SAIT

Graphene for Electronic Applications

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creation+

SAMSUNG
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Graphene

: Carbon allotrope with hexagonal arrangemnt in one-atomic-thick sheet.

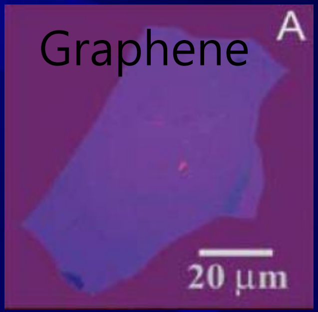
- Andre Geim and Konstantin Novoselov (Manchester University) (2004)
- Nobel Prize in Physics (2010)

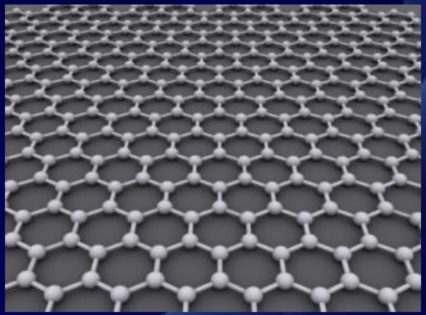
  “Groundbreaking experiments regarding the two dimensional materials graphene”

Isolation of Graphene

Isolated multi-layer Graphene from Graphite using scotch tape

⇒

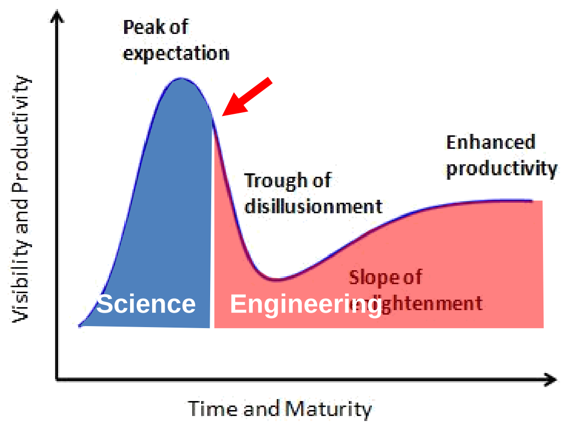


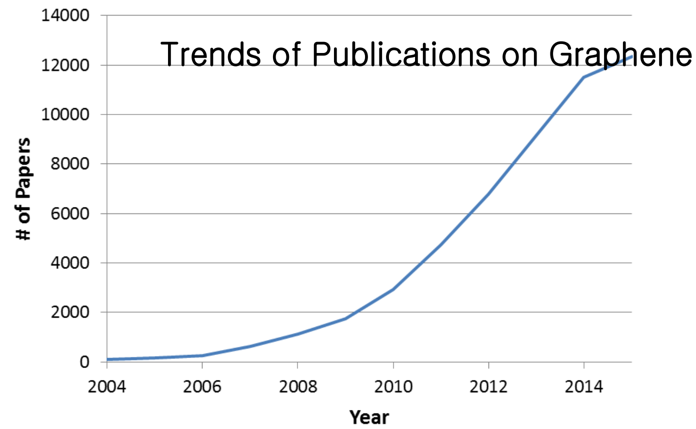


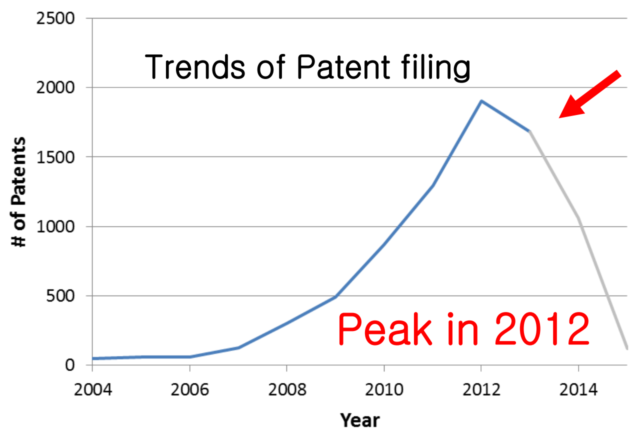
KS Novoselov, *et al.*, *Science*, **306** 666 (2004)

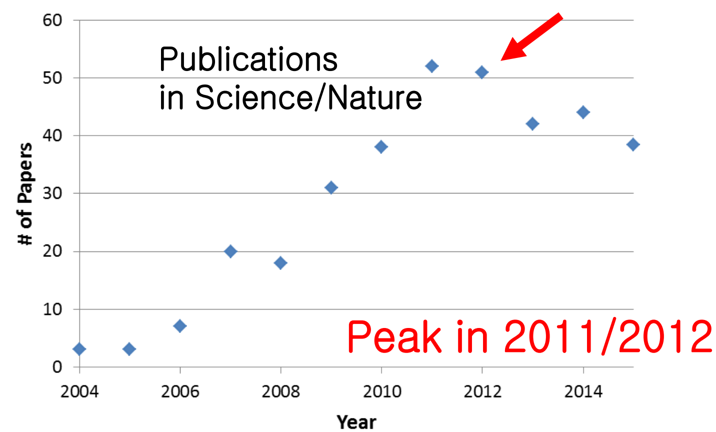
Properties of Graphene

Where are we?
: Gartner's Hype Cycle



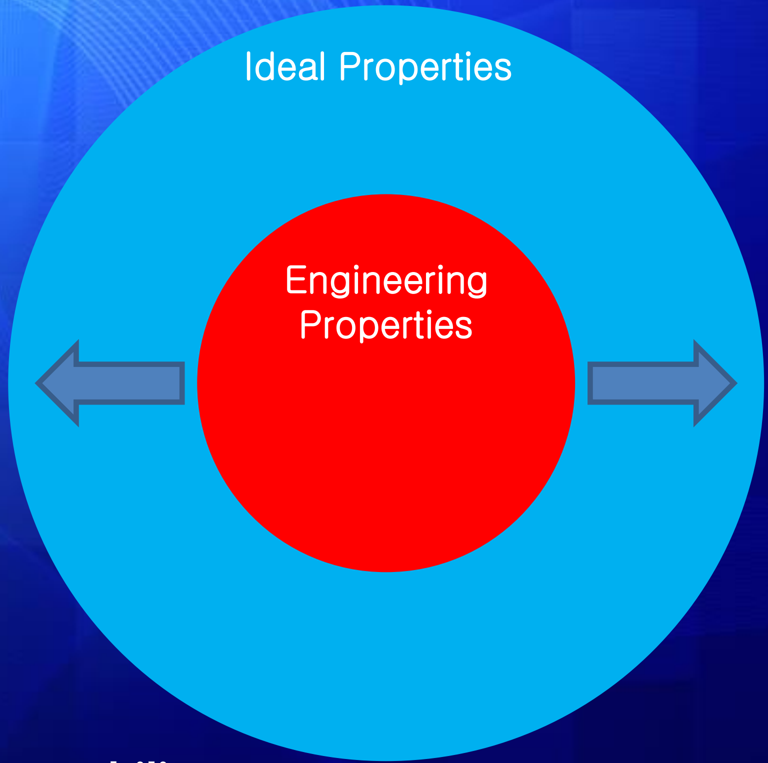


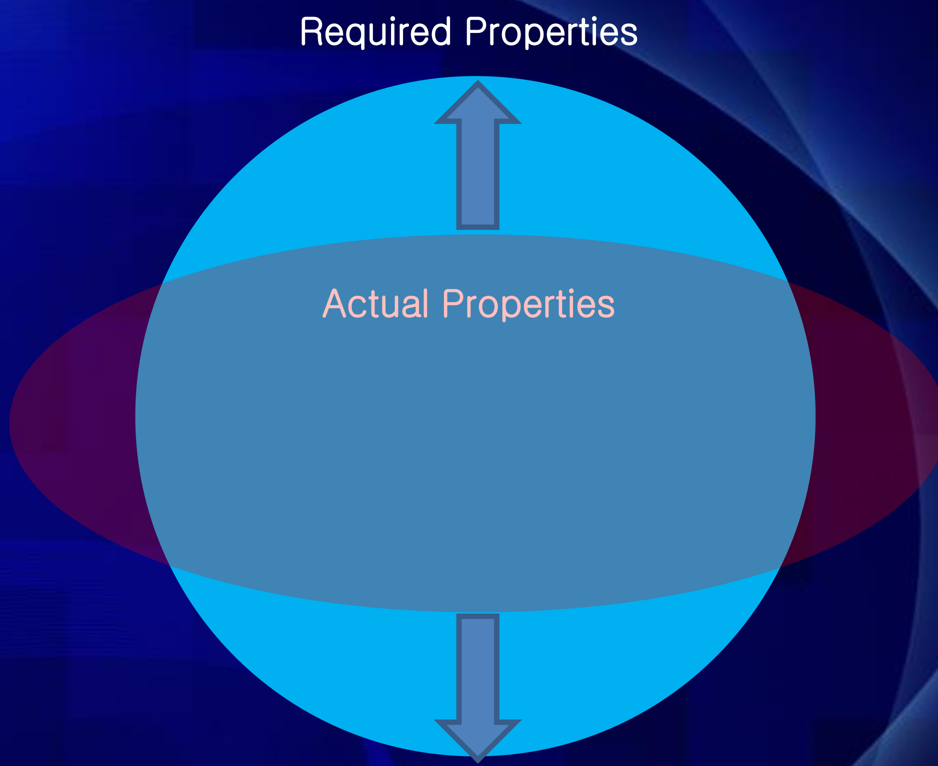




Year 2015 data: Estim

Properties? Properties!
: Filling the gaps in properties



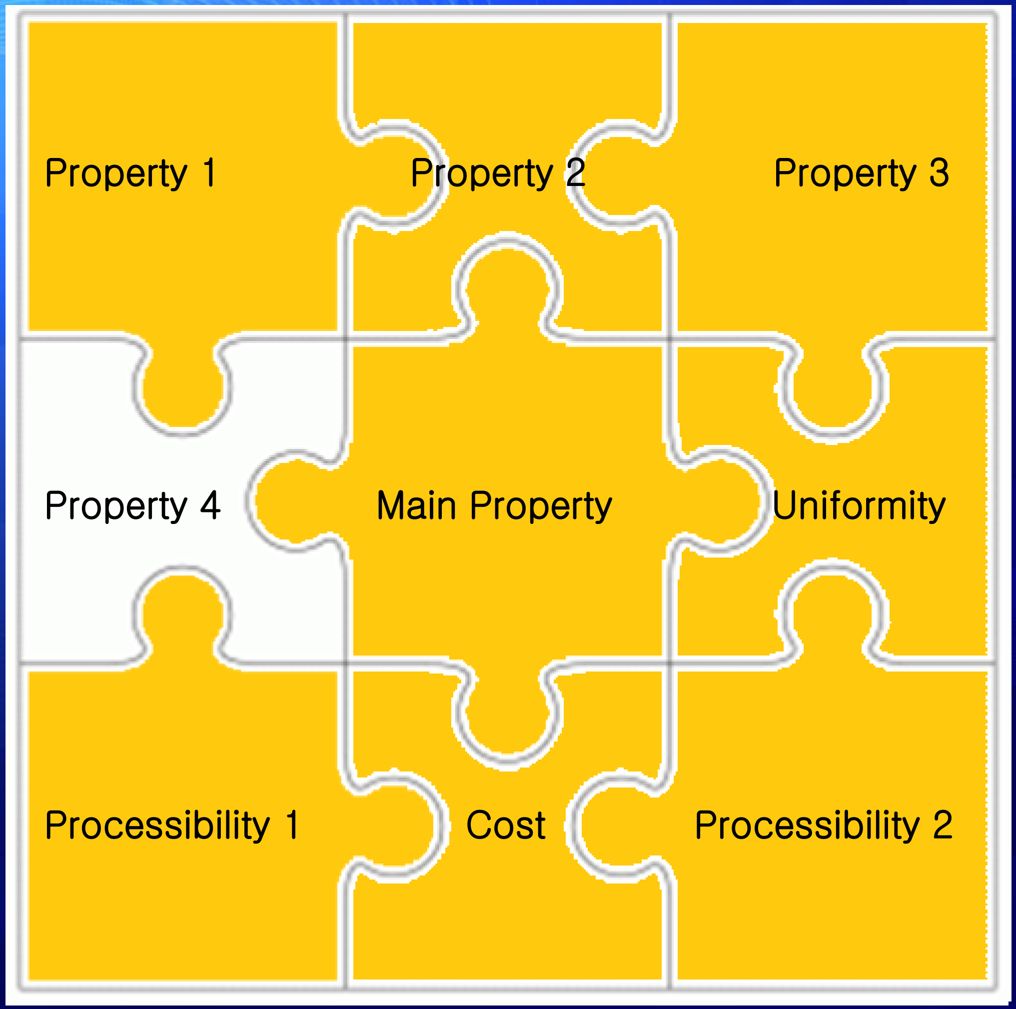


- **Mobility**
  - $200{,}000 cm^2/Vs \rightarrow \sim 2000 cm^2/Vs$
- **Thermal Conductivity**
  - $5300 W/m \cdot K \rightarrow \sim 1000 W/m \cdot K$

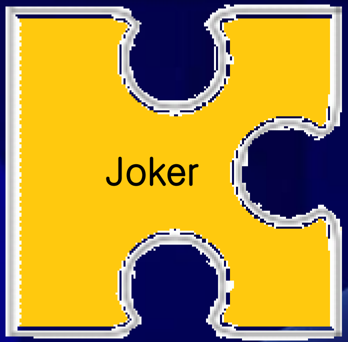
- **Mobility**
  - $200{,}000 cm^2/Vs > 1400 cm^2/Vs$ (Si)
- **On/Off**
  - $\sim 10 \ll 10^4 \sim 10^{11}$ (Si)

Filling the Puzzles

: All puzzles need to be filled to be commercialized.



