Graphene Devices: from Transistor to Barristor

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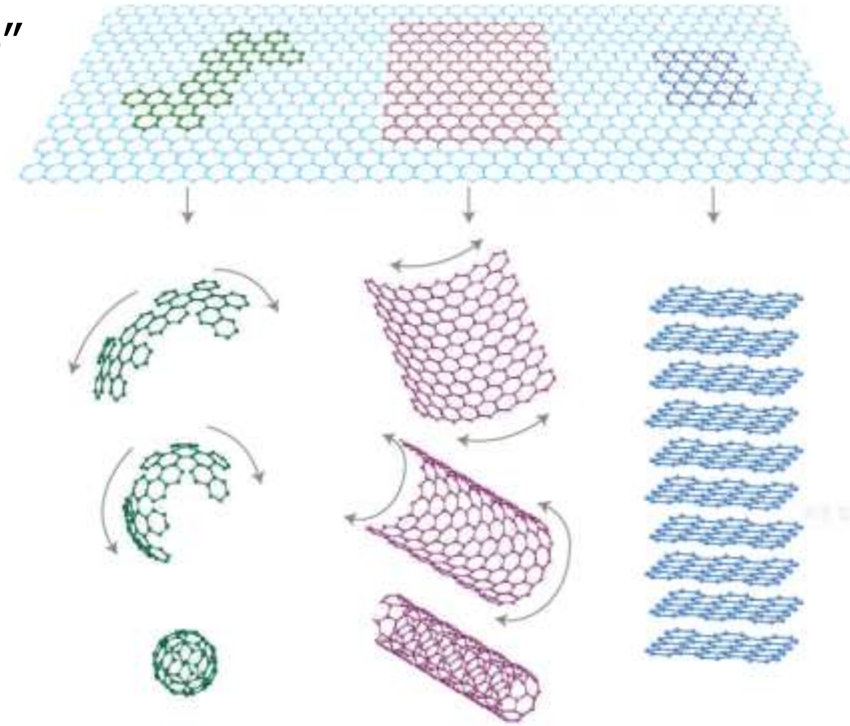
Graphene

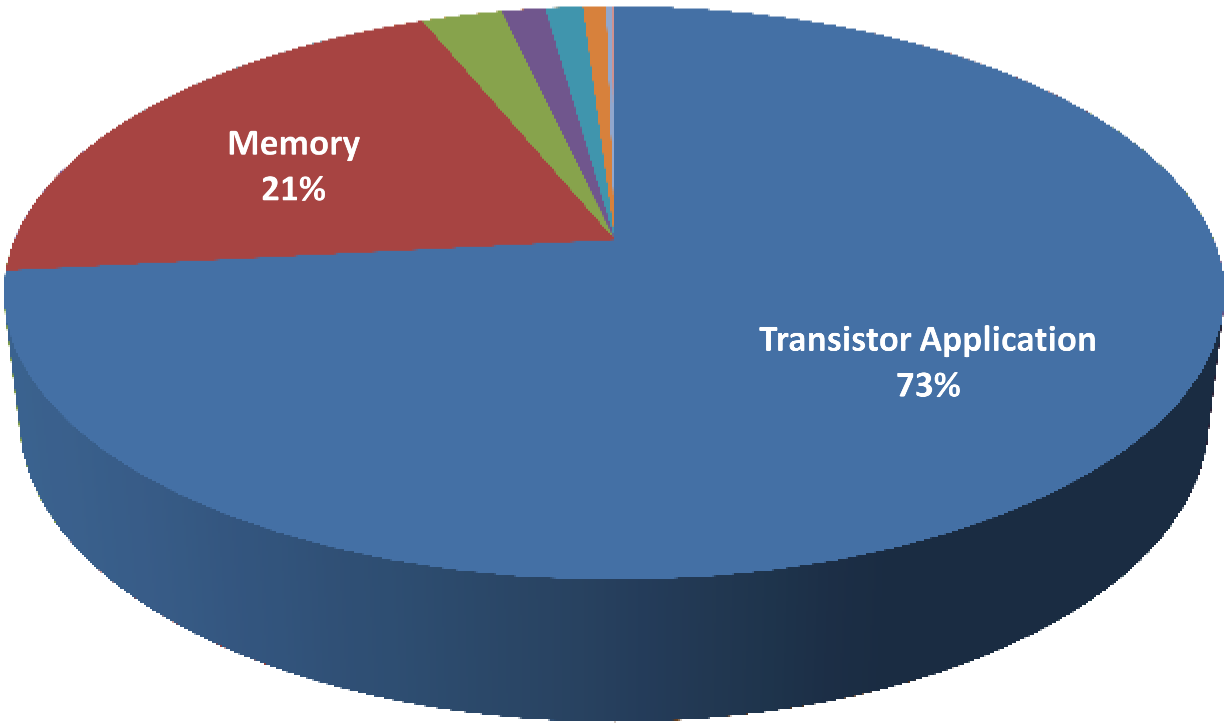
from "Rise of Graphene"



Property	Value
Conductivity	1.0 μΩcm
Mobility	~ 200,000 cm^2/Vs
Thermal conductivity	5300 W/mK
Mechanical property	Young's modulus: 1 Tpa Tensile strength: 20 Gpa
Flexibility	Failure strain > 20%
Transparency	97 % @ 1 layer
High surface	2,630 m^2/g

- Thinnest material
- Mechanical strength: 5 times steel
- Thermal conductor: 2 times diamond
- Resistivity: Half of Copper
- Mobility : 100 times Silicon's
- Current density : 100 times Copper

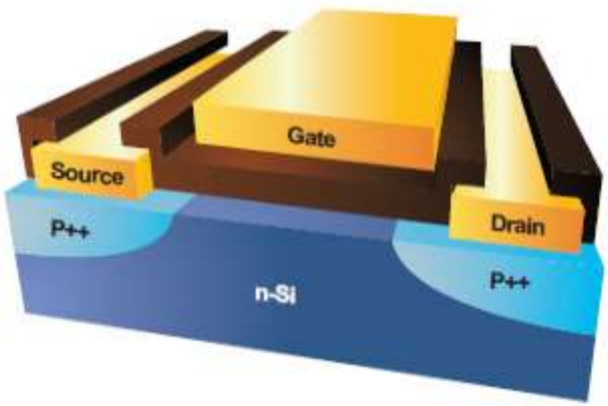
Application



Market Size (BCC Research Report 2011 and IT SOC magazine 2009)

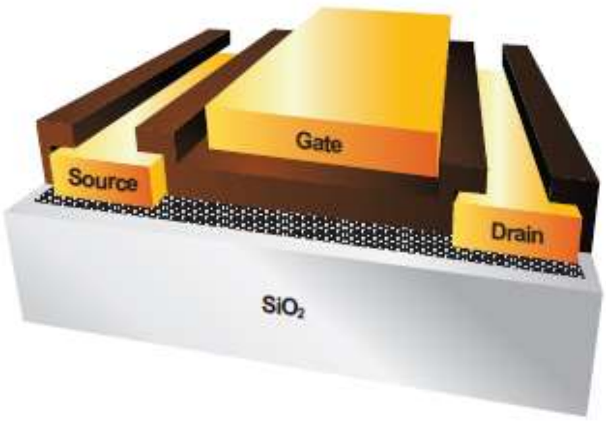
Structure

Silicon Transistor



mobility	~ 1,400 cm^2/Vs
bandgap	1.05 eV
e vs. *h*	asymmetric mobility

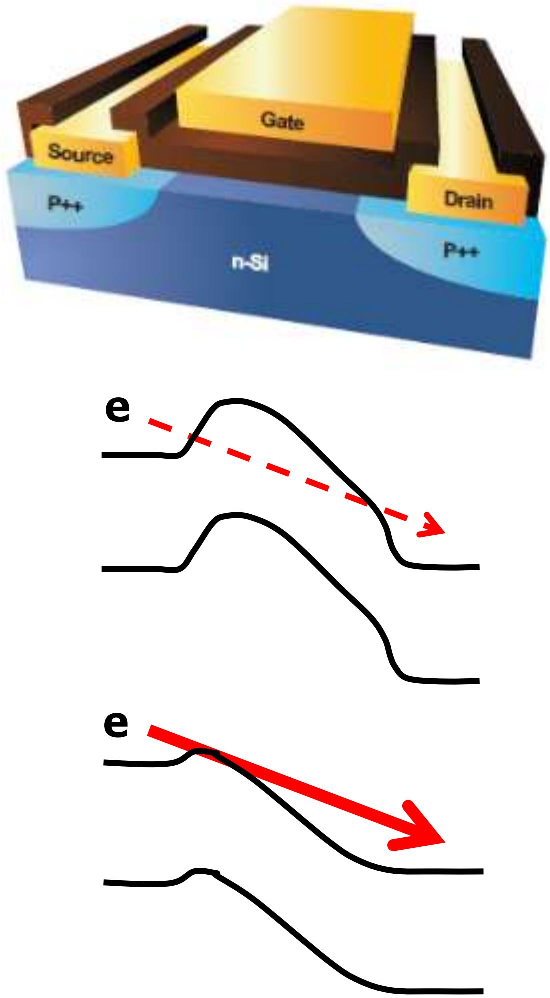
Graphene Transistor



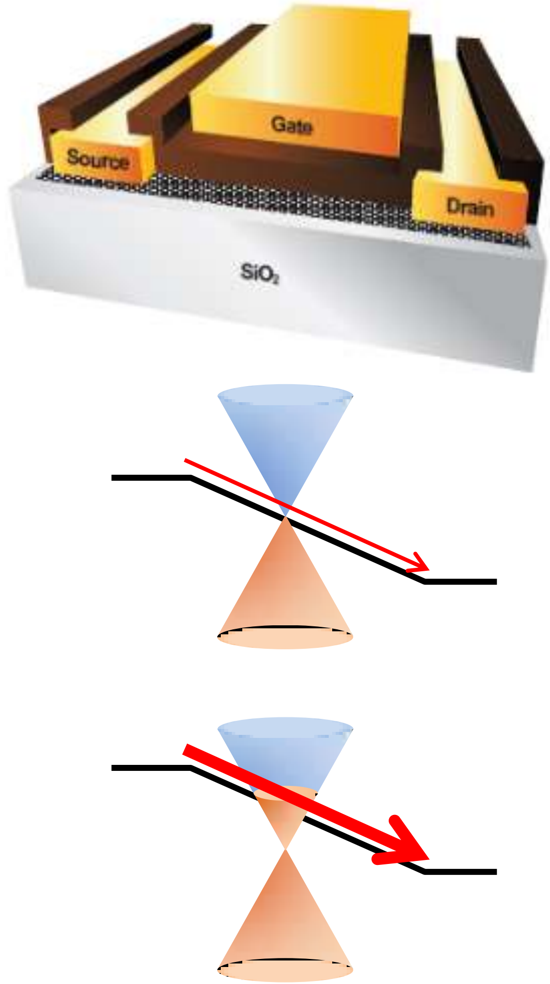
mobility	~ 200,000 cm^2/Vs
bandgap	0 eV
e vs. *h*	massless

Turning off the device, ... NO!

