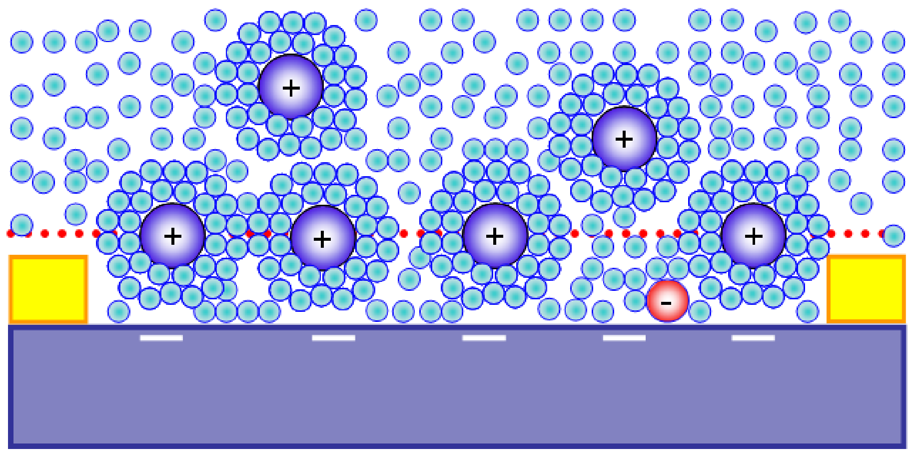
非平衡固液界面の電子物性

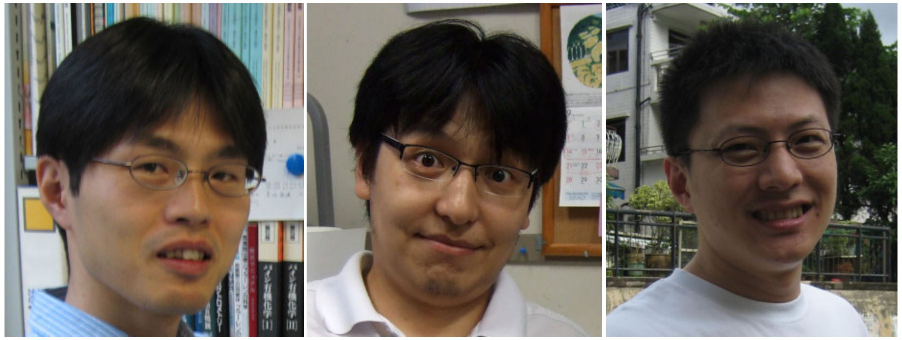
岩佐義宏

東北大学　金属材料研究所



Acknowledgement

Organics, and Nitrides:
<u>H. Shimotani, H. T. Yuan, J. T. Ye,</u>
(IMR, Tohoku U)



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A.Ohtomo, A. Tsukazaki
(WPI-AMR, Tohoku U)

LT Physics:
<u>T. Nojima, S. Nakamura,</u>
H. Aoki, N. Kimura
(IMR, Tohoku U)

OUTLINE

- はじめに: 電界効果トランジスタ (FET) と電界誘起超伝導
- 電気2重層トランジスタ (EDLT)
- 様々な物質への応用

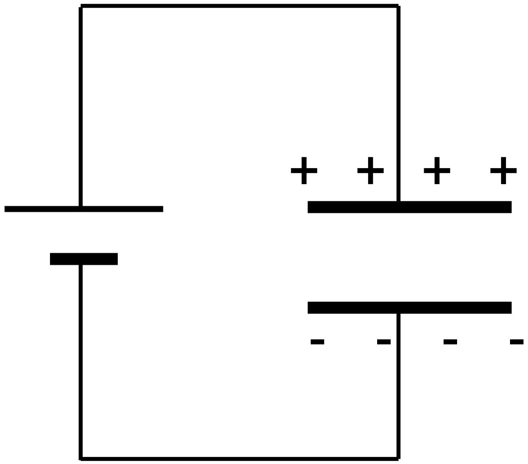
  有機半導体

  酸化物半導体　ZnO、$SrTiO_3$

  イオン液体

Physical control of carrier density
: Electric field effect

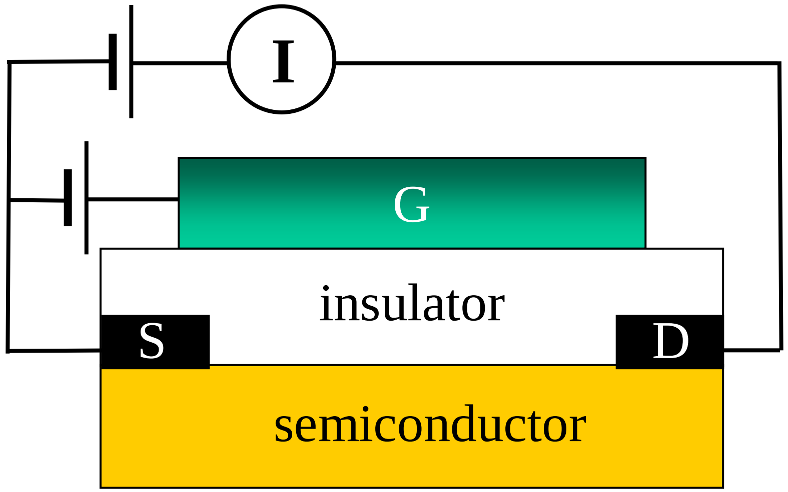
Capacitor
Charge accumulation device



Resistance measurement
of capacitor electrodes (1906)

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

Field Effect Transistor (FET)
Current switching device



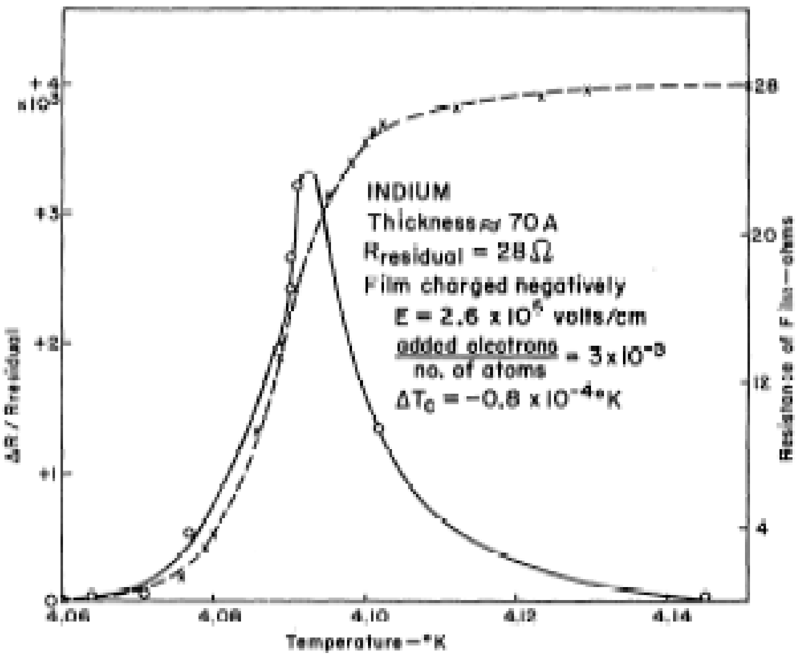
Patent of MOS-FET (1930s)

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

History 1

Electric Field Control of Tc in superconductor

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



Indium

Tc = 4.1 K, ΔTc = - 0.8 x 10^{-4} K

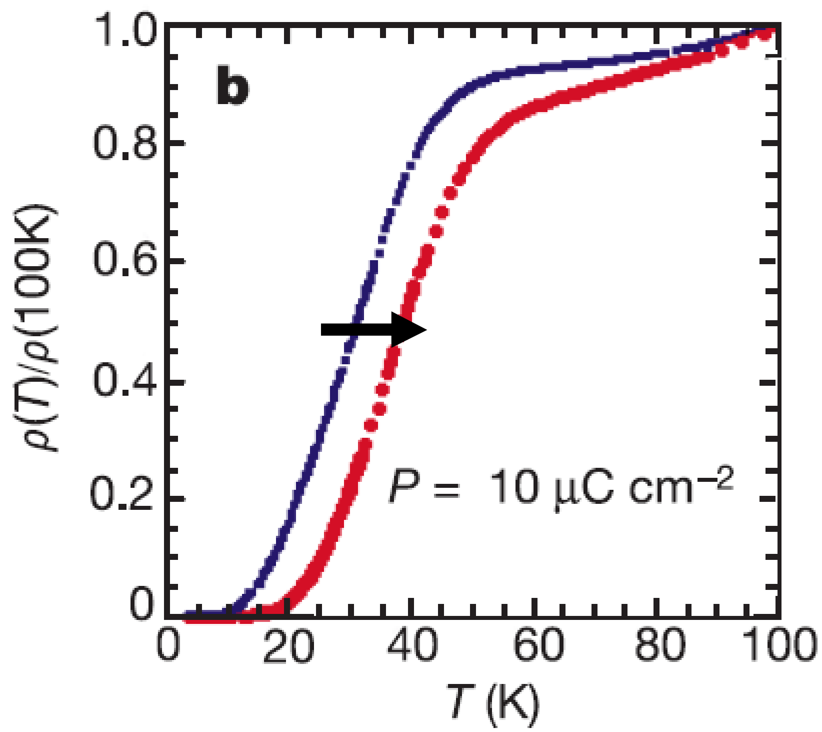
Question:
Can you increase Tc from zero to finite?

