Enhanced and Continuous Electrostatic Carrier Density Control for Mottronics


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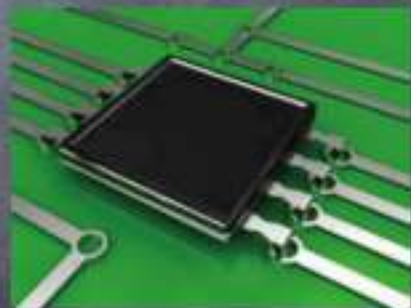
What are expected for Mott FET

I. Overcome the "**Miniaturisation Limit**"

II. **High Speed** but **Low Power** Consumption



III. **Multi**-functionality

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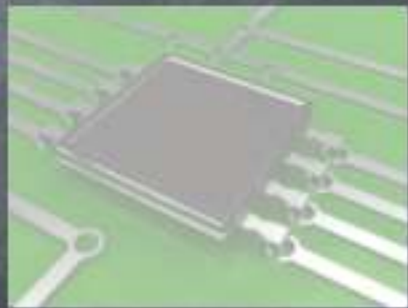
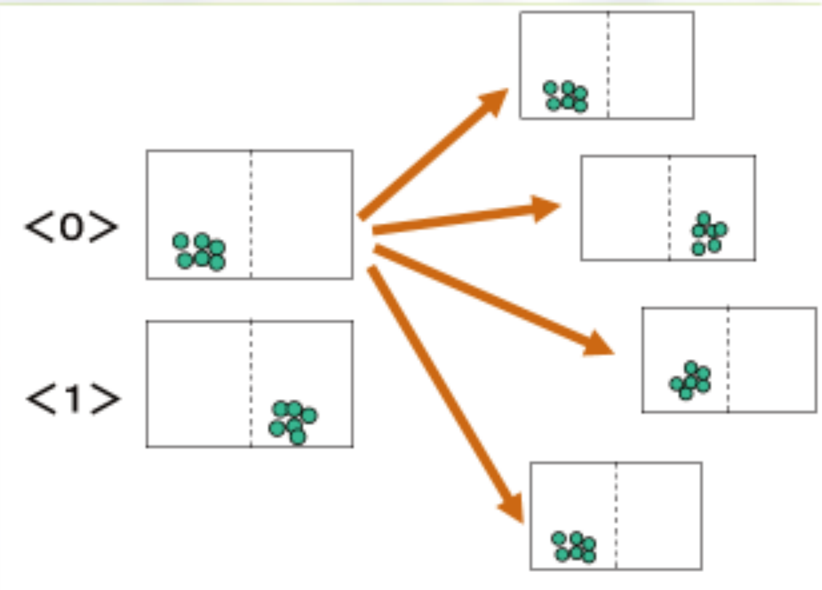
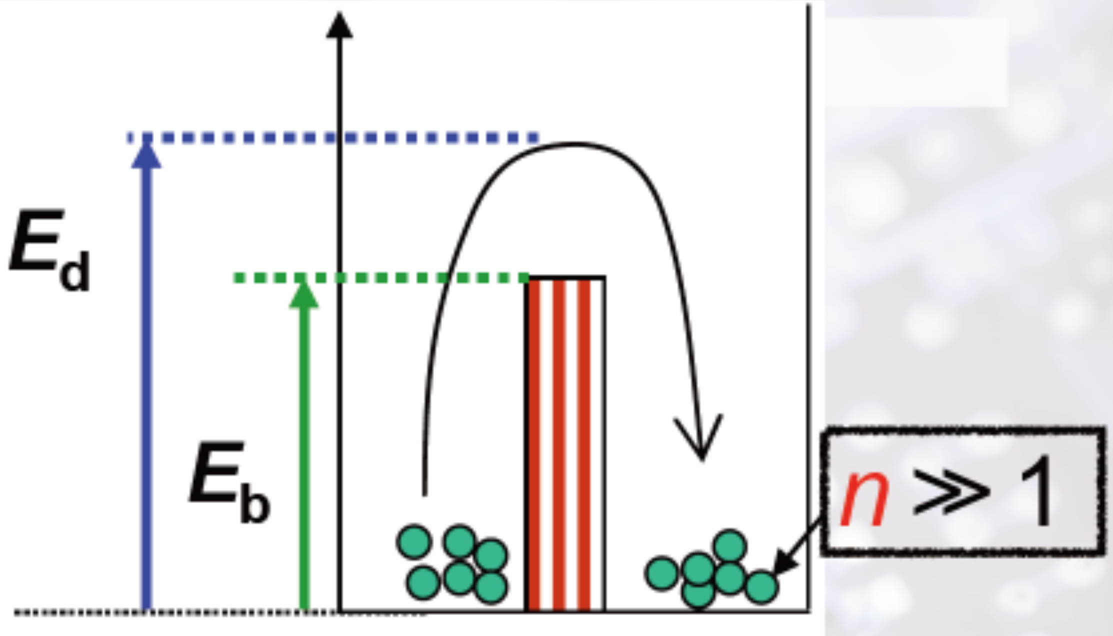


III. Multi-functionality

Switching energy of a transistor



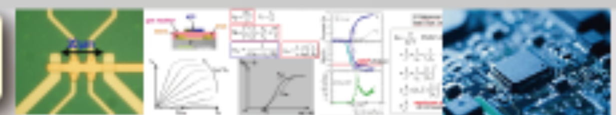


each <0> and <1> must be clearly distinguished and controlled

switching energy
$nE_d \gg 100k_BT \sim 2.6eV$

$E_d = E_b$ + dissipation

$100k_BT$ = thermal noise limit

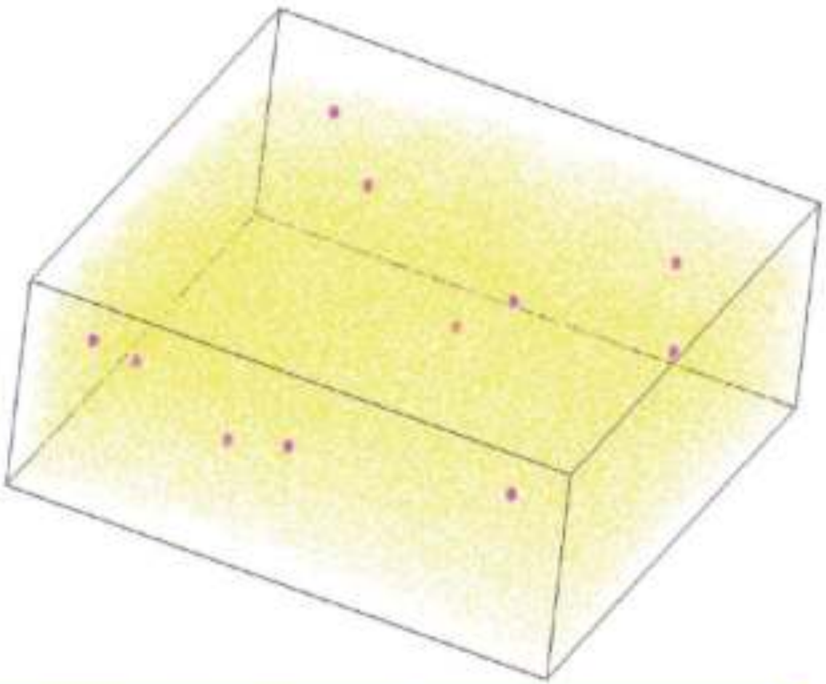



MOSFET in ~2020

Figure 3 **Three-dimensional atom probe (3DAP) reconstruction of 11 boron dopants (large pink dots) in silicon (small yellow dots). The analysed volume is 20 nm × 20 nm × 5 nm. The 3DAP technique can detect the position and chemical species of dopant atoms within a small volume, but it cannot yet provide crucial information about their electrical activity.**

Image courtesy of Alfred Cerezo (University of Oxford) and David Larson (Seagate Technology).

M. R. Castell et al., Nature Materials **2**, 129 (2003)

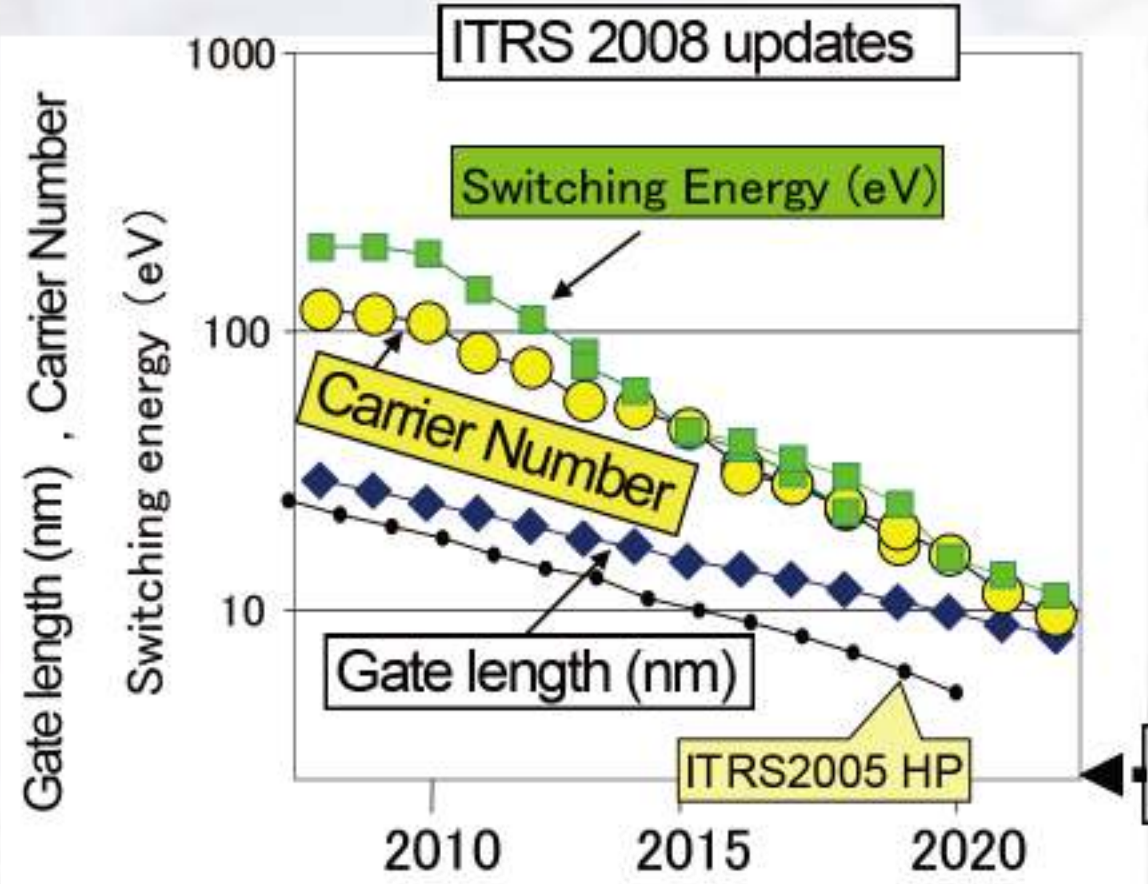


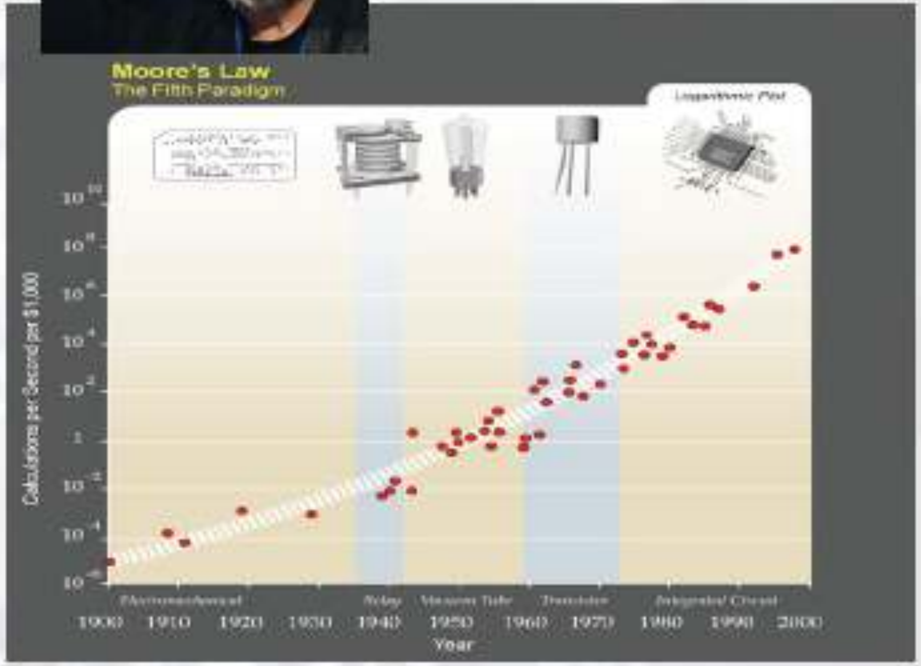
20nm device has only 11 carriers.