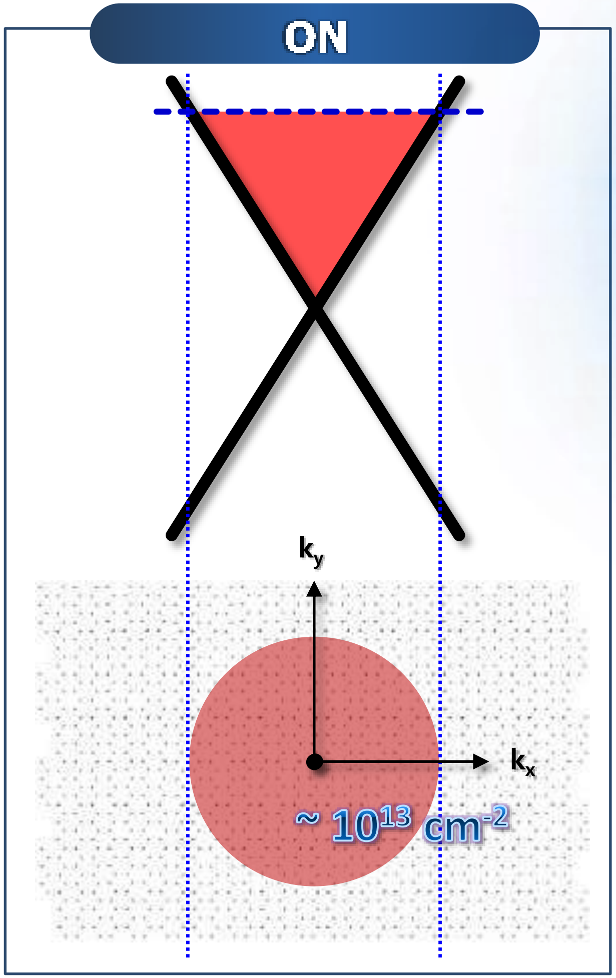
Silicon Transistor

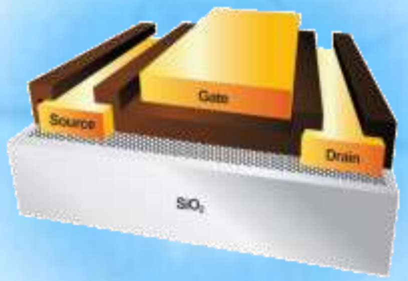


Graphene Transistor



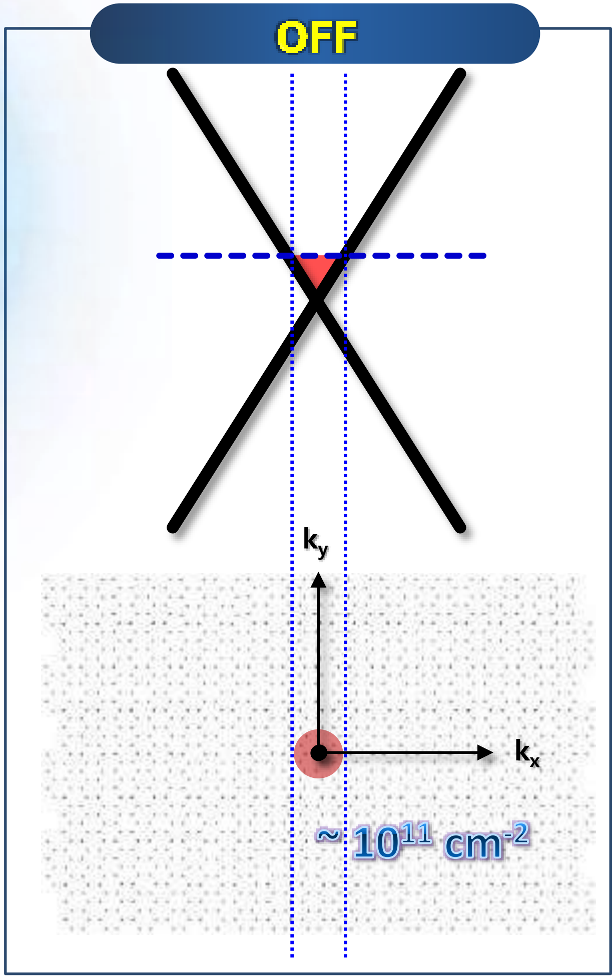
How Badly Turned off?





$$\frac{I_{ON}}{I_{OFF}} \sim \frac{10^{13}}{10^{11}} \sim 100$$

Density control
HARDLY
turns off
the device.

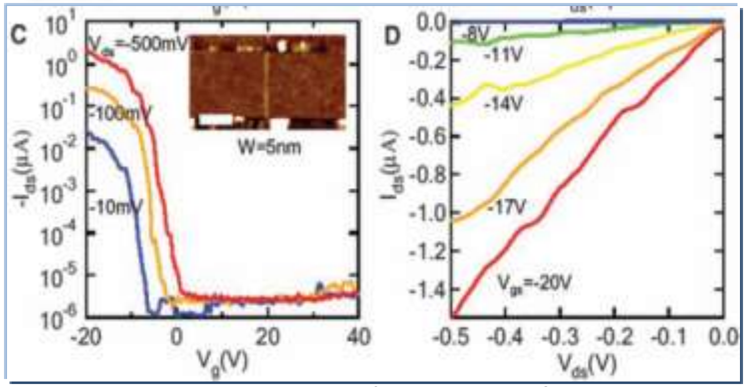


1st Approach: Bandgap of Graphene

Quantum Confinement

GNR

X. Li et al. Science (2008)

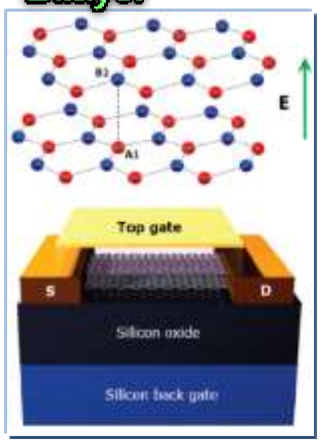


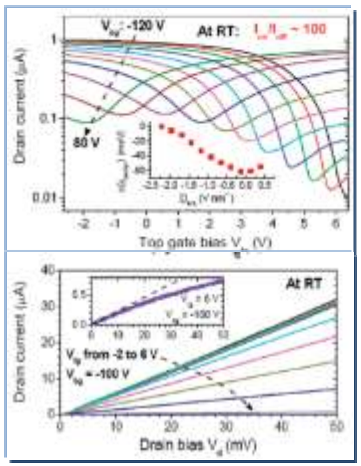
w=5nm, I_{on}/I_{off}~10^6, μ=100-200cm²/Vs

Symmetry Breaking

Bilayer

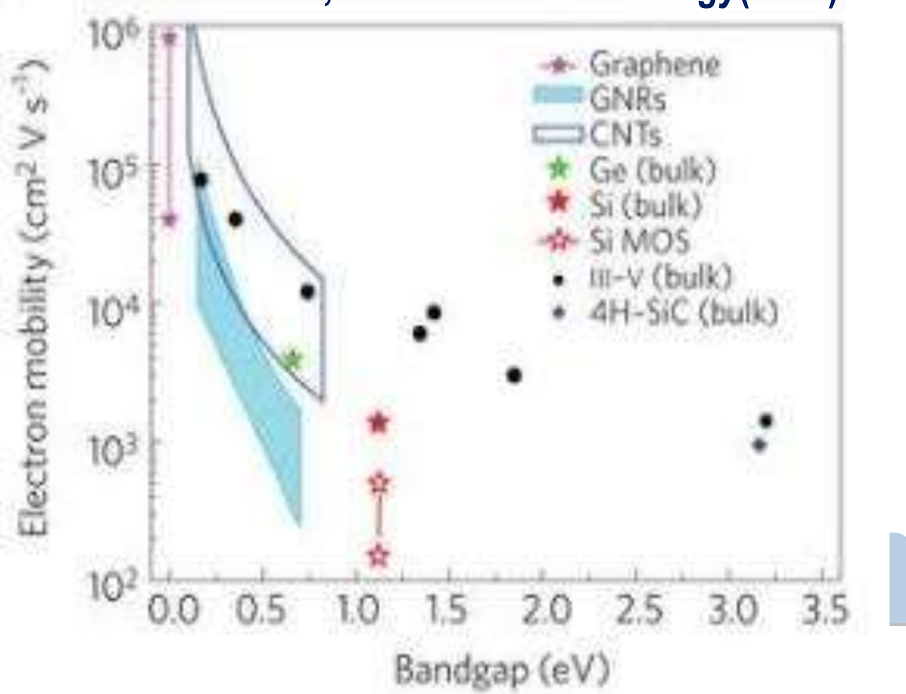
F. Xia et al. Nano Lett.. (2010)