- Properties → Processibility (Industry) → Cost (?) → Uniformity (Equipment)
- Everything needs to be satisfied all together
  - Actual/Engineering Properties
  - Processibility
  - Cost: $281 for 5cm X 5cm (on Cu foil) → ~ $700,000/m^2
  - Uniformity

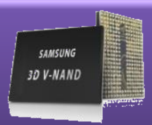


Samsung Electronics

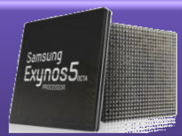
Semiconductor

DRAM
(39%, 1st in 2014)

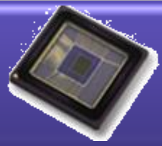
NAND
(30%, 1st in 2014)



AP
(4%, 4th in 2014)



CIS
(29%, 2nd in 2014)



Mobile

Smart Phone
(31%, 1st in 2014.Q1)

Smart Watch
(23%, 1st in 2014)

Tablet
(18%, 2nd in 2014)

Appliances and other electronics

LCD TV
(22%, 1st in 2014)

French door refrigerator
(40%, 1st in 2010)

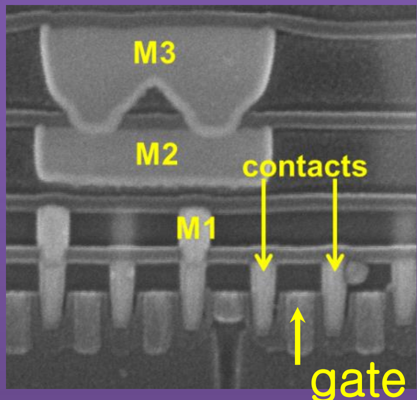
PC Monitor
(13%, 2nd in 2014)

Digital Camera
(23%, 2nd in 2014.H2)

www.Statista.com; www.IDC.com; www.SmartWatchGroup.com Wikipedia, Gartner

Graphene Applications

Semiconductor



Active Materials
Components

Mobile

Touch Screen
Battery

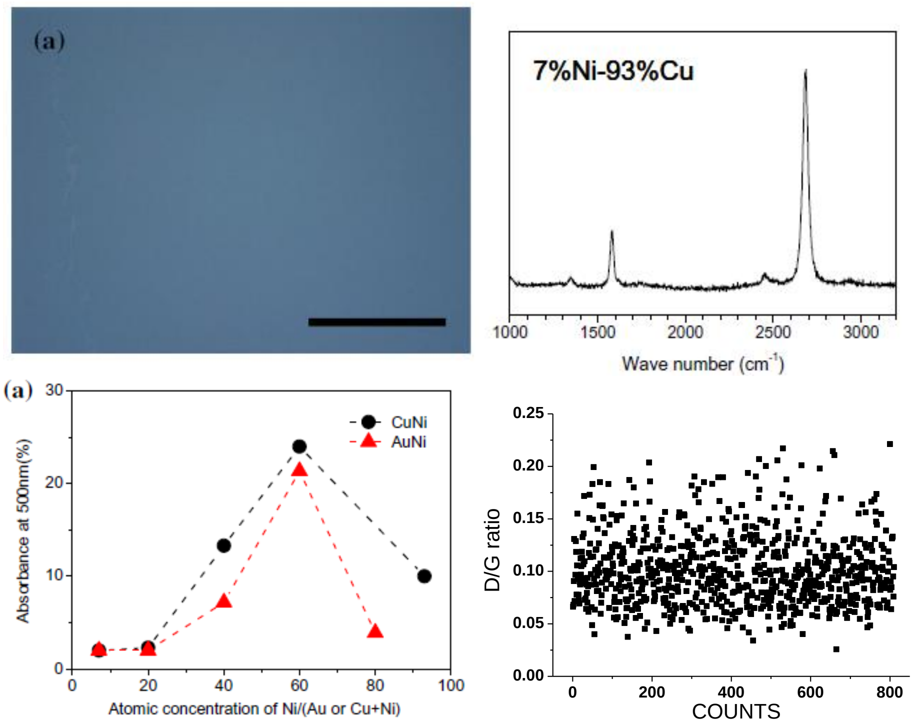
Appliances and other electronics

External Case

Growth

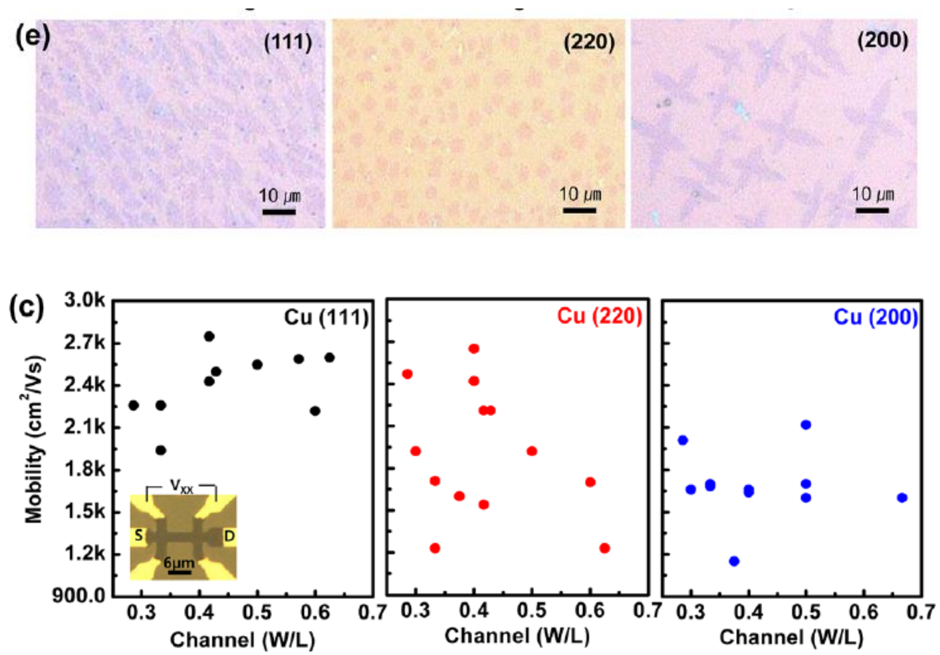
Graphene Growth on Metal Catalyst

Low temperature growth on Metal catalyst with ICP CVD



Y S Woo *et al. Carbon*, **64** 315 (2013)

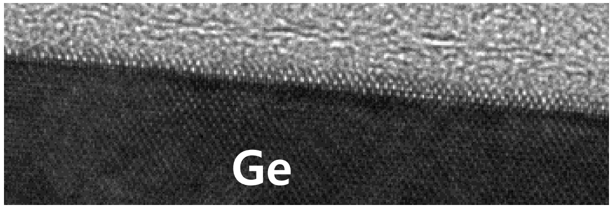
Graphene Growth on various Cu orientations



H-J Shin *et al. APL*, **102**, 163102 (2013)

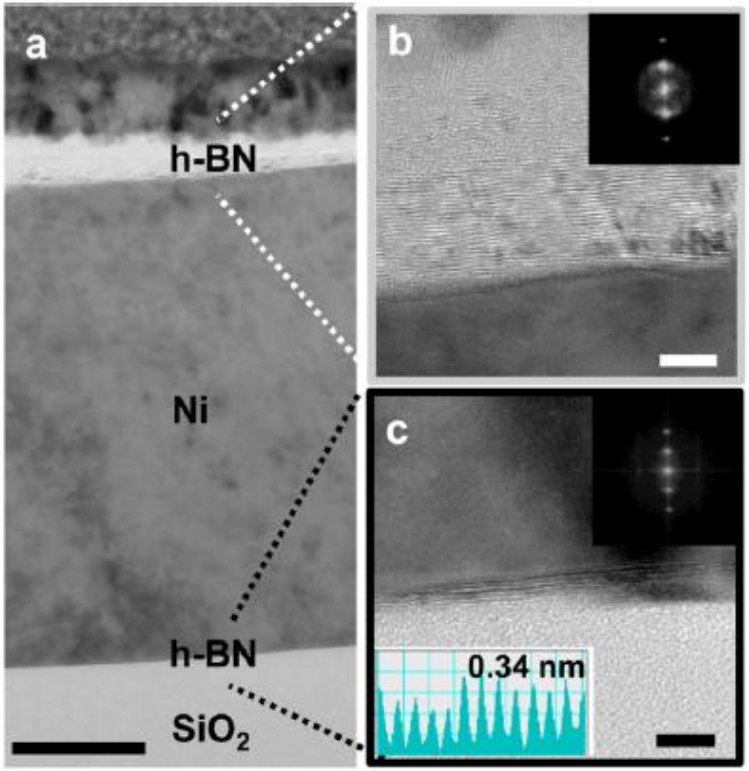
Direct Growth

Graphene can be grown on Semiconductor



Y S Woo *et al*. *Carbon*, **64** 315 (2013)

Growth of h-BN on and underneath of Ni



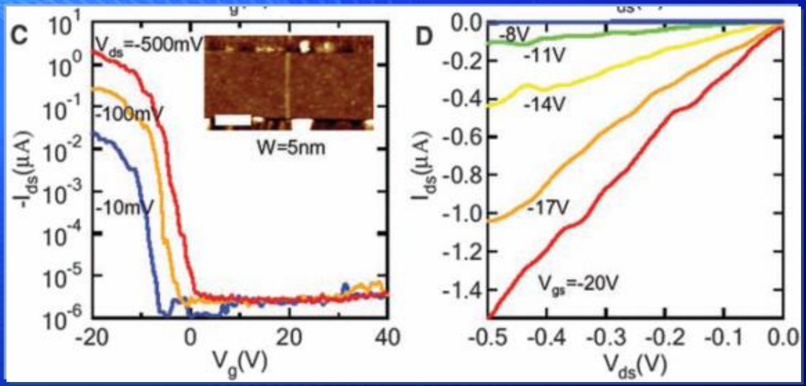
S Park *et al*. *ACS Nano*, **9**, 633 (2015)

Wafer-scale Integration of Graphene Tunneling Barristor

How to Achieve Low Off Current

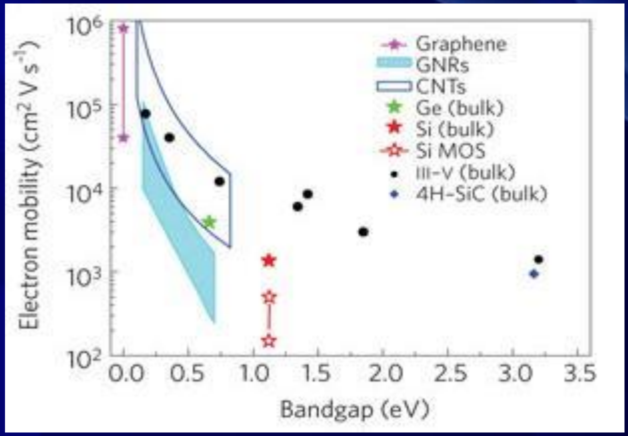
Quantum Confinement: GNR

X. Li et al. Science (2008)



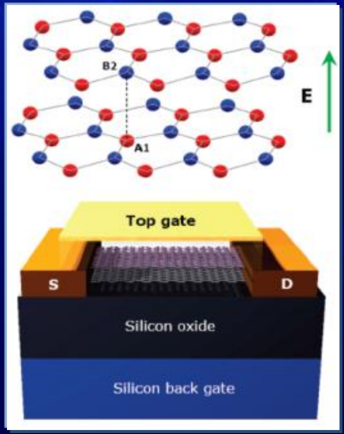
w=5nm, I_{on}/I_{off}~10^6, μ=100-200cm²/Vs

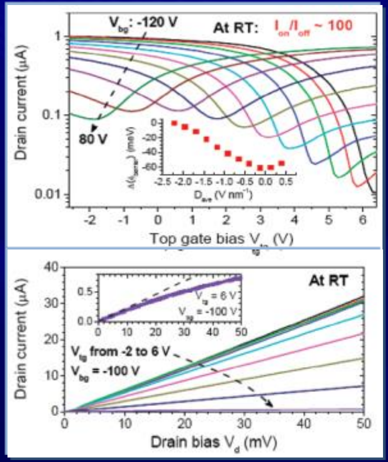
F. Schwierz, Nature Nanotechnology(2012)



Symmetry Breaking: Bilayer

F. Xia et al. Nano Lett.. (2010)

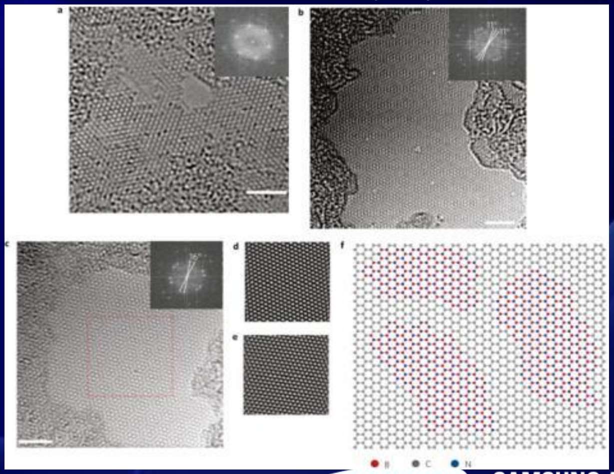




I_{on}/I_{off}~10^2, D=2.2V/nm

h-BCN

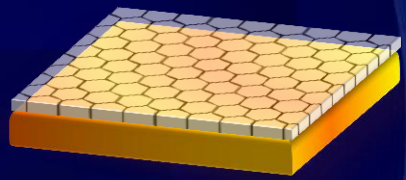
L. Ci, Nature Materials(2012)



