- $2\Delta/k_B T_c$ : **Pairing interaction INCREASES**

Enhancement of $T_c$ is due to pairing interaction not due to DOS.

- Spin susceptibility **INCREASES**

Magnetic fluctuations is enhanced toward the band insulator as *x* is reduced.

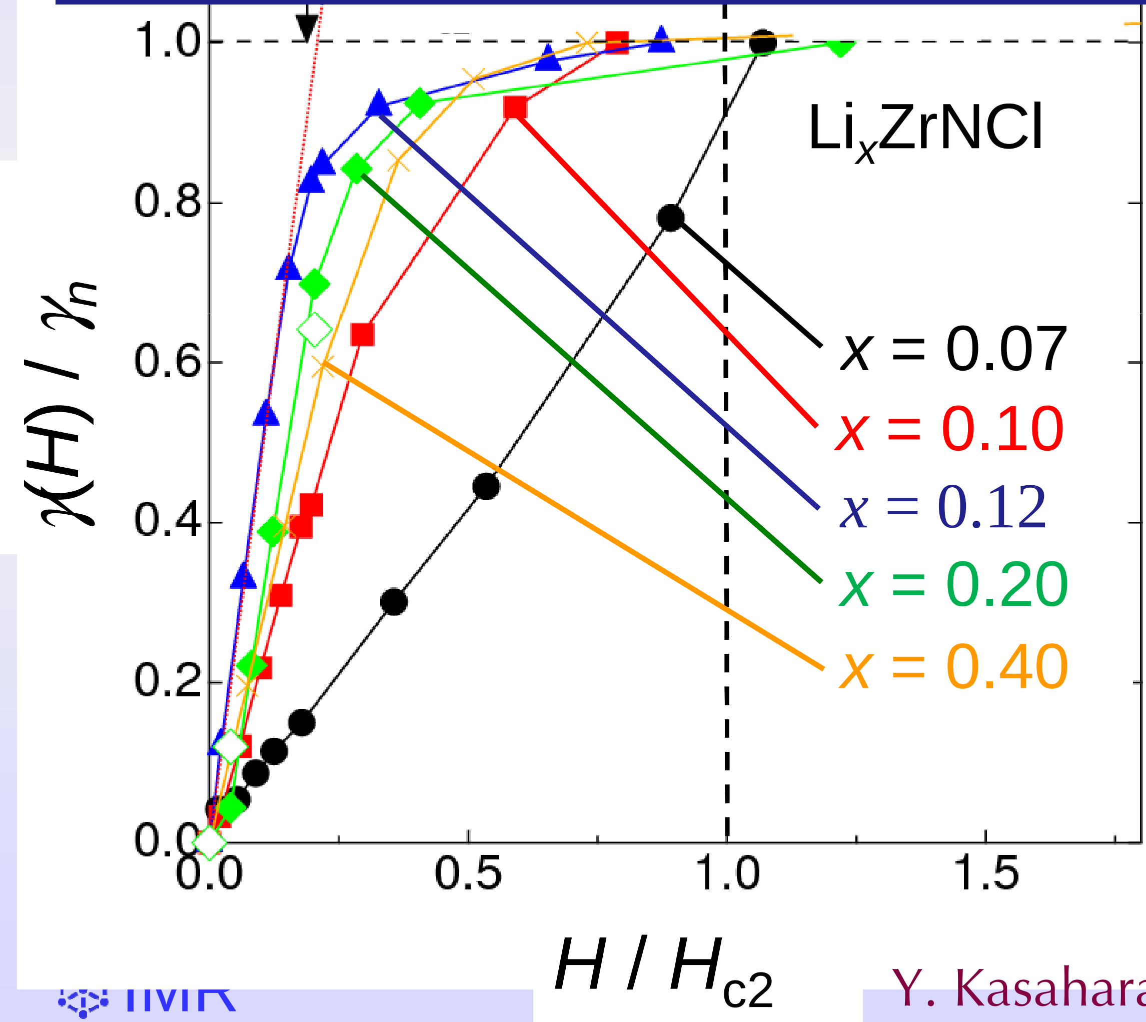
Y. Kasahara *et al.*, PRL**103**, 077004 (2009)