History 2

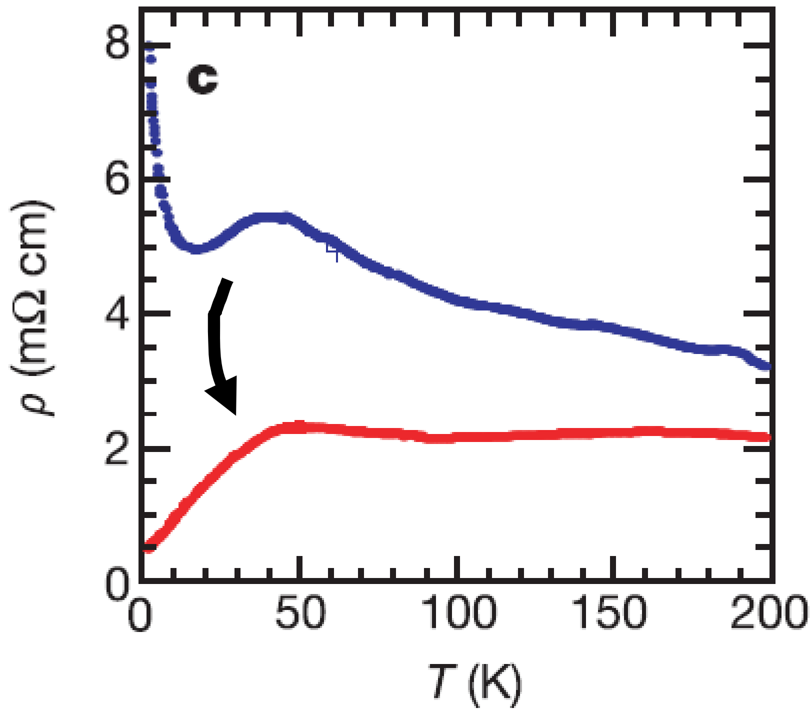
Discovery of high Tc cuprates and its field effect

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

$YBa_2Cu_3O_{7-\delta}$



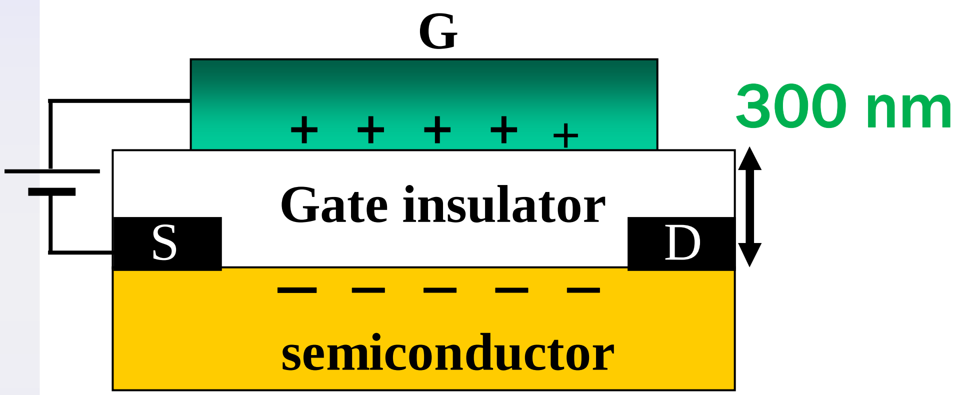
C. H. Ahn, J.-M. Triscone, and J. Mannhart
Nature 423, 1015 (2003).



Conventional FET

Our approach (2004～)

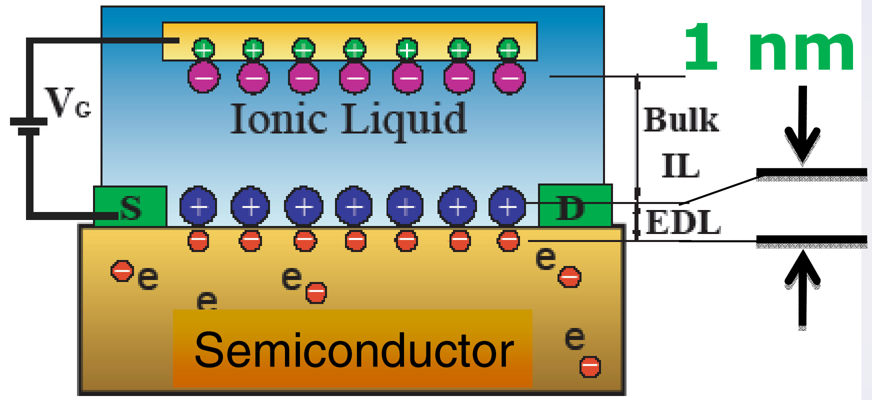
Solid Gate



Weak electric field
～1MV/cm
< 1 x 10^{13} cm^{-2}

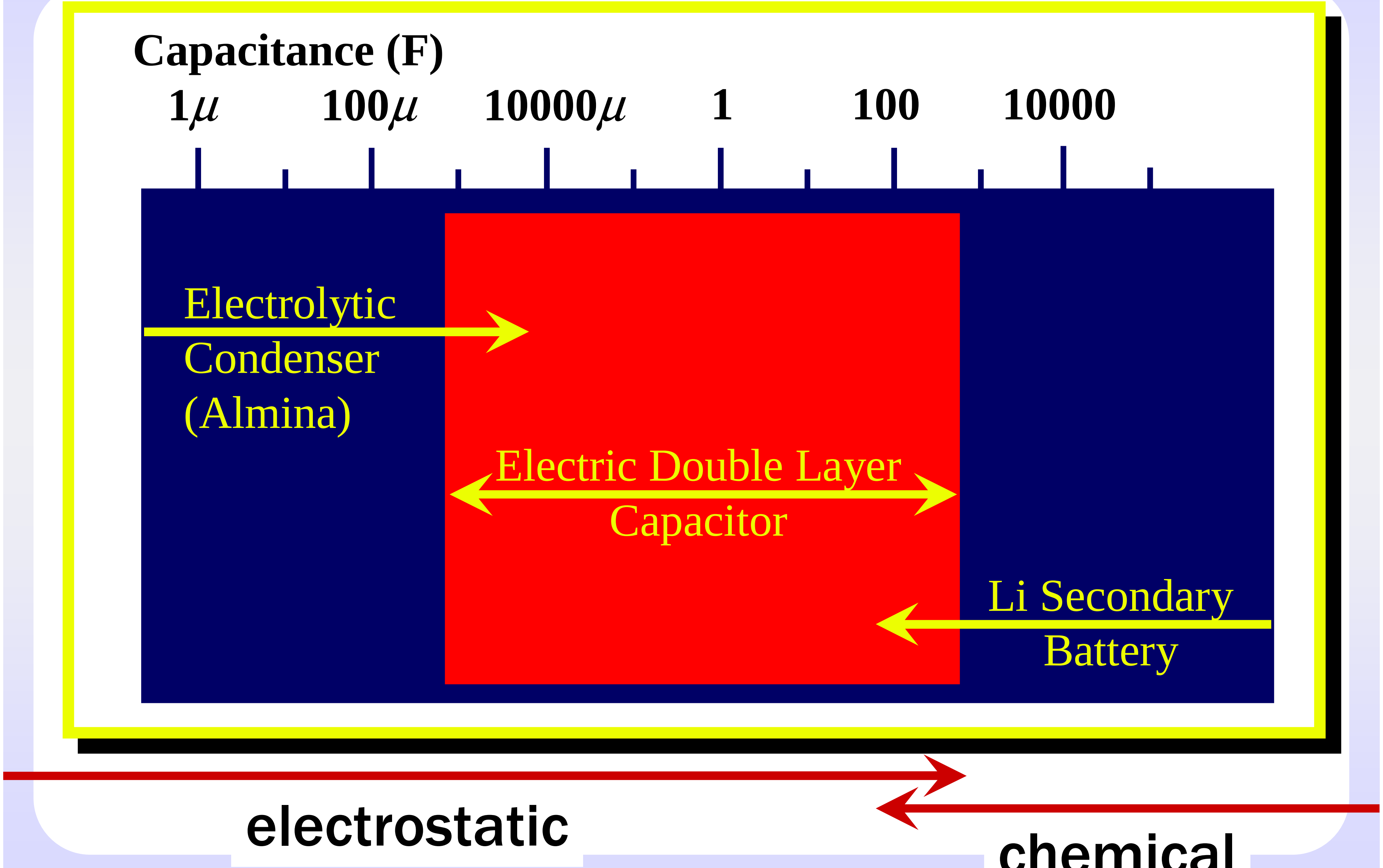
Liquid gate

(electric double layer transistor)