Doping
: DFT simulations on metal doped graphene Work functions

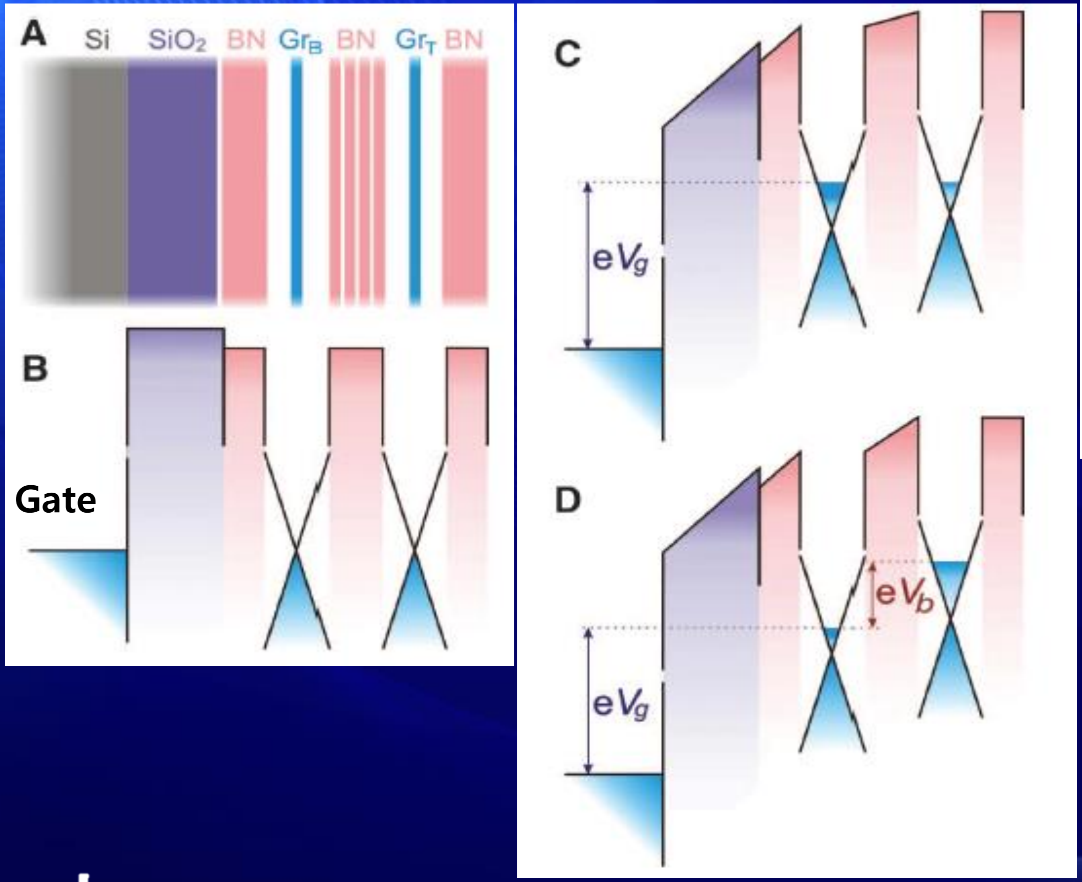
eV	Graphene	Ni	Co	Pd	Al	Ag	Cu	Au	Pt
WF Metal		5.47	5.44	5.67	4.22	4.92	5.22	5.54	6.13
WF Simulation	4.48	3.66	3.78	4.03	4.04	4.24	4.40	4.74	4.87
WF Exp	4.6	3.9		4.3					4.8

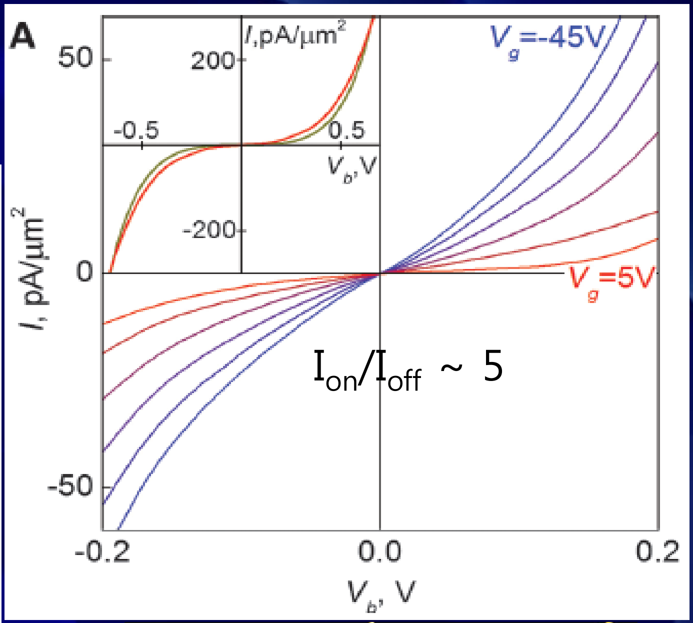
G Giovannetti *et al.*, *PRL*, **101** 026803 (2008)

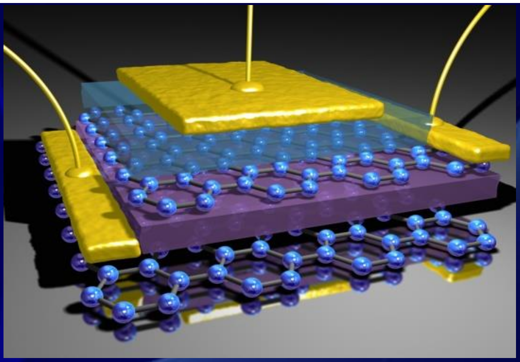


Tunneling Transistor
: h-BN, I_{on} ~ 70pA/μm^2, I_{off} ~ 12pA/μm^2, I_{on}/I_{off} = 50 @ V_b = 0.2V

With MoS_2, I_{on}/I_{off} = 7000



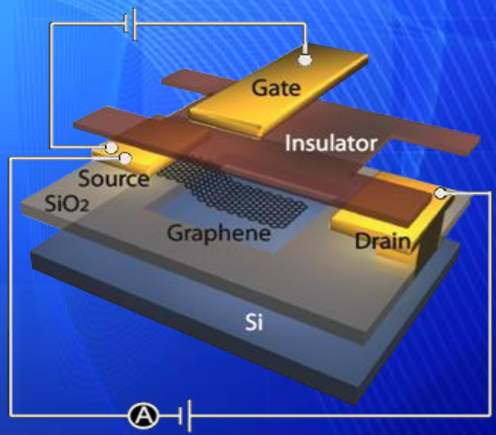


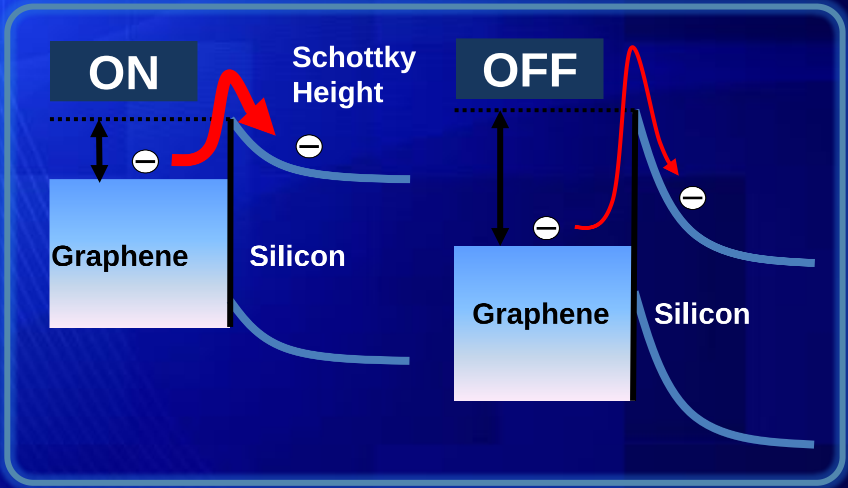


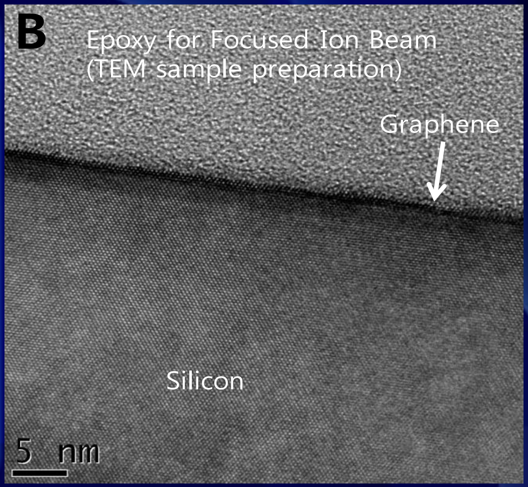
L Britnell *et al.*, *Science* **335** 947 (2012)

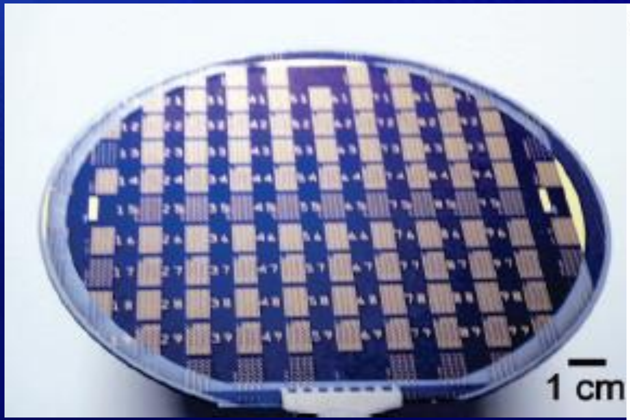
Graphene Barristor

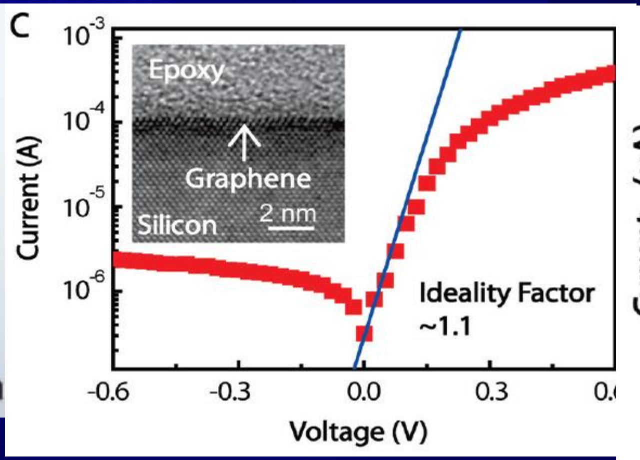
: Si, I_{on} ~ 10μA/μm², I_{on}/I_{off} = 10^5

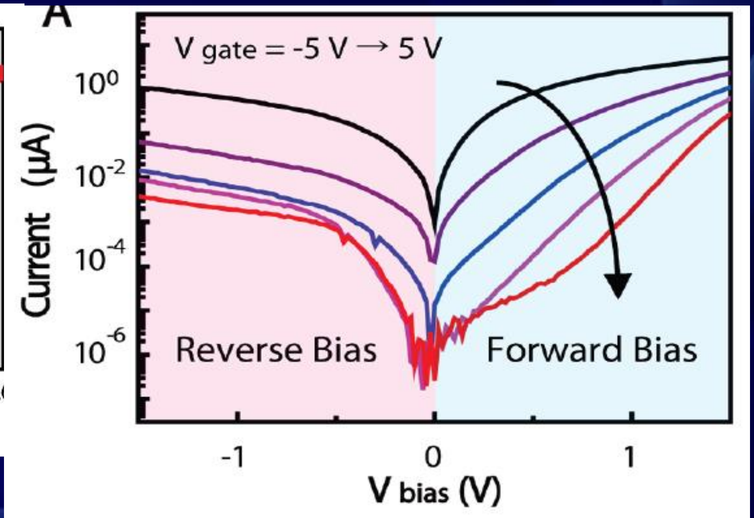








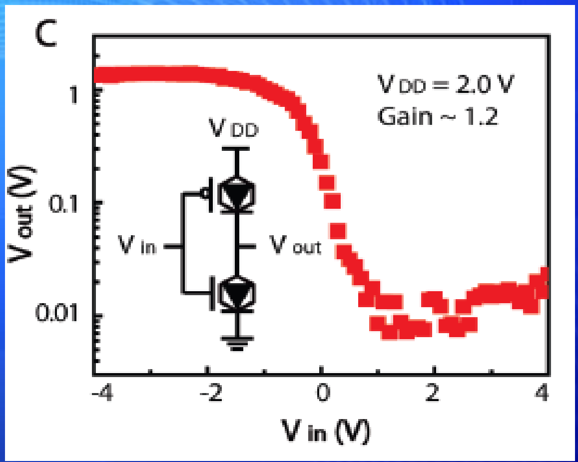


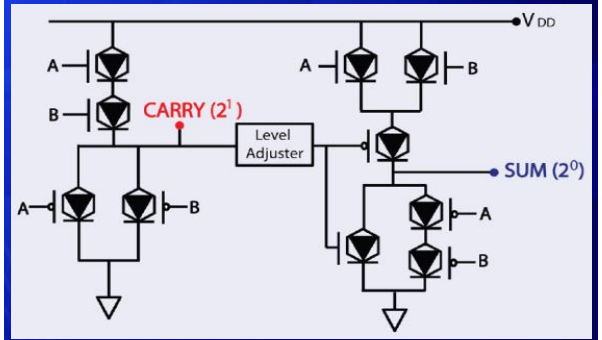


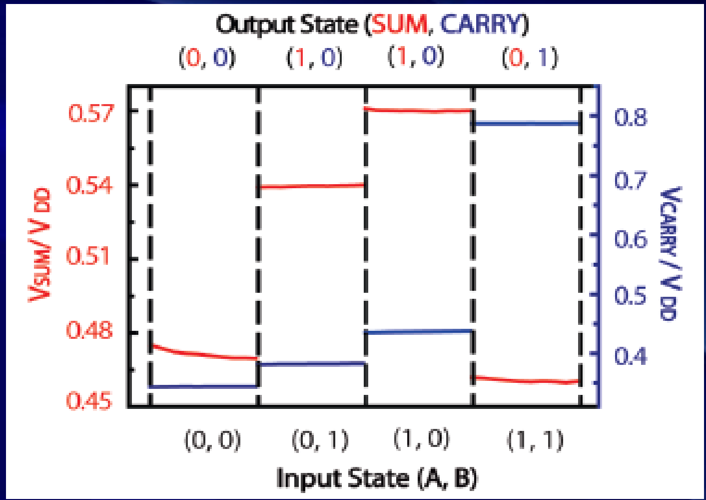
H Yang *et al.*, *Science* **336** 1140 (2012)

