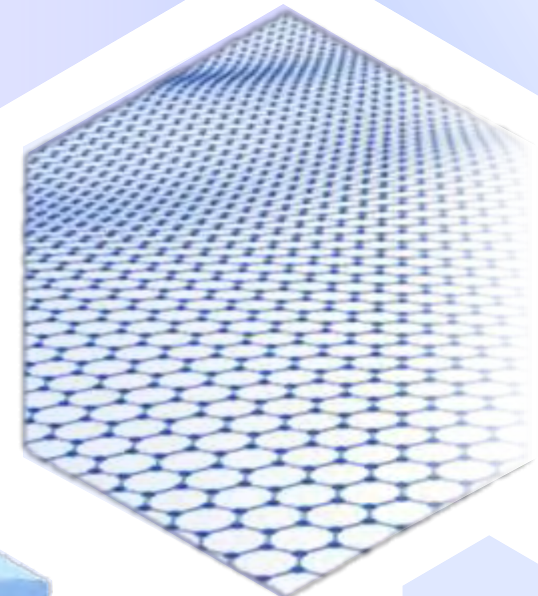
3rd Berkeley Symposium on Energy Efficient Electronic Systems

2D Tunnel Devices and Circuits on Graphene: Opportunities and Challenges



Jiahao Kang, Wei Cao, Deblina Sarkar,
Yasin Khatami, Wei Liu and Kaustav Banerjee

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University of California Santa Barbara
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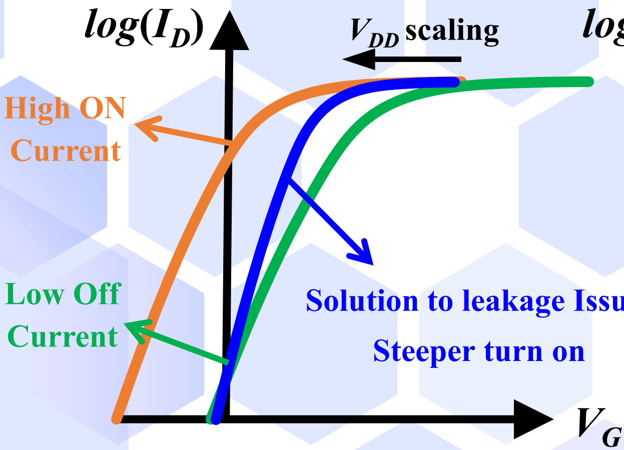
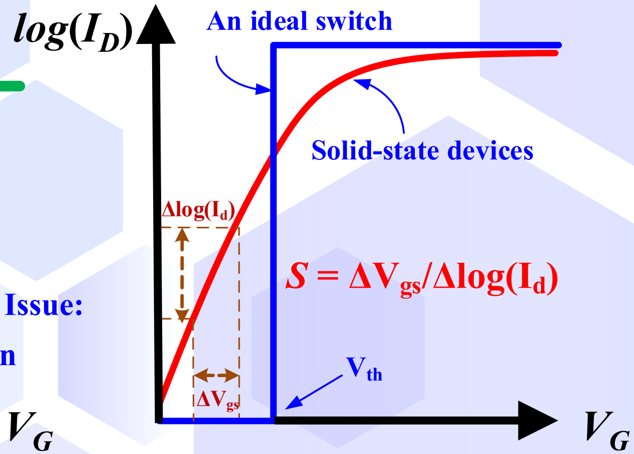
Oct. 29, 2013