switching energy

$nE_d \sim 100k_BT \sim 2.6eV$

Miniaturisation limit

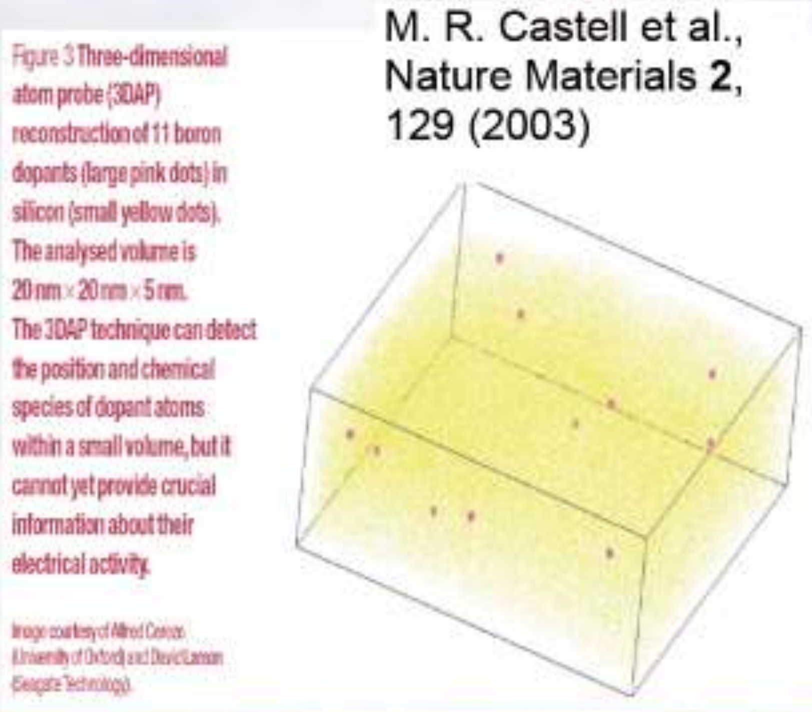




Is Mott FET better?

MOSFET in 2020

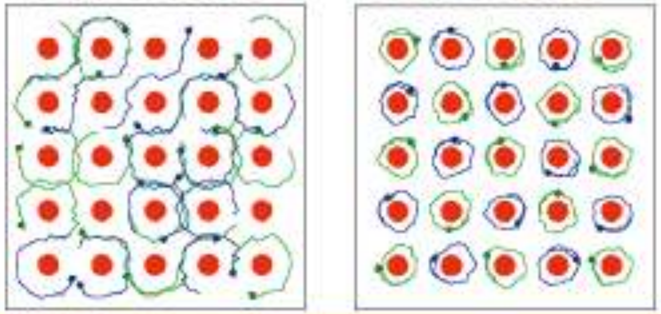
M. R. Castell et al., Nature Materials **2**, 129 (2003)



20nm device has only 11 carriers. Almost the end of the minituarisation

Mott FET

On State / Off State



20nm device has more than 100,000 carriers. Carrier density is independent of device sizes.

Analogous with "self-similar" Peano curves

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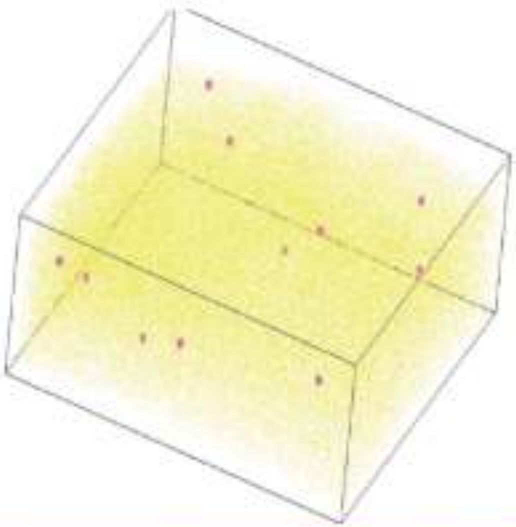
Figure 3 Three-dimensional atom probe (3DAP) reconstruction of 11 boron dopants (large pink dots) in silicon (small yellow dots). The analysed volume is 20 nm × 20 nm × 5 nm. The 3DAP technique can detect the position and chemical species of dopant atoms within a small volume, but it cannot yet provide crucial information about their electrical activity.



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On State Off State

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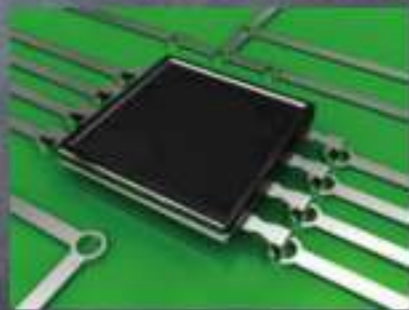
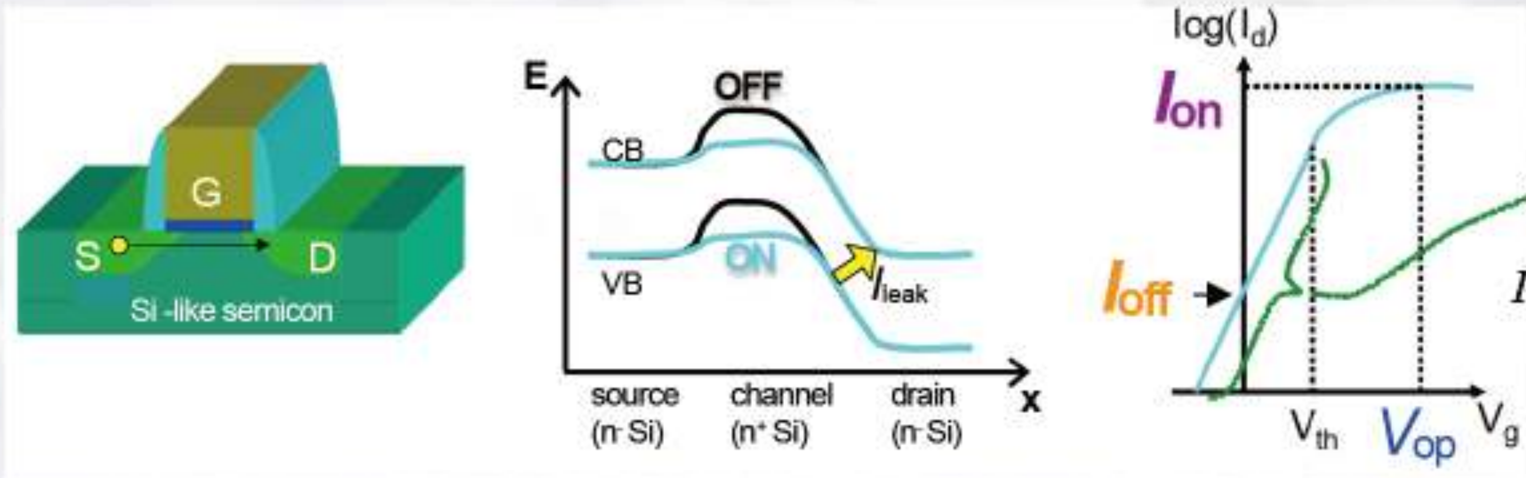


III. Multi-functionality

Sophisticated Si FET



$$I_{\rm leak} \propto \exp\left(-\frac{V_{\rm th} - V_{\rm G}}{k_{\rm B}T}\right)$$

$$I_{\rm off} \propto \exp\left(-\frac{V_{\rm th}}{k_{\rm B}T}\right)$$

Total Power Consumption = Operating Power + Standby Power

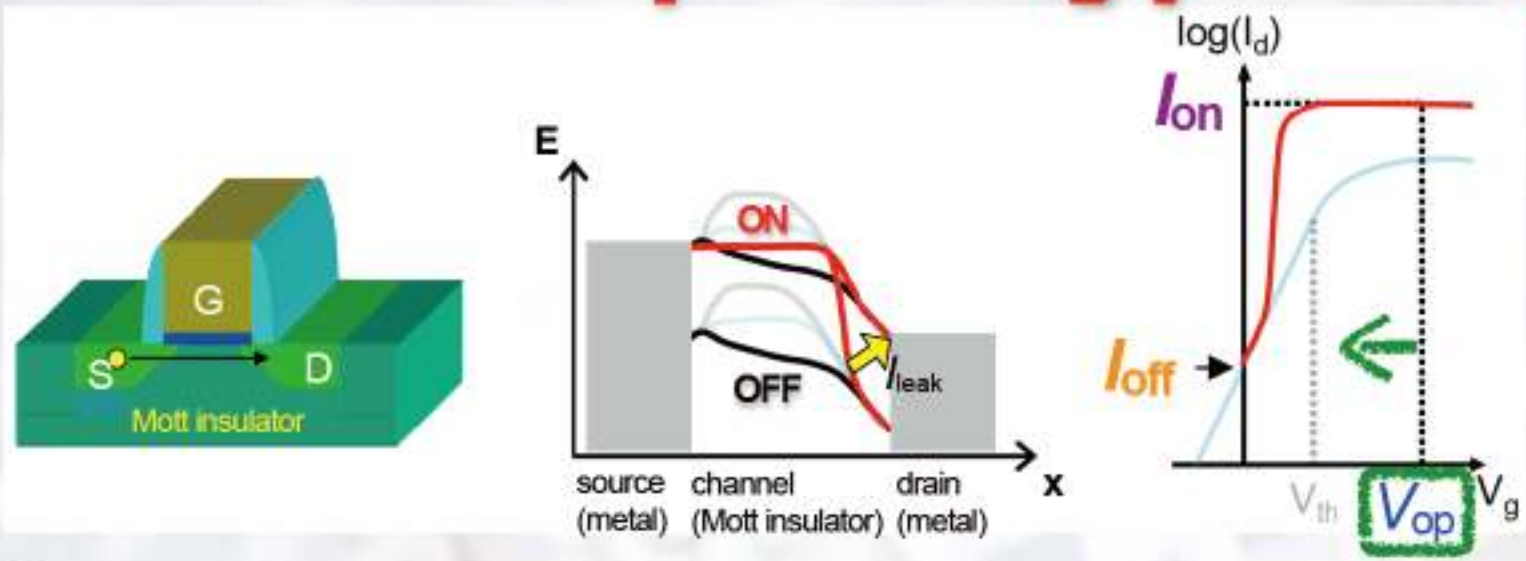
Operating Power $\propto f \cdot C \cdot V_{op}^{2}$ Standby Power $\propto I_{off} \cdot V_{op}$

Switching Speed $\propto \dfrac{I_{on}}{CV_{op}}$

requires

- CV_{op}^2 ⬇ more than f ⬆ ✗
- V_{op} ⬇ and I_{off} ⬇ ✓
- CV_{op} ⬇ and I_{on} ⬆ ✗

Mott FET prototype at present



Total Power Consumption = Operating Power + Standby Power

$\propto f \cdot C \cdot V_{op}^{\;2}$ $\qquad \propto I_{off} \cdot V_{op}$

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- CV_{op}^2 ⬇ more than f ⬆ ✗
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i.inoue@aist.go.jp http://staff.aist.go.jp/i.inoue/

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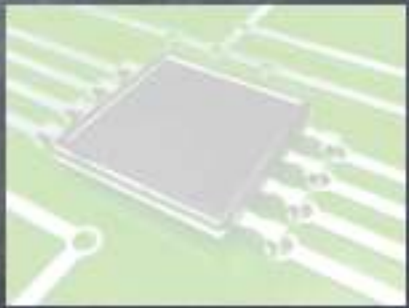


III. **Multi**-functionality

Multi-functionality

Action of the electromagnetic field

$$S_0 = \frac{1}{8\pi}\int d^3x dt \left(\varepsilon \mathbf{E}^2 - \frac{1}{\mu}\mathbf{B}^2 \right)$$

Adding this scalar term does **not affect** the Maxwell's equations

$$S_\theta = \left(\frac{\theta}{2\pi}\right)\left(\frac{\alpha}{2\pi}\right)\int d^3x dt \mathbf{E}\cdot\mathbf{B} \qquad \alpha = \frac{e^2}{\hbar c}$$