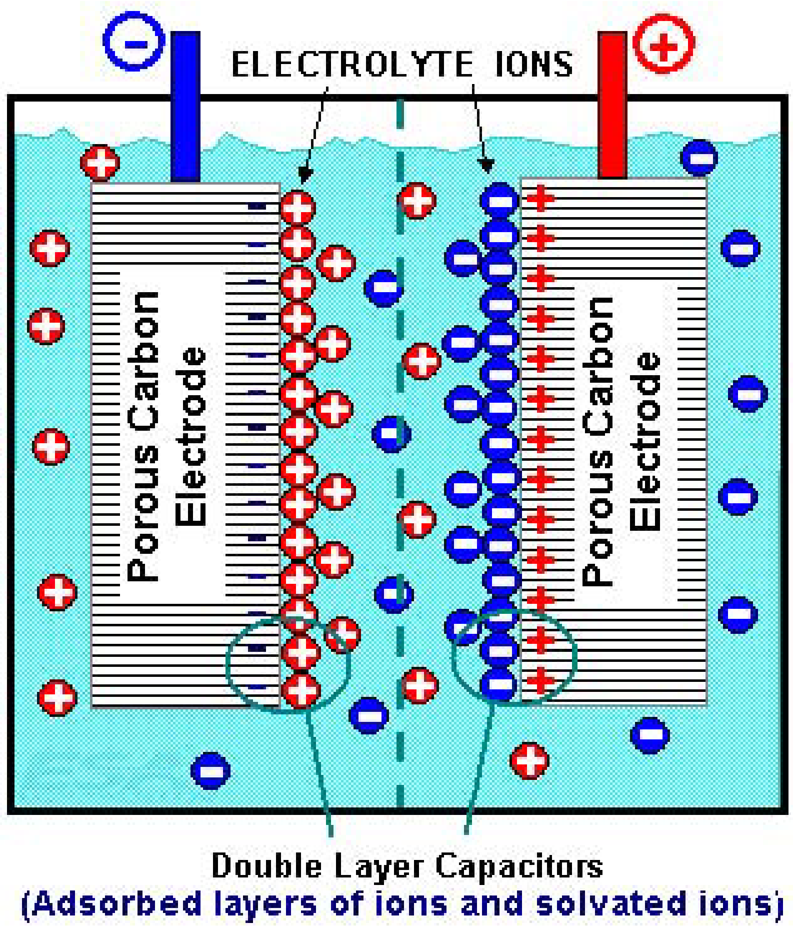
Strong electric field
>10MV/cm
～ 1 x 10^{15} cm^{-2}

Charge Accumulation Devices

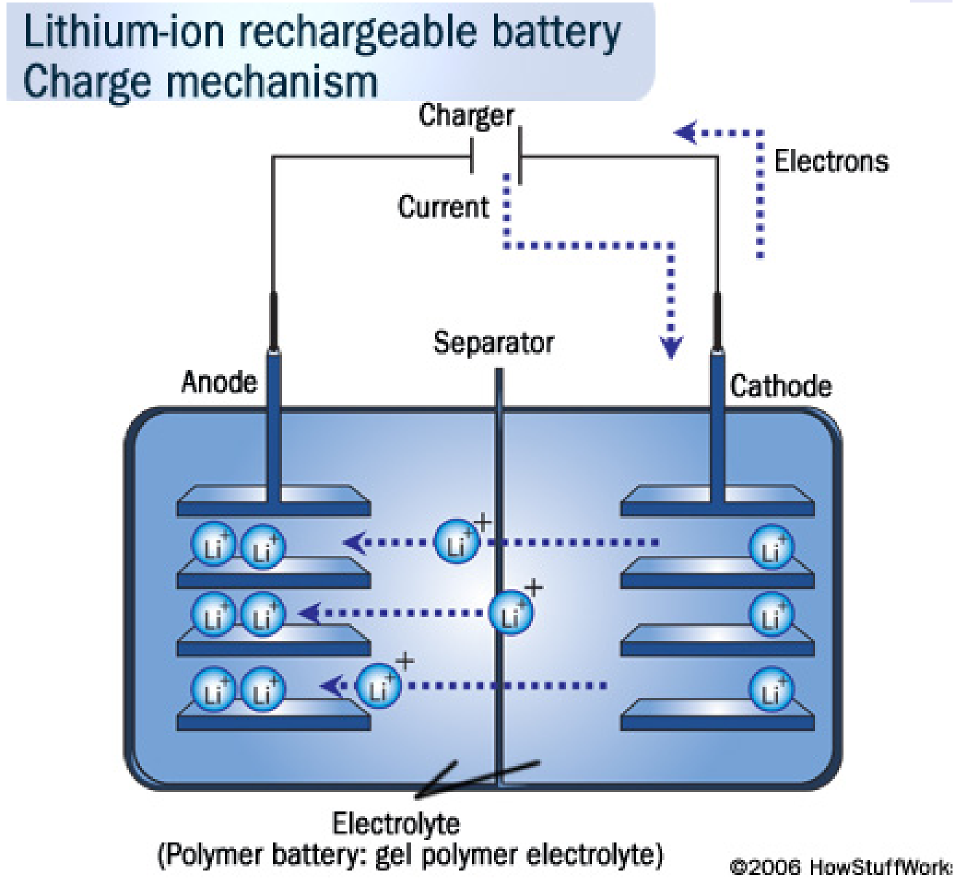


Comparison of charge accumulation devices

<u>Electric Double Layer Capacitor</u>

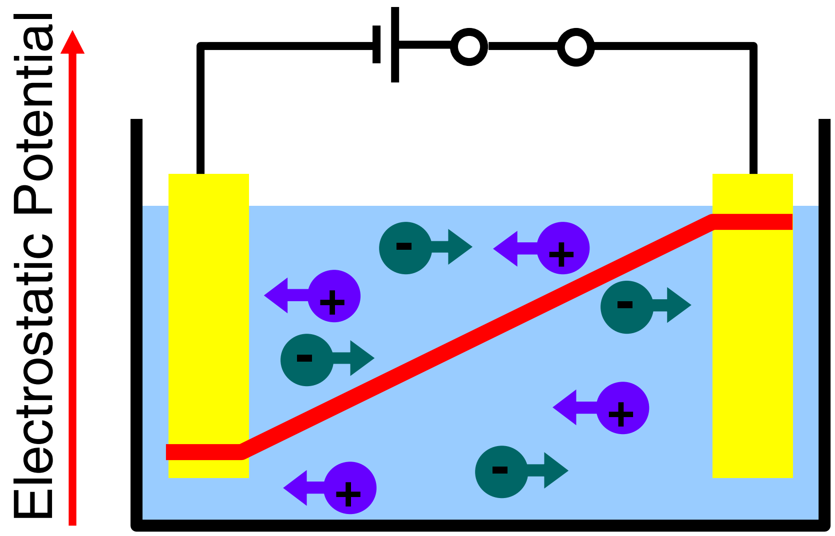


<u>Lithium Ion Secondary Battery</u>



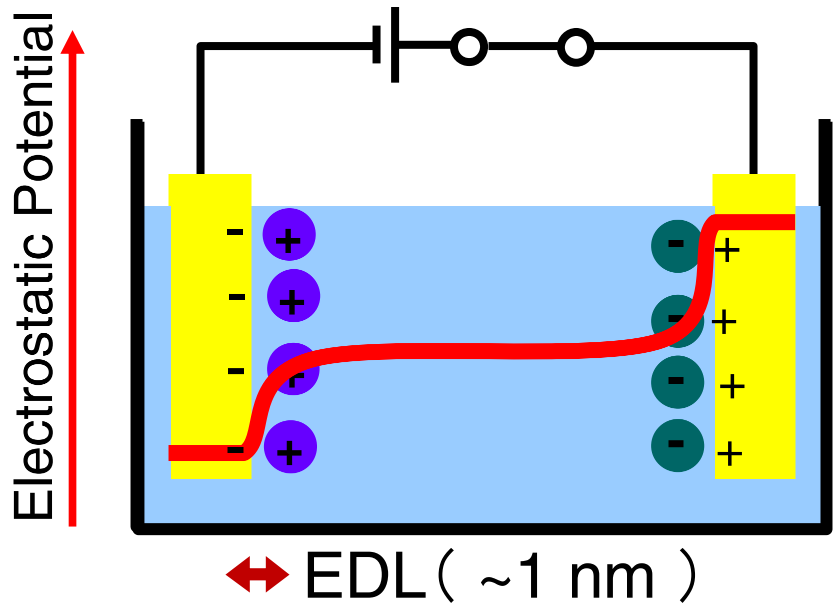
Electric Double Layer (EDL)

Electric Double Layer Capacitor (EDLC)

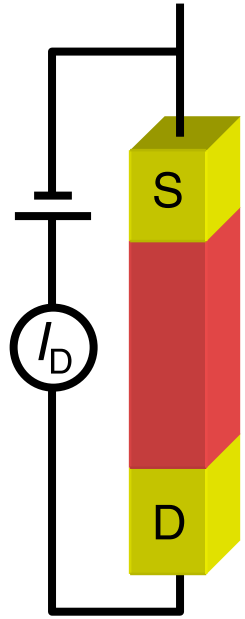


Electric Double Layer (EDL)

Electric Double Layer Capacitor (EDLC)



Replace one of the electrodes by



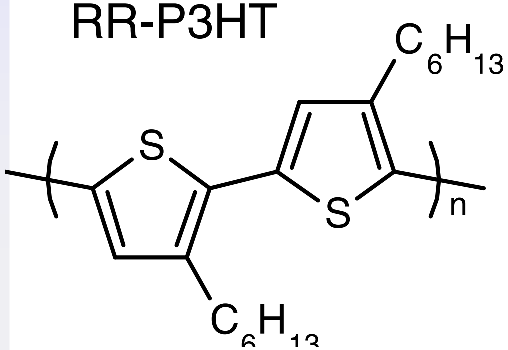
EDLC on market (Japan Chemicon Inc.)