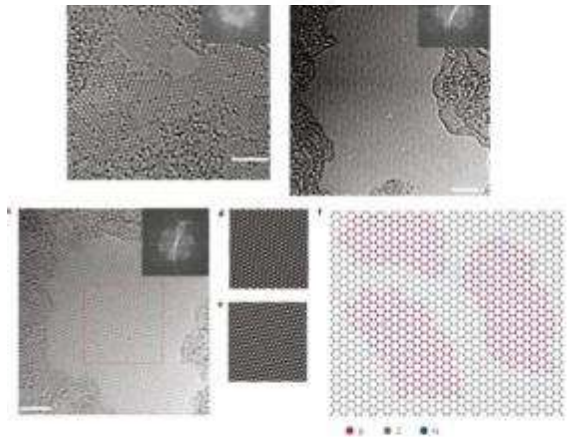




I_{on}/I_{off}~10^2, D=2.2V/nm

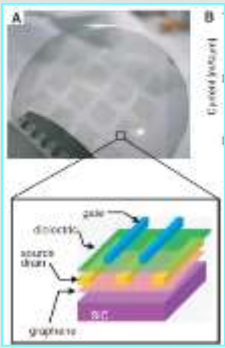
F. Schwierz, Nature Nanotechnology(2012)



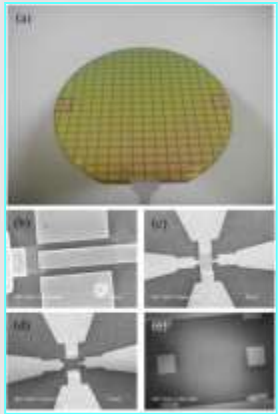


2nd Application: RF Transistor

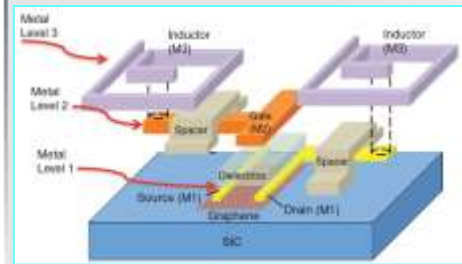
2009
IBM: 2 inch



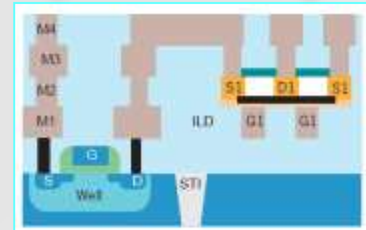
2010
SAIT: 6 inch



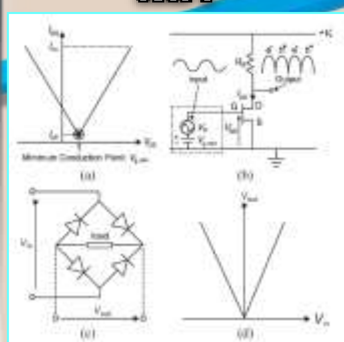
2011
IBM: The First IC



2011
Graphene-Si Hybrid



2009
MIT



2010
UCLA

Graphene Tr. in the Industry's Viewpoint

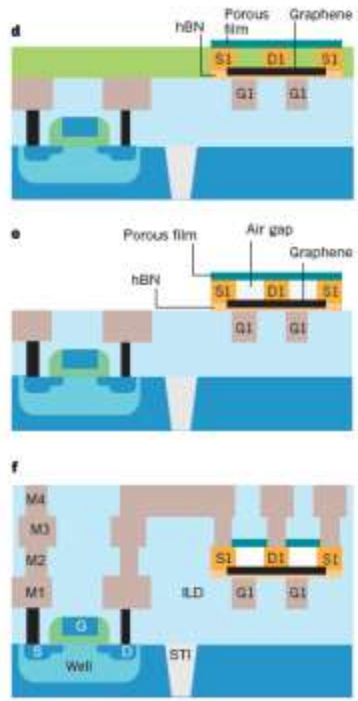
- Is it satisfactory? ➔ No!
- However, maybe, possibly, it could take one part of Si circuit…

Review

Table 1 | Properties of radio-frequency transistors

Transistor	f_t (GHz)	f_{max} (GHz)	L_g (nm)	W_g (µm)	Fingers	g_m (mS µm^{-1})	Mobility (cm^2 V^{-1} s^{-1})	Specific contact resistance (Ω µm^2)
Graphene								
Estimated[17]*	1,420	–	56	2	1	2.3	>10,000	
Measured[12]*	300	–	144	10	1	1.27		7.5 (ref. 23)
CVD grown[18]	155	<10	40	30	2	0.02	500–600	
Epitaxial[21]	100	–	240	–	2	0.15	1,000–1,500	
Silicon								
Silicon[13]	485	–	29	30	30	1.3	1,400‡	0.1§
ITRS 2011	310	330	29	–	–	–		
ITRS 2014†	480	540	18	–	–	–		
III–V								
InP[14]	385	>1,100	<50	40	2	1.2	15,000	0.5 (ref. 16)
InAs[15]	628	331	30	100	2	1.62	13,200	

*Flake graphene; †Target specification; ‡Electron mobility; §100 nm × 100 nm NiSi/Si. L_g gate length; W_g gate width.



Processes for Nothing-on-Graphene Structure

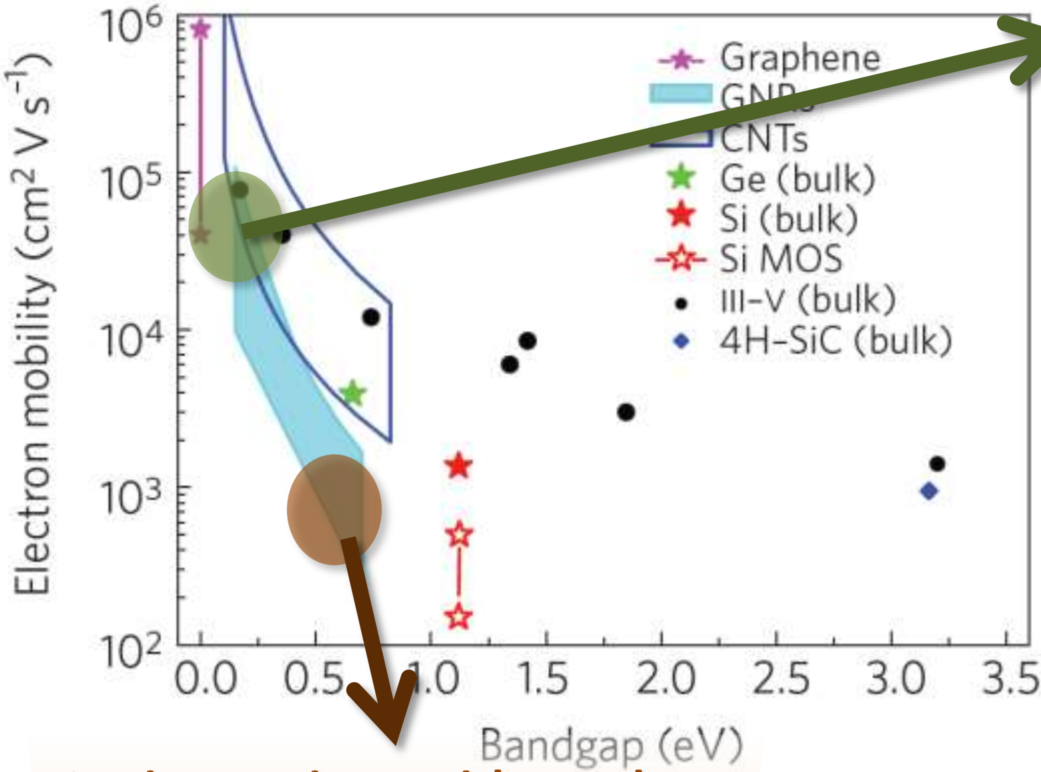
1. Taking one part in Si circuits
   1. Nothing-on-Graphene Structure
2. Greater f_{MAX} for amplification
   1. 'pinch-off' like condition.
   2. Maybe bandgap required.
3. Higher on-/off-current ratio.
   1. Bandgap > 0.36eV for logic

Table 2 | On/Offcurrent ratios for a 20-nm Si logic process

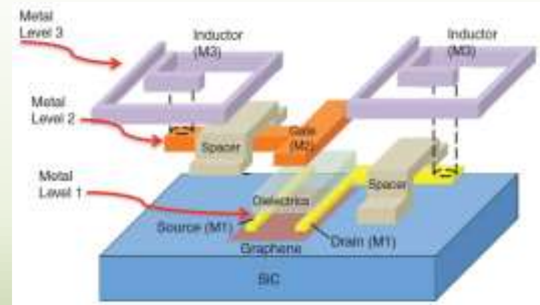
Property	Type 1*	Type 2†	Type 3‡	Type 4§
On/Off ratio	~2 × 10^6	~2 × 10^5	~4 × 10^4	~5 × 10^3
I_{ON} (µA µm^{-1})	~800	~1,000	~1,100	~1,300

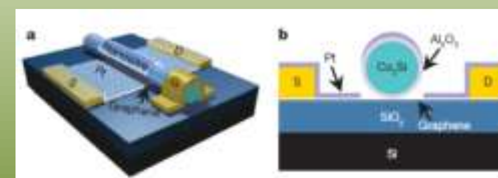
All transistor types are needed for 20-nm silicon CMOS logic circuits. *Low on current, highest on/off ratio; †Medium on current, high on/off ratio; ‡Medium on current, medium on/off ratio; §High on current, low on/off ratio.

Summary of Graphene Transistors

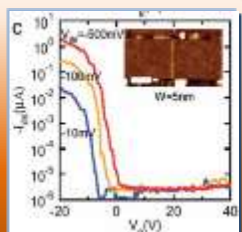


RF Transistor without Bandgap





Logic Transistor with Bandgap



Switching without Mobility ⟵ **Dilemma** ⟶ **Mobility without Switching**

Question!!!

HOW TO

TURN OFF THE DEVICE

W/O BANDGAP?

Graphene, Again!