Nano Research Lab

UCSB Engineering

CMOS Device Scaling Issue

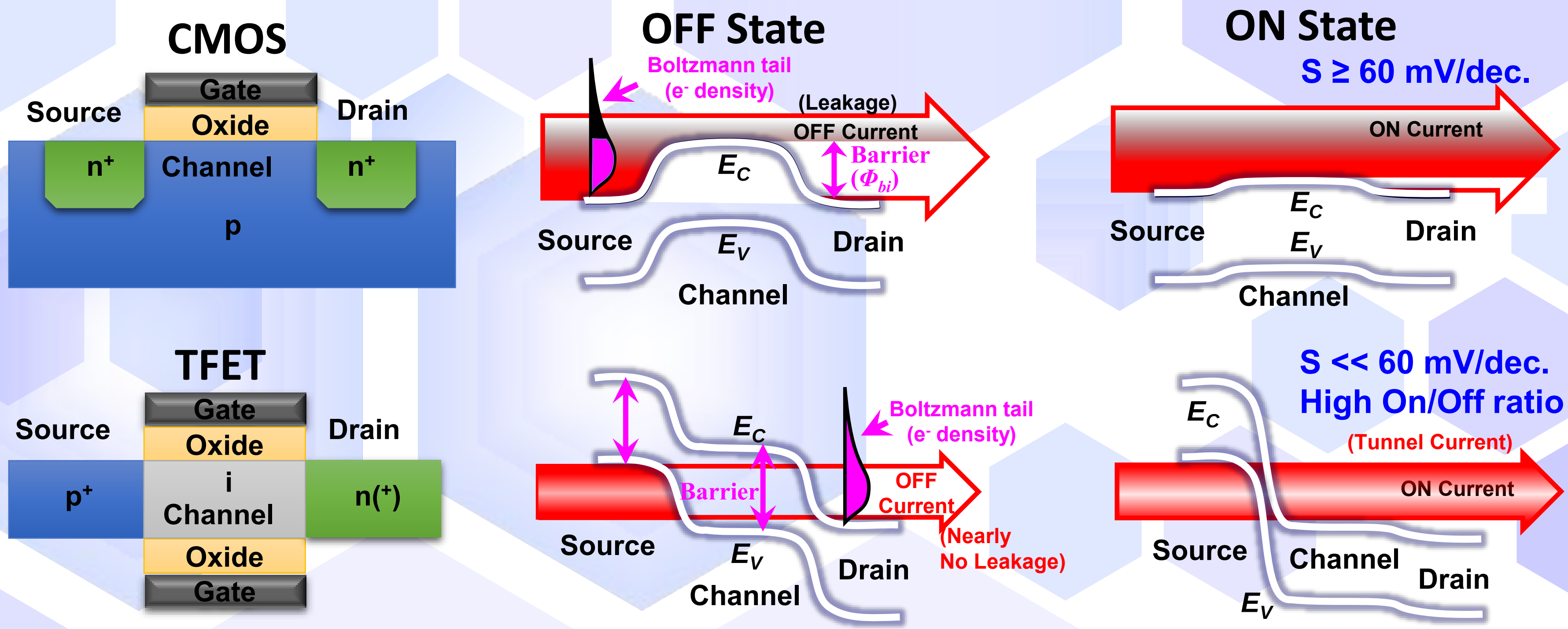




Aggressive scaling leads to an exponential increase in leakage power.