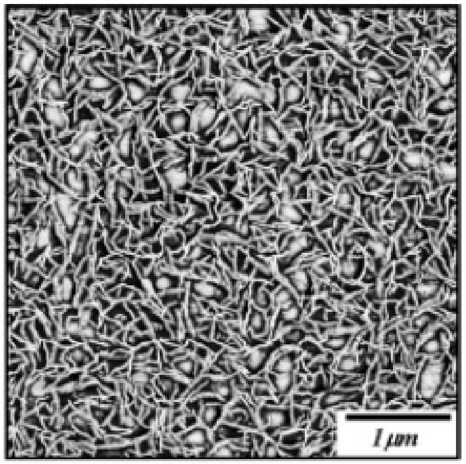
EDL-transistor (EDLT)

{ large capacitance
large charge density }

Application of EDLTs to high density charge accumulation in organic semiconductors

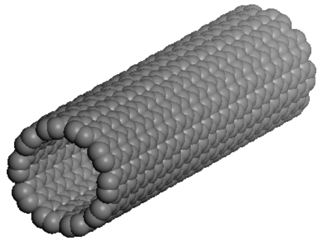
polythiophene
RR-P3HT

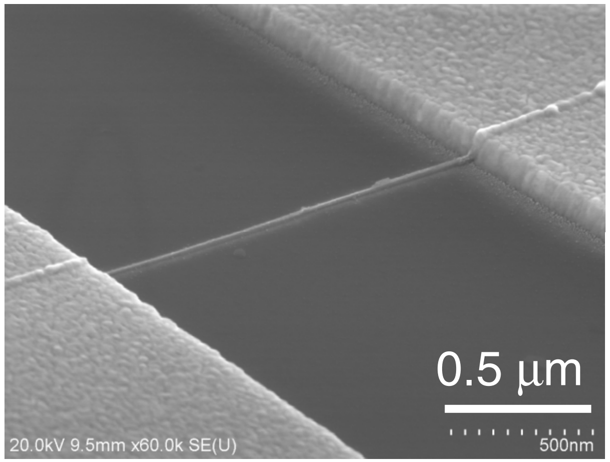




H. Shimotani *et al.*,
APL (2005)

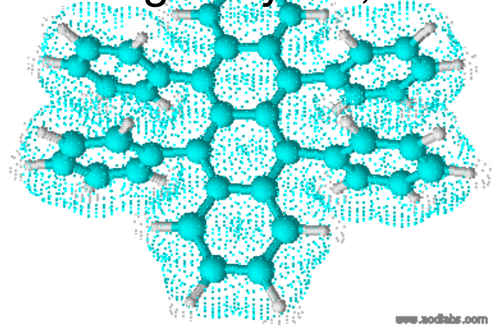
Single walled carbon nanotubes
SWNT

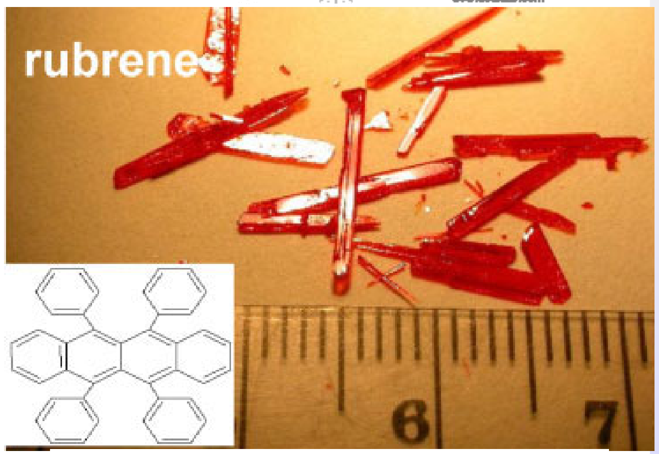




H. Shimotani *et al.*,
APL (2006)

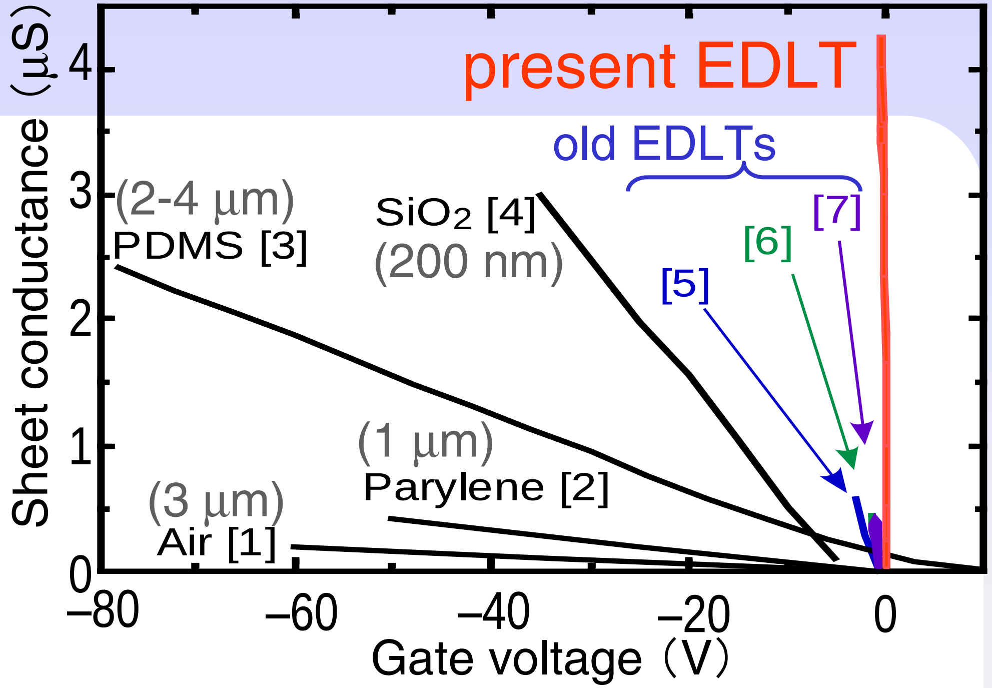
Organic semiconductor
Single crystal, Rubrene





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

有機トランジスタへの展開

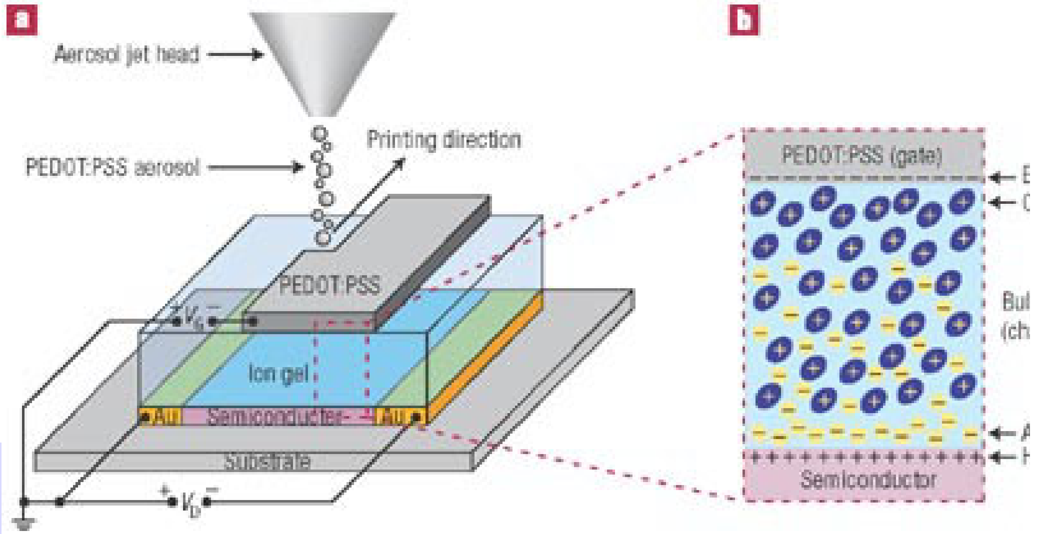


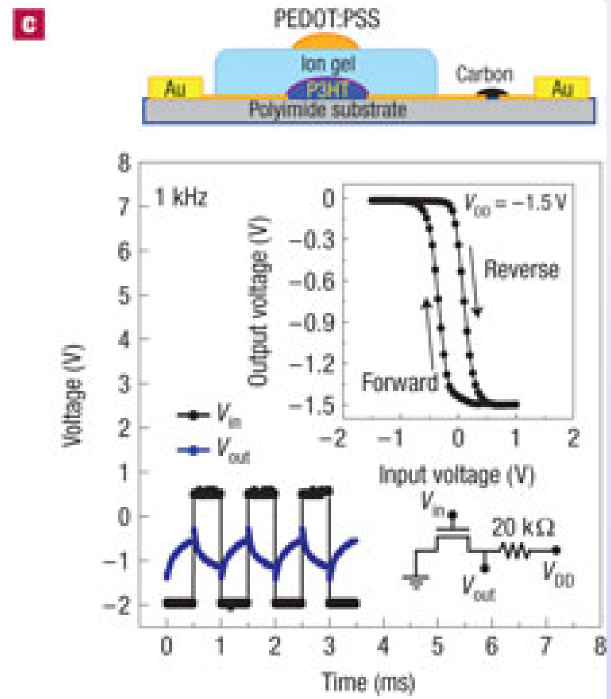
基礎: 有機単結晶を用いた低電圧動作

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

応用: イオンゲルをゲートに用いるトランジスタを印刷で作製

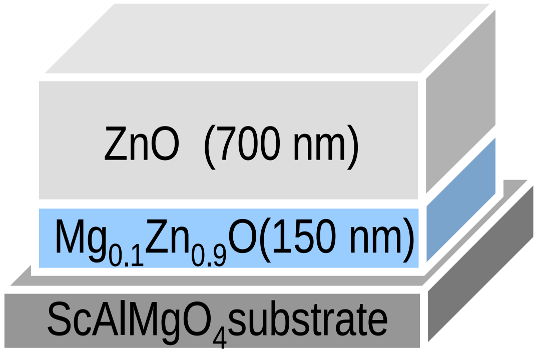
C. D. Frisbie et al., *Nat. Mater*. 7, 900 (2008).