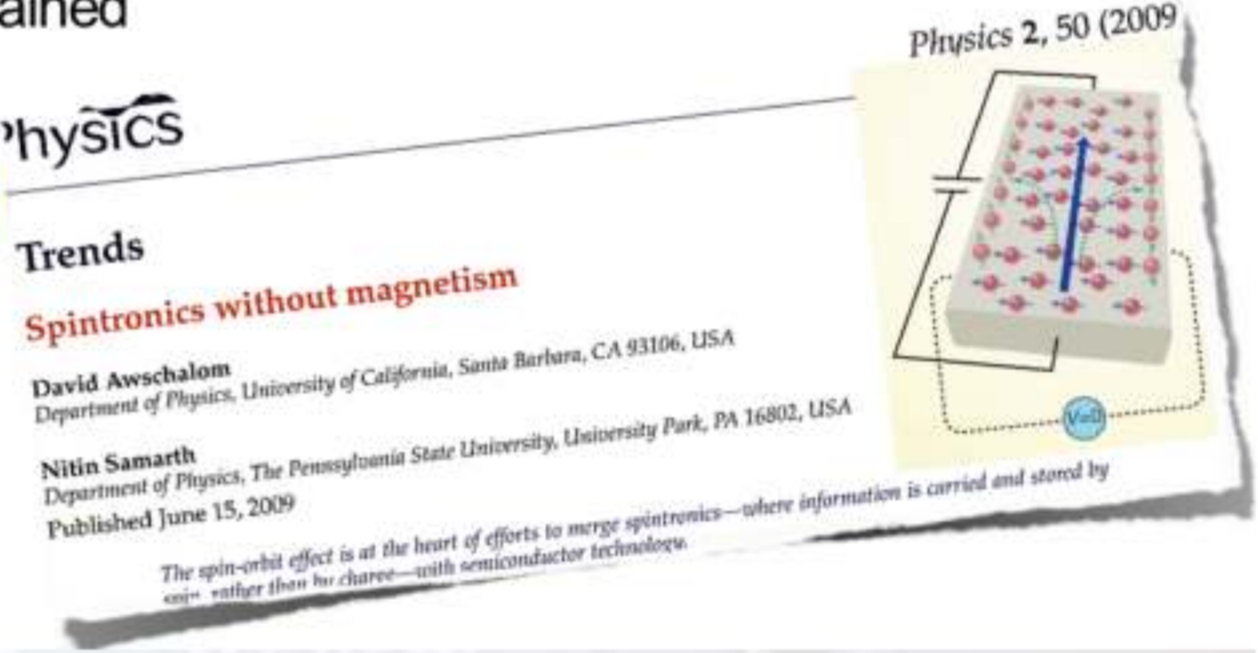
Then, the following relations are obtained

$$\mathbf{D} = \mathbf{E} + 4\pi\boxed{\mathbf{P}} - 2\alpha P_3\boxed{\mathbf{B}}$$

$$\mathbf{H} = \mathbf{B} - 4\pi\boxed{\mathbf{M}} + 2\alpha P_3\boxed{\mathbf{E}}$$

$$P_3(x) = \theta(x)/2\pi$$

S_θ is a kind of spin-orbit interaction



Physics 2, 50 (2009

Physics

Trends

Spintronics without magnetism

David Awschalom
Department of Physics, University of California, Santa Barbara, CA 93106, USA

Nitin Samarth
Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

Published June 15, 2009

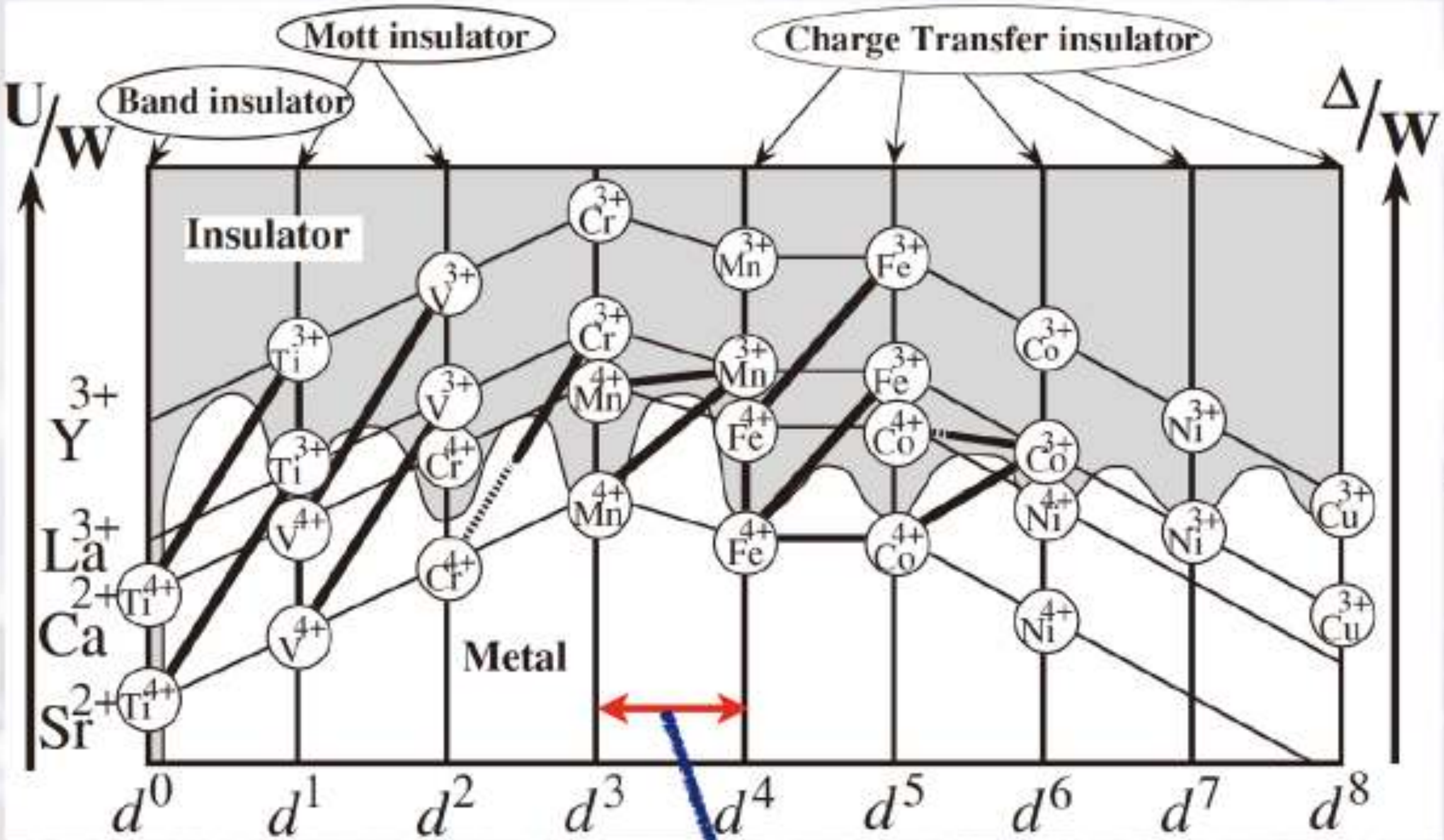
The spin-orbit effect is at the heart of efforts to merge spintronics—where information is carried and stored by rather than by charge—with semiconductor technology.

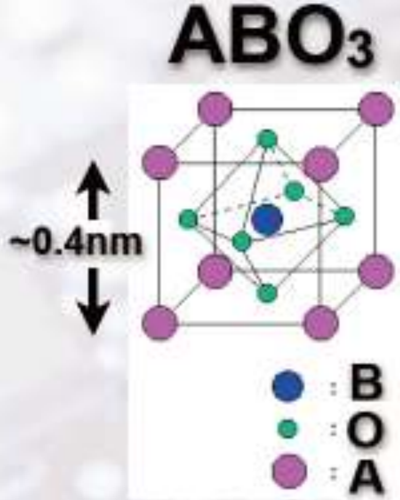
Obstacles to the Mott FET

I. **Huge** amount of **carrier density** control

II. Correlated materials
≈ ionic crystals = **Defects** form easily.

Huge carrier density control





I. H. Inoue,
Semicond. Sci. Technol.
20, 1 (2005)

$\sim 1.6 \times 10^{22}$ cm^{-3}

$= \sim 6 \times 10^{15}$ cm^{-2} / 4 nm

Obstacles to the Mott FET

I. **Huge** amount of **carrier density** control

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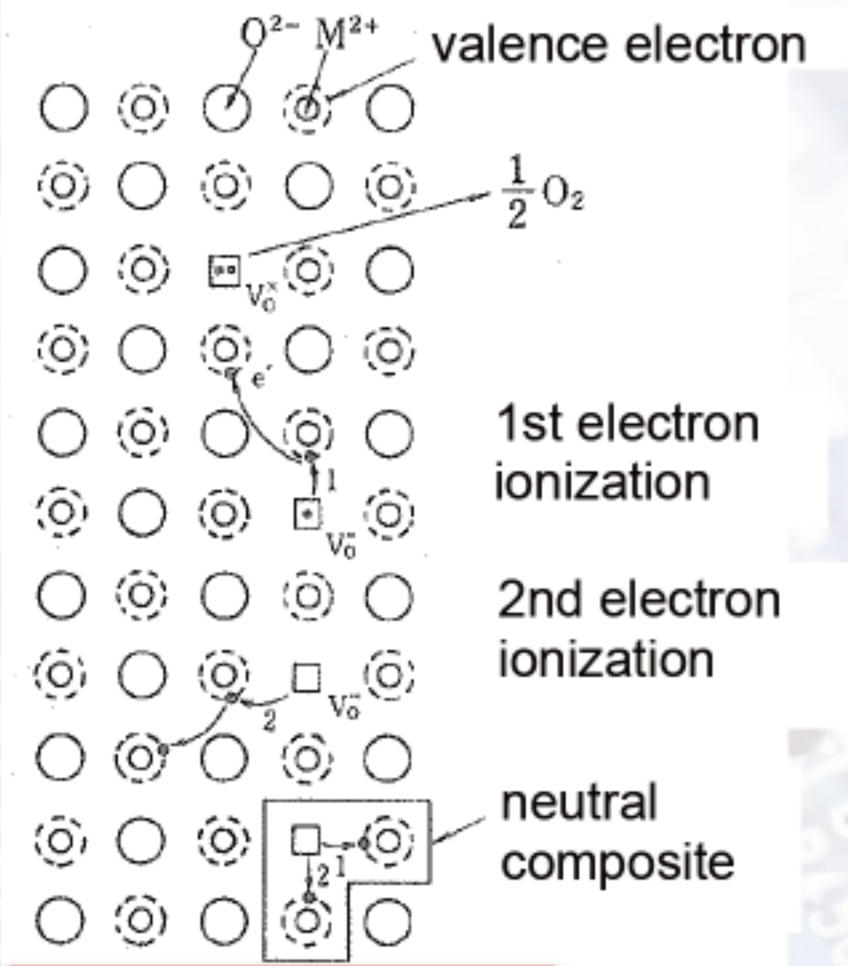
≈ ionic crystals = **Defects** form easily.

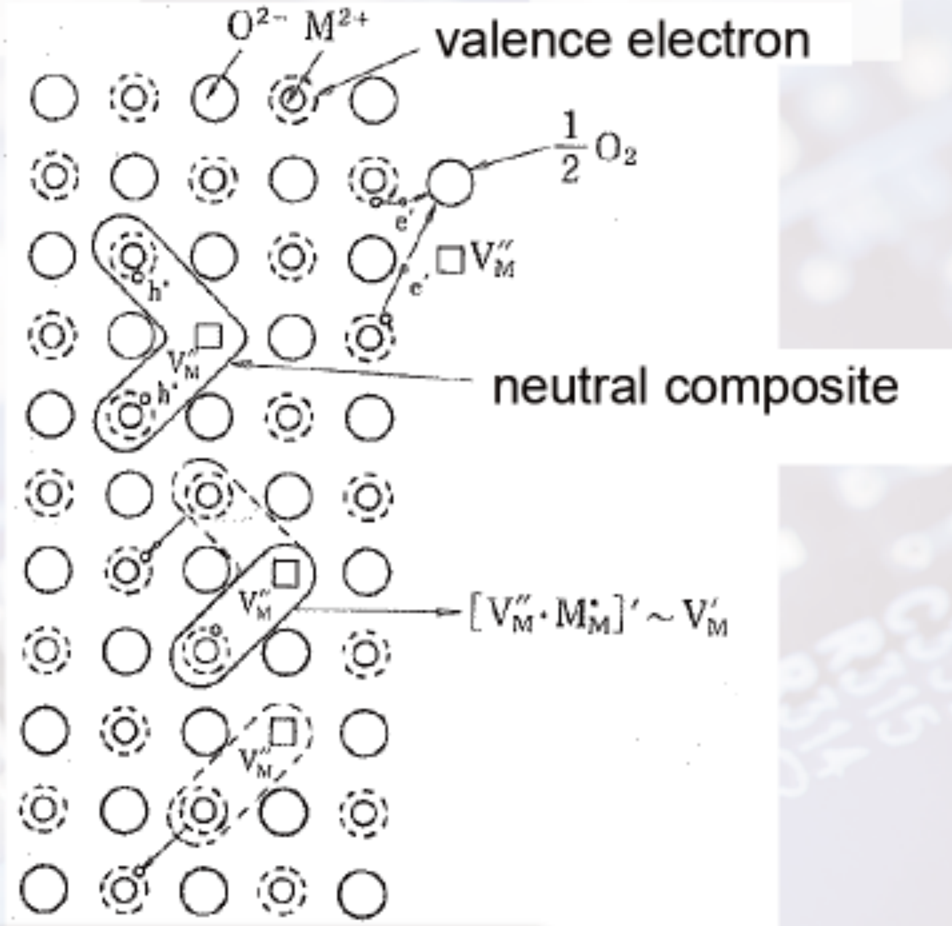
Defects in transition-metal oxides

TiO_{2-x}



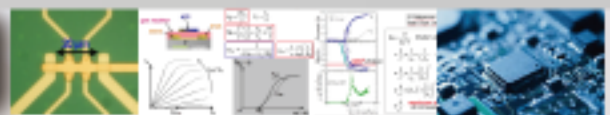
$$O_O + 2M_M \rightarrow V_O^{\bullet\bullet} + 2M_M' + \frac{1}{2}O_2$$