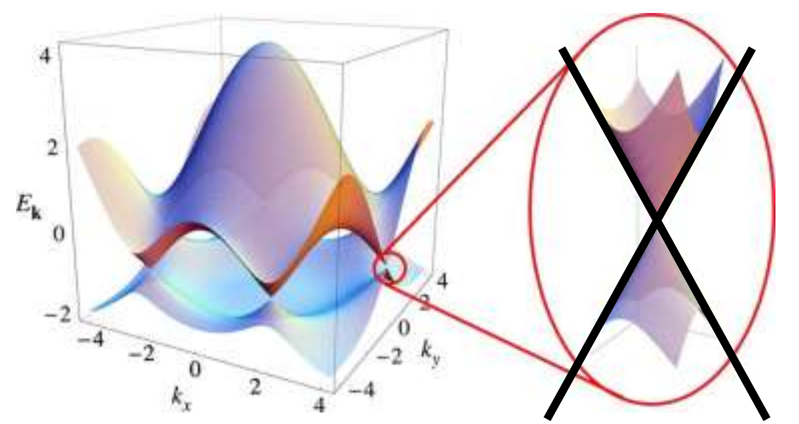
Klein Tunneling

High Mobility

Zero Bandgap

Linear Dispersion

Strength



$v_F \sim c/300$

π-Bonding

Zero Mass

Stiffness

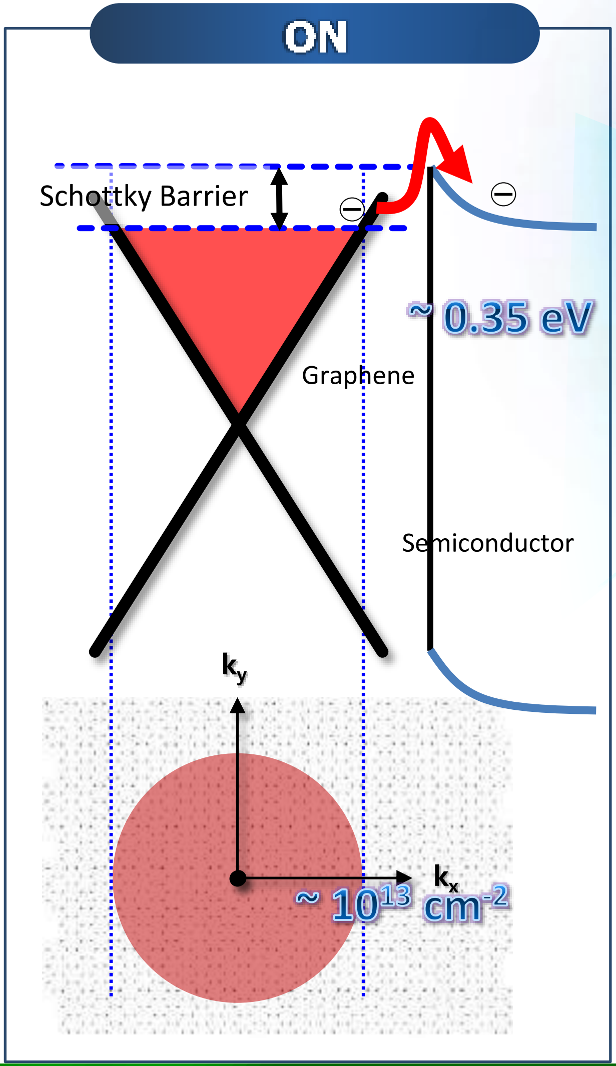
Low Density

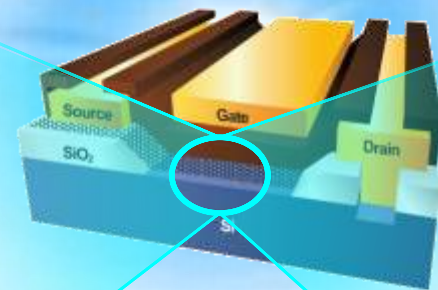
Transparency

Work Function Modulation

New approach to turn off!!!

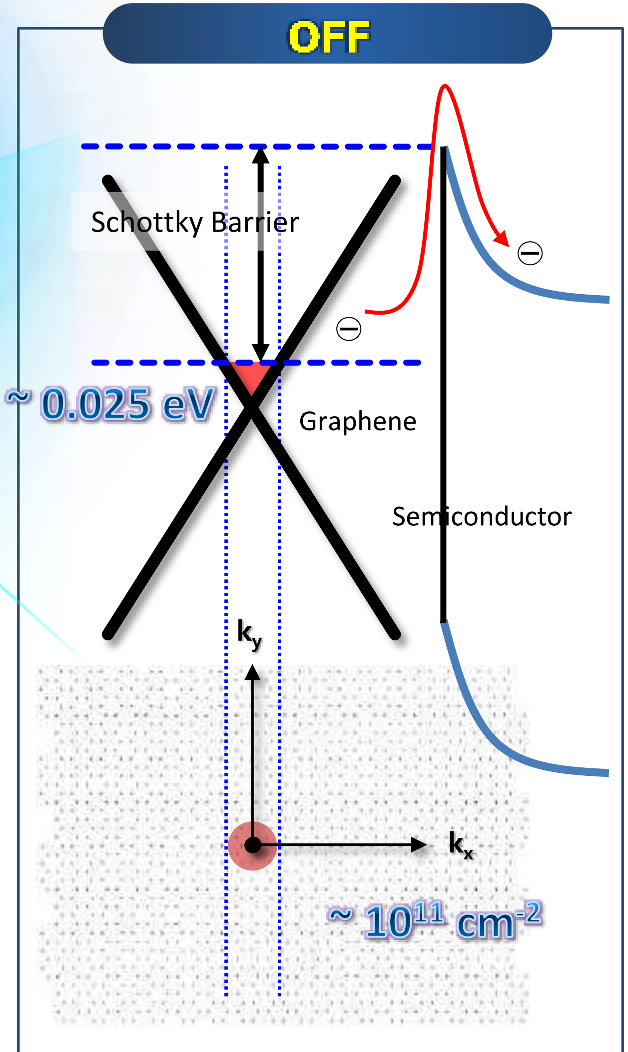
- **Key Idea: Density Control ➔ Barrier Control**





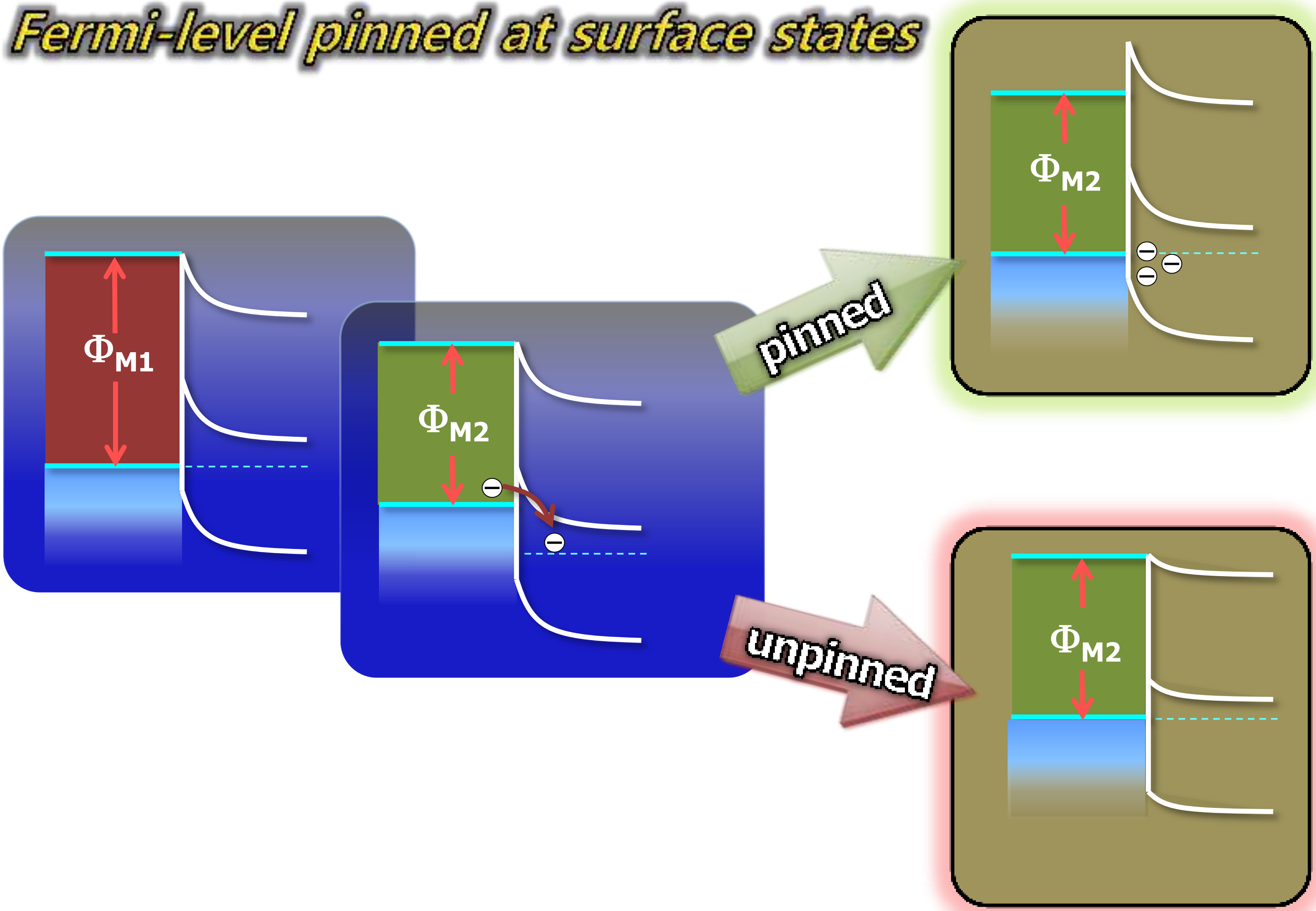
$$\frac{I_{ON}}{I_{OFF}} \approx \exp\left(\frac{0.35eV}{0.025eV}\right) > 1\times10^{6}$$

Barrier control POSSIBLY turns off the device.