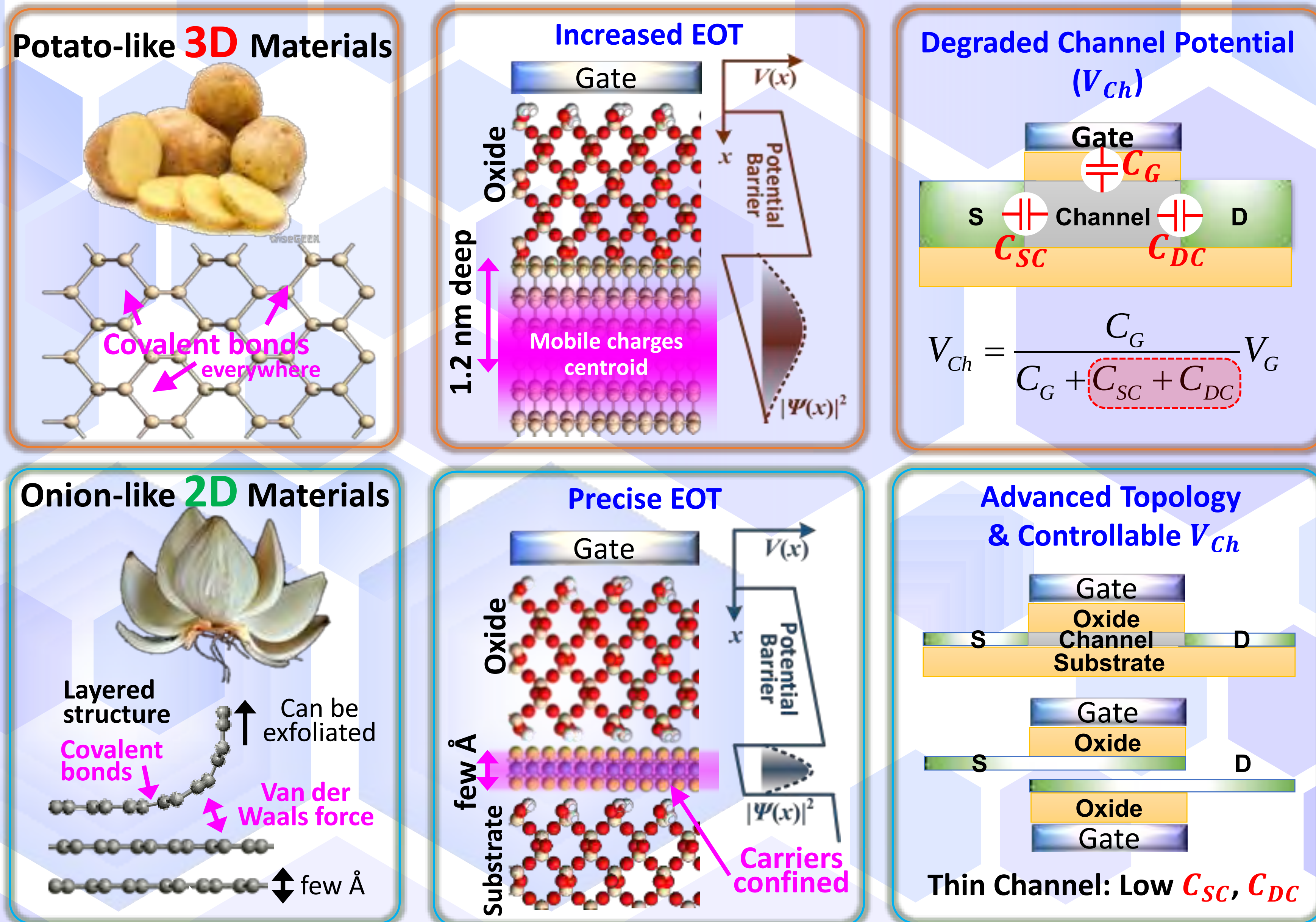
Subthreshold Swing (**S**) should be as low as possible.

Current ***On/Off ratio*** should be as high as possible.



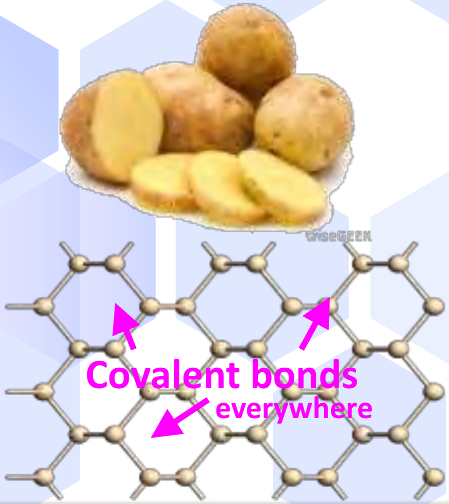
Y. Khatami and K. Banerjee, TED, vol. 56, no. 11, 2009.