$Co_{1-x}O$, $Fe_{1-x}O$, $Ni_{1-x}O$



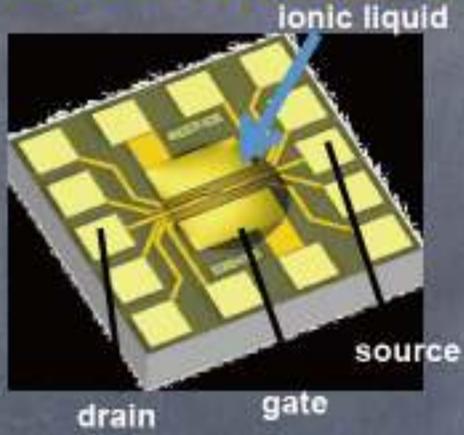
$$\frac{1}{2}O_2 + 2M_M \rightarrow V_M'' + 2M_M^{\bullet} + O_O$$

i.inoue@aist.go.jp http://staff.aist.go.jp/i.inoue/



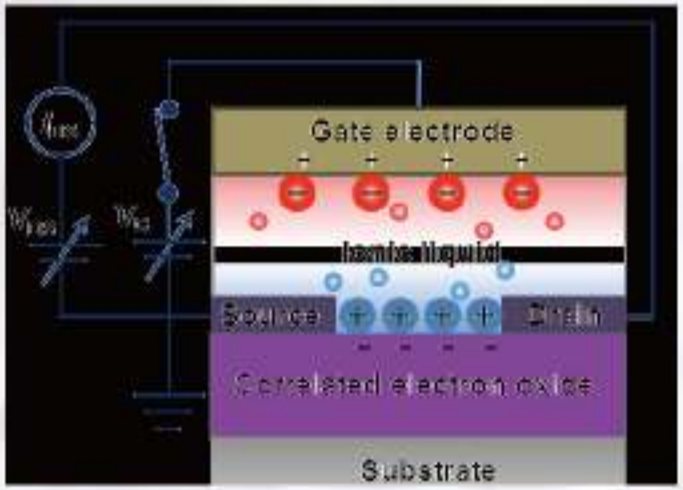
Candidates of the Mott FET

I. Electric double layer FET

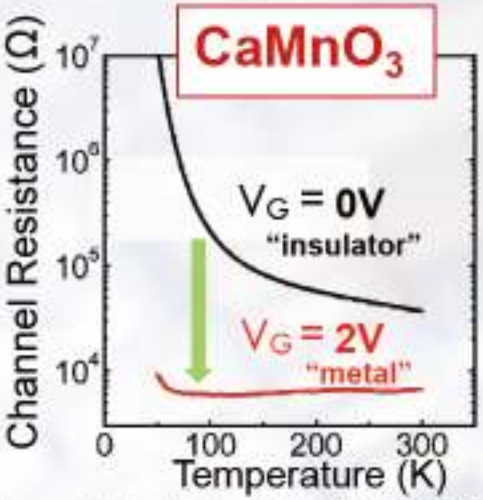


II. Hybrid gate-insulator FET

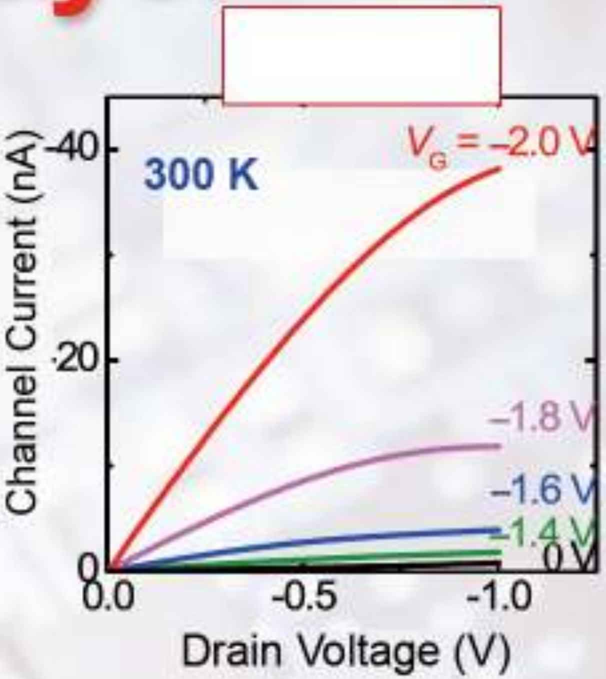
Electric Double Layer



$10\ \mu F/cm^2 \times 2\ V = 1.25 \times 10^{14}\ e\ /\ cm^2$

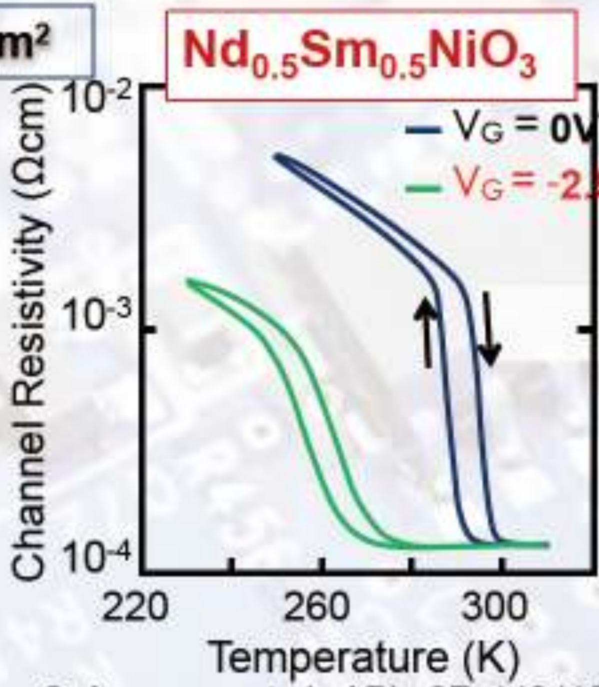


P.H.Xiang et al., Adv. Mat. **23**, 5822 (2011)

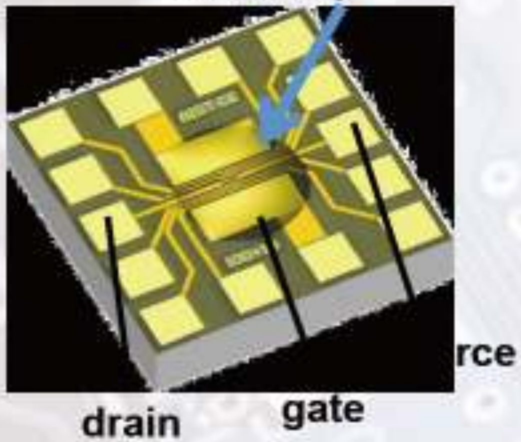


P.H.Xiang et al., submitted to APL

ionic liquid
[N,N-diethyl-N-(2-methoxyethyl)-N-methylammonium tetrafluoroborate DEME-BF4]

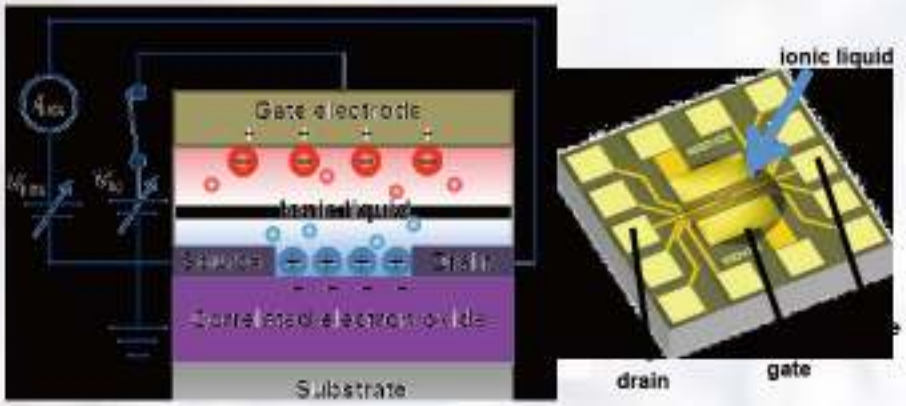


S. Asanuma et al., APL. **97**, 142110 (2010)

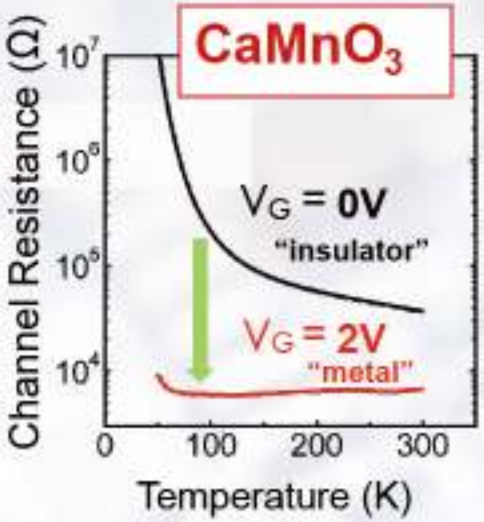


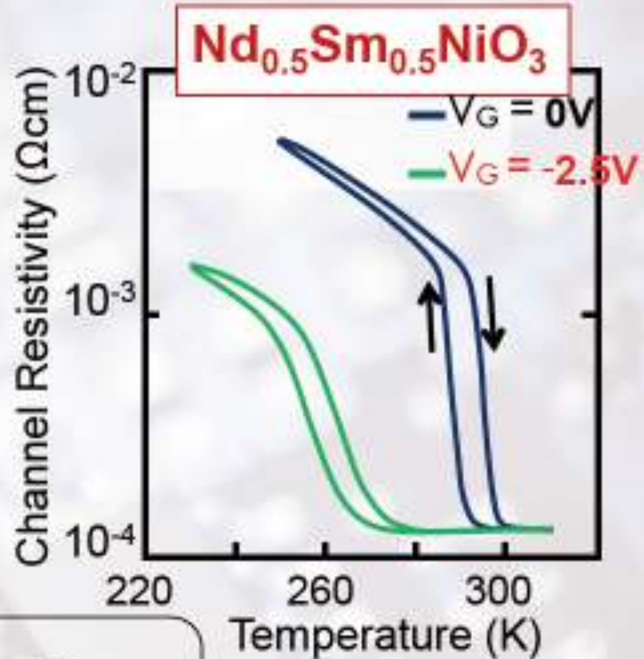
Very Promising!!

Electric Double Layer



10 μF/cm² × 2 V = 1.25 × 10¹⁴ e / cm²





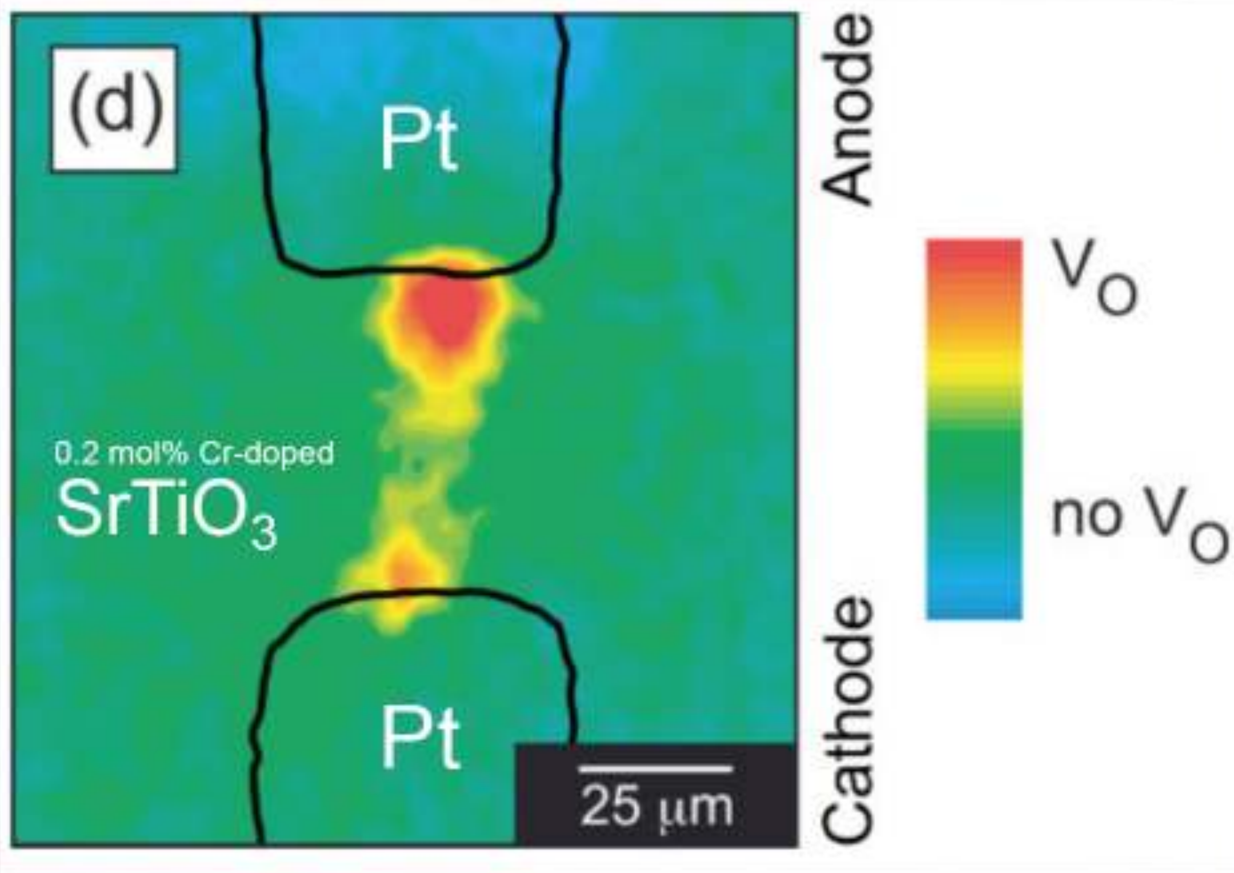
Total Power Consumption = Operating Power + Standby Power