Graphene Barristor

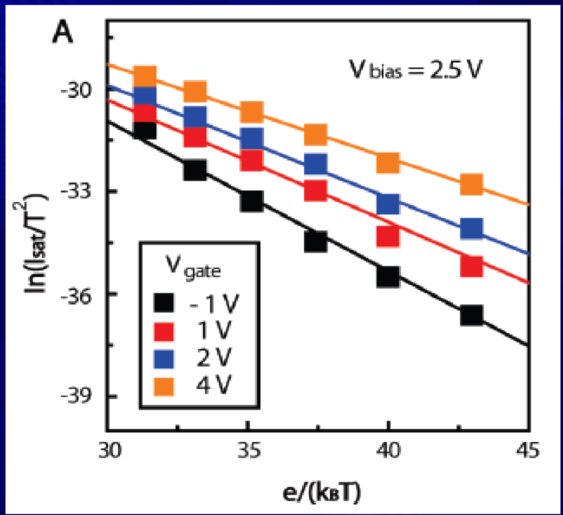
: Half adder & 1:1 Matching btw work function and Fermi level changes

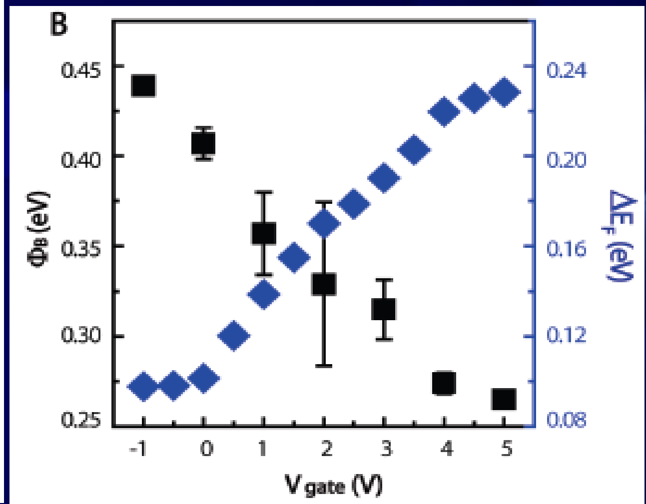






H Yang *et al.*, *Science* **336** 1140 (2012)



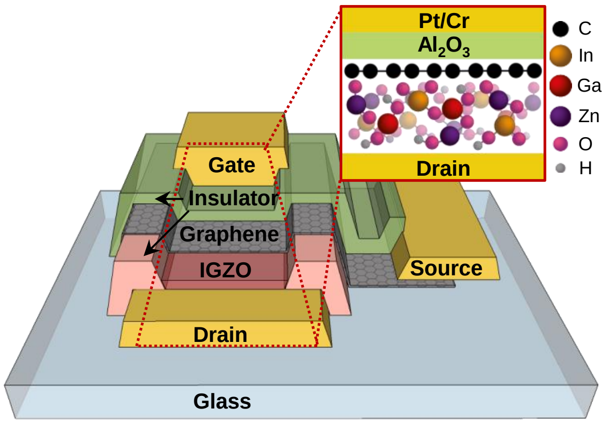


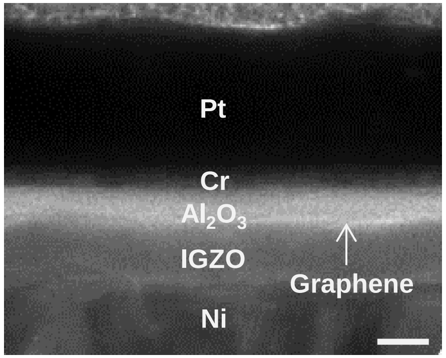
Barrier Materials

- **Various Barrier Materials explored:**
  - 2D materials: MoS_2, WS_2
  - Semiconductor: Si
  - Graphene Family: Graphene Fluoride

	Barrier	On/Off (I_{on})
U. Manchester Science (2012)	MoS_2	10^4 (0.1 μA/μm^2)
SAIT Science (2012)	Si	10^5 (0.1 μA/μm^2)
U. Manchester Nature Nano (2013)	WS_2	10^6 (a few μA/μm^2)
UCLA Nature Mat (2013)	MoS_2	10^3 (50 μA/μm^2)
HRL EDL (2013)	Graphene Fluoride	10^5 (5 μA/μm^2)

- **Exploring Barrier Materials: IGZO**

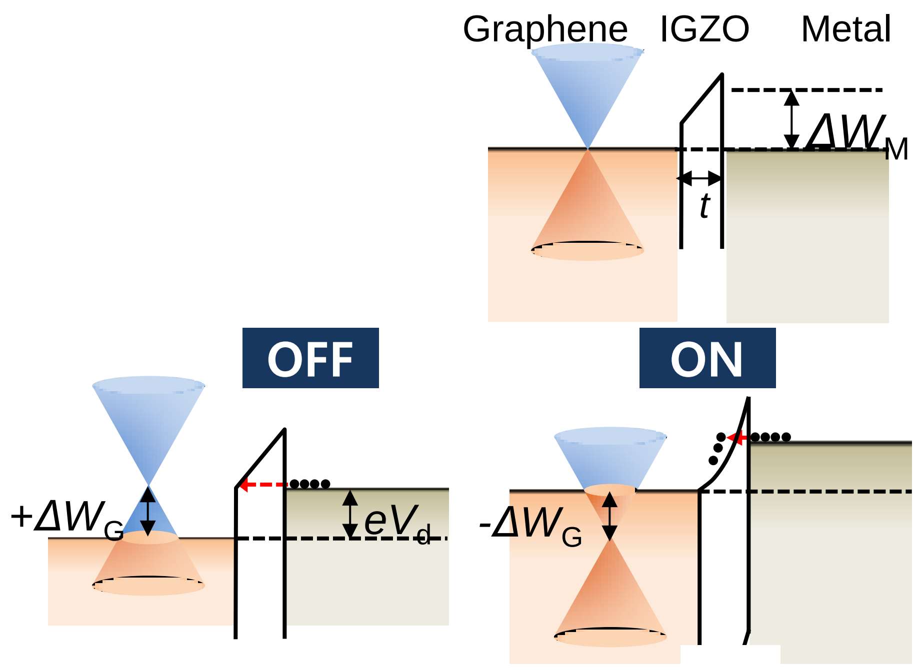




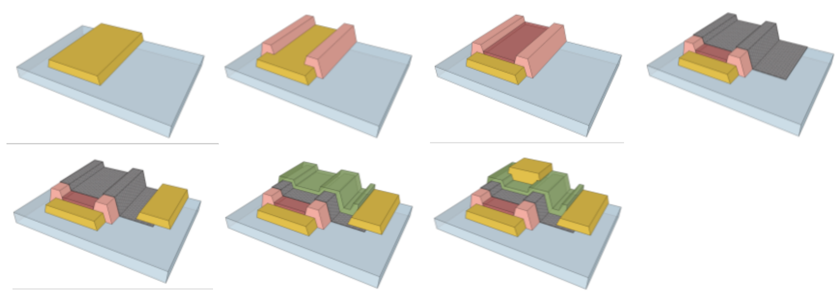
Tunneling Barristor

: Working Principles: Barrier Thickness Modulations

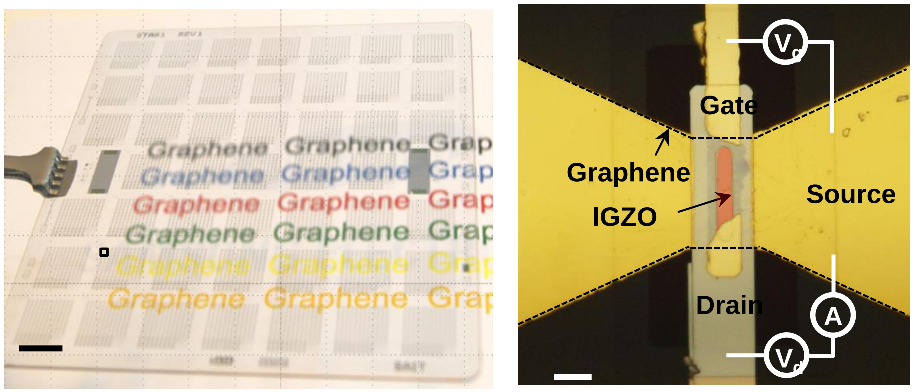
- **Barrier Thickness Modulations**
  - Modulated thickness of tunneling Barrier



- **Conventional Fabrication Processes**

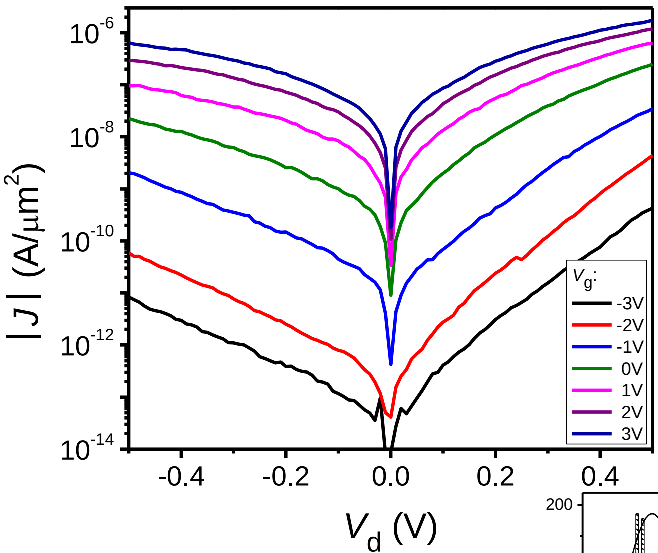


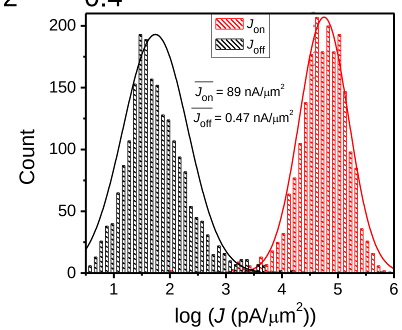
Fabricated on $(15cm)^2$ glass



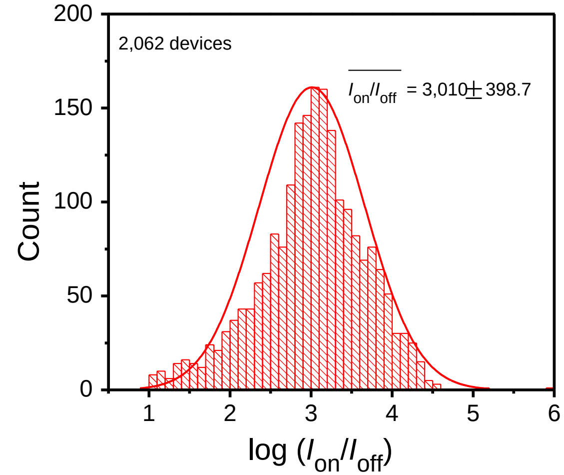
IV Curves
: High On/Off even at 0.1 VDS

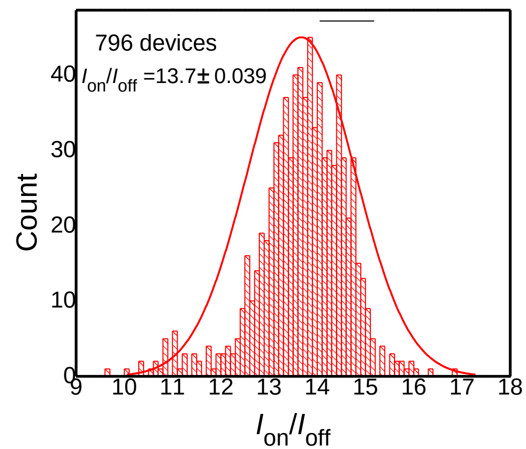
- **Device Behavior**
  - Ion/Ioff > 10^6 @ 0.1 V





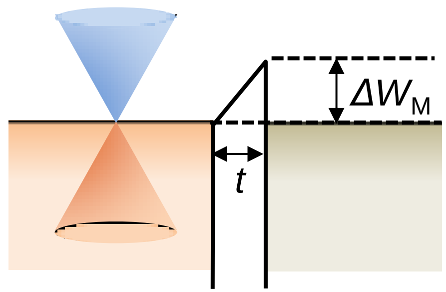
- **Statistics**

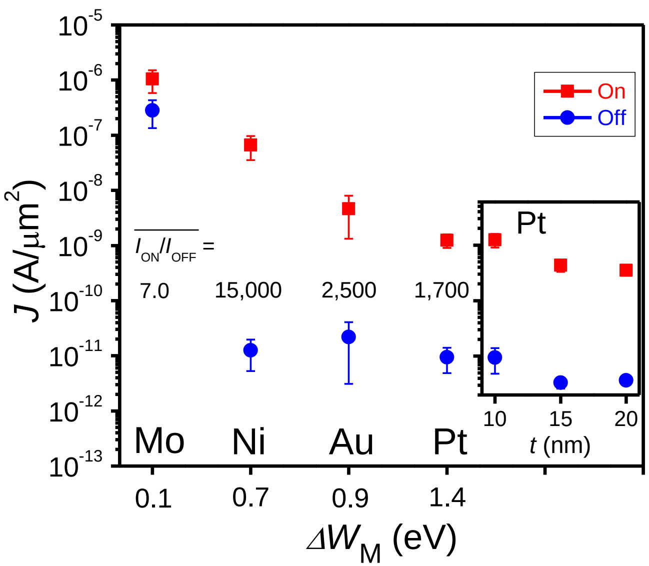




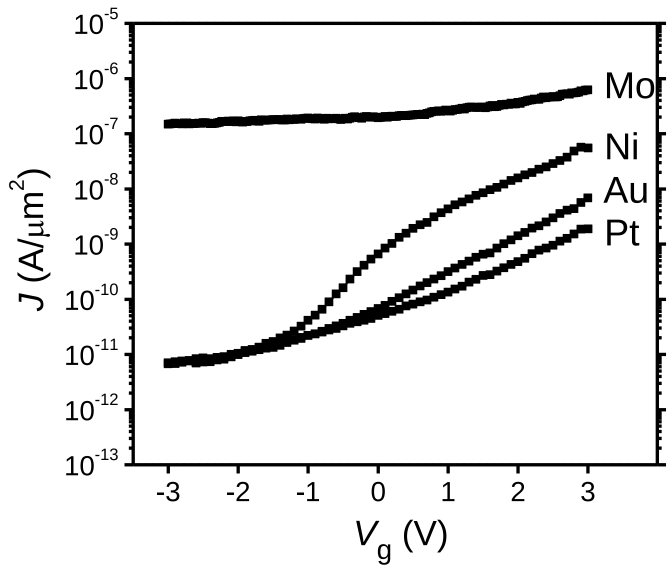
Barrier Design
: Barrier Modulation with metal work function