Device fabrication

■ ZnO single crystalline thin film

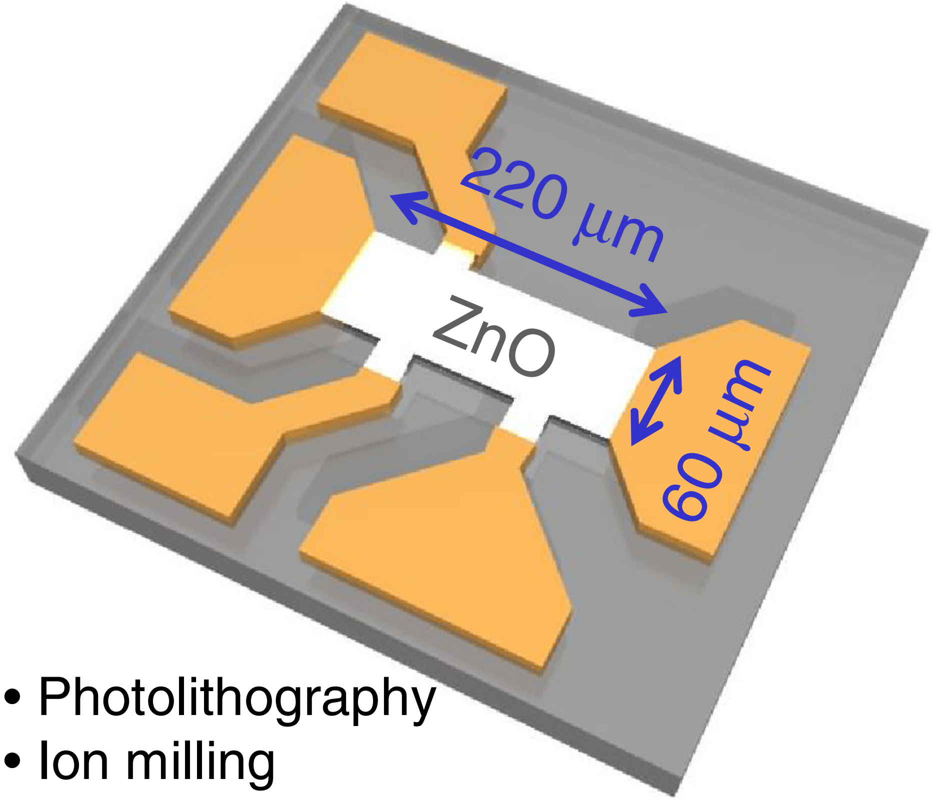


Low carrier density and high mobility

$$\left(\begin{array}{l} \mu = 100\ \mathrm{cm^2V^{-1}s^{-1}} \\ n = 7.7 \times 10^{15}\ \mathrm{cm^{-3}} \end{array}\right)$$

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

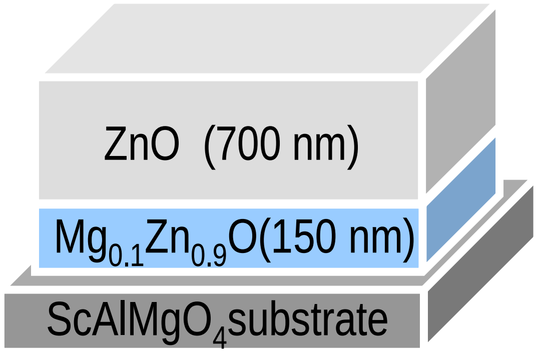
■ EDL-FET



- Photolithography
- Ion milling

Device fabrication

■ ZnO single crystalline thin film



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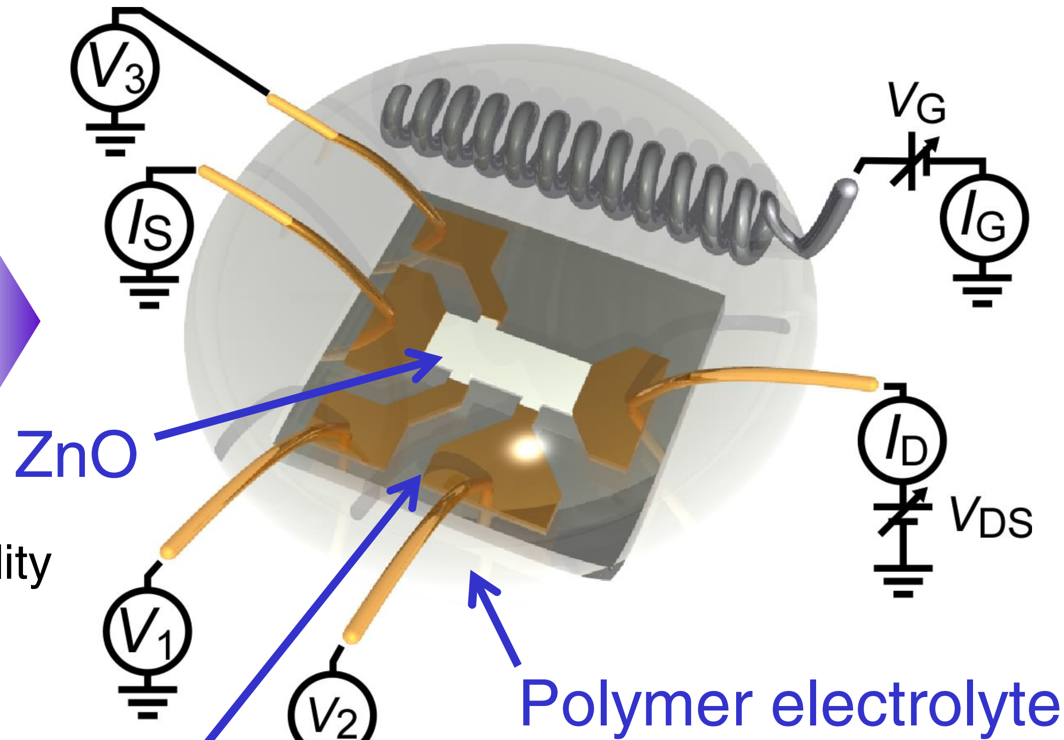


Ti/Au electrode

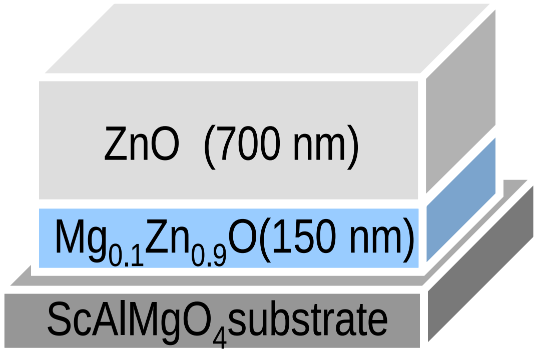
- polyethyleneoxyde $-\!\!\left[CH_2CH_2-O\right]\!\!-_n$
- $KClO_4$ ([O]/[K] = 20/1)

IMR

Electric Double Layer Transistor

Device fabrication

■ ZnO single crystalline thin film



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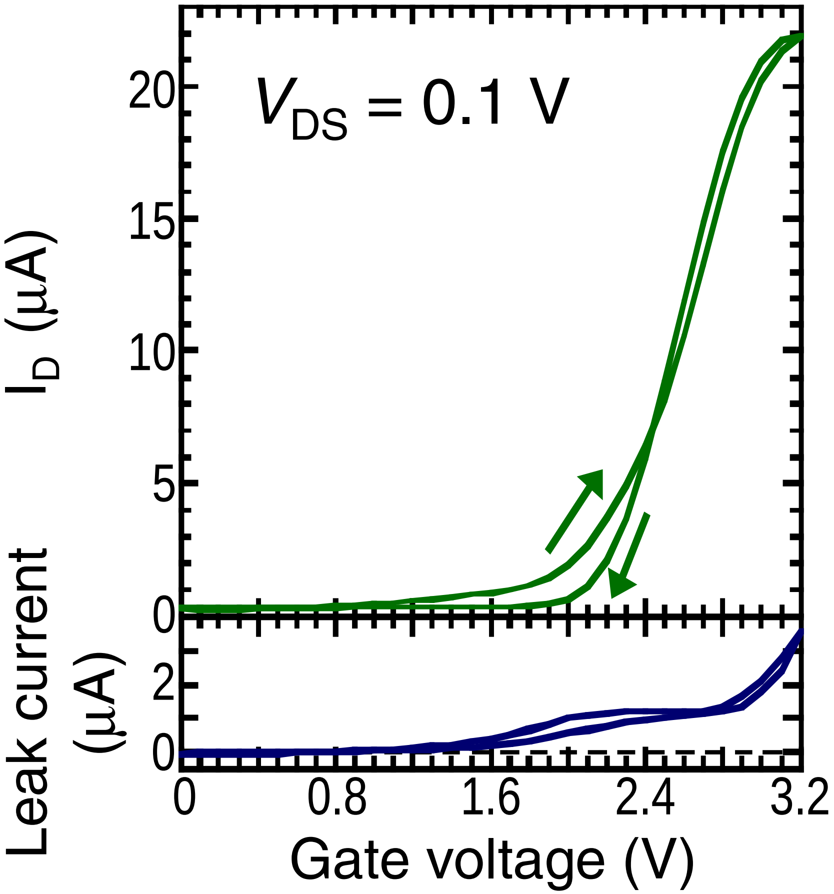
Tsukazaki et al., APL 88, 152106 (2006)