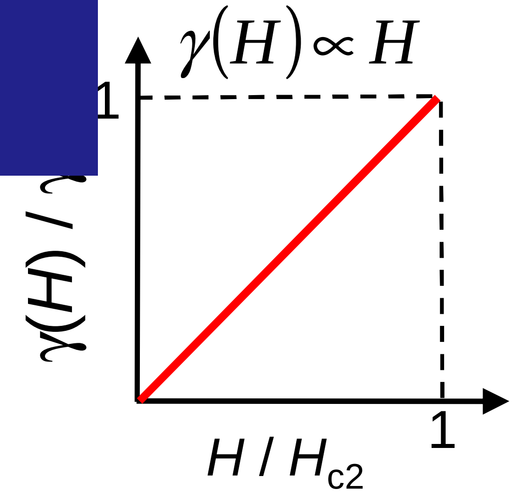

IMR

# Possible anisotropic superconducting gap

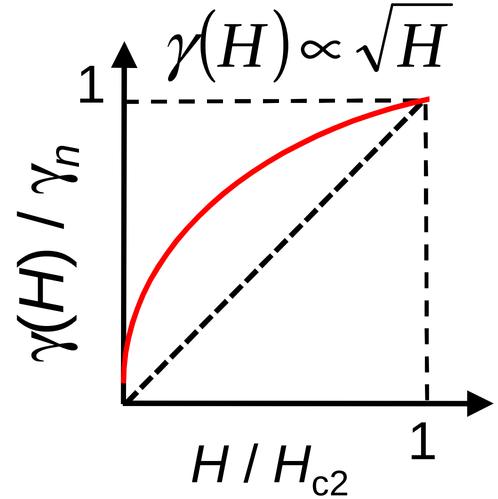
Crossover from isotropic gap (light doping)
to anisotropic gap (high doping)
in agreement with μSR
(Hiraishi et al., PRB81.014525 (2010).)