Fermi-level Pinning

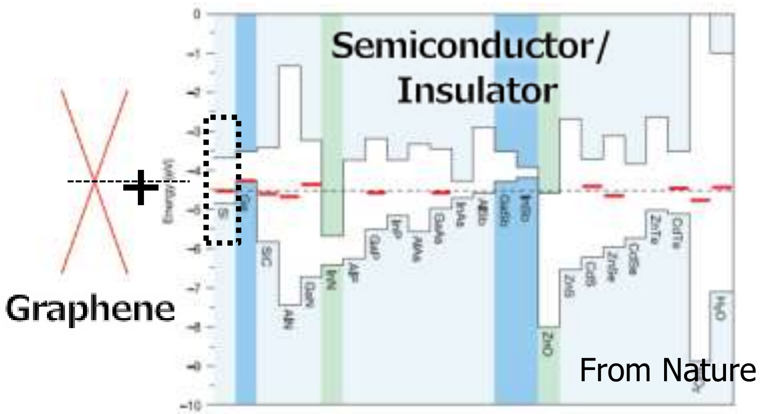
- *Fermi-level pinned at surface states*



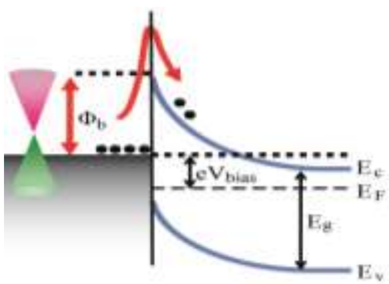
Fabrication

- **Considering Band alignment - Si**

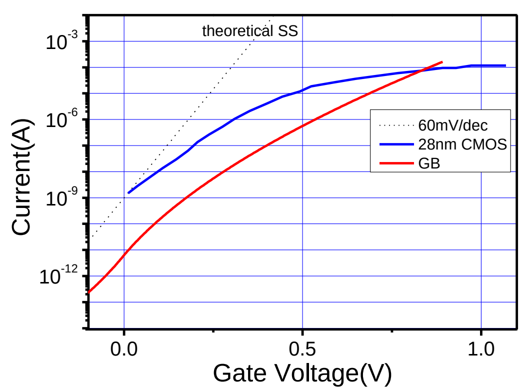
Material Search



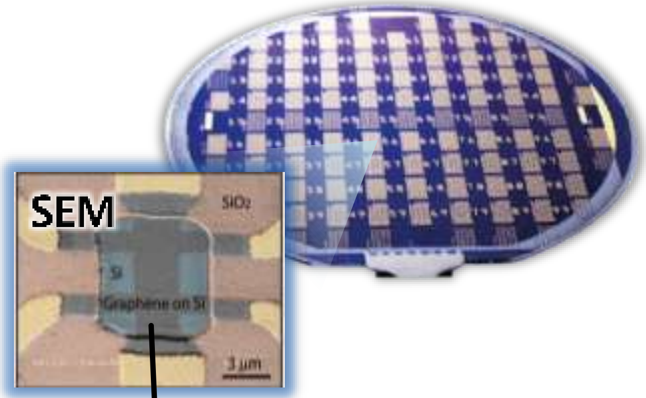
Principle :Thermionic Emission



$$I = AA^{*}T^{2}\exp\left(\frac{-\Phi_B}{kT}\right)\left[\exp\left(\frac{eV}{\eta kT}\right)-1\right]$$

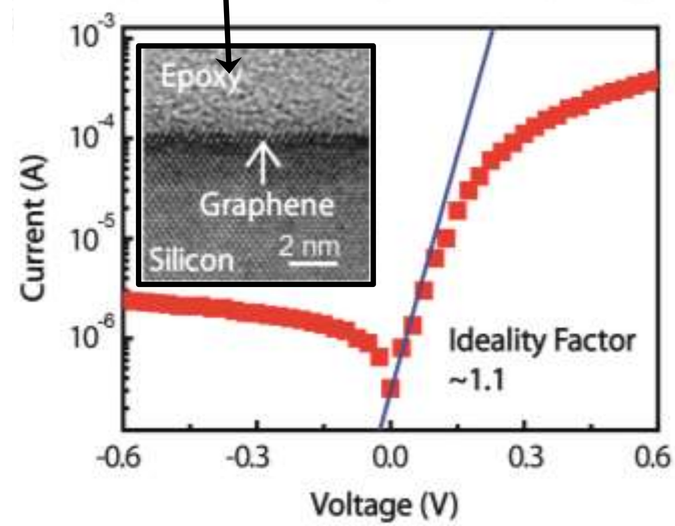


6 inch Process



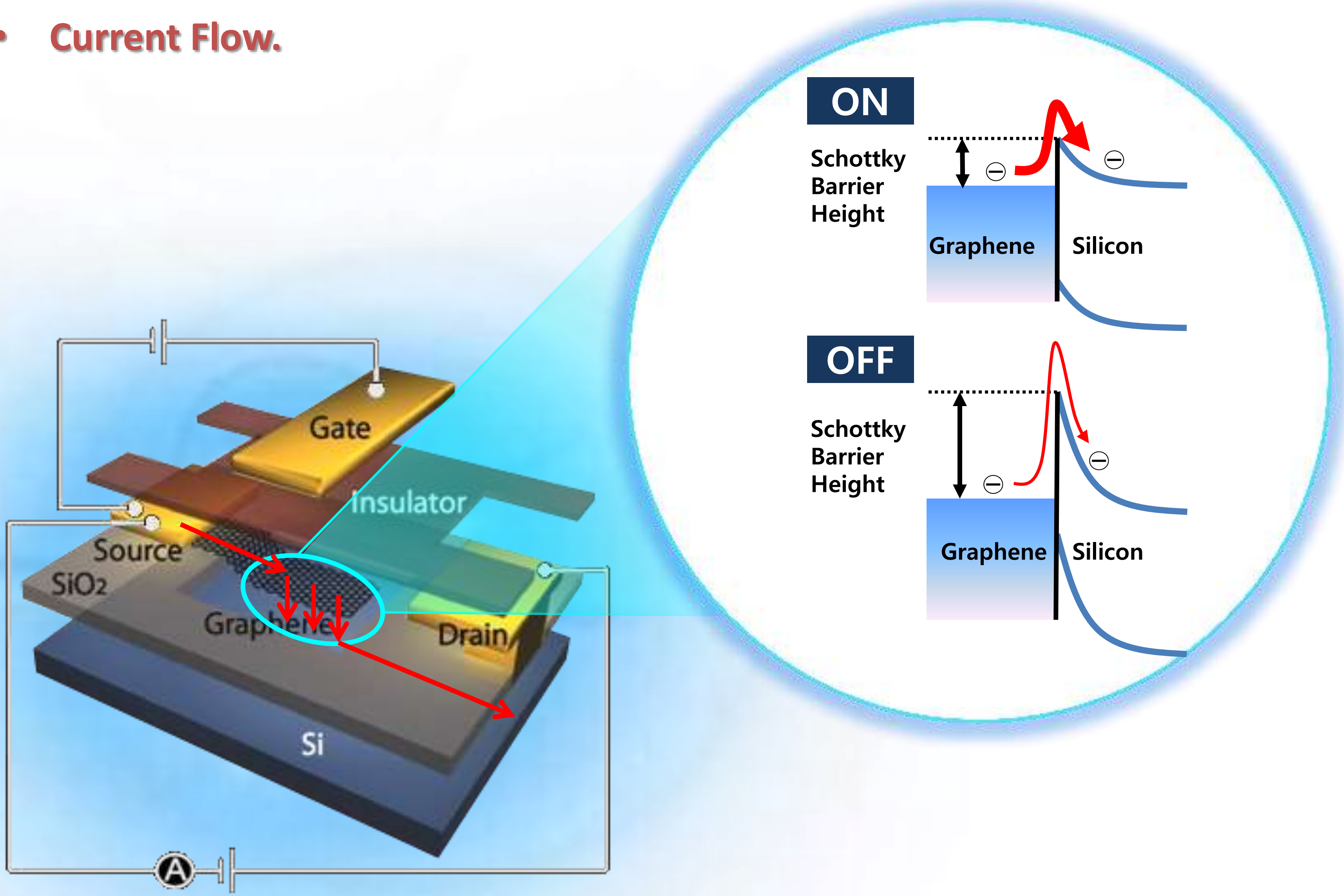
TEM & IV

Well defined interface
(Saturated Si + Graphene → no pinning)