$\propto f \cdot C \cdot V_{\mathrm{op}}{}^2$ $\quad\propto I_{\mathrm{off}} \cdot V_{\mathrm{op}}$

Switching Speed $\propto \dfrac{I_{\mathrm{on}}}{C \cdot V_{\mathrm{op}}}$

- **Miniaturisation is difficult**...
- *C* is too large compared to I_{on}/V_{op}...
- Continuous control of *n* is difficult...
- Moreover...

Oxygen vacancies are created



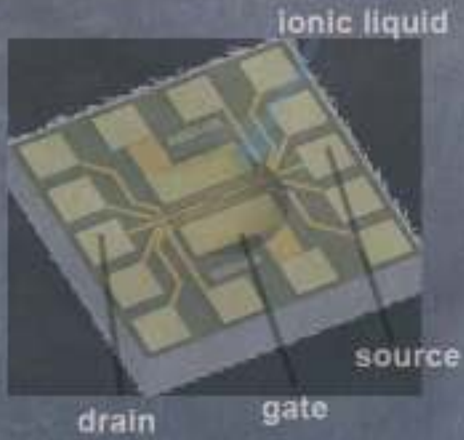
M. Janousch et al., Adv. Mat. **19**, 2232 (2007)

By applying 10^5V/cm for about 30 min

Oxygen vacancies are created, and distributed in the channel, and form a **metallic path**.

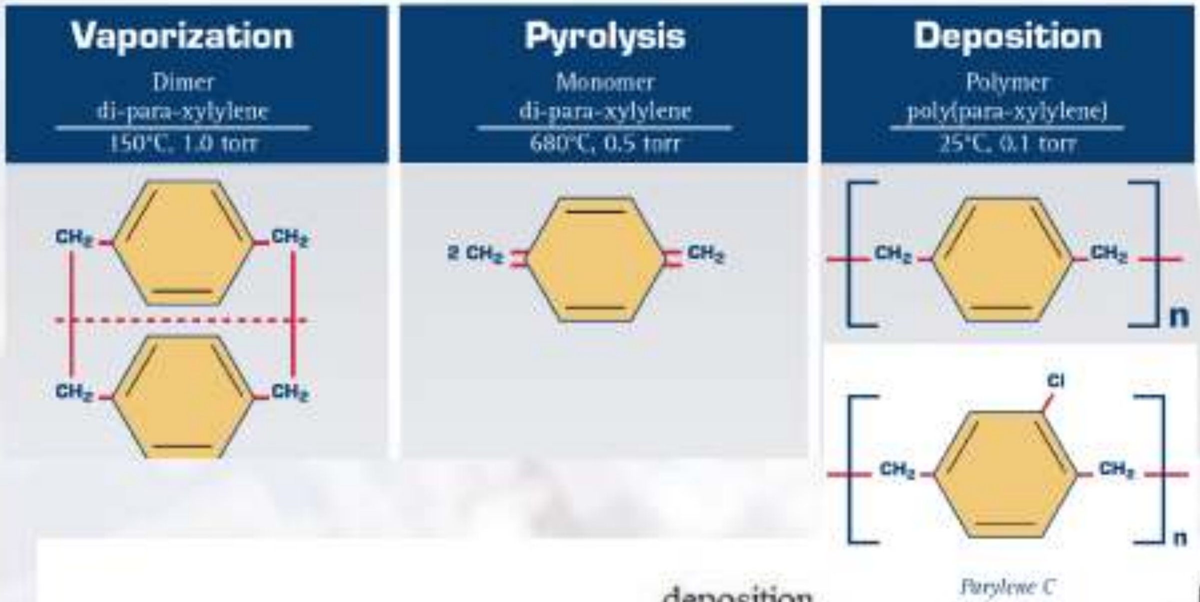
Candidates of the Mott FET

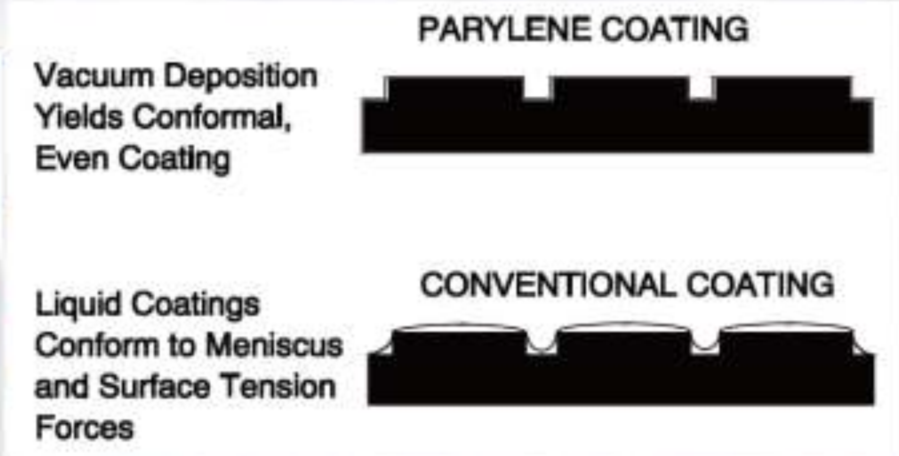
I. Electric double layer FET

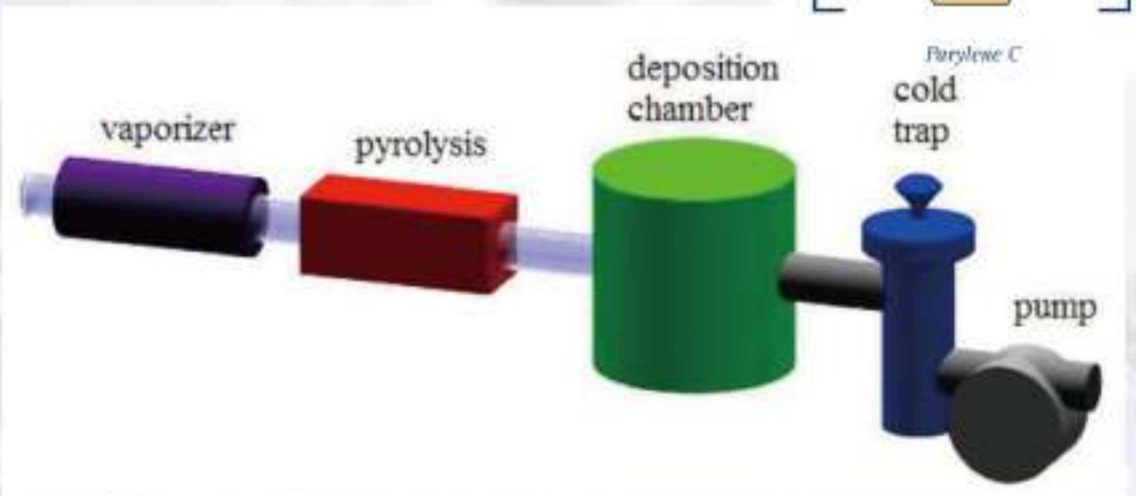


II. Hybrid gate-insulator FET

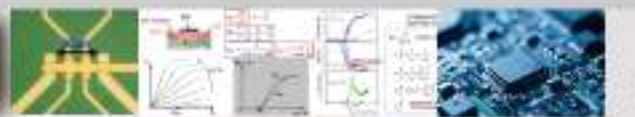
Parylene to protect oxide surface



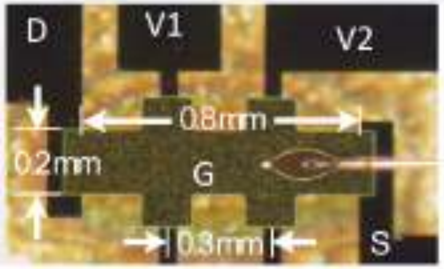


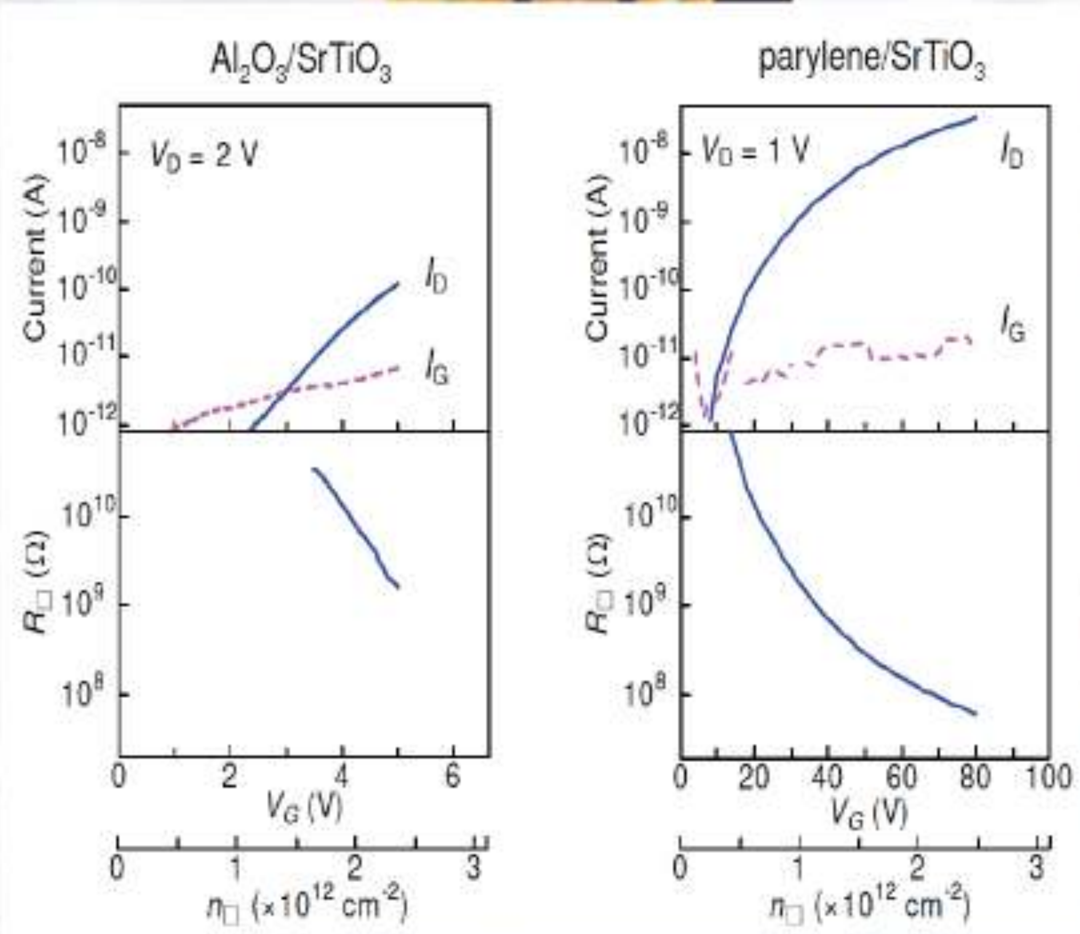


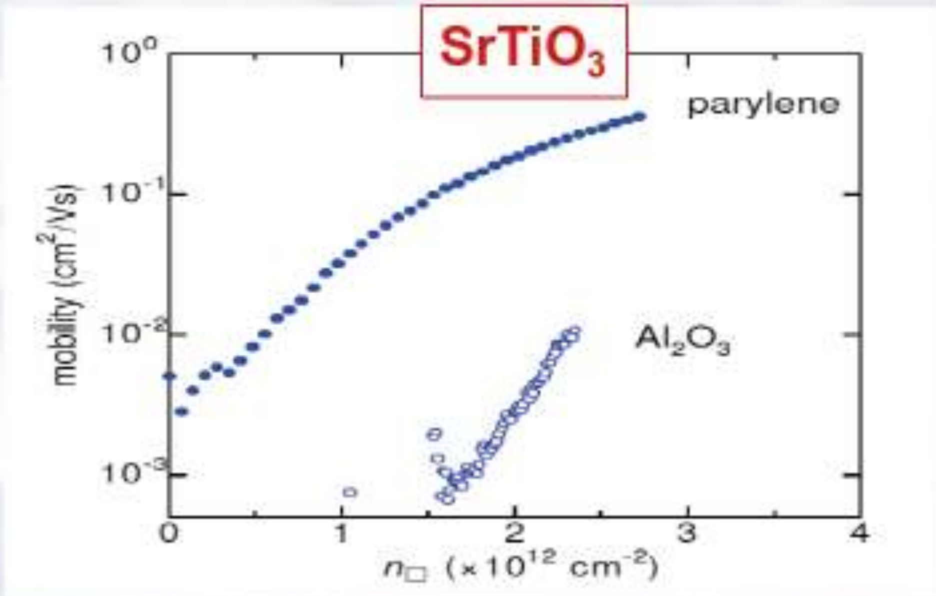
Creation of oxygen vacancies is suppressed.
Channel is kept clean.