Isotropic gap

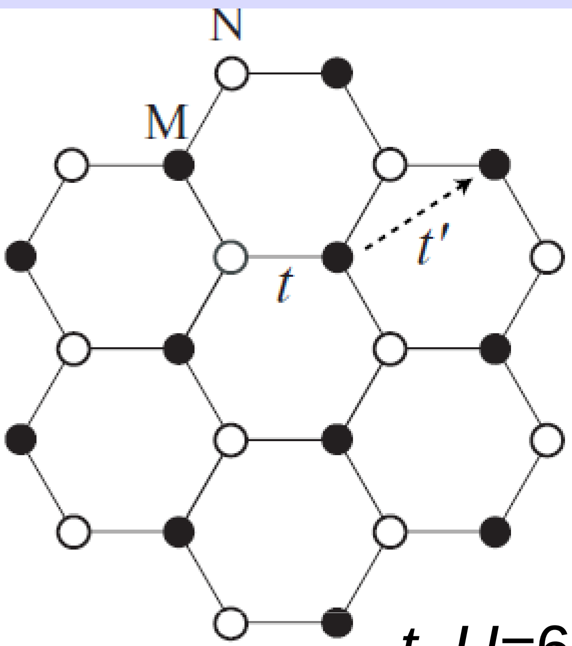



anisotropic gap




Y. Kasahara *et al.*, PRL **103**, 077004 (2009)

# Fluctuation exchange (FLEX) approximation theory on A-B honeycomb lattice with U

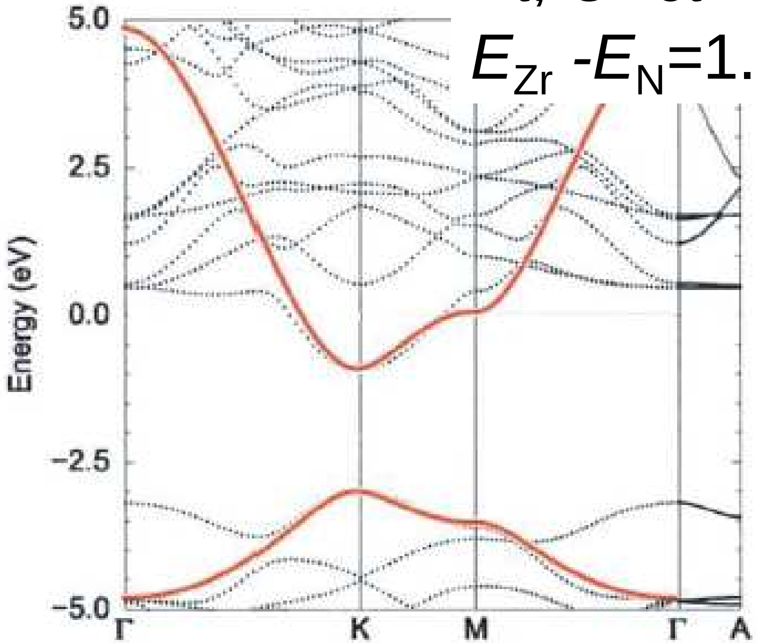


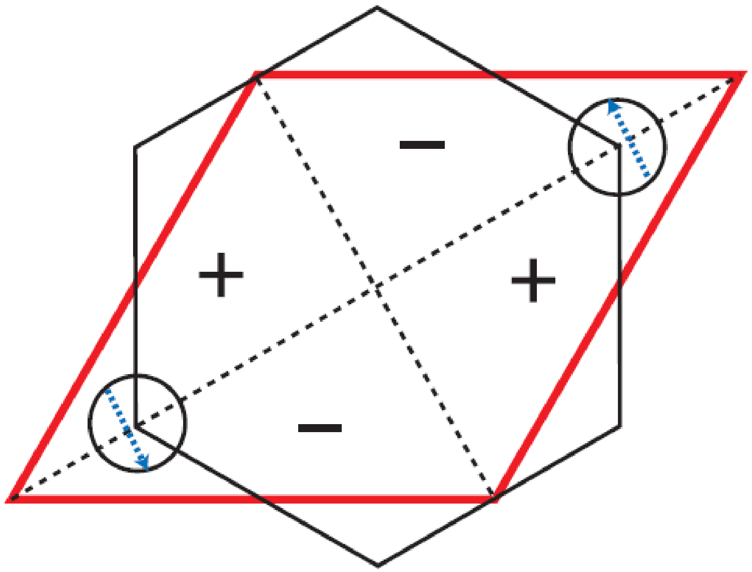

**K. Kuroki,**
*Sci. Technol. Adv. Mater.* **9,** 044202 (2008).
*Phys. Rev. B* **81,** 104502 (2010**)**

Antiferromagnetic fluctuation develops causing d + id’ paring, even in doped BAND insulator