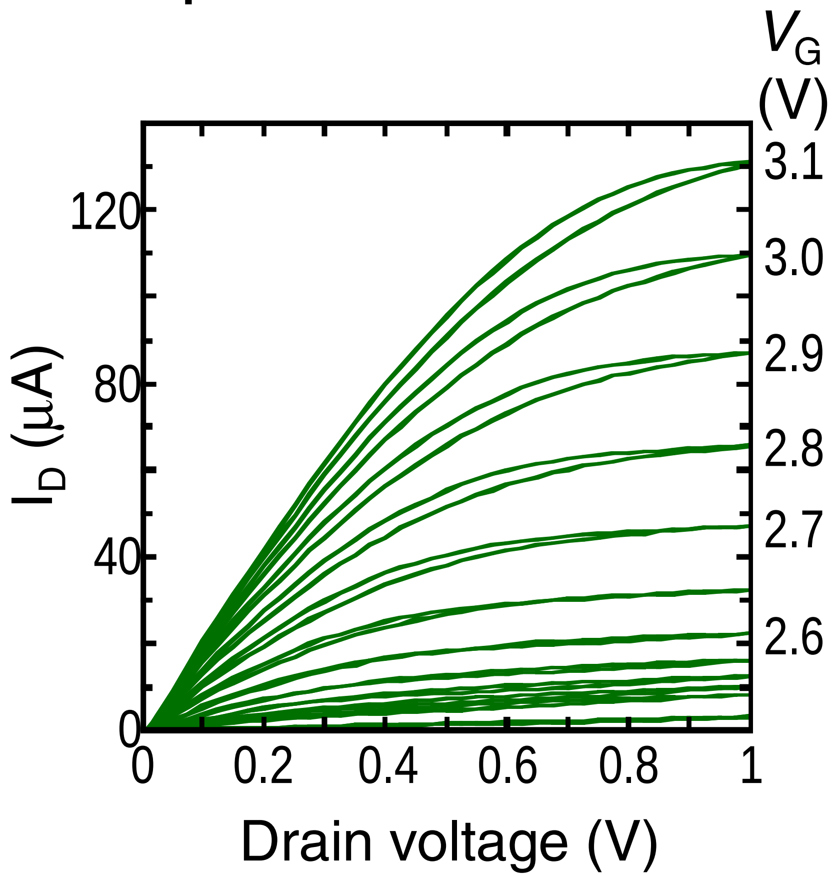
■ EDL-FET

Characteristics of ZnO-EDLT

■ Transfer curve



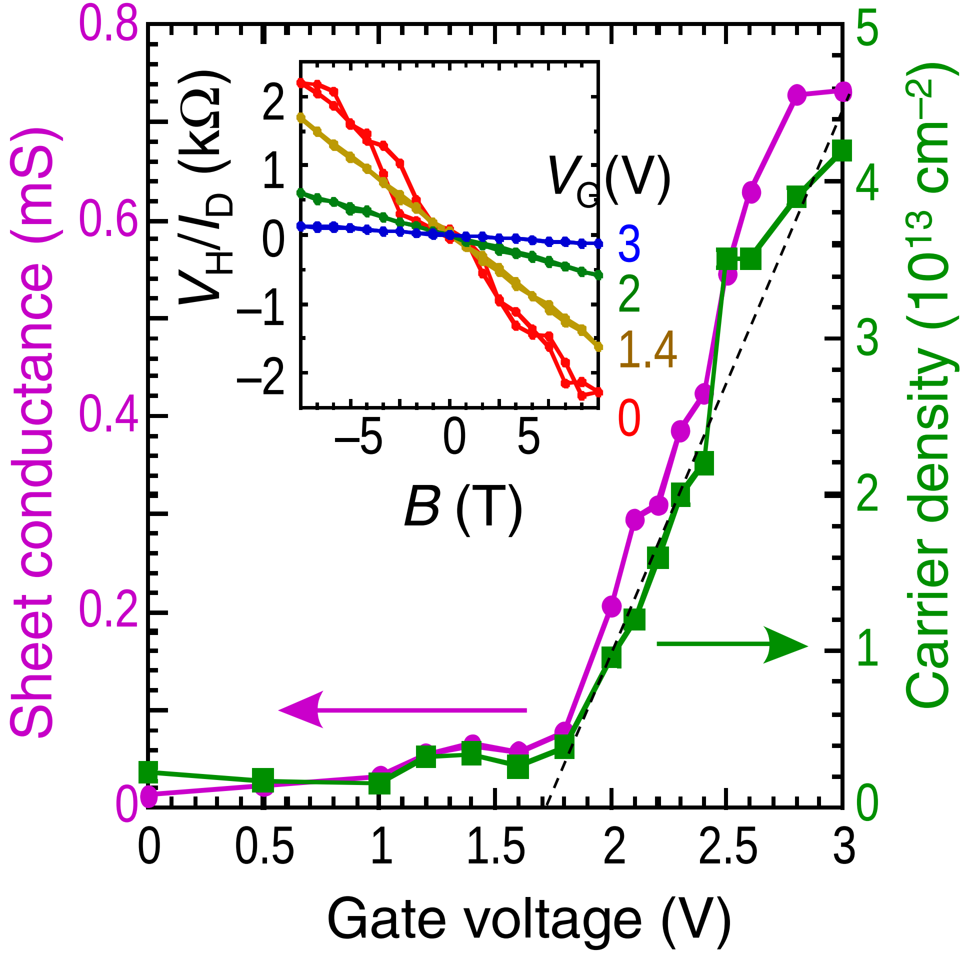
■ Output curve



n-type operation

Direct measurement of carrier density (Hall effect)

ZnO



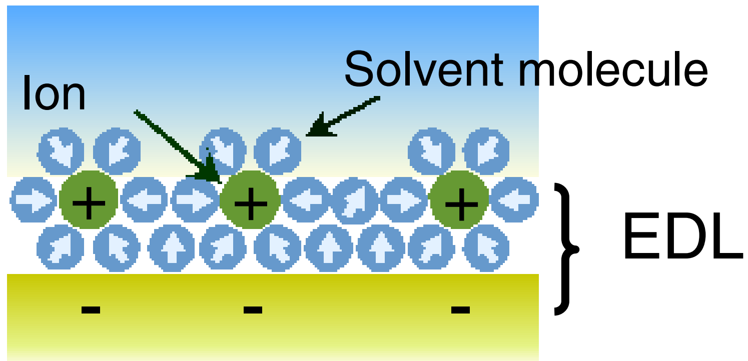
ne = Q = CV

C ~ 7.8 μF/cm²

(cf. 15 μF/cm² on Au)

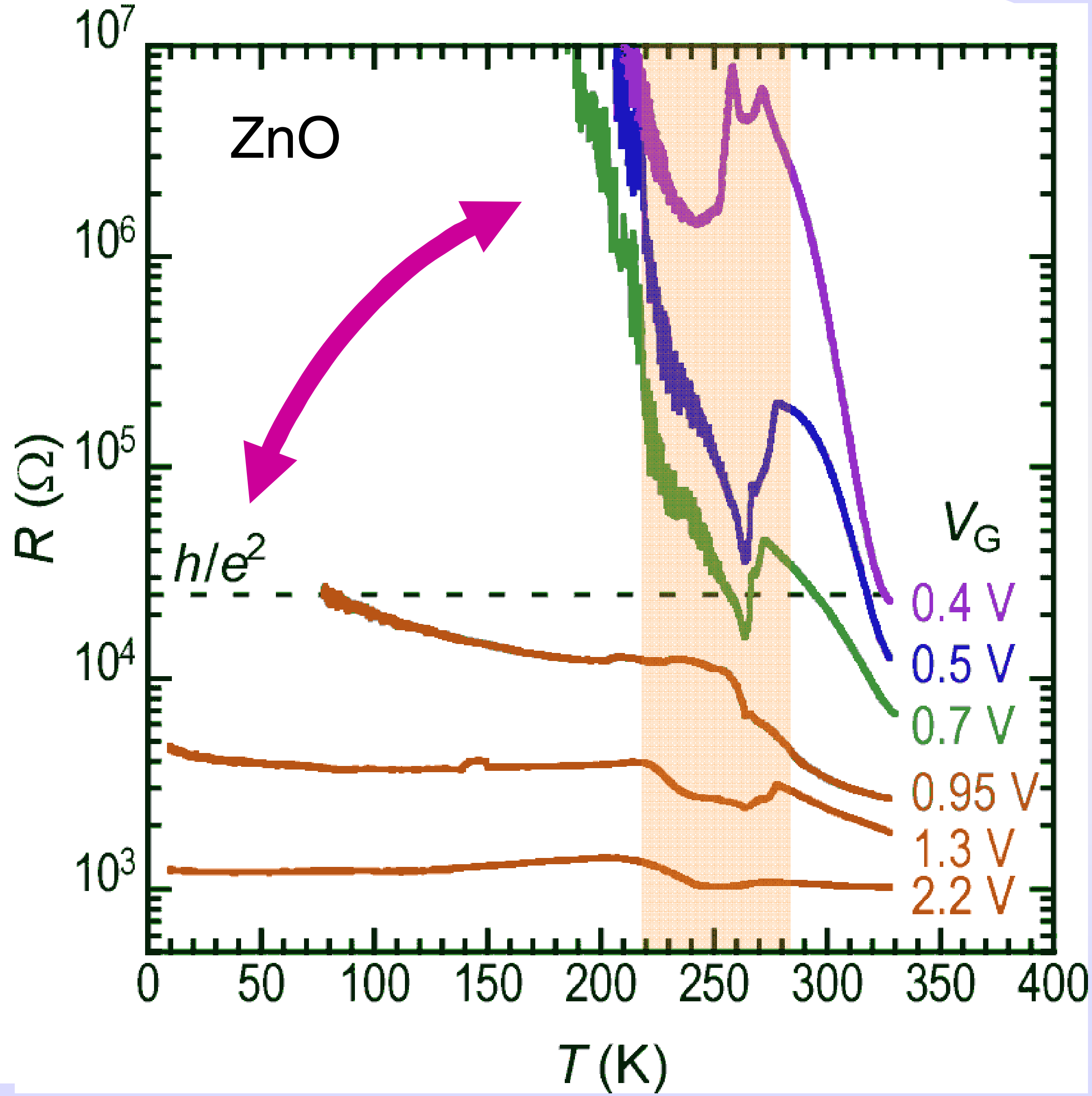
(ε = 10 ε_0 for PEO solvent)