Parylene as a gate insulator

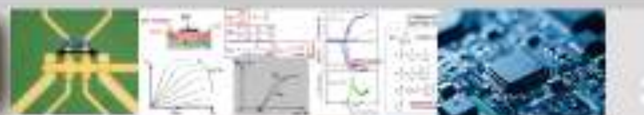




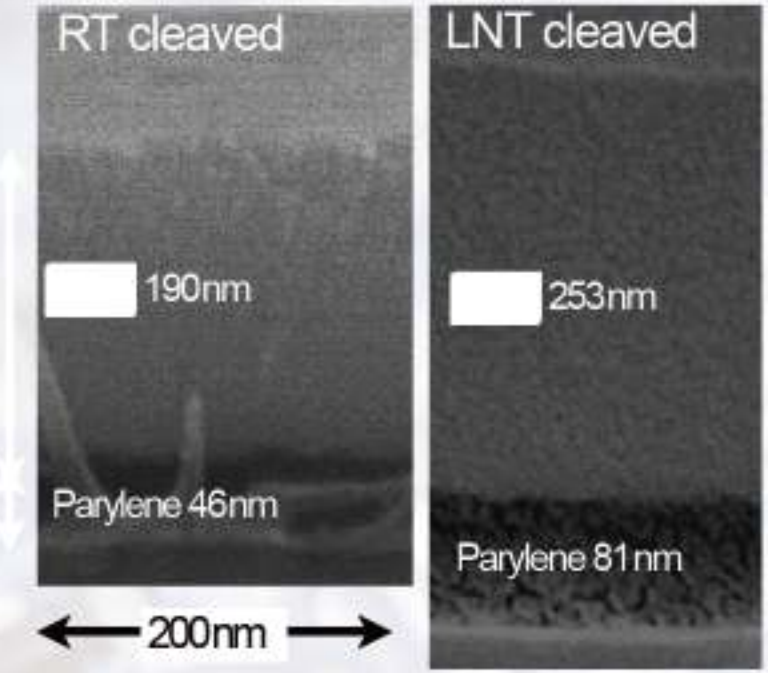


Using Parylene for the gate insulator, mobility is drastically enhanced.

But carrier density is too small...

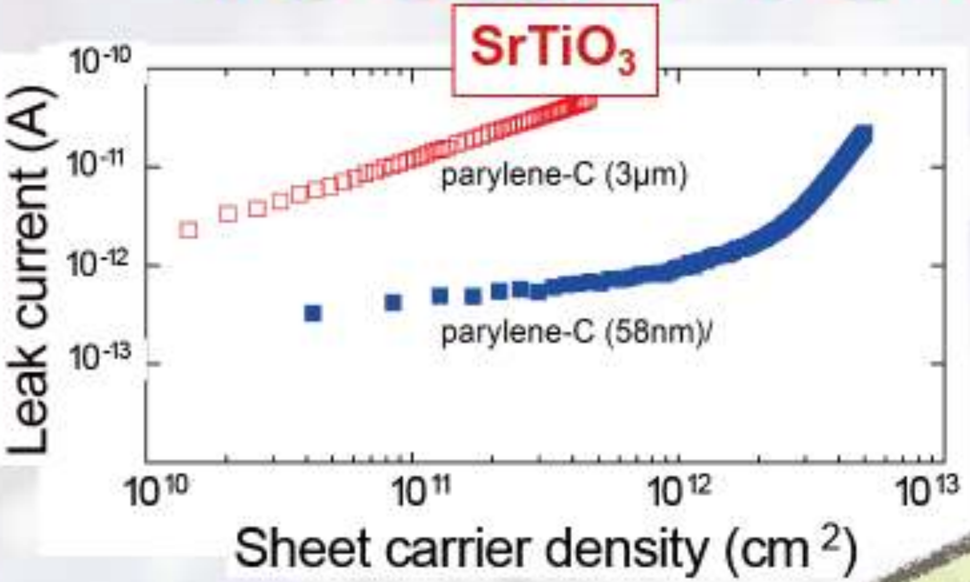


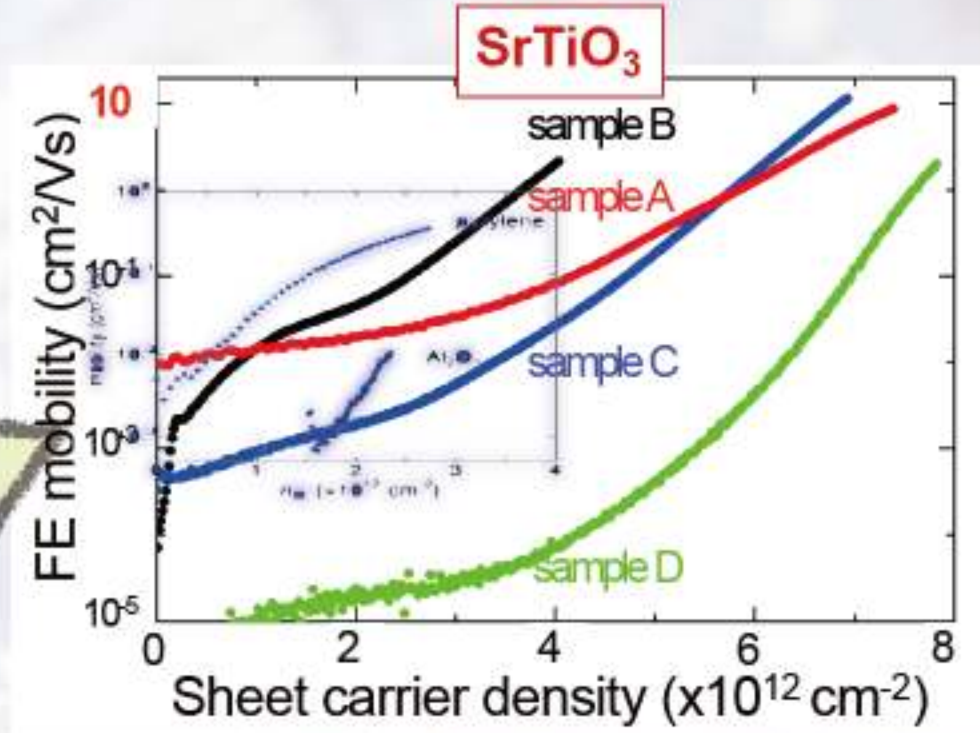
Bilayer Gate Insulator

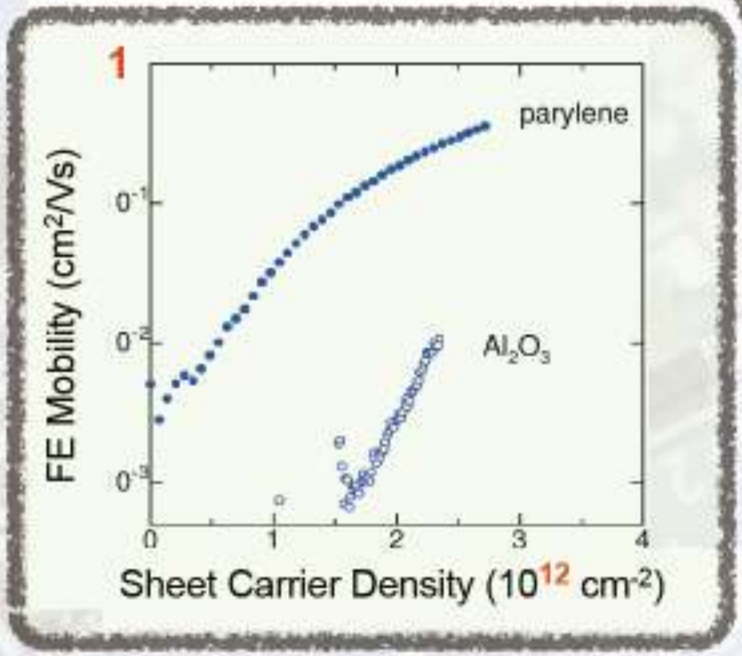


deposition of
on the top of **Parylene-C (ε=3.2)**

10 cm²/Vs & ~10¹³cm⁻²





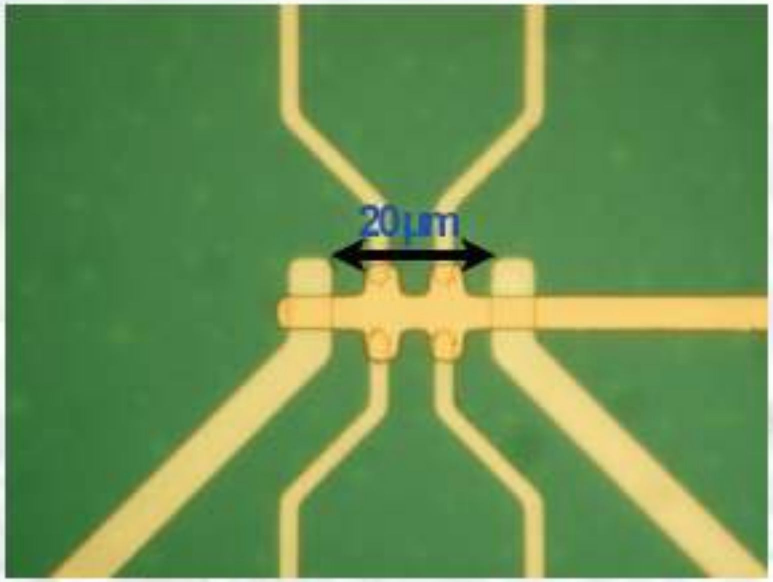


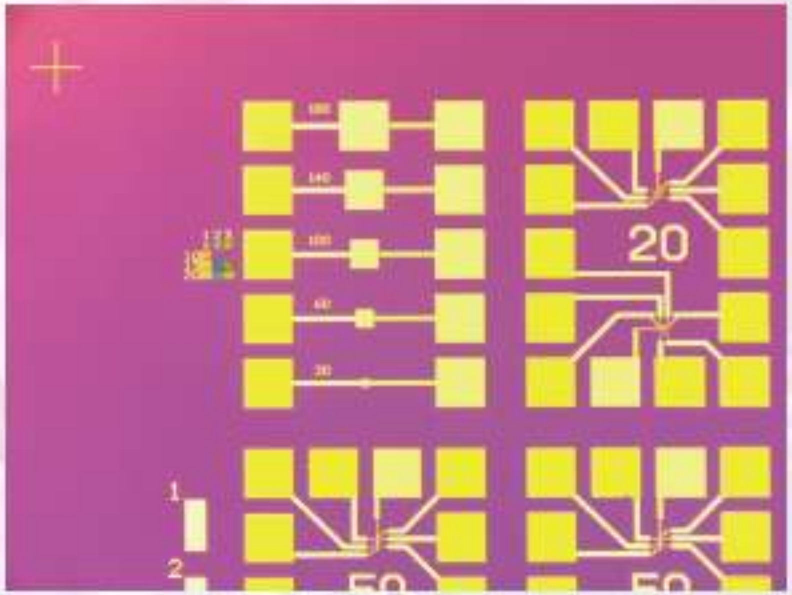
Parylene/ bilayer gate insulator gives **extremely large mobility of 10 cm²/Vs**.

Carrier density reaches ~**10¹³ /cm⁻²** !!

Versatile to photolithography

- Oxide **surface** is first covered by Parylene-C and is **kept clean**
- Parylene-C can be as thin as 5-20nm





Prototype device is coming soon !!