*t*, *U*=6*t*

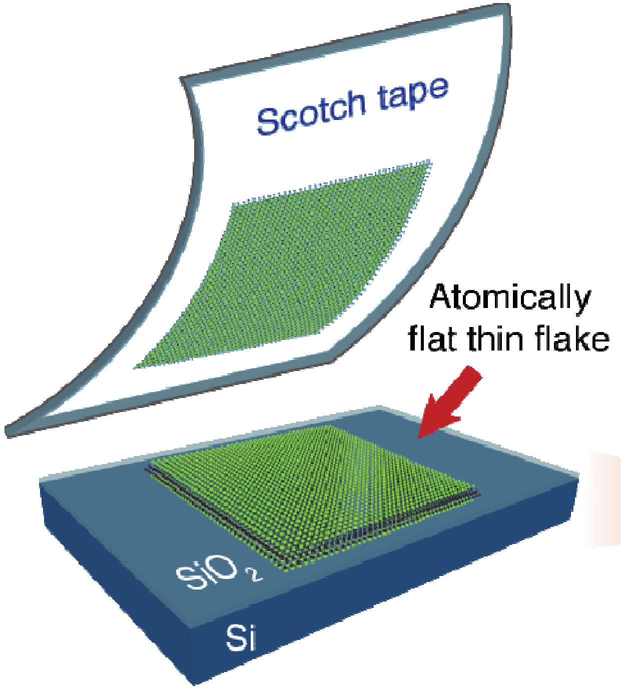
$E_{Zr} - E_N = 1.65t$

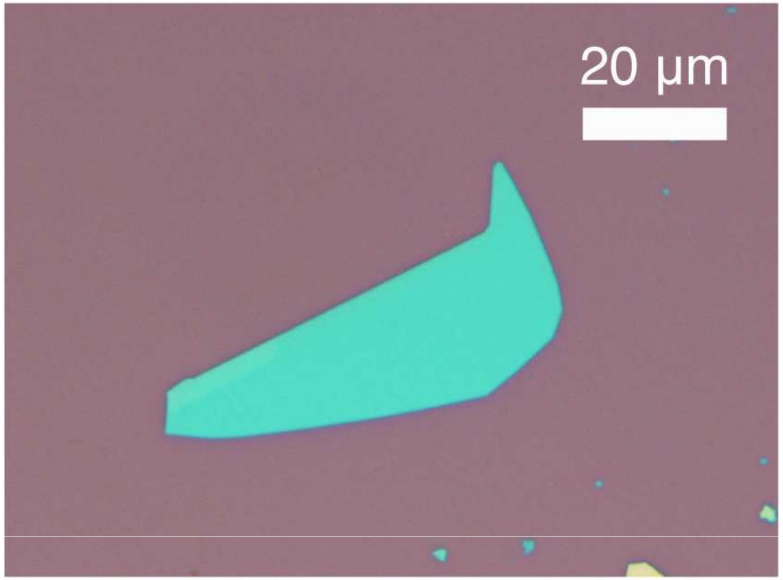


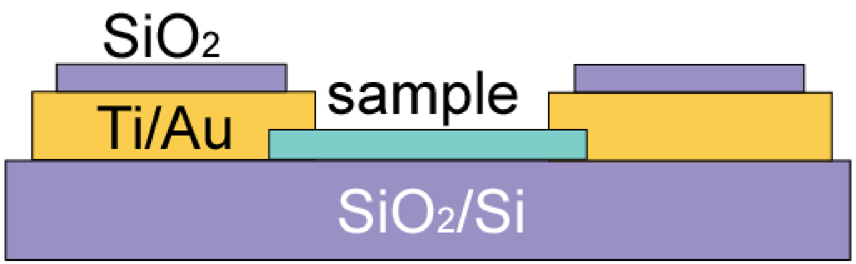