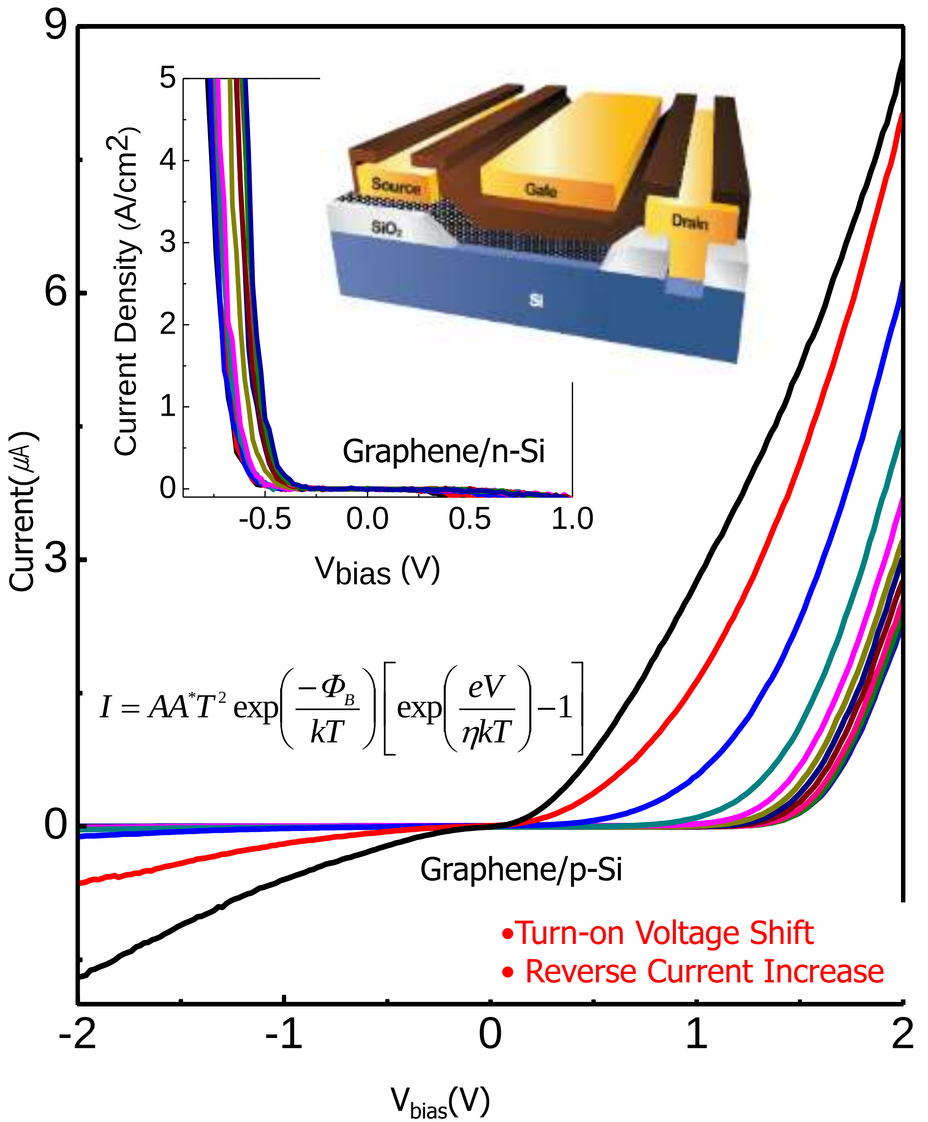
Remind

- **Current Flow.**

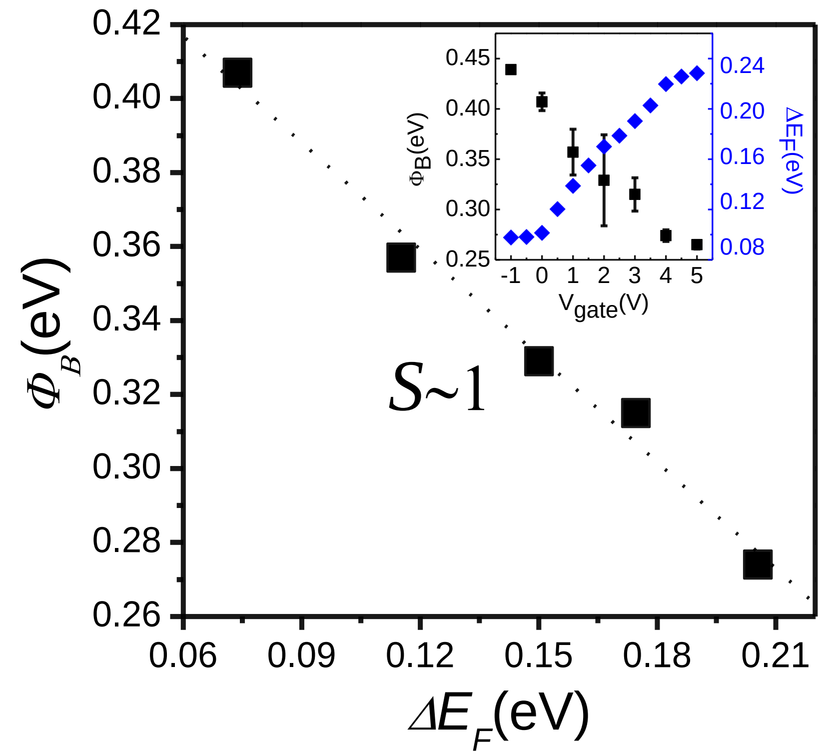


I-V Characteristic

Output Characteristics

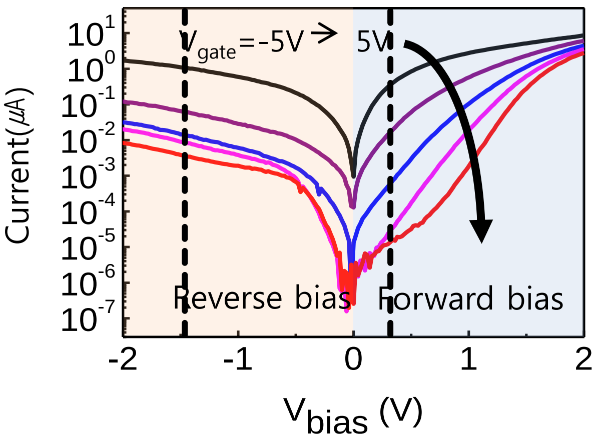


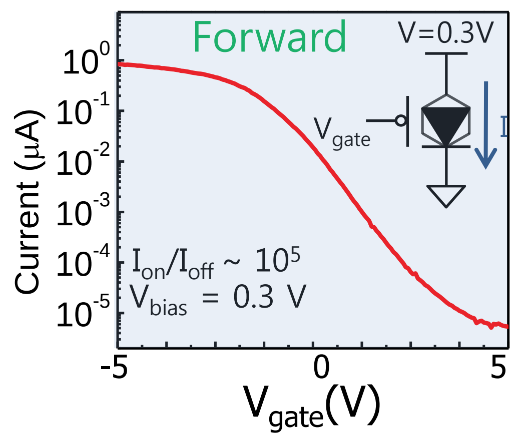
Principle

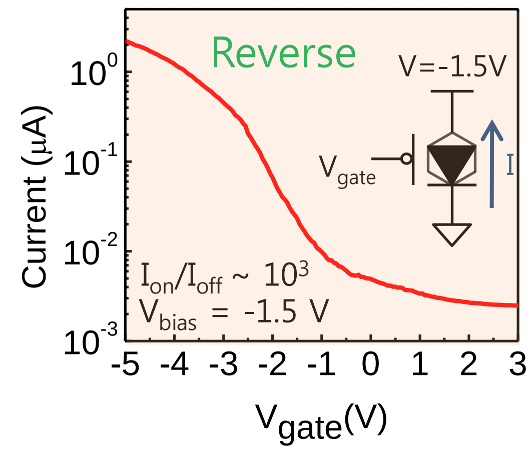


Application: Barristor Logic

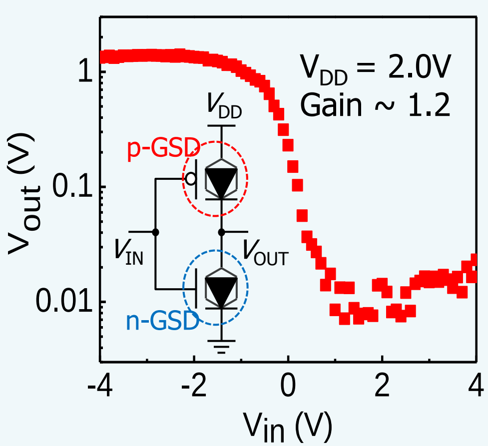
Output Characteristics



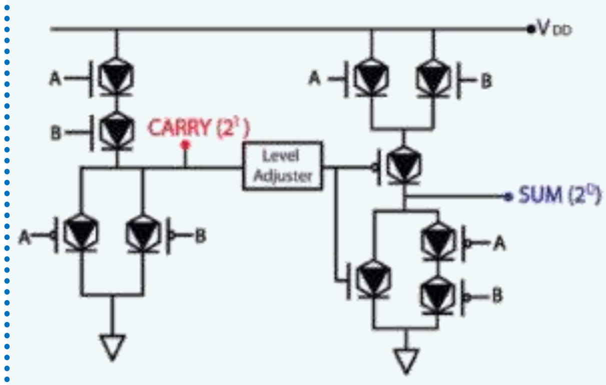


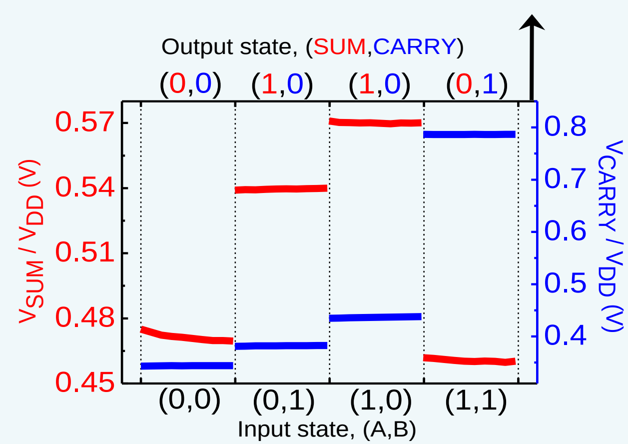


Inverte



Half-Adder





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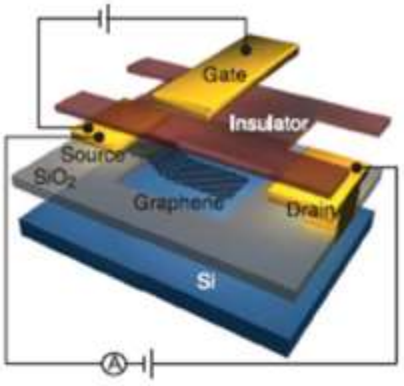
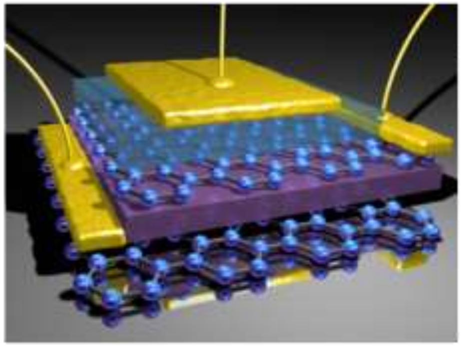
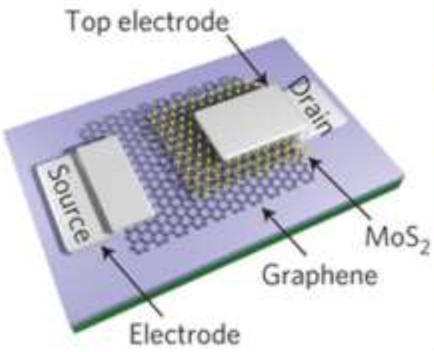
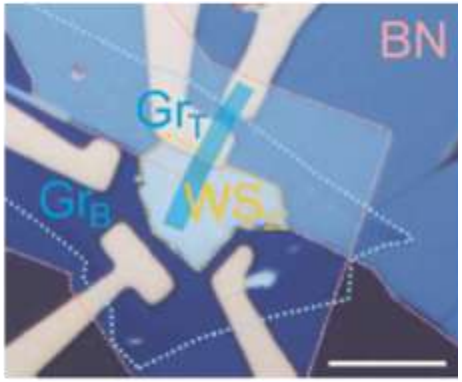
Barristor or Tunneling Transistor