thickness of EDL ~ 1 nm



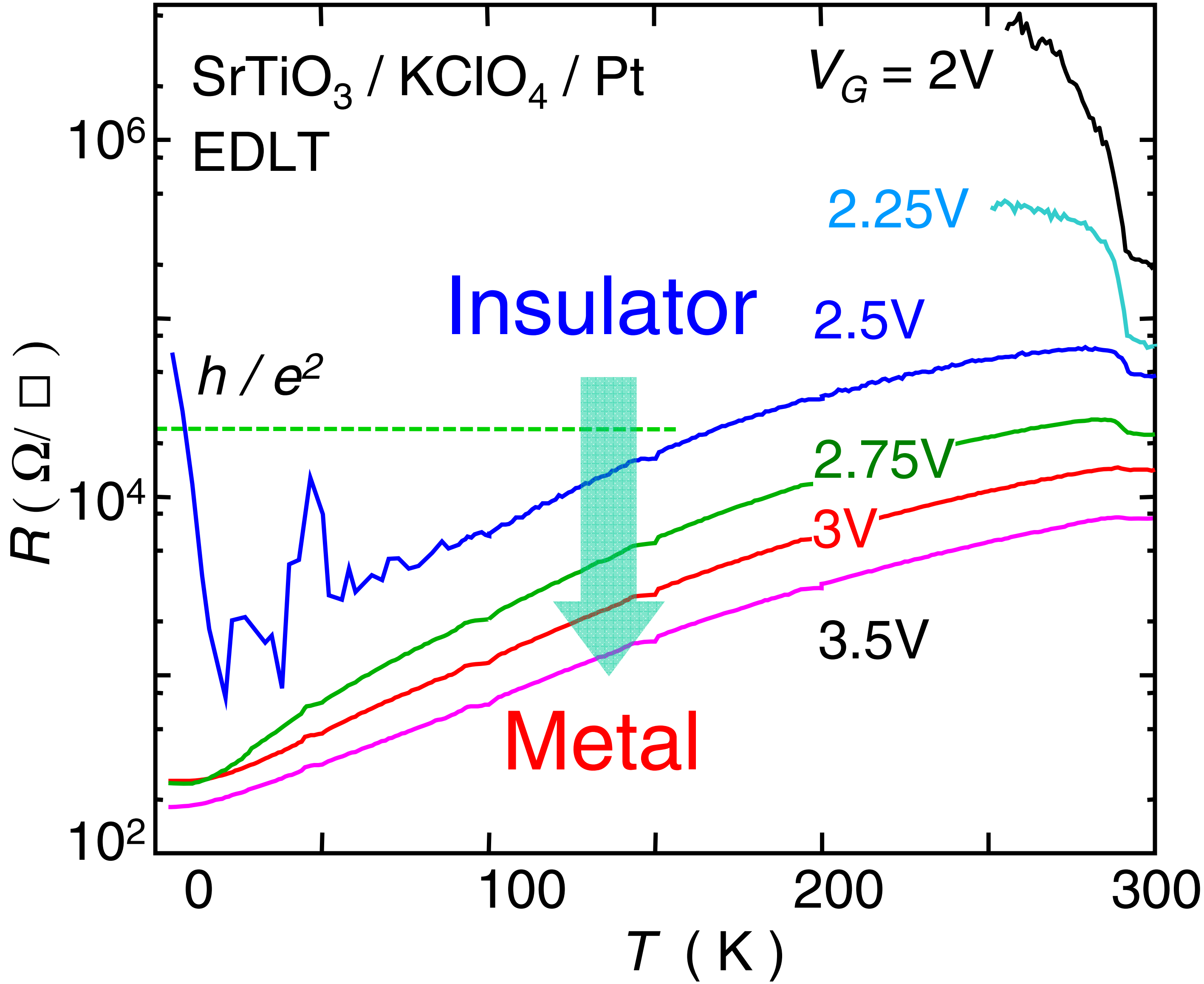
H. Shimotani et al. *APL* 91, 082106 (2007)