Summary

Expected for future transistors

I. Overcome the "**Miniaturisation Limit**"

II. **High Speed** but **Low Power** Consumption

III. **Multi**-functionality

Obstacles to the Mott FET

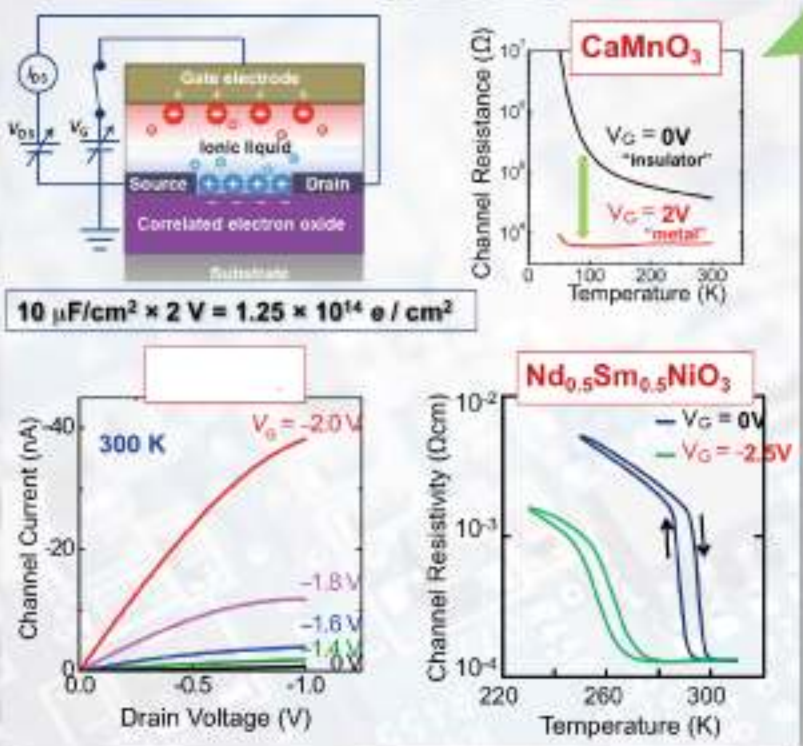
I. **Huge** amount of **carrier density control**

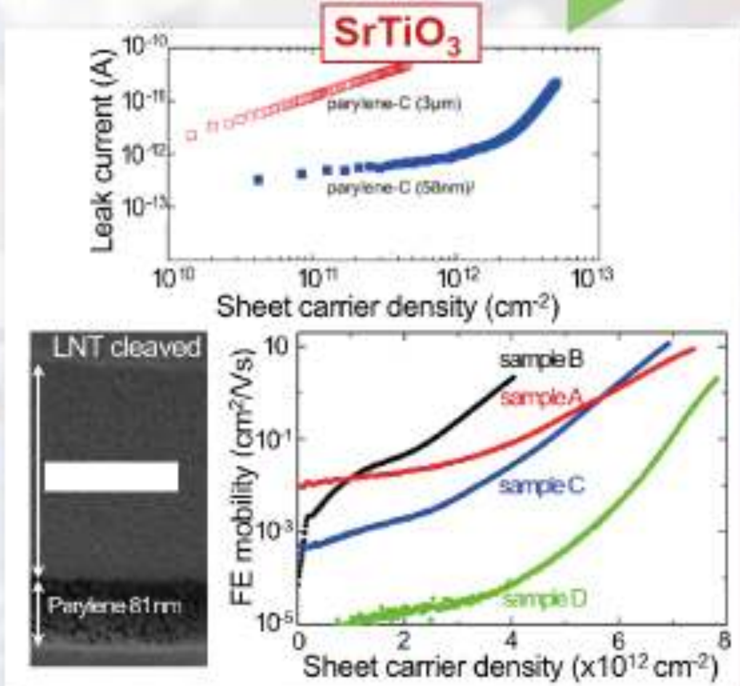
II. Correlated materials ≈ ionic crystals = **Defects** form easily.

Candidates of the Mott FET

I. **Electric double layer** FET

II. **Hybrid gate-insulator** FET

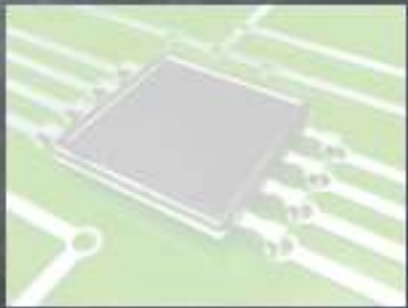




In addition, ...

I. Overcome the "Miniaturisation Limit"

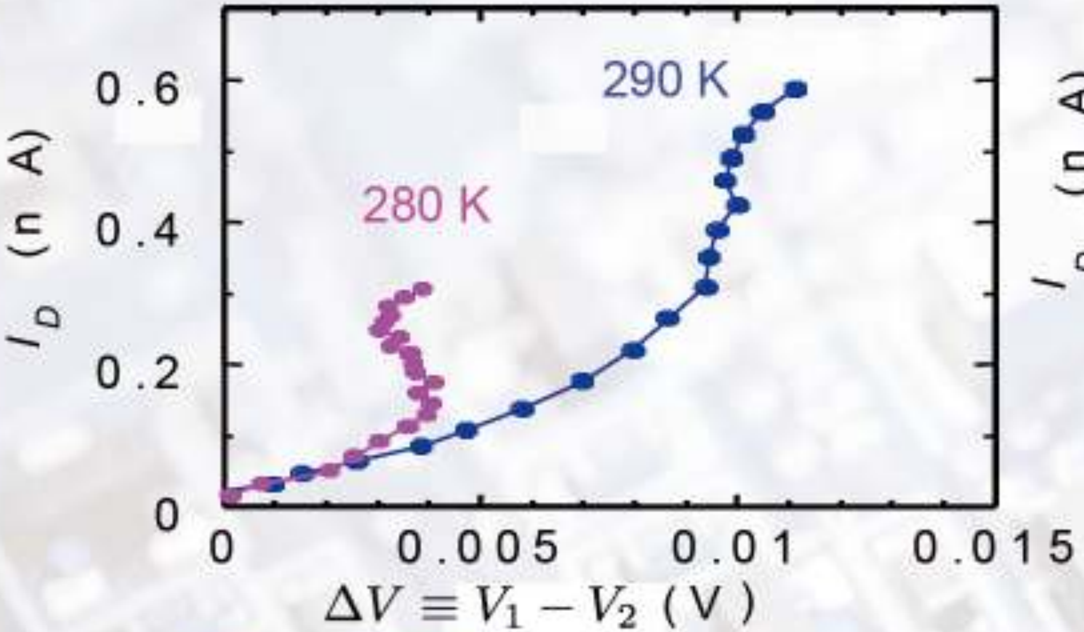
II. High Speed but Low Power Consumption

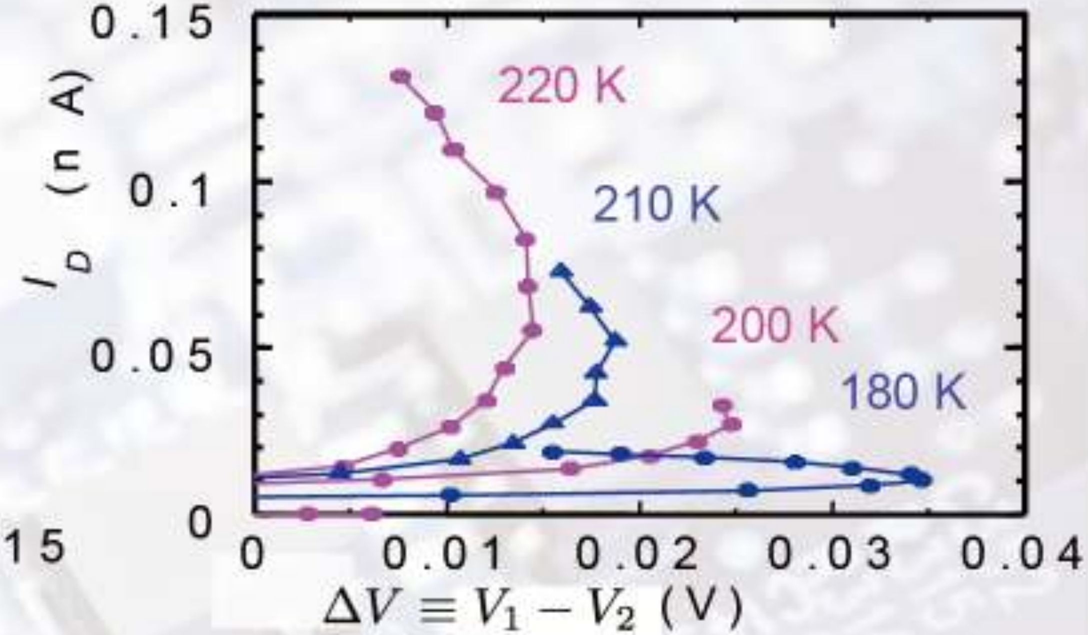


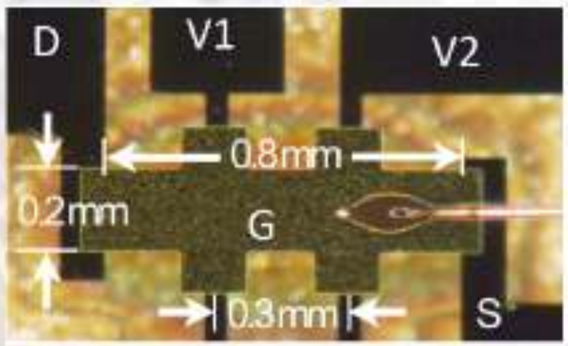
III. **Multi**-functionality

S-shape I-V Curves

Parylene/$SrTiO_3$







Hardly seen in $Al_2O_3/SrTiO_3$

$Al_2O_3/SrTiO_3$ has some amount of carriers from the first

Filamentary Path Formation

Specific Negative Resistance in Solids

By B. K. RIDLEY

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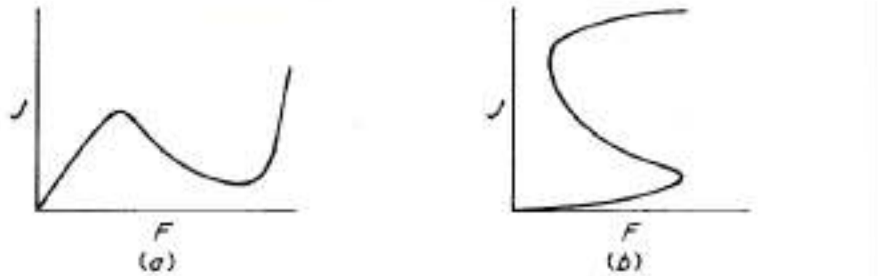


Figure 1. The two types of differential negative resistance: (*a*) voltage-controlled; (*b*) current-controlled.

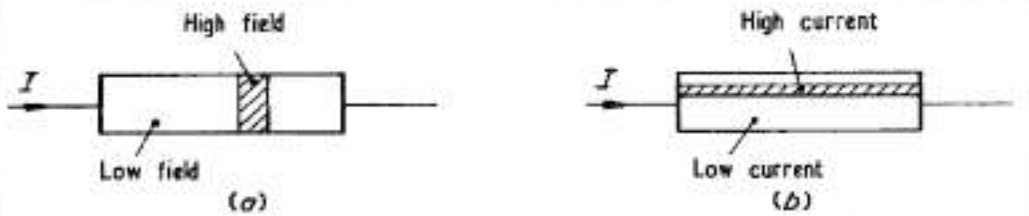
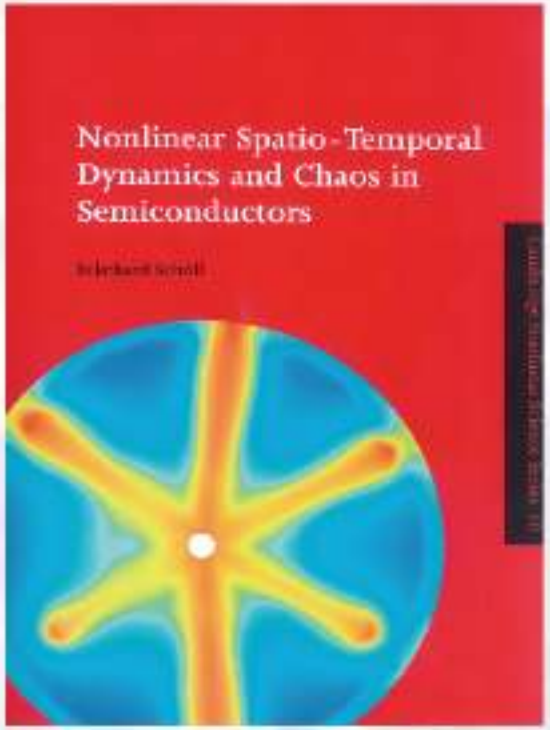


Figure 2. Domain and filament formation: (*a*) domain; (*b*) filament.