# Device fabrication for ZrNCl

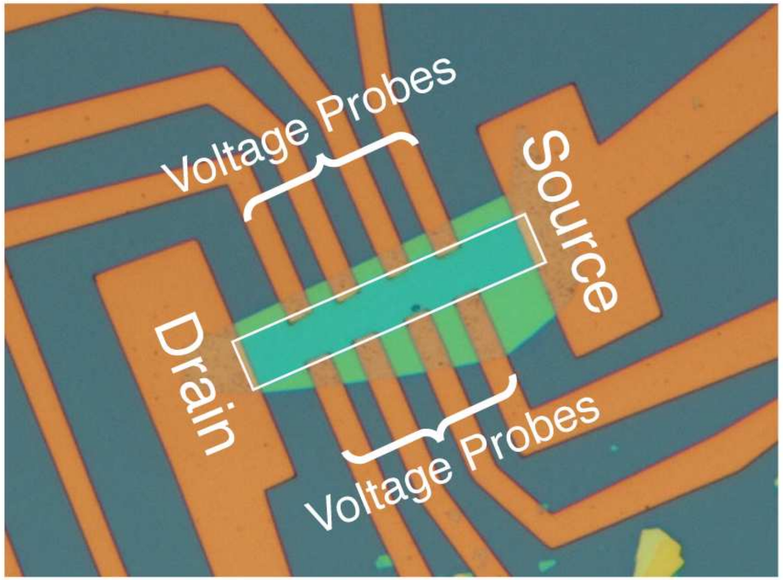
1.Exfoliating single crystals



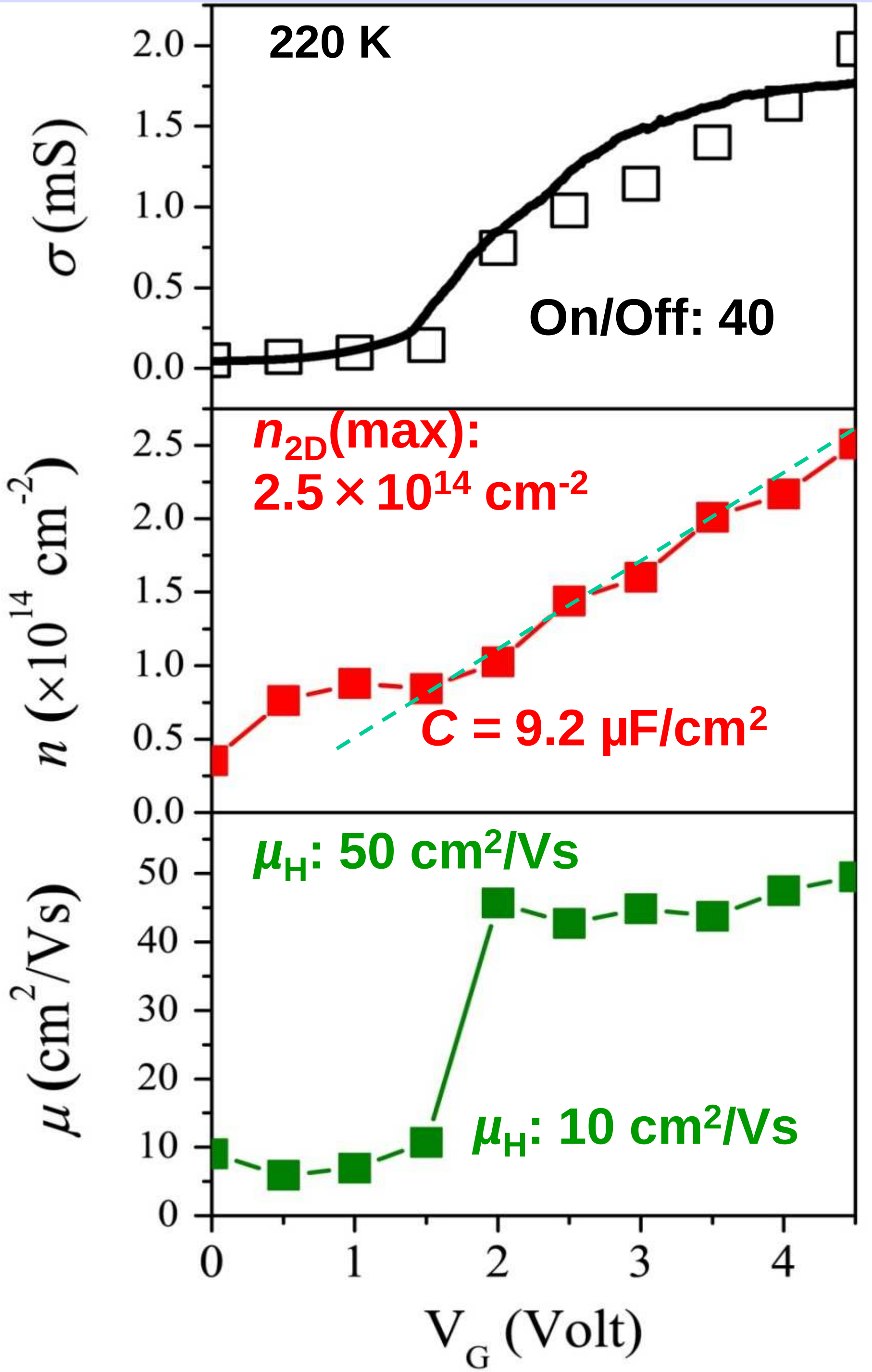