Gate-induced Insulator-metal transition in ZnO

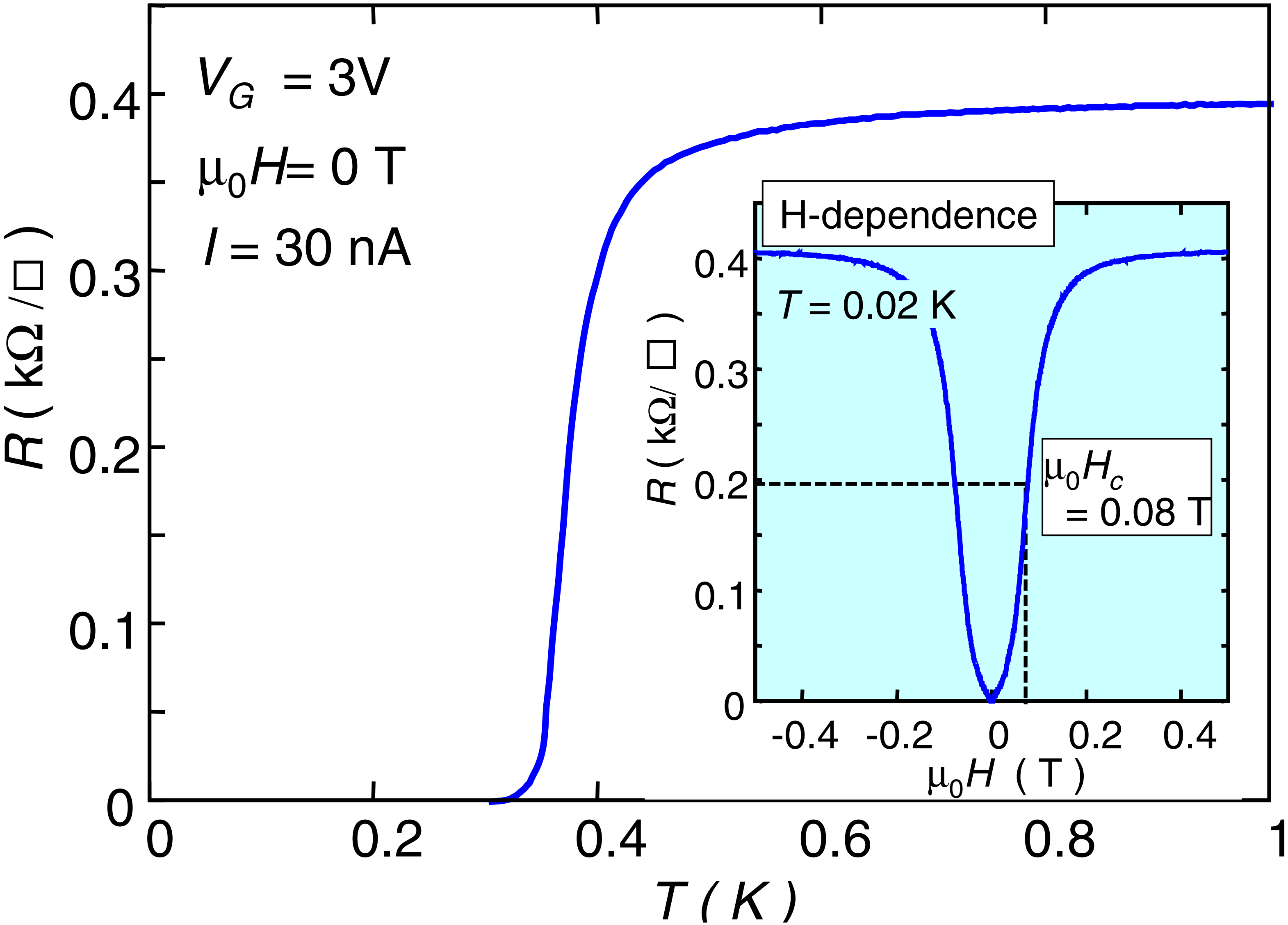


H. Shimotani et al. Appl. Phys. Lett. **91**, 082106 (2007)

Temperature dependence of resistance in $SrTiO_3$ EDLT



Electric field-induced superconductivity in $SrTiO_3$

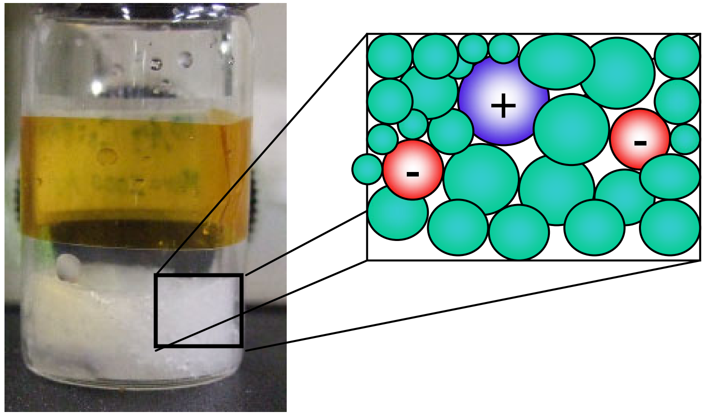


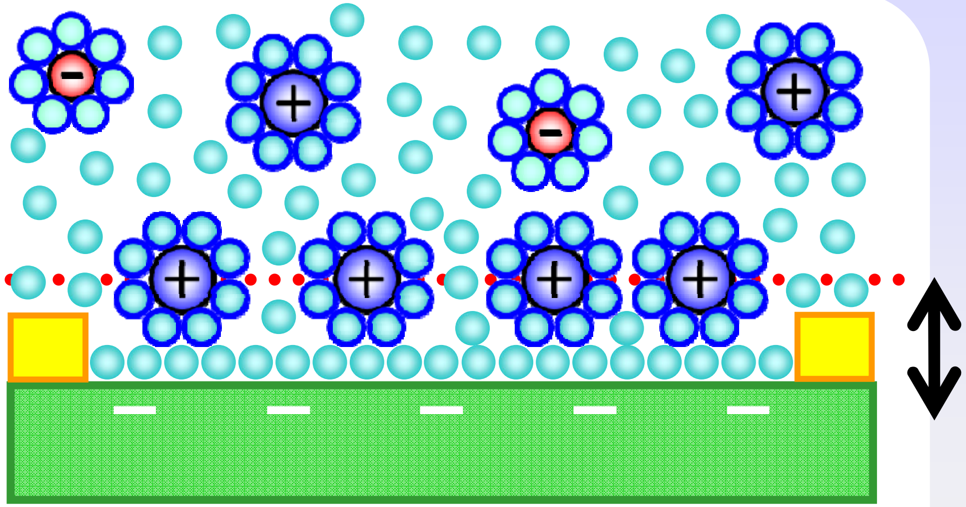
K. Ueno et al., Nat. Mater. 7, 855 (2008)

Two kinds of ionic conductors

Polymer Electrolyte

Solvent + Salt

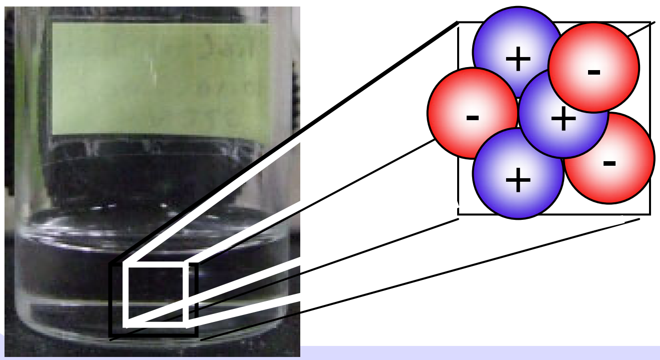


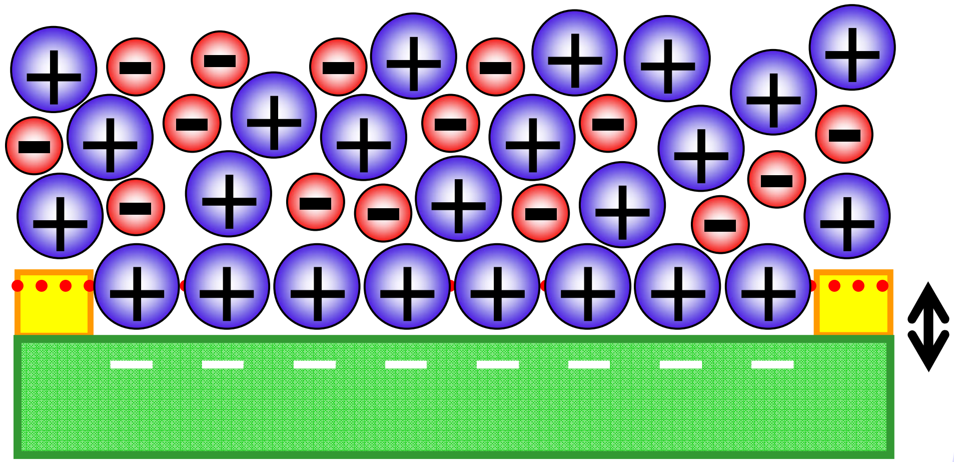


d ~ size of solvent molecule

Ionic Liquid

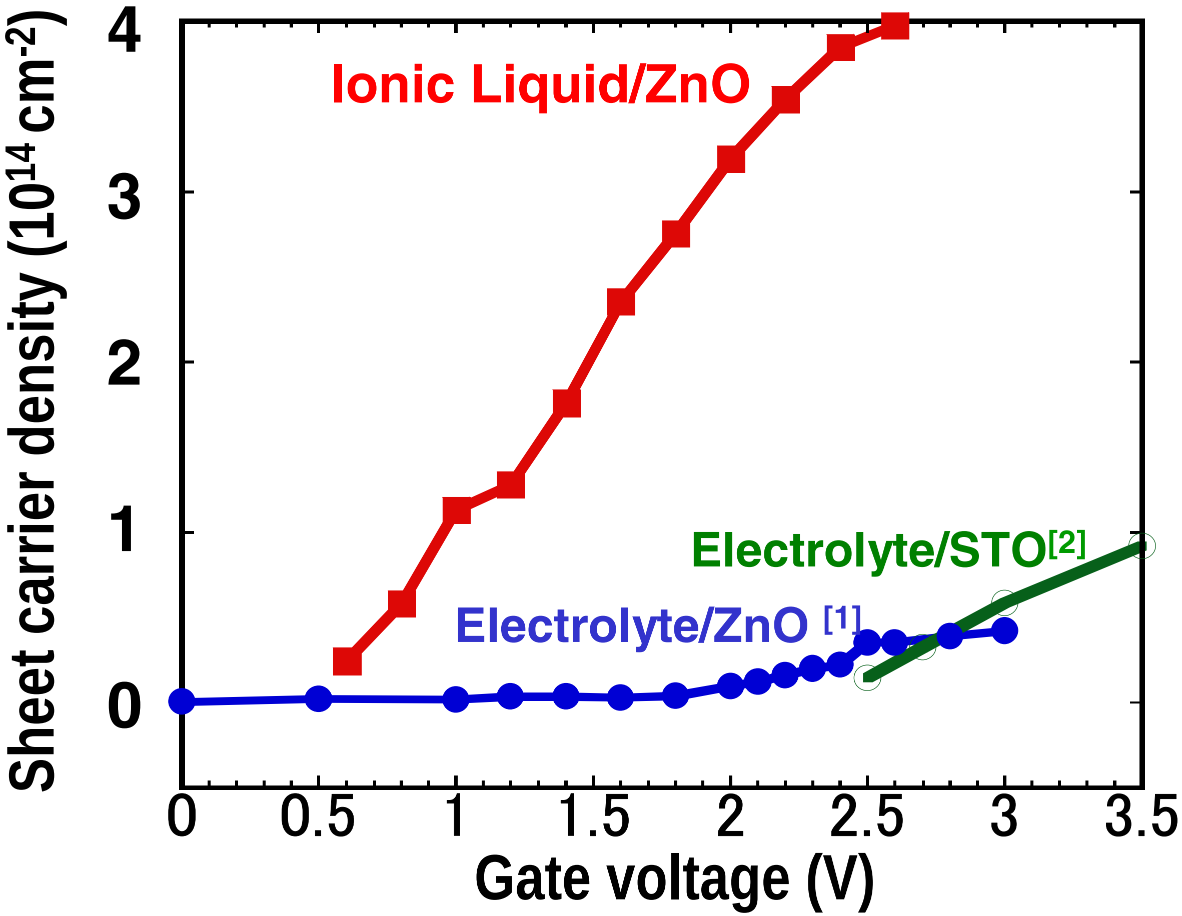
Melt at RT





d ~ size of cation molecule smaller than electrolyte

Carrier density from Hall effect using Ionic Liquid



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

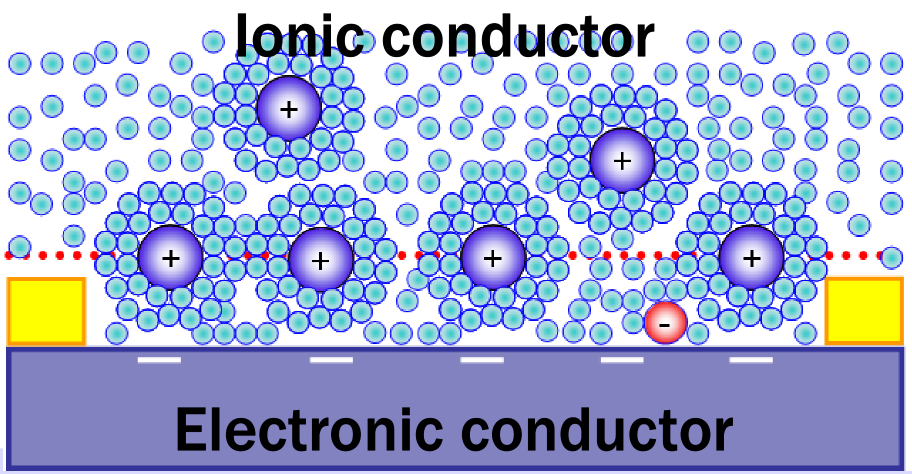
[1] H. Shimotani *et.al., APL.* ***91***,082106 (2007)

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

Summary

非平衡固液界面 ＋ 電界誘起超伝導

- Challenge: Increase Tc
  Discover new superconductors
- Multidisciplinary materials science
  in non- equilibrium states at solid-liquid interfaces



Electric Double Layer Transistor