Samsung	Manchester University	UCLA	Manchester University
Graphene-Si	Graphene-hBN	Graphene-MoS_2	Graphene-WS_2
Science 2012	Science 2012	Nature Mat. 2013	Nature Nano. 2012

Current Mechanisms

- **Thermionic Emission Current**

$$I = AA^{*}T^{2}\exp\left(\frac{-q\phi_b}{k_B T}\right)\left[\exp\left(\frac{qV_{bias}}{\eta_{id} k_B T}\right) - 1\right]$$

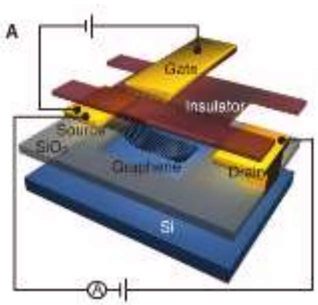
- **Tunneling Current**

$$I(V) = \frac{A_{eff}\sqrt{m\phi_B}\,q^2 V}{h^2 d}\exp\left[\frac{-4\pi\sqrt{m\phi_B}\,d}{h}\right]$$

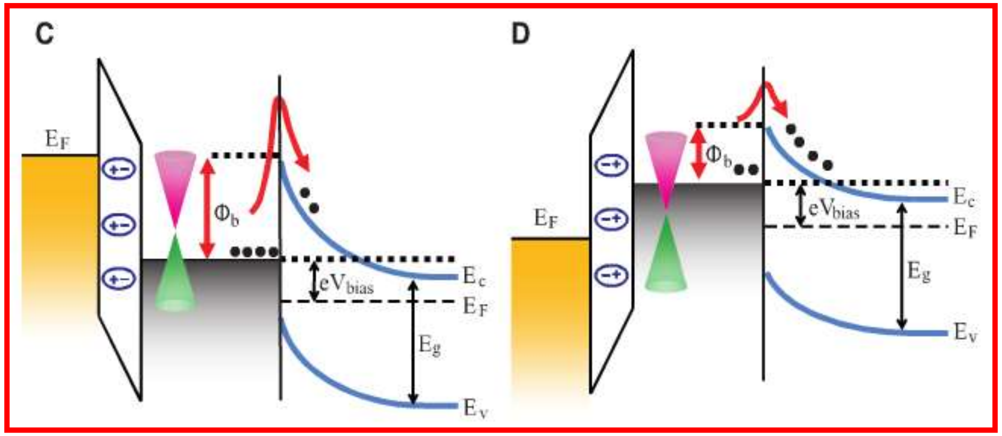
Thermionic Emission Current

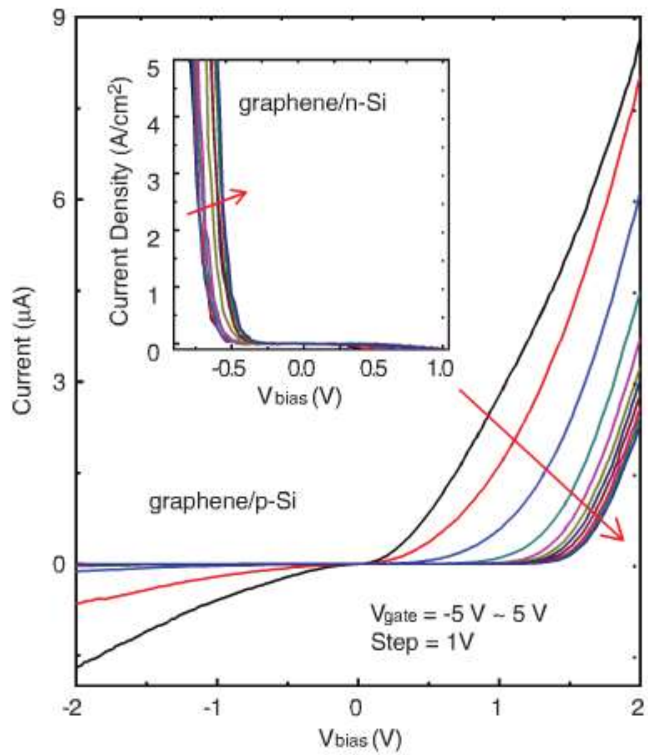
- **Current through Graphene-Semiconductor Junction: Graphene-Si (Graphene-MoS_2)**
- **On/Off ratio limited by Workfunction Modulation**

$$\frac{I_{ON}}{I_{OFF}} \approx \exp\left(\frac{0.35eV}{0.025eV}\right) > 1\times10^{6}$$



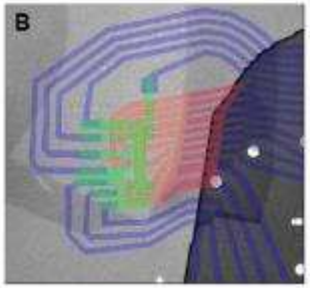
Yang *et. al* **Science** (2012)



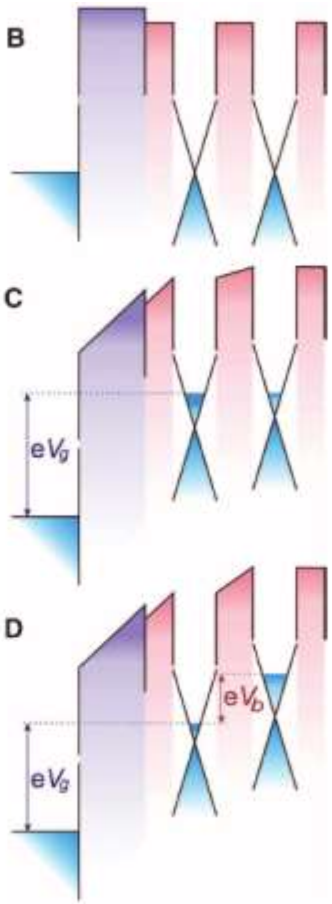


Tunneling Current

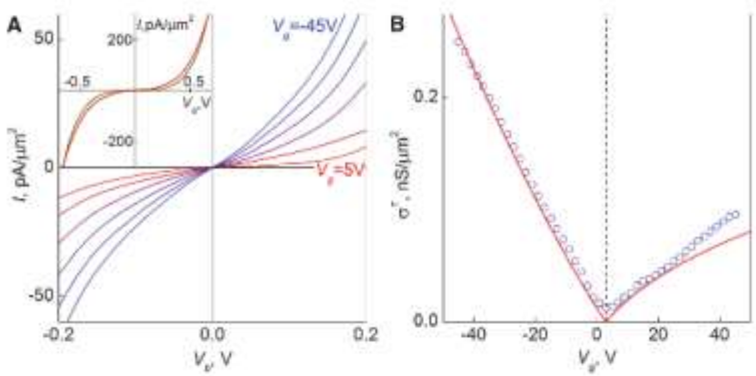
- **Current through Graphene-Insulator Junction**
- **Depends mostly on density of states:**
  therefore has the same problem with transistor
- **Low Voltage Operation**



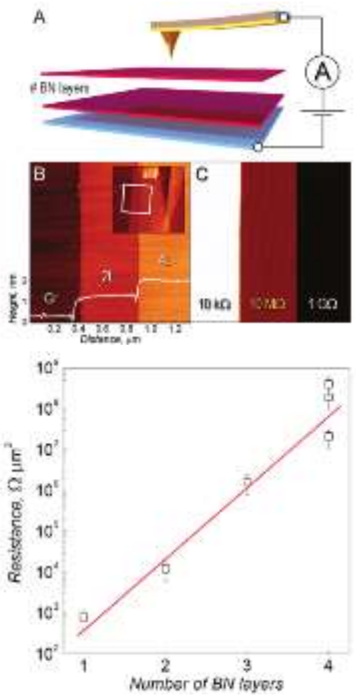
Britnell *et. al* **Science** (2012)



$$I(V) \propto \int dE\, \boxed{\mathrm{DoS_B}(E)\mathrm{DoS_T}(E-\mathrm{eV})}\, T(E)[f(E-\mathrm{eV})-f(E)]$$



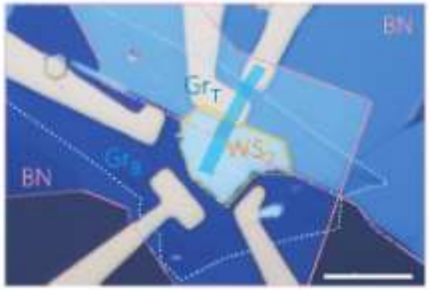
Britnell *et. al* **Science** (2012)



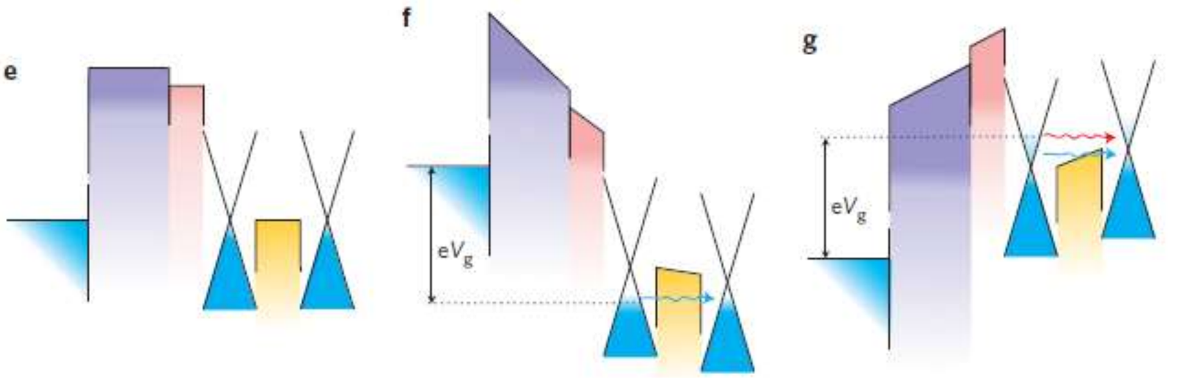
Britnell *et. al* **Nano Lett.** (2013)