- **Barrier Modulation with Metal**
  - Large Barrier
    → Low I_{On}
  - Small Barrier
    → High I_{Off}



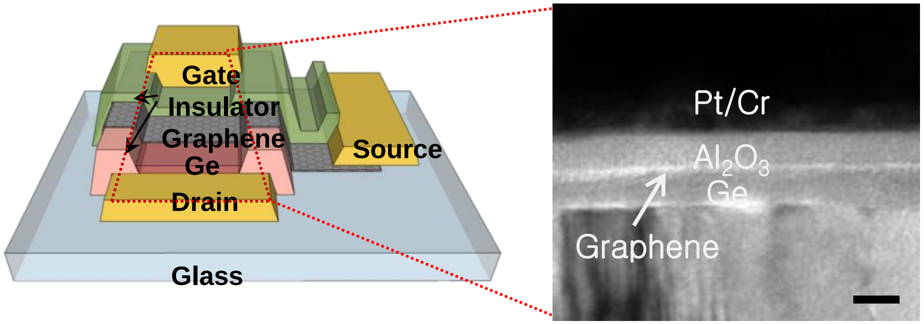


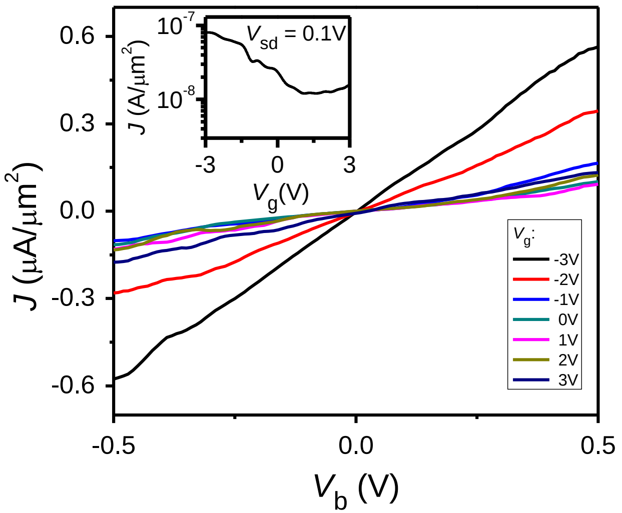
- **Exploring Barrier Materials**
  - Mo: Small response to gate and high off
  - Pt: Small on current
  - Ni: Small off current and high on current



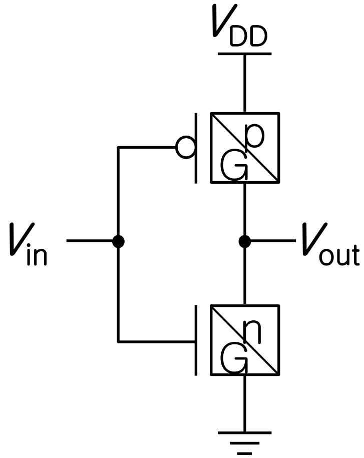
Inverter

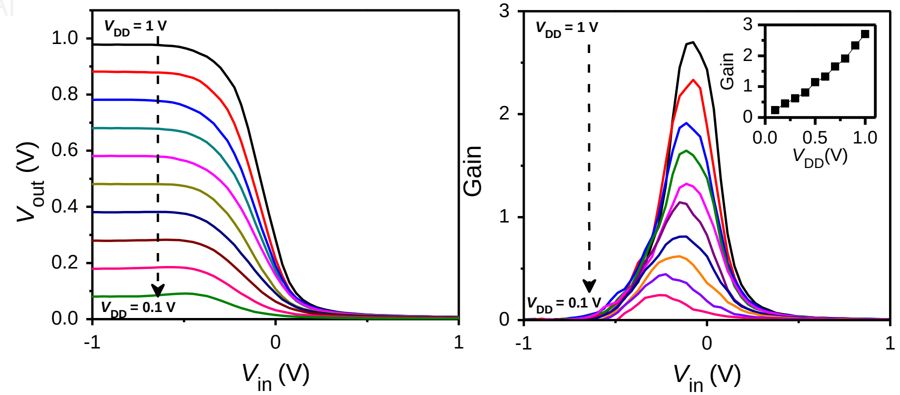
- **p-type Barrier: Ge**





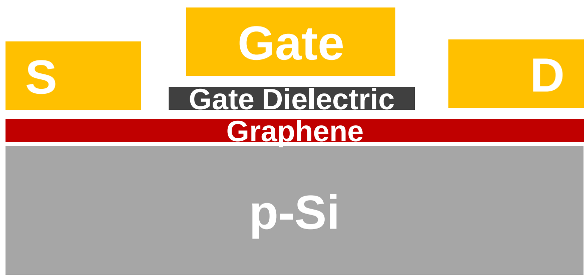
- **Logic Inverter**





ALD on Graphene

Graphene Incorporated Device Challenges



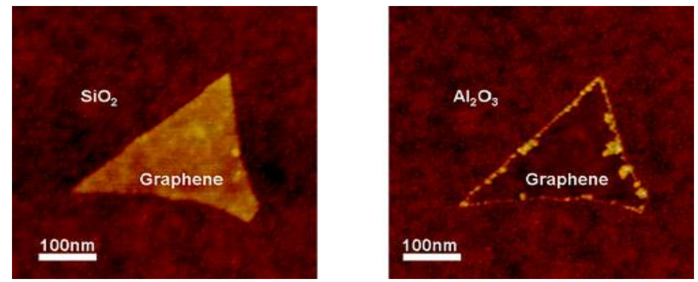
Materials
- Direct Growth
- Analysis Tools

Transfer
- Lamination
- Delamination
- Residue

Interface
- ALD
- Metal contact

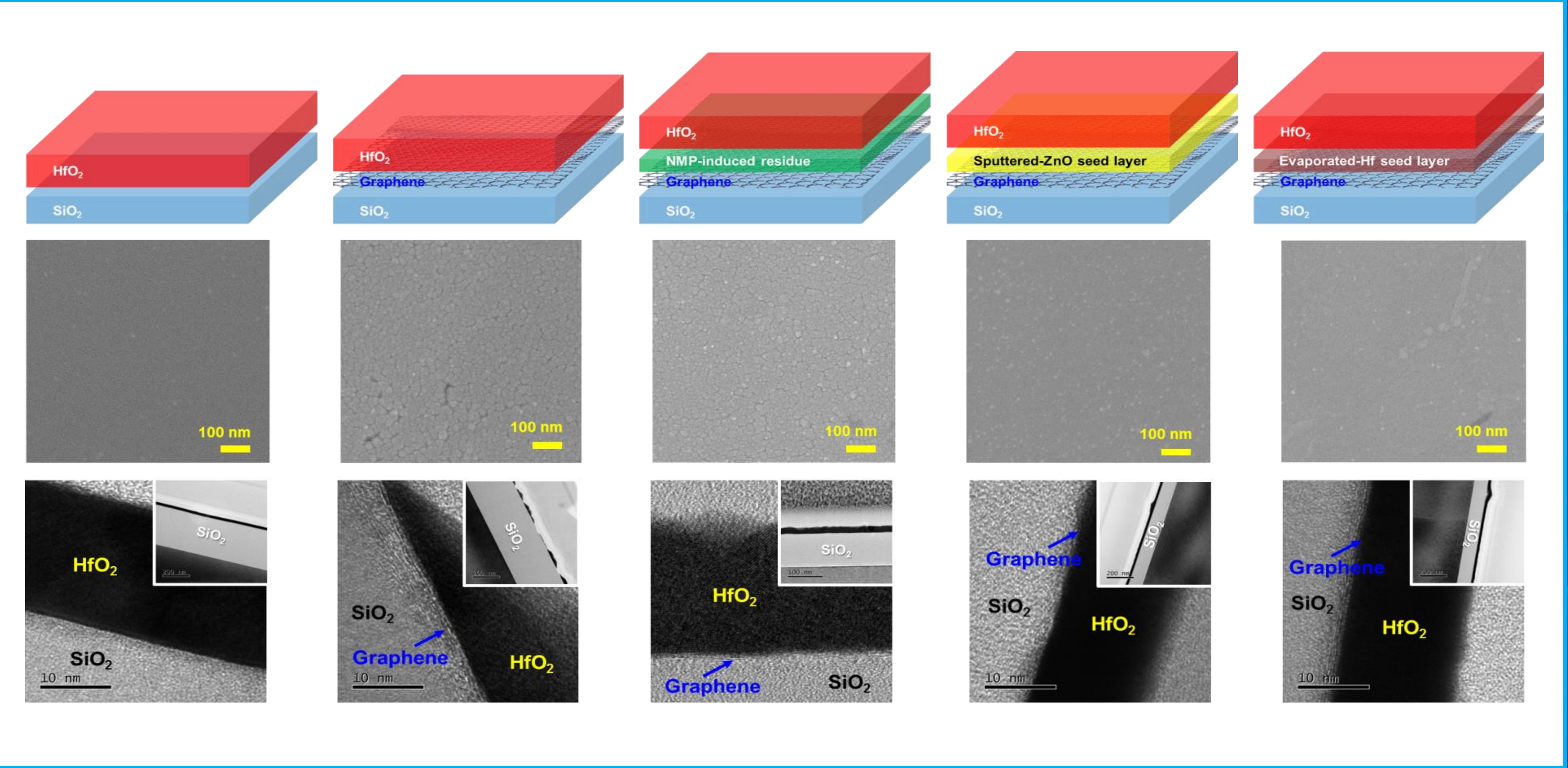
ALD High-*k* Film on Graphene

:Non-conformal growth of high-*k* dielectric films



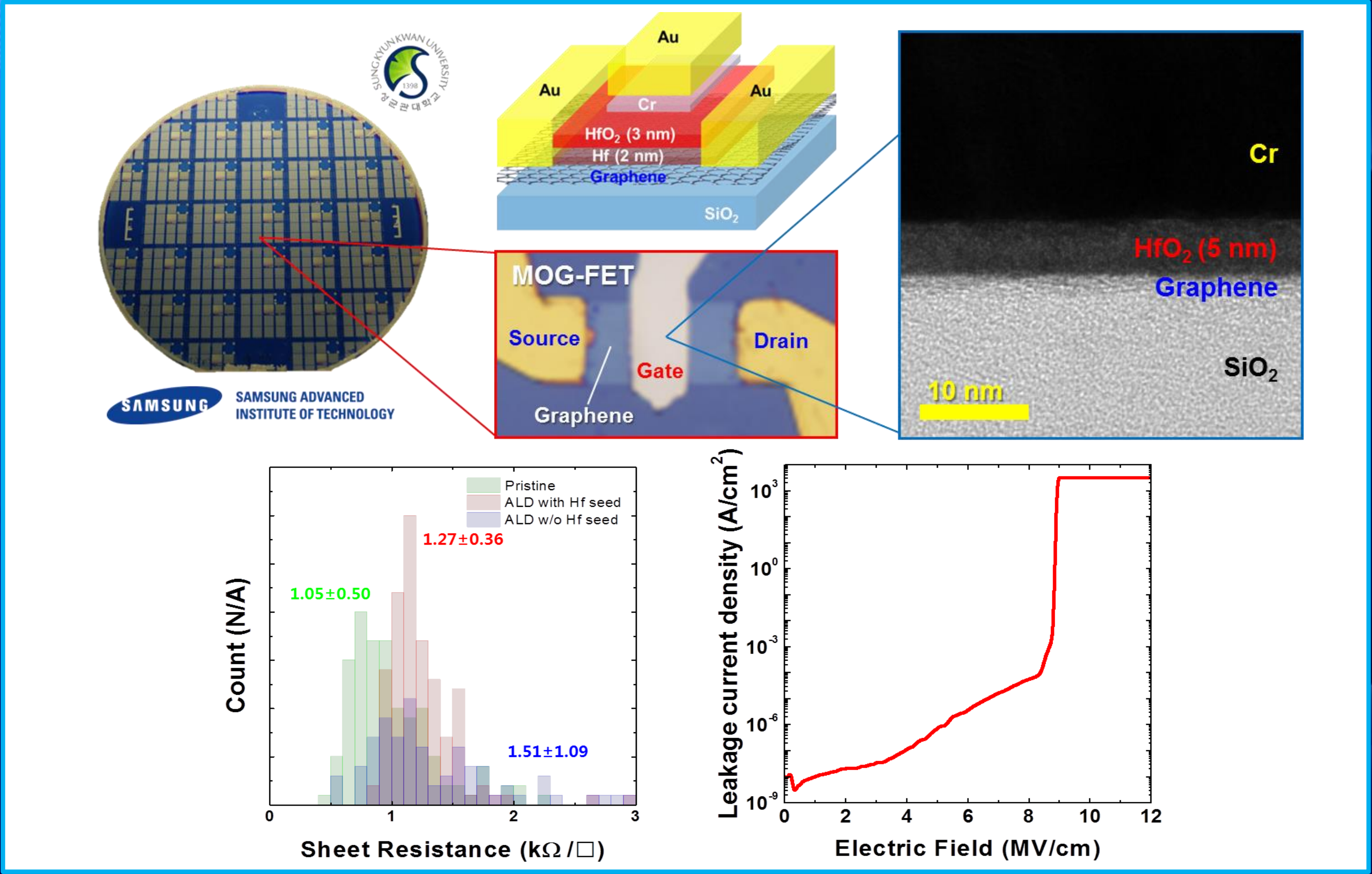
X. Wang *et al.* , ***JACS***, 130(26), 8152 (2008)