2.Electrodes by EB lithography

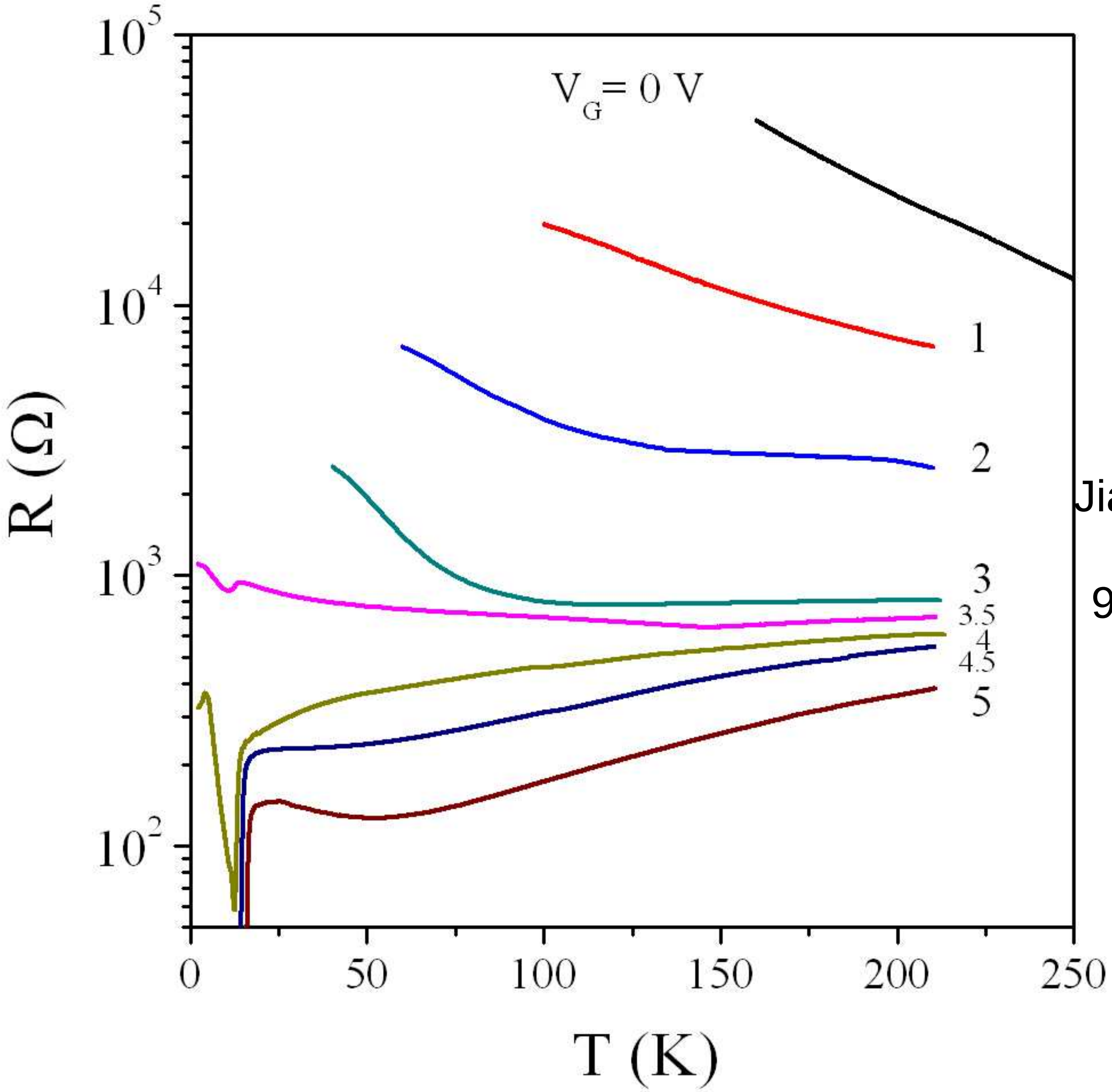


# FET Characteristics

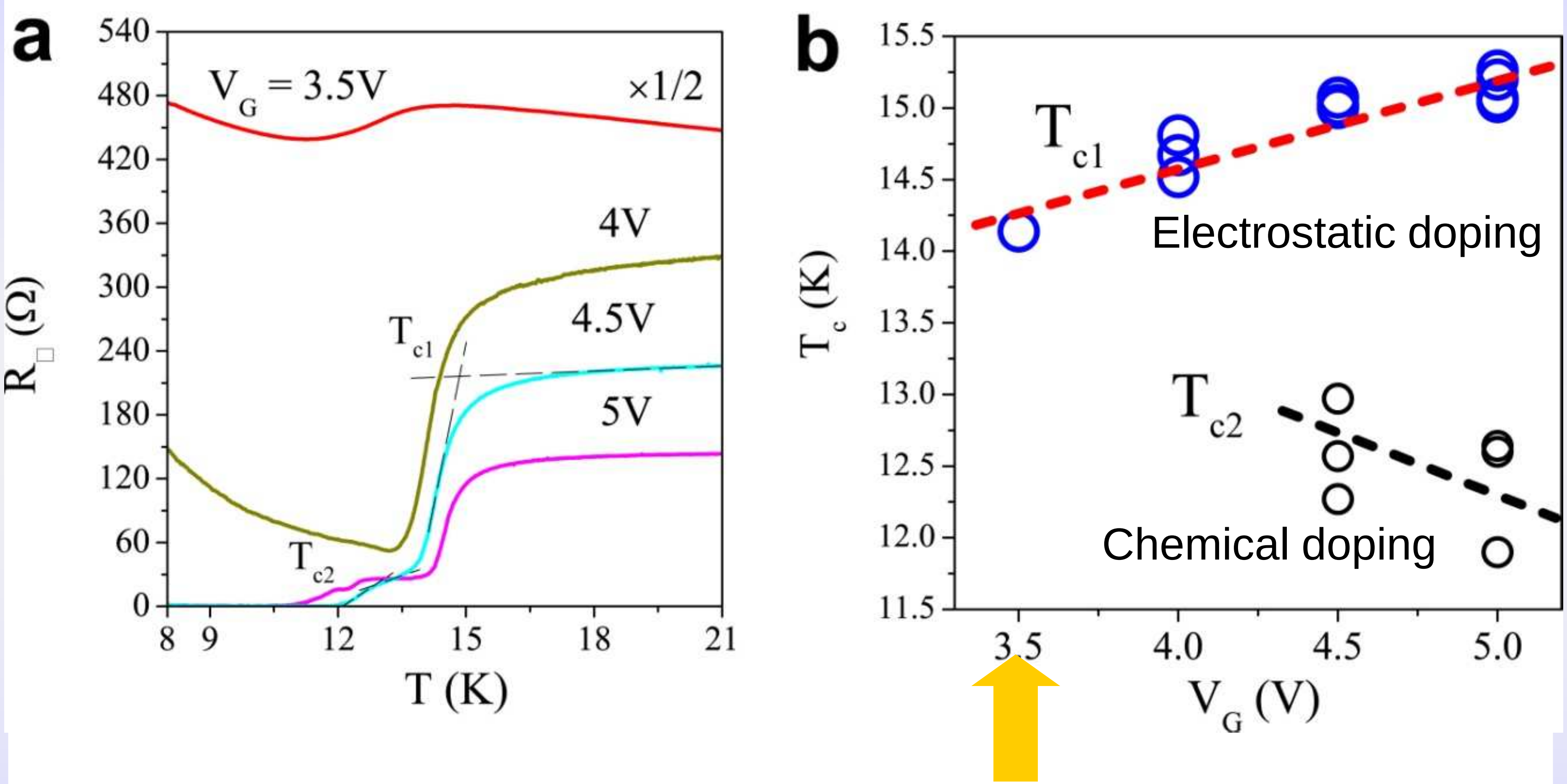