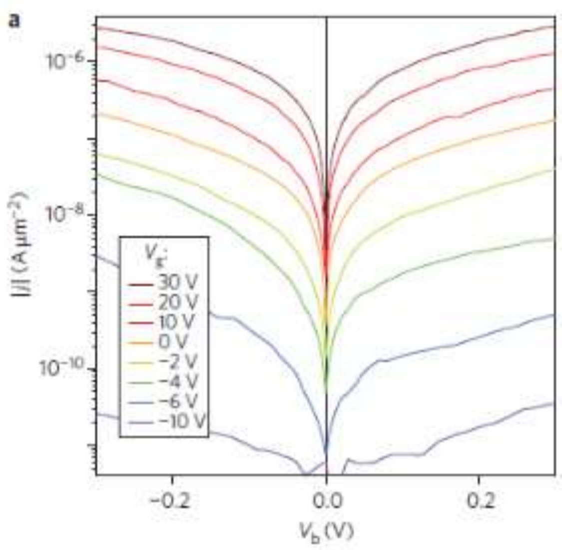
Tunneling + Thermionic Current

- **Current through Graphene-Insulator Junction**
- **Determined by more complex way.**
- **High Voltage Operation. However, …**



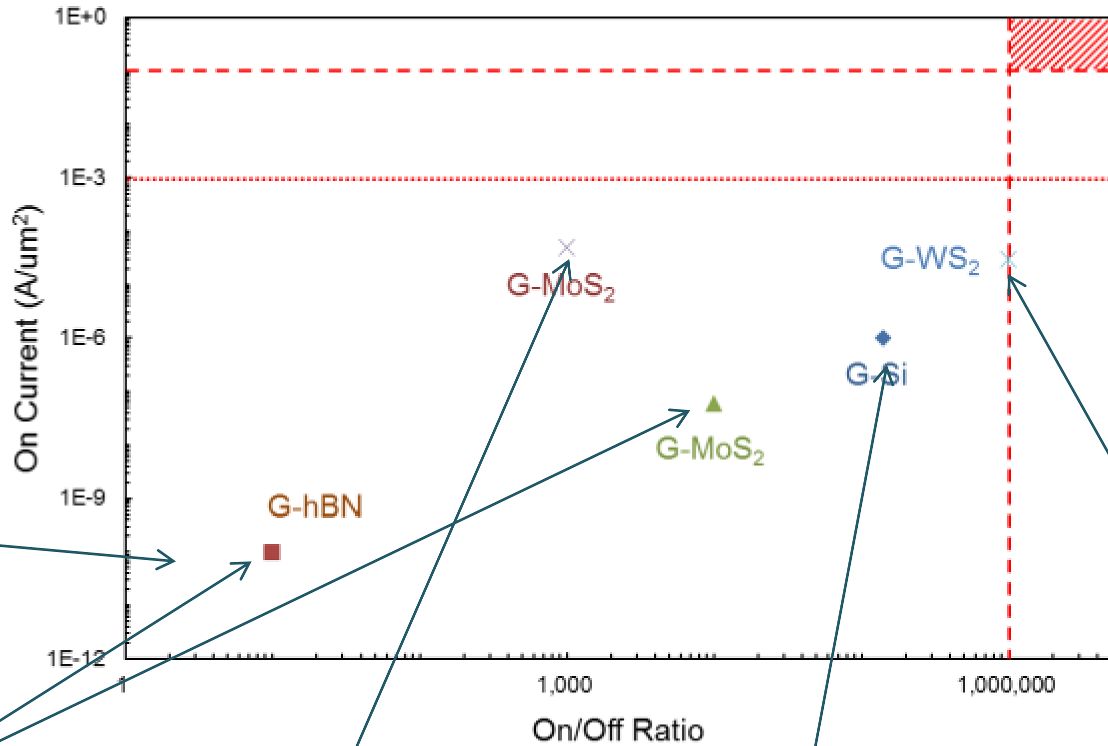
Georgiou *et. al* **Nat. Nano.** (2012)

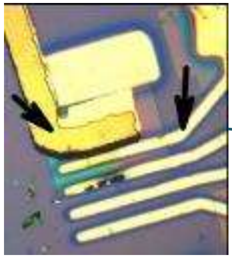




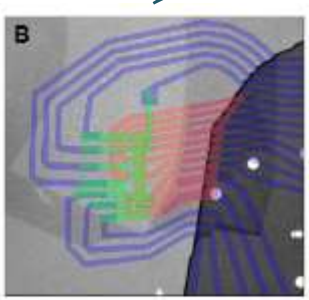
Where are we?

Barristor and Vertical Tunneling Transistor

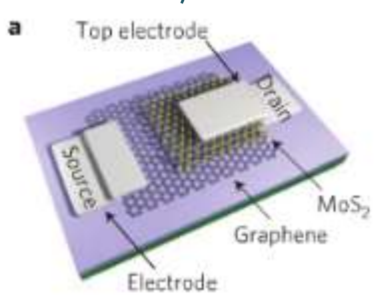




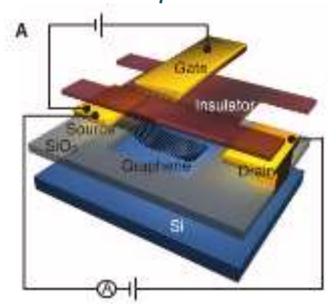
Ojeda-Aristizaval *et. al* **Arxiv**



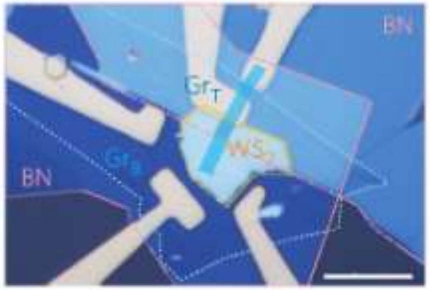
Britnell *et. al* **Science** (2012)



Yu *et. al* **Nat. Mat.** (2012)



Yang *et. al* **Science** (2012)



Georgiou *et. al* **Nat. Nano.** (2012)

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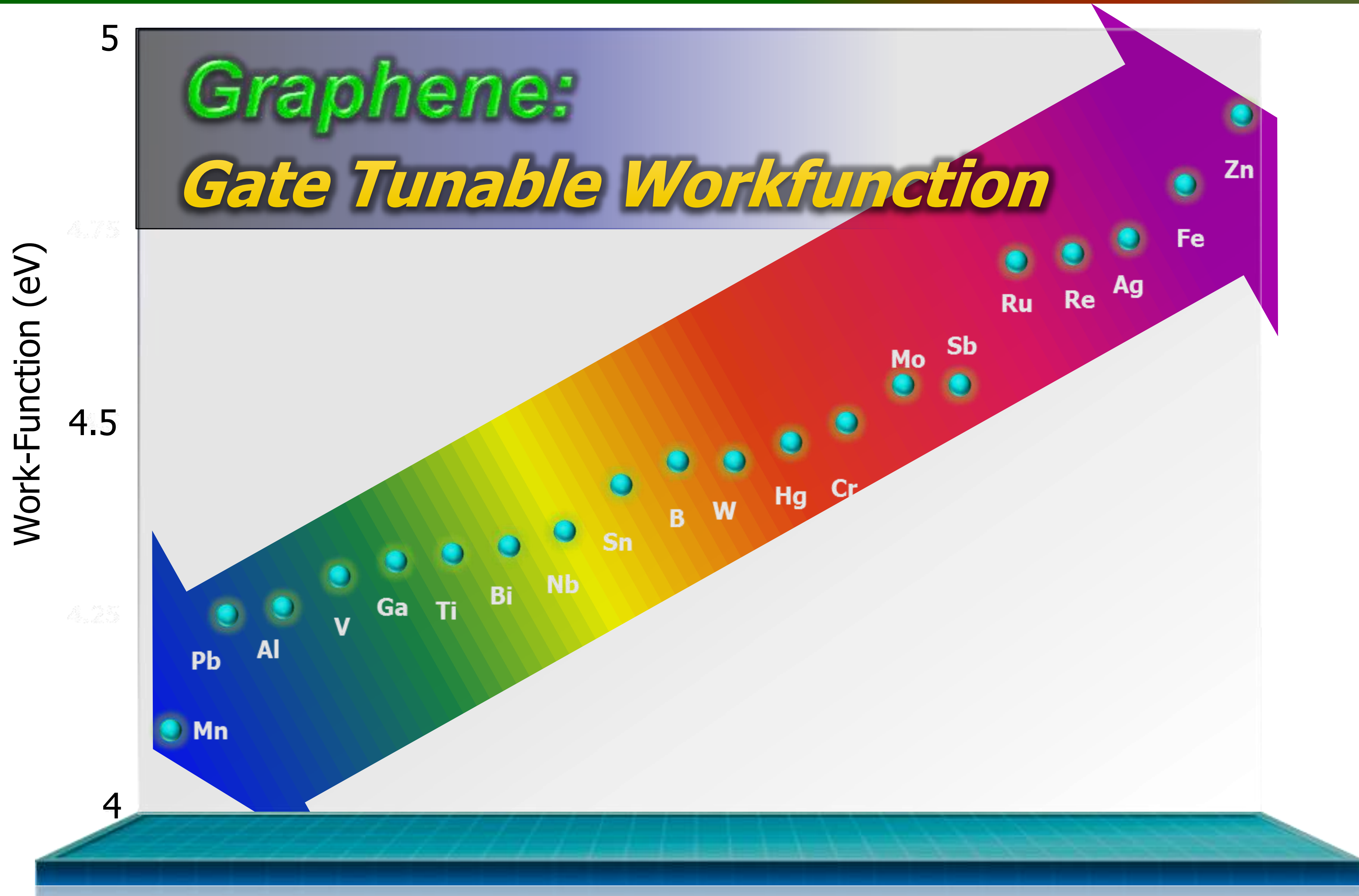
What is Graphene?



Thank you

for any discussions and comments

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