ALD HfO_2 Films on Graphene
: The effects of various surface modifications



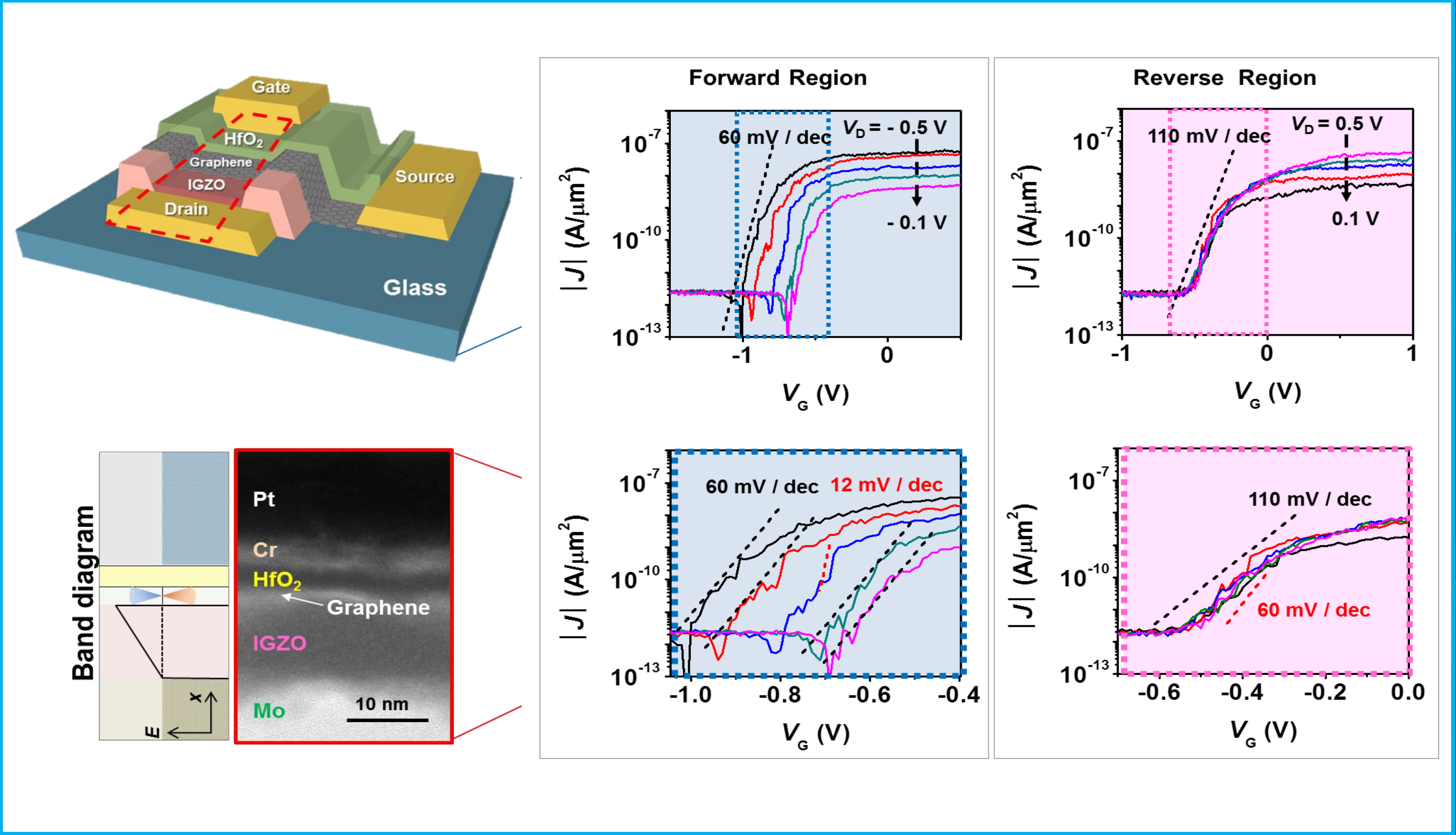
S-J Jeong, *et al.* (Submitted)

Downscaling and Electrical Evaluation of ALD HfO_2 Films on Graphene



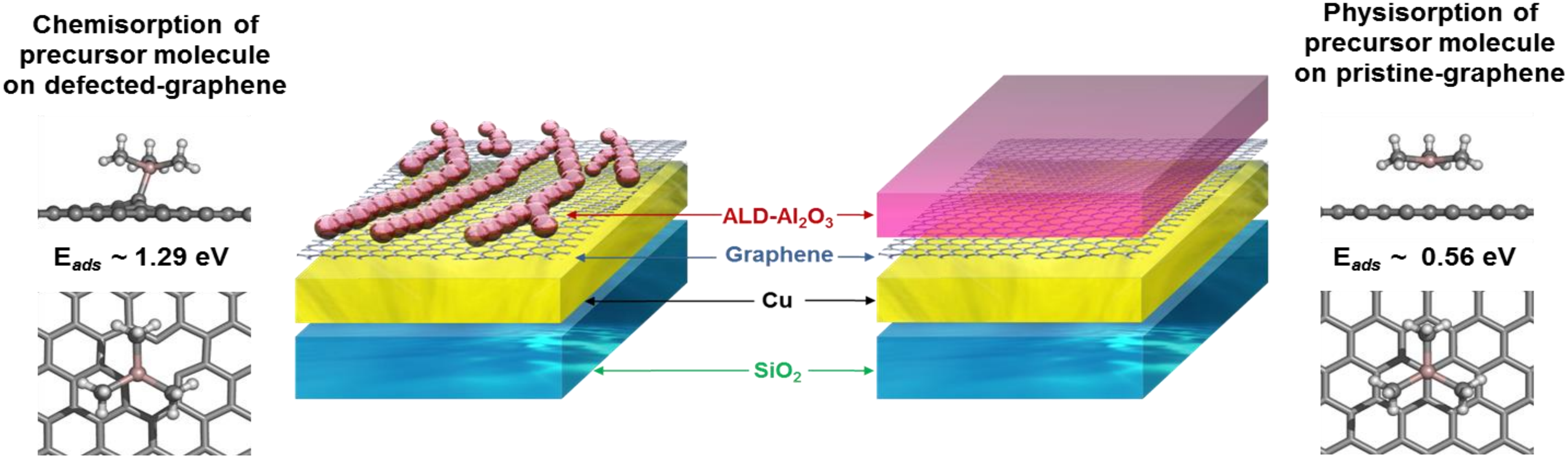
S-J Jeong, *et al.* (Submitted)

Graphene Tunnelling Transistors



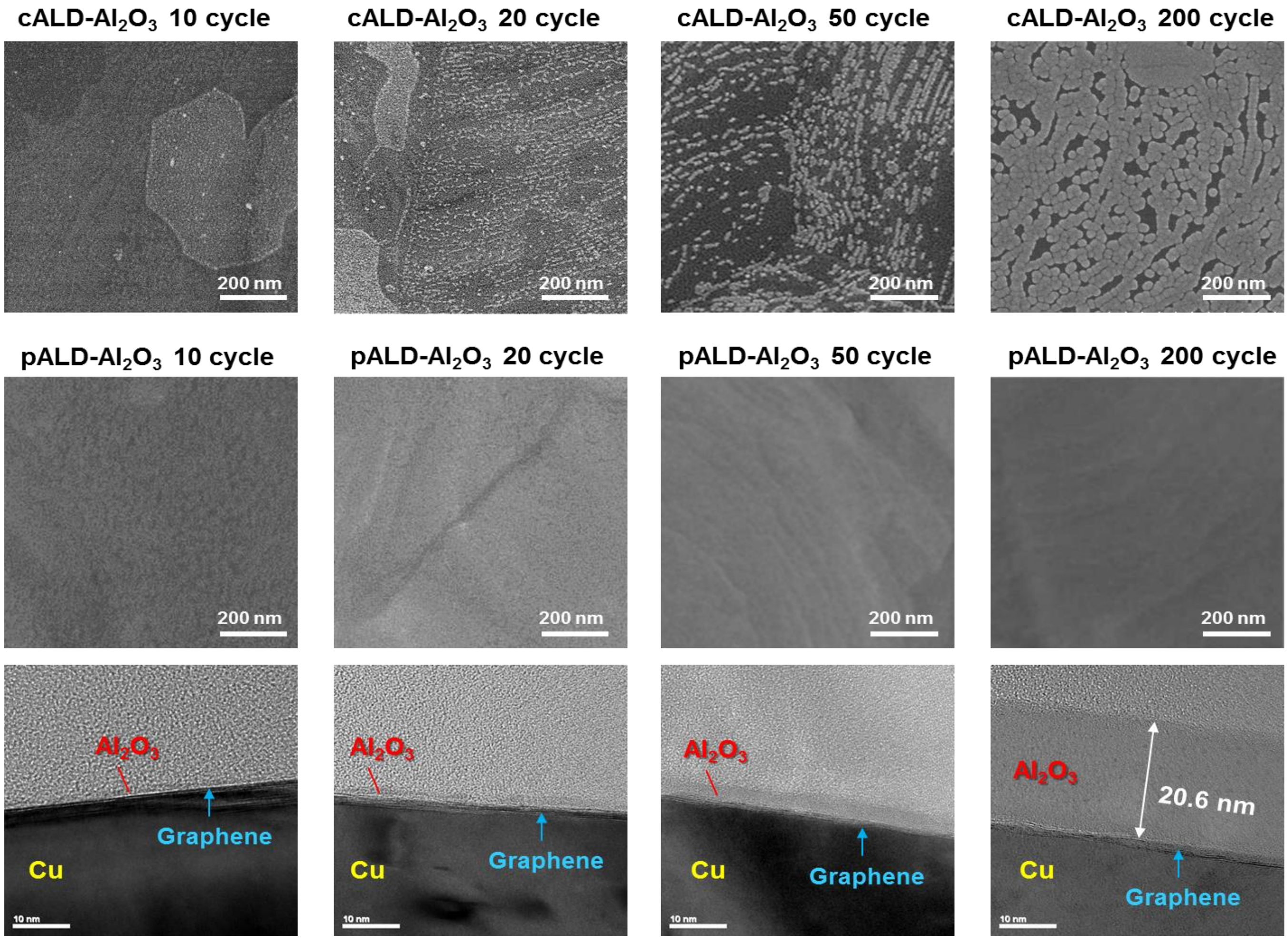
S-J Jeong, *et al.* (Submitted)

Direct Growth of Metal Oxide Films on Graphene



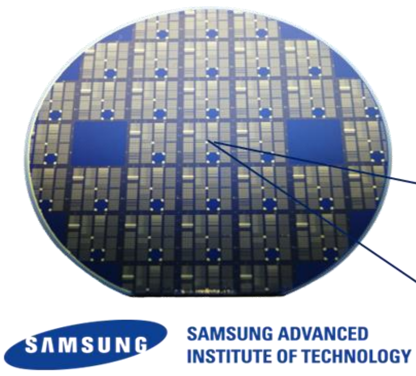
S-J Jeong, *et al.* (In preparation)

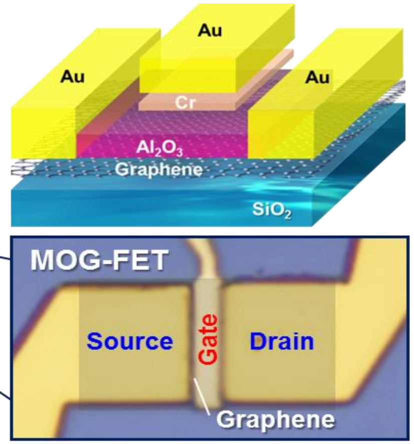
Surface Morphology Evolution of pALD and cALD-Al_2O_3 thin films on Graphene

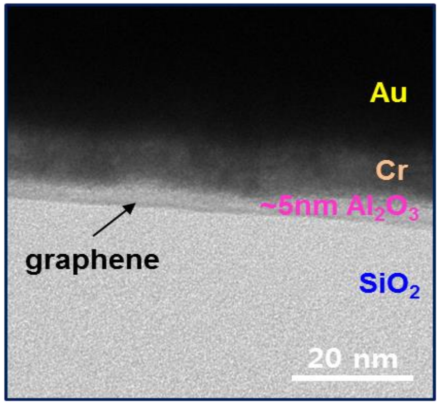


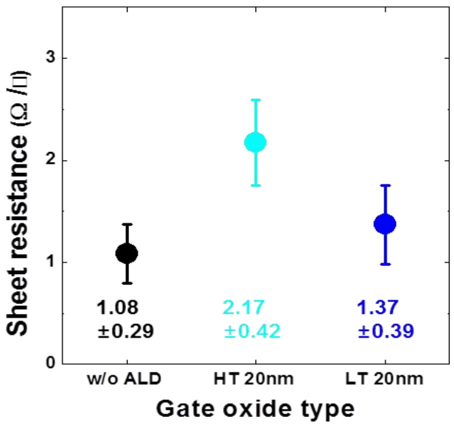
S-J Jeong, *et al.* (In preparation)

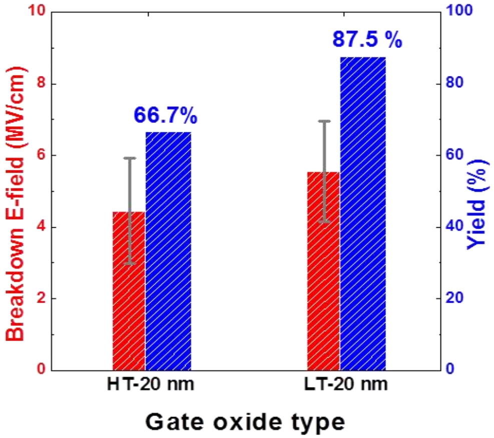
Electrical Evaluation of pALD Al_2O_3 Films on Graphene in a Wafer Scale