# Gate-induced superconductivity in ZrNCl (Tc ~ 15K)



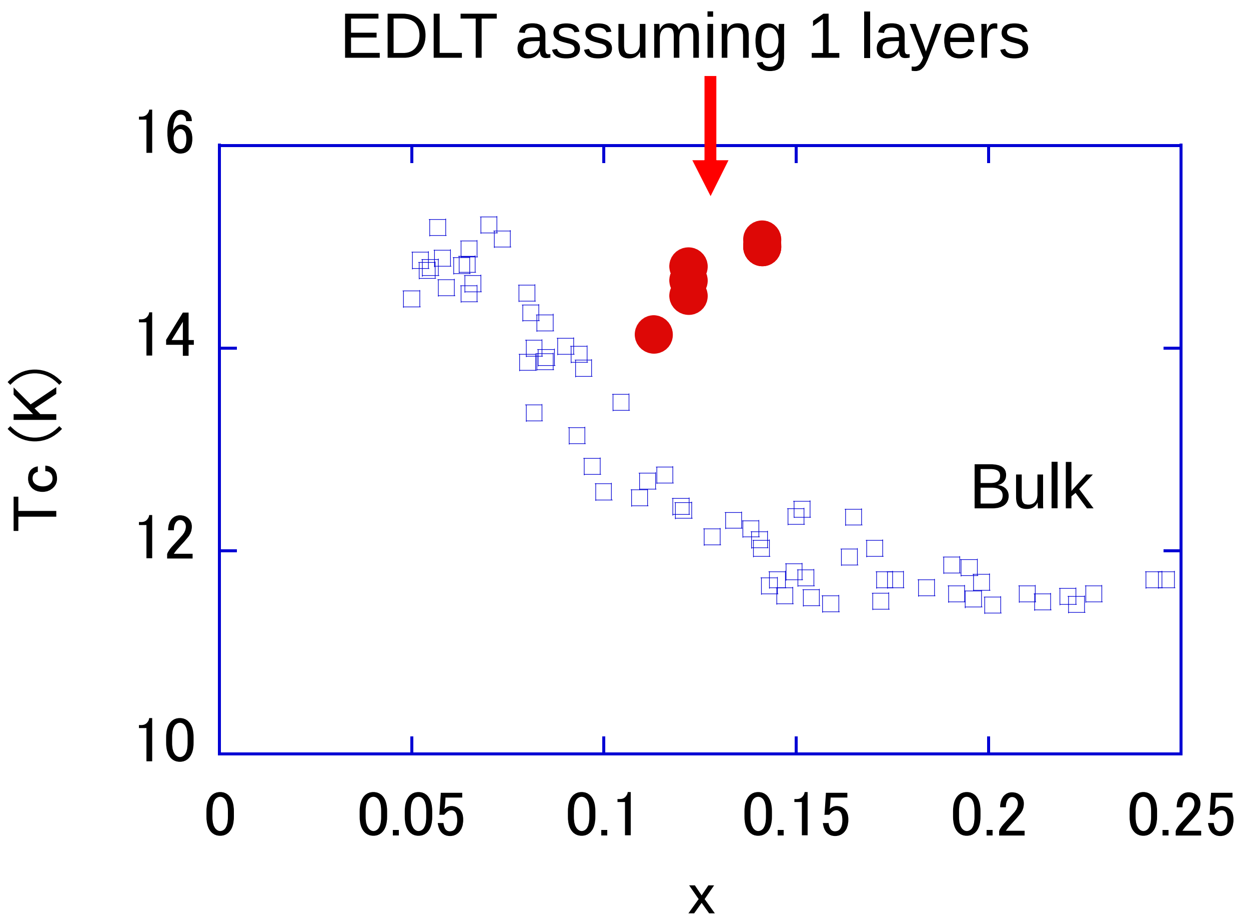

Jianting Ye et al.
Nat. Mater.
9, 125 (2010)