"Nonlinear…"
by E. Scholl,
Cambridge Univ. Press
(2001)

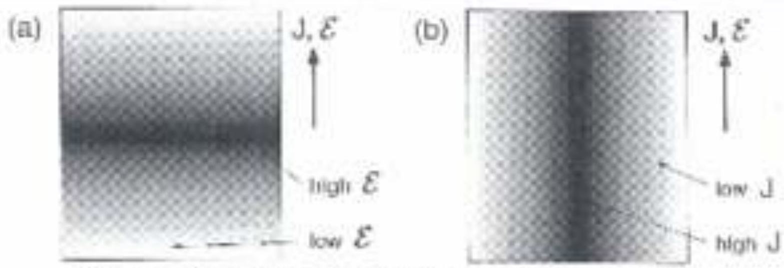
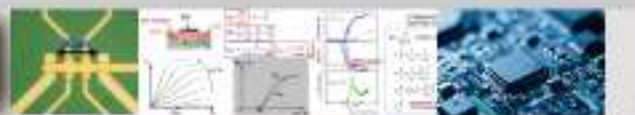
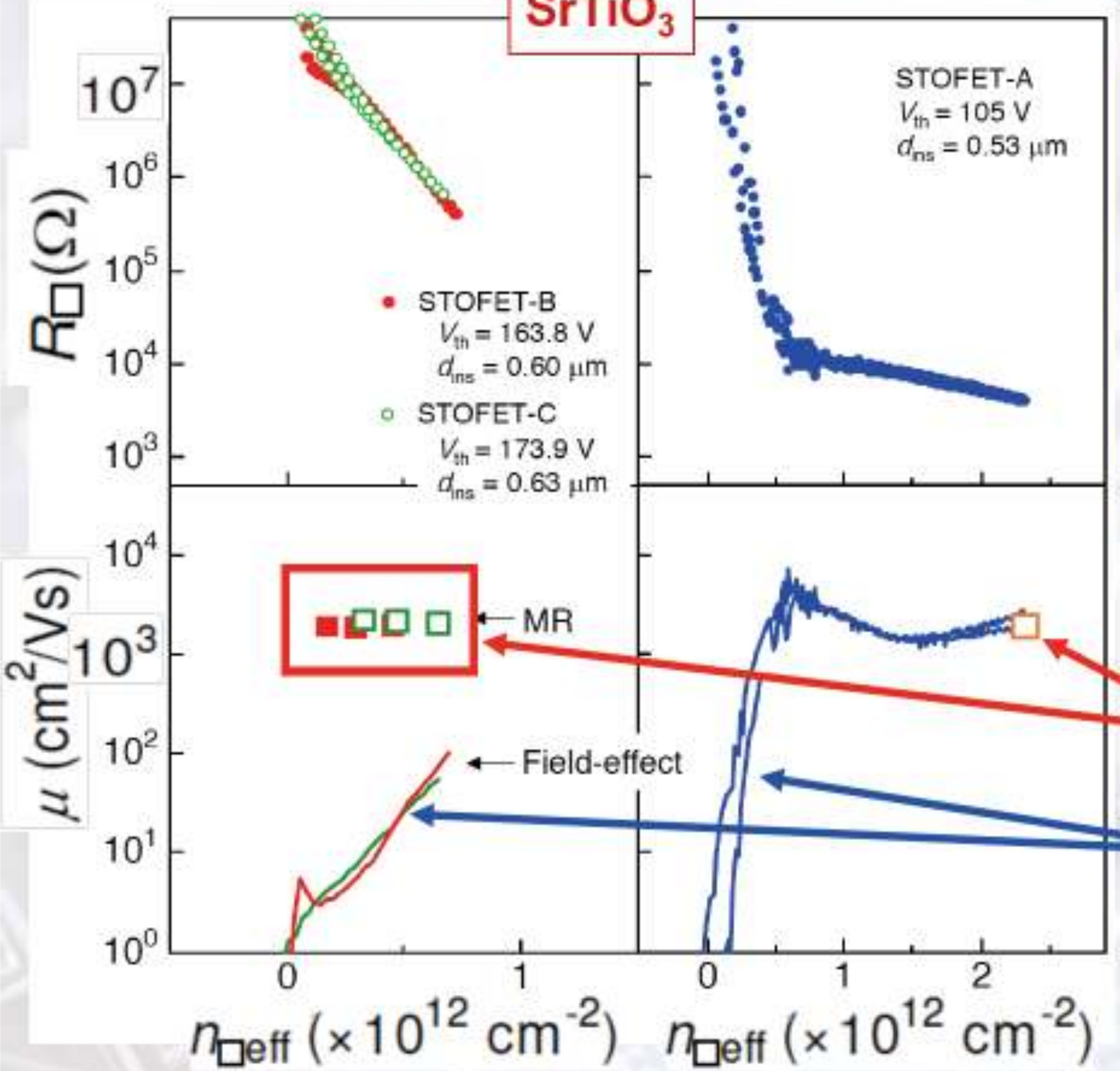


Figure 3.6. Sketches of (a) a high-field domain, and (b) a high current filament, where J is the current density and $\mathcal{E}$ is the electric field.

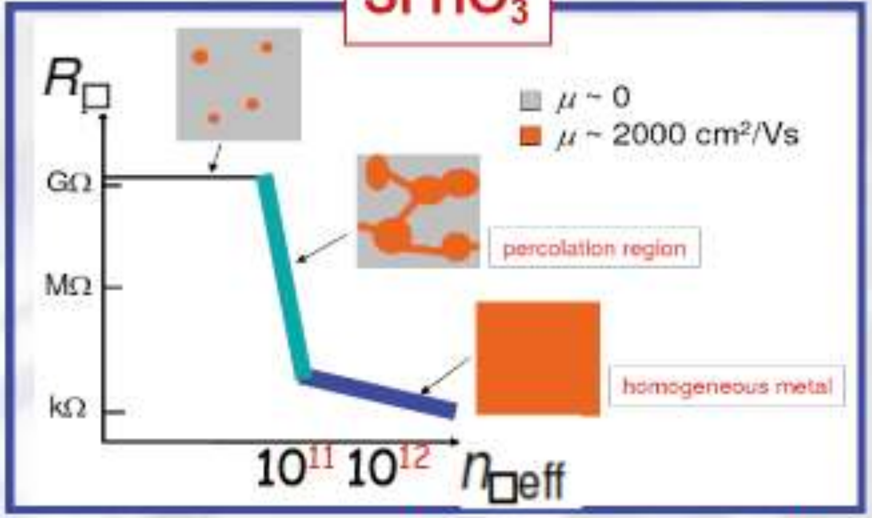


Percolation Model of MI transition

SrTiO$_3$



SrTiO$_3$



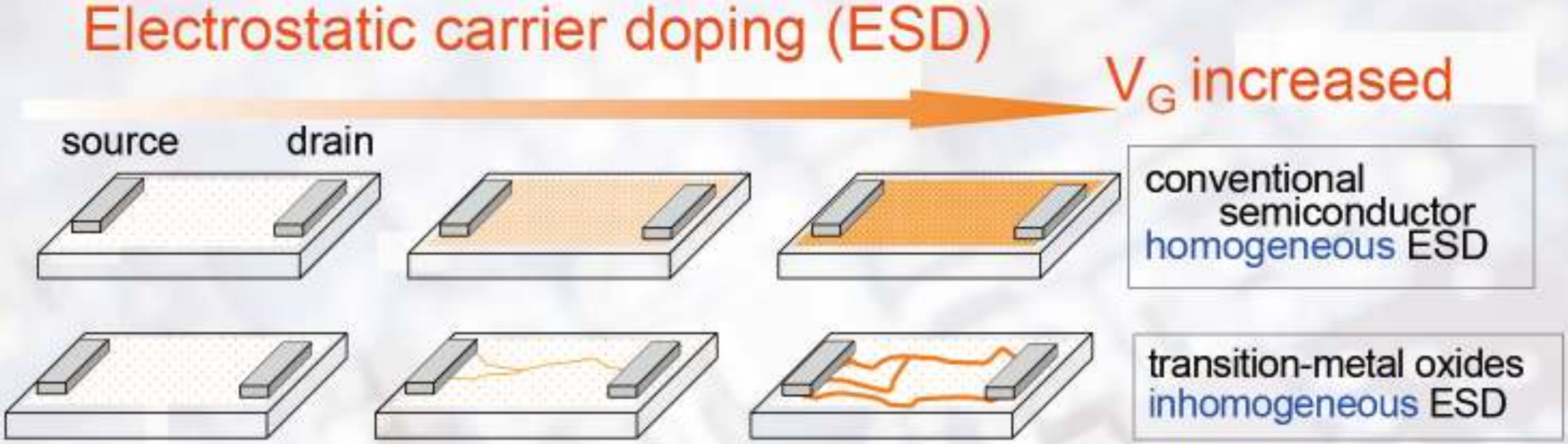
$$\mu_{\mathrm{MR}} = \frac{1}{B}\sqrt{\frac{\Delta R}{R_0}}$$

reflects highest mobility domain in the channel

reflects averaged mobility in the whole channel

$$\mu_{\mathrm{FE}} = \frac{1}{e}\frac{\partial}{\partial n_\square}\left(\frac{1}{R_\square}\right)$$

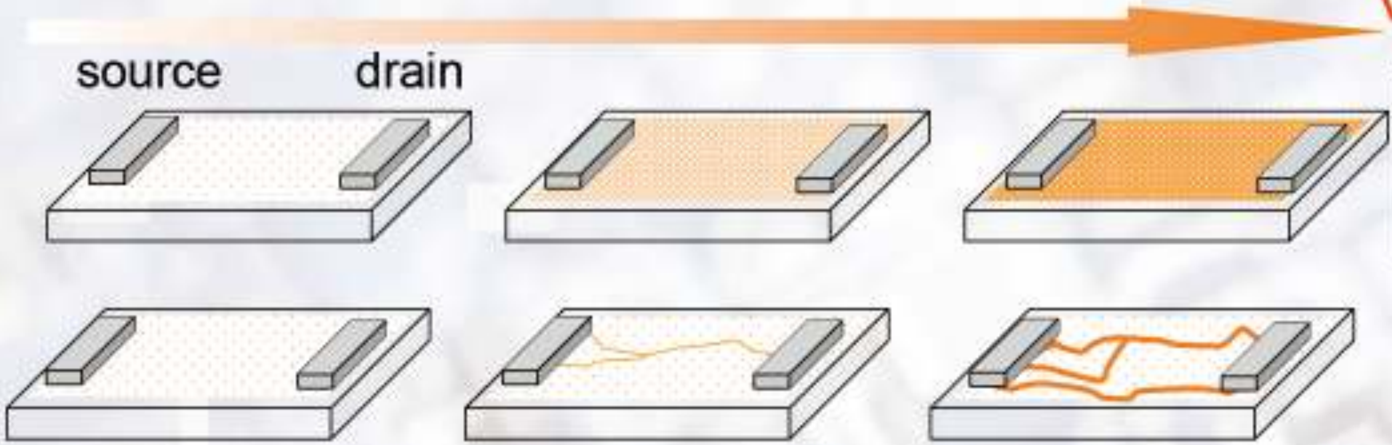
Homo. Channel or Filaments



Homo. Channel or Filaments

Electrostatic carrier doping (ESD)

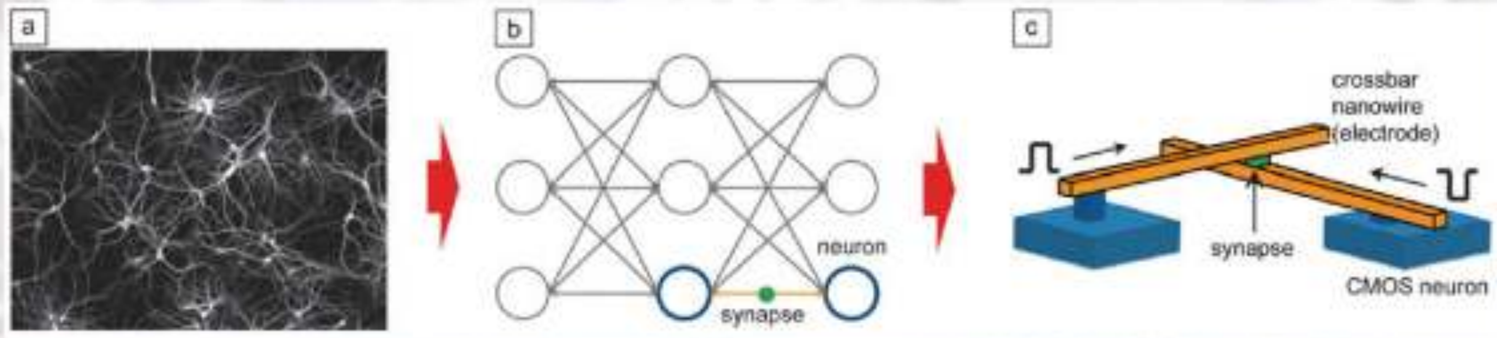
V_G increased



conventional semiconductor
homogeneous ESD

transition-metal oxides
inhomogeneous ESD

Main topic of resistive switching memory --- adaptive electronics



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