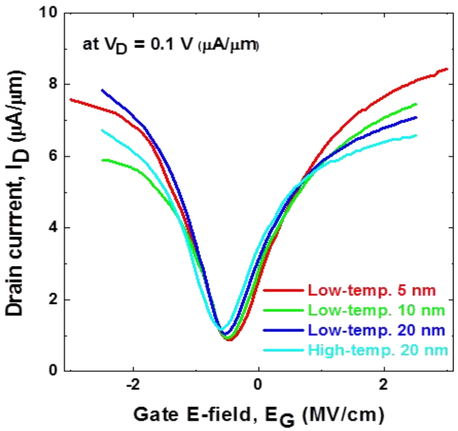








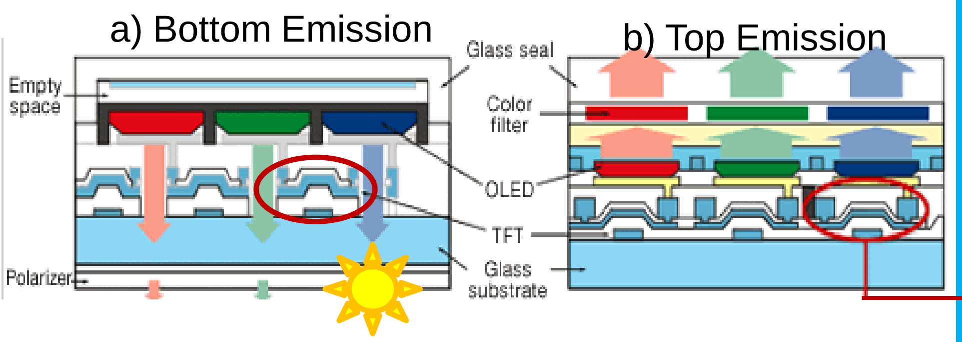




S-J Jeong, *et al.* (In preparation)

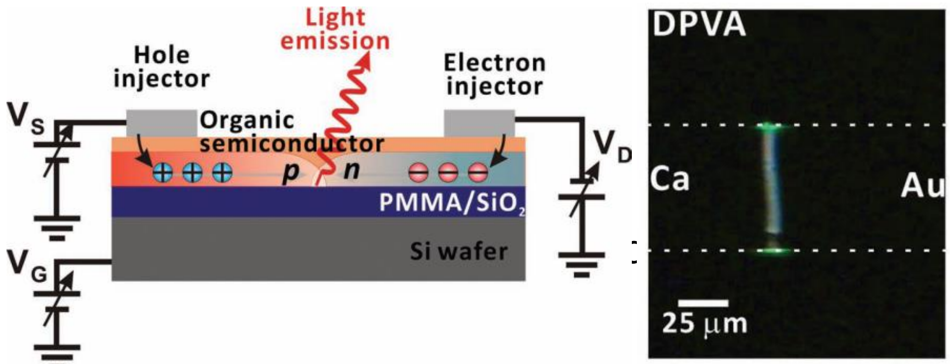
Organic Light Emitting Transistor

Emission type of AMOLED



	Bottom emission	Top emission
Adv.	- Simple fabrication process	- Low power consumption - High colour purity - High resolution
Dis-Adv.	- Physical limitation - Low resolution (<1000dpi)	- Complexity of the fabrication process
Needs	Need to improvement light efficiency	Need to adapt large size device such as TV

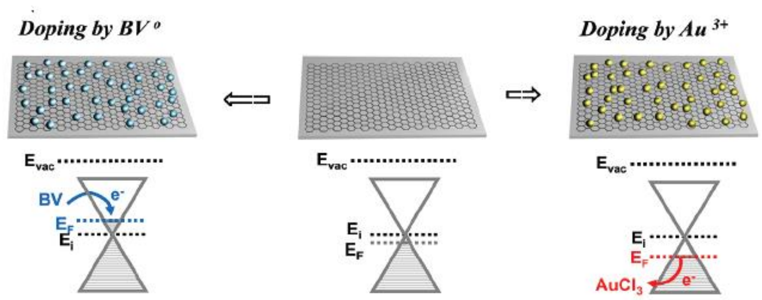
- **Thin-film transistor based on an organic semiconductor**
  - The organic light-emitting field-effect transistor (OLET) emits light during transistor operation.



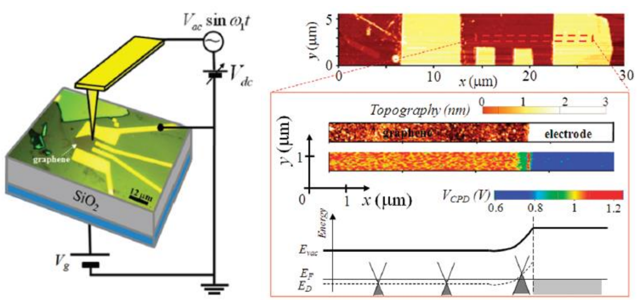
Graphene Electrode

: 97.7% transparent and controllable work function with doping

- **Transparency ~ 97.7%**
- **Work function can easily modulated by chemical and electric field**

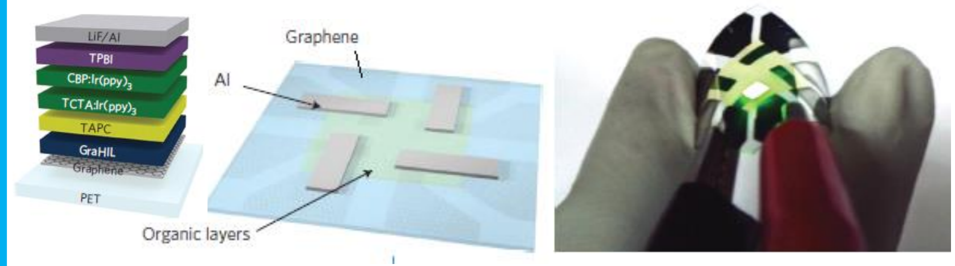


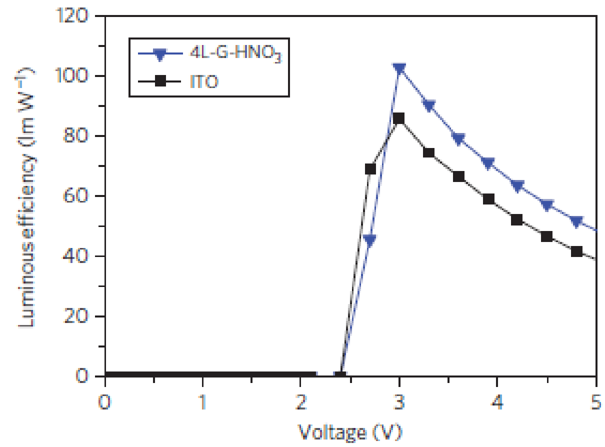
Shin *et al.*, *J. Am. Chem. Soc.*, **132**, 15603–15609, 2010



Yu *et al.*, *Nano Lett.*., **9**, 3430–3434, 2009

- **Device performance with graphene electrode is similar to that with ITO**





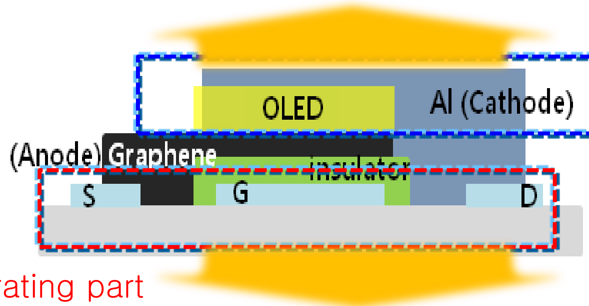
Ahn *et al.*, *Nature Photonics*, **6**, 105–110, 2012

Vertically Stacked OLED and Graphene

: Graphene is used both electrode of OLED and channel in TFT

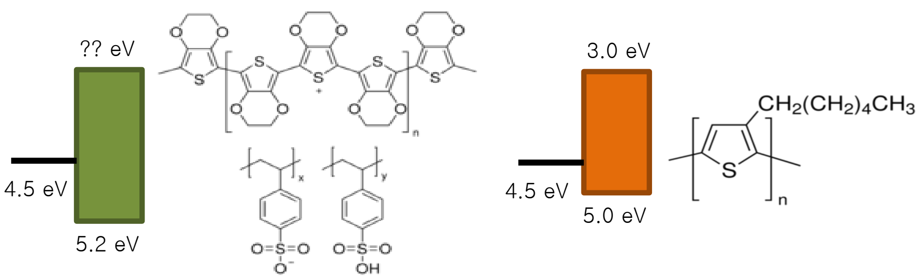
- **Graphene together work as channel and electrode**

Emitting part
(EL with Graphene electrode



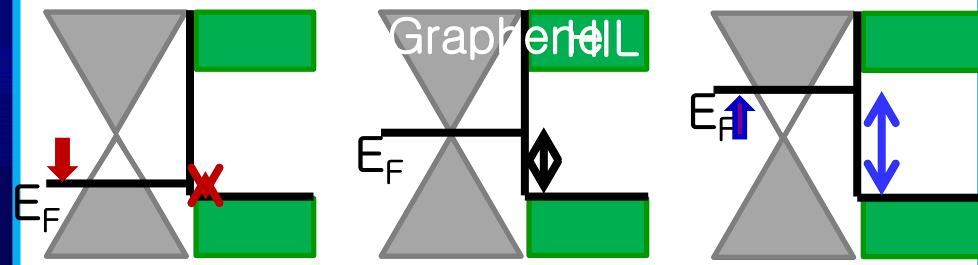
Operating part
(GB with Graphene channel)

- **Hole injection layer**



- **Controlling the number of injection hole by gate bias**
  - if Gate bias < 0, Graphene W/F increased speed of hole injection is faster
  - if Gate bias > 0, Graphene W/F decreased speed of hole injection is slower

Gate bias < 0 ⬅ Gate bias = 0 ➡ Gate bias > 0

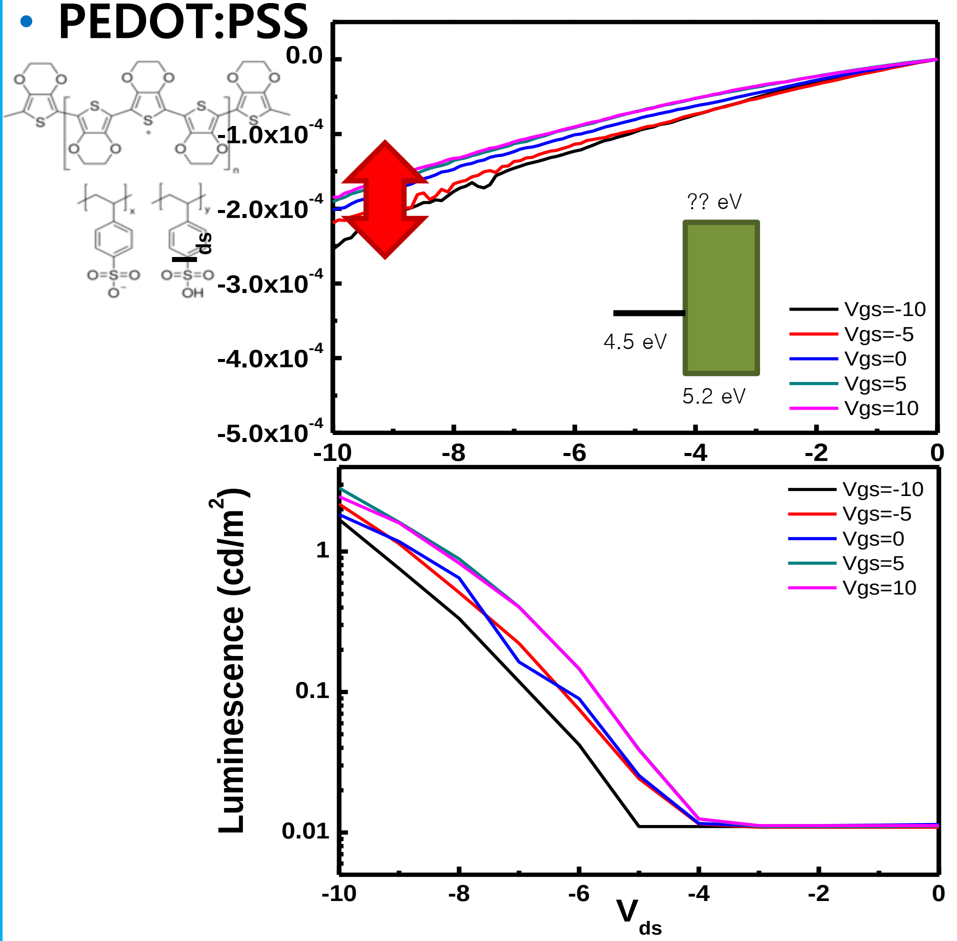


- **Hole injection and recombination can be controlled by gate bias.**

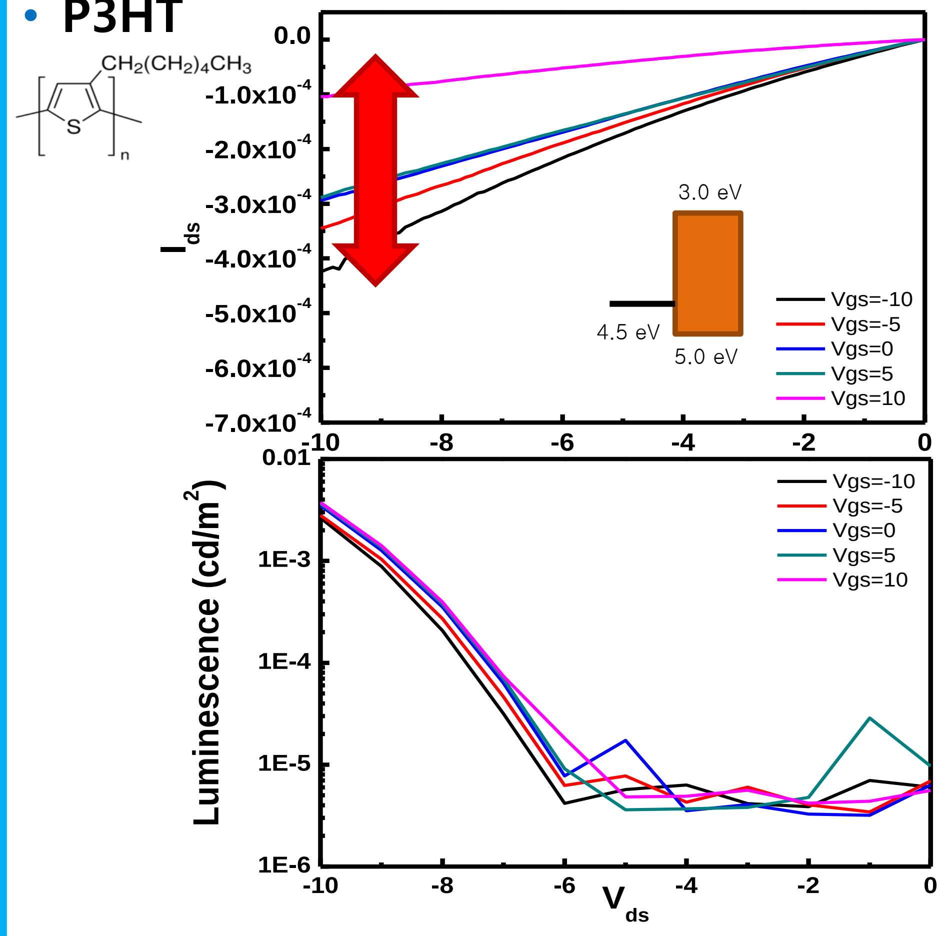
Operation of OLEB (OLE Barristor)