# $V_G$ dependence

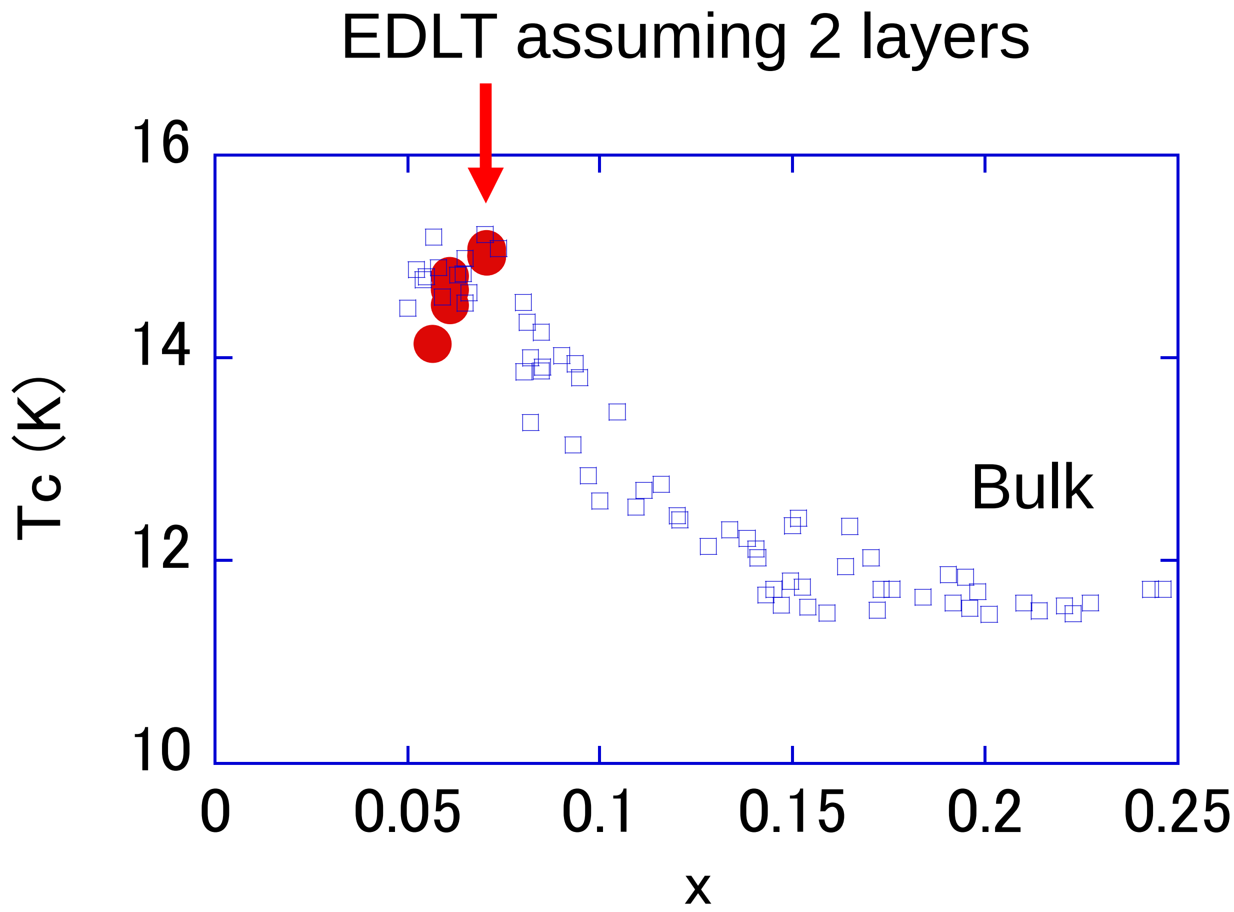



$n_{2D}$ = 1.7 x $10^{14}$ $cm^{-2}$

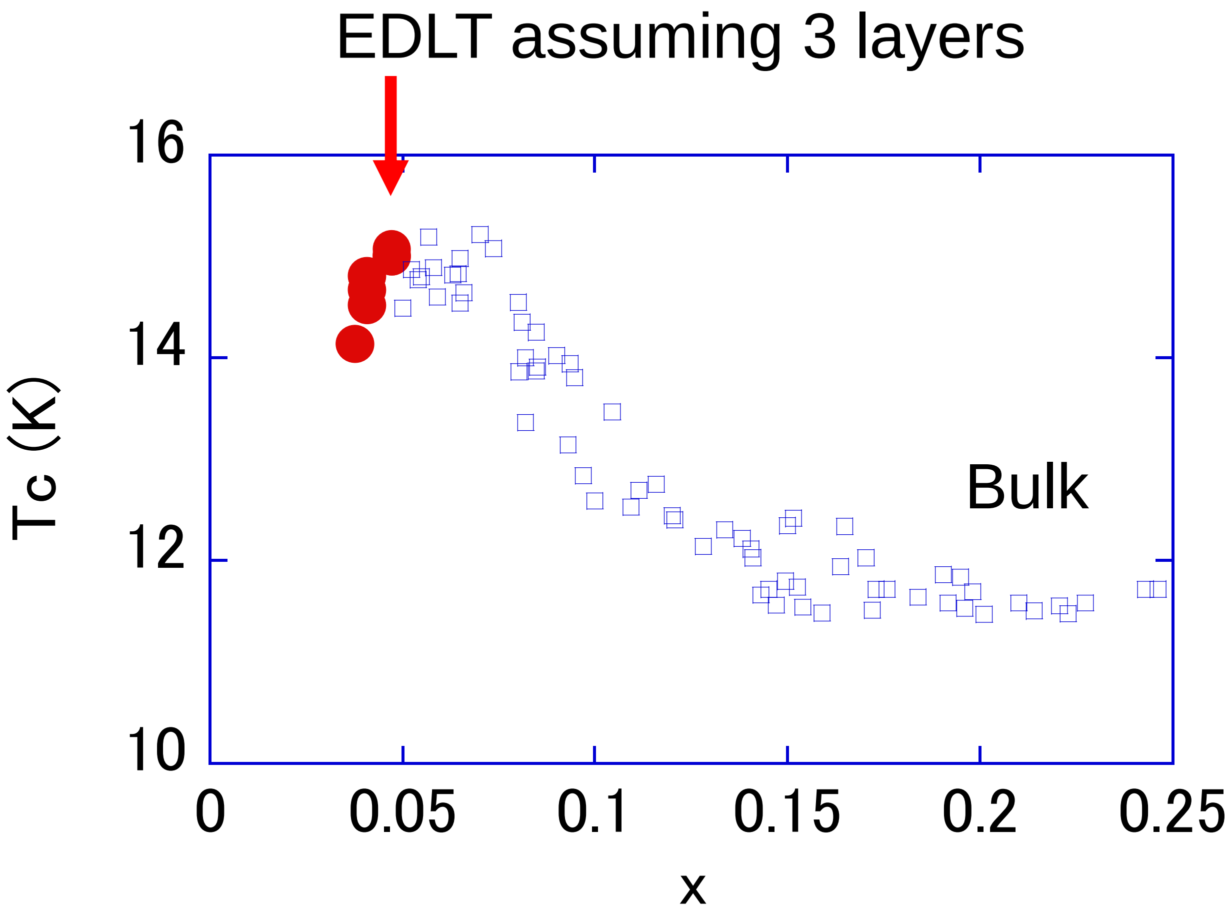
# $T_c$- $x$ phase diagram for ZrNCl EDLT



# $T_c$- $x$ phase diagram for ZrNCl EDLT



# $T_c$- $x$ phase diagram for ZrNCl EDLT




**Potentially unified phase diagram**

**EDLT is covering the low x region?**

# Summary

EDLT + E-field induced superconductivity

- **New tunable 2D systems**
- **Challenge: Increase Tc**
  **Discover new superconductors**
- **New states at interfaces, which are inaccessible by conventional chemistry**

**Solid/liquid interfaces**