: Drain current and luminescence efficiencies can be controlled by gating

- **PEDOT:PSS**



- **P3HT**



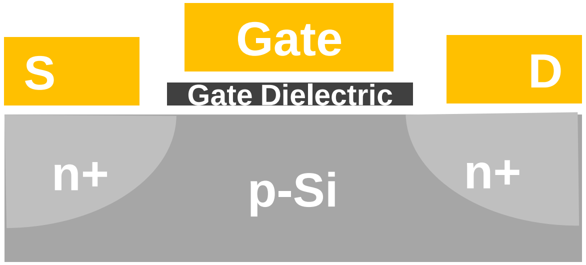
Graphene for Si True Ohmic Contact

Source/Drain Contact

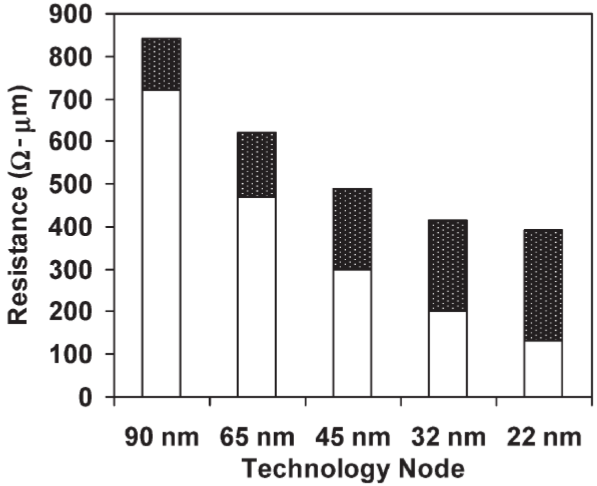
: Contact Resistance became serious portion of total resistance of devices

- **Total Resistance of Device**
  - Channel Resistance is getting smaller as the device getting smaller
  - Specific contact resistance is constant and contact resistance is getting bigger as the contact area is getting smaller

$$R_{Total} = R_C(S/n+) + R(p\text{-}Si) + R_C(n+/D)$$



- **Contact resistance of logic devices**
  - From 32 nm, contact resistance is higher than channel resistance.

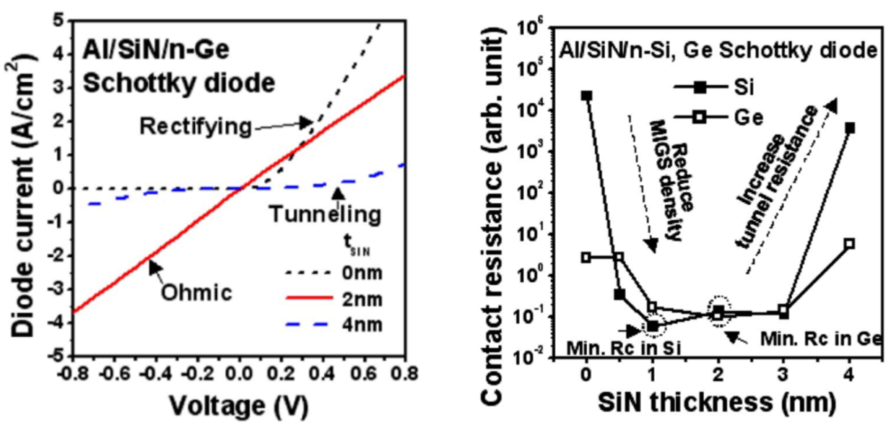


  - 9.1% of PMOS's and 37.5% of NMOS's contact resistances are due to Schottky barrier between contact metal silicide and Si.

IEEE Trans Elec Dev **55**, 1259 (2008)

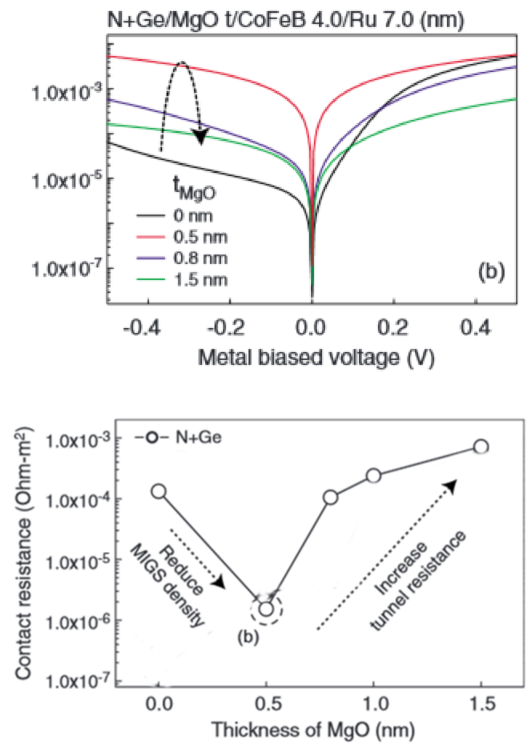
De-pinning
: Some may de-pin Si surfaces but hard to control its thickness (< 1 nm)

- **De-pinning by inserting interfacial layer**
  - 1nm SiN ⇒ Ohmic contact & contact resistance reduction by 10^6 times



J. Appl. Phys. **105**, 023702 (2009)

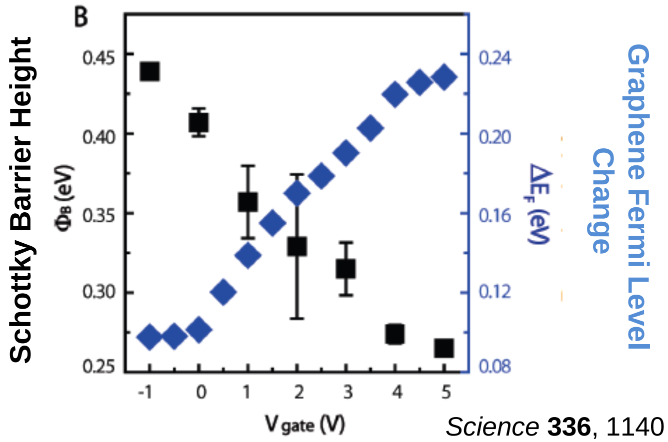
- **0.5nm MgO ⇒ Ohmic contact & contact resistance reduction by 100 times**



Appl. Phys. Lett. **96**, 052514 (2010)

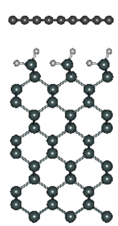
Graphene for De-pinning
: AFM results show that Graphene improved contact resistances.

- **De-pinning for Graphene on fully saturated Si**
  - 1:1 relationship btw work function & Schottky barrier height



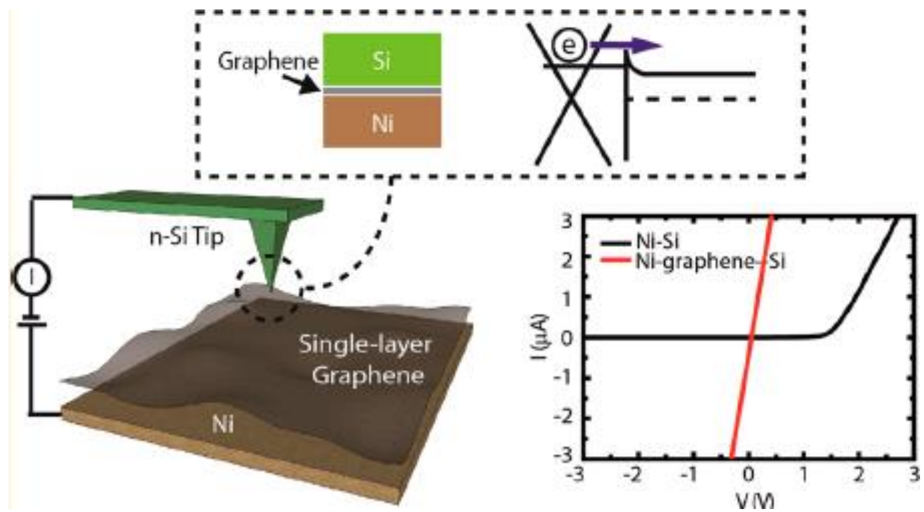
Science **336**, 1140 (2012)

  - Fully saturated Si Surface with 0.5 nm Separation with Graphene



J. Appl. Phys. **105**, 023702 (2009)

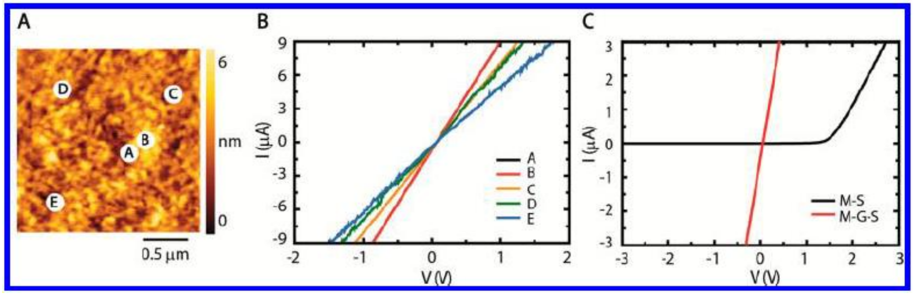
- **Demonstrated that Schottky barrier height reduction**
  - Contact resistance was measured with AFM (Atomic Force Microscopy) and was 10^{-8} ~ 10^{-9} Ωcm^2 (n-Si 10^{17} cm^{-3}).



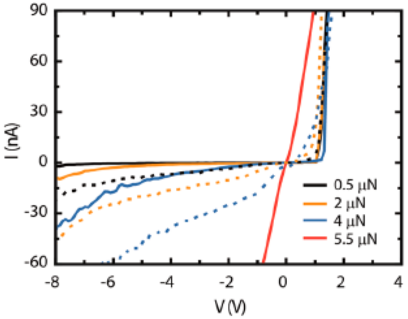
Nano Letters **13**, 4001 (2013)

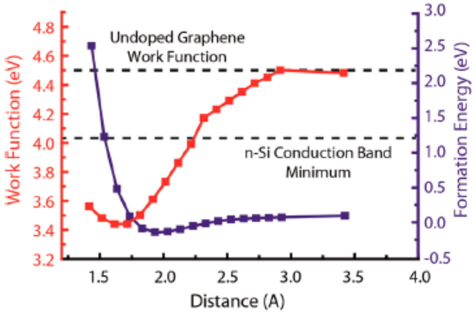
Graphene for Ohmic Contact
: Ohmic Contact between Ni and Si with Graphene insertion

- **Ohmic contact was demonstrated**
  - 1:1 relationship btw work function & Schottky barrier height

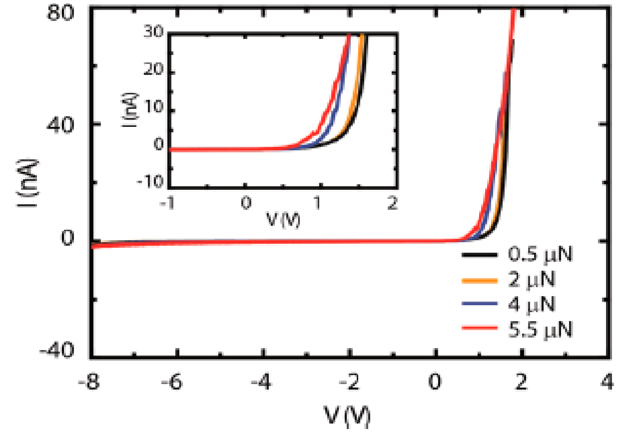


  - Some cases shows Schottky but can be corrected

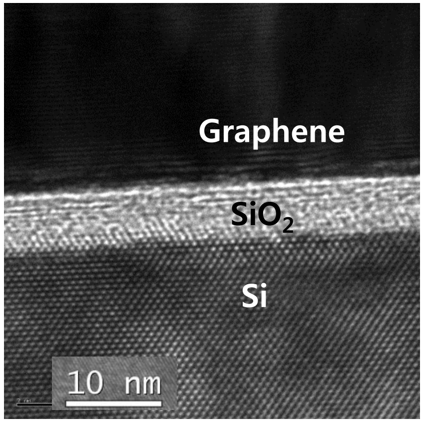




- **Schottky Contact for Metal/Si**



- **Interface Issues**



Summary

- Graphene Propoerties
  - High mobility, conductance, current density, transparency, chemical inertness
  - Surface area, thermal conductivity, ultimate strength

- Applications
  - New device concept: Gate-Tunable Schottky Diode / Barristor
  - High current on-off ratio (>10^5) achieved
  - OLET
  - S/D Contacts

- Too early to say what will happen: The Long Game
  - Nature, Editorials, May 2011
  - It typically takes any technology some 20 years to emerge from the lab and be commercialized.

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