Advantages of 2D Materials for Tunnel Devices: 1. Electrostatics

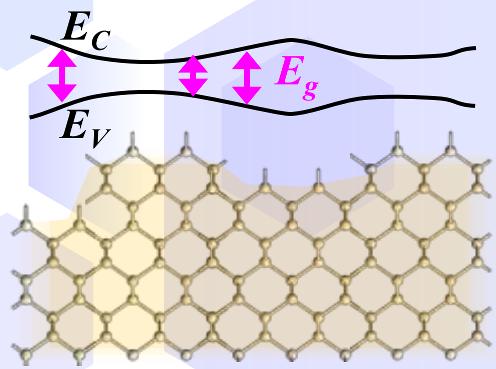


Advantages of 2D Materials for Tunnel Devices: 2. Variations

Potato-like 3D Materials

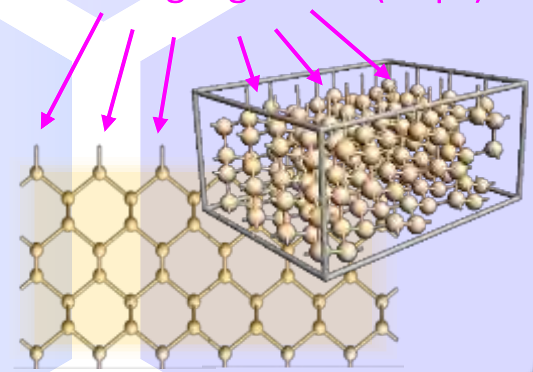


Thickness Roughness
→ Band gap Variation
→ Performance Variation

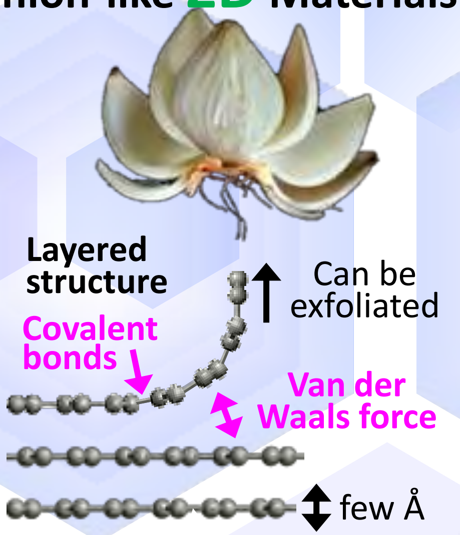


Interface Variations (Traps)

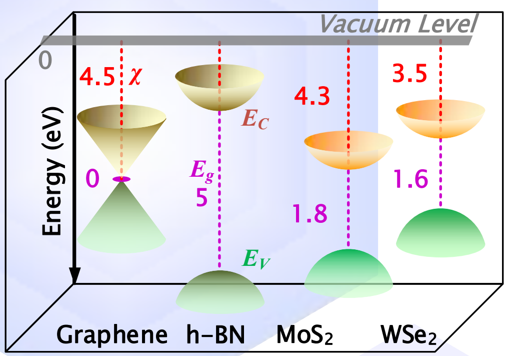
Unsaturated atoms on surfaces
→ Dangling bonds (traps)



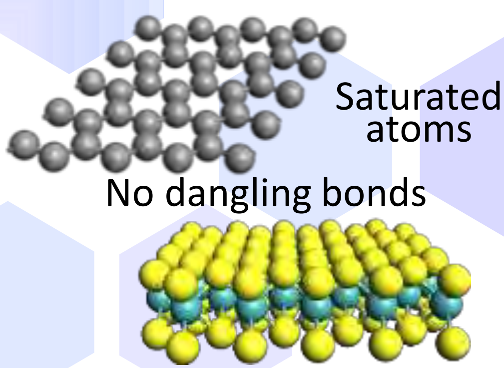
Onion-like 2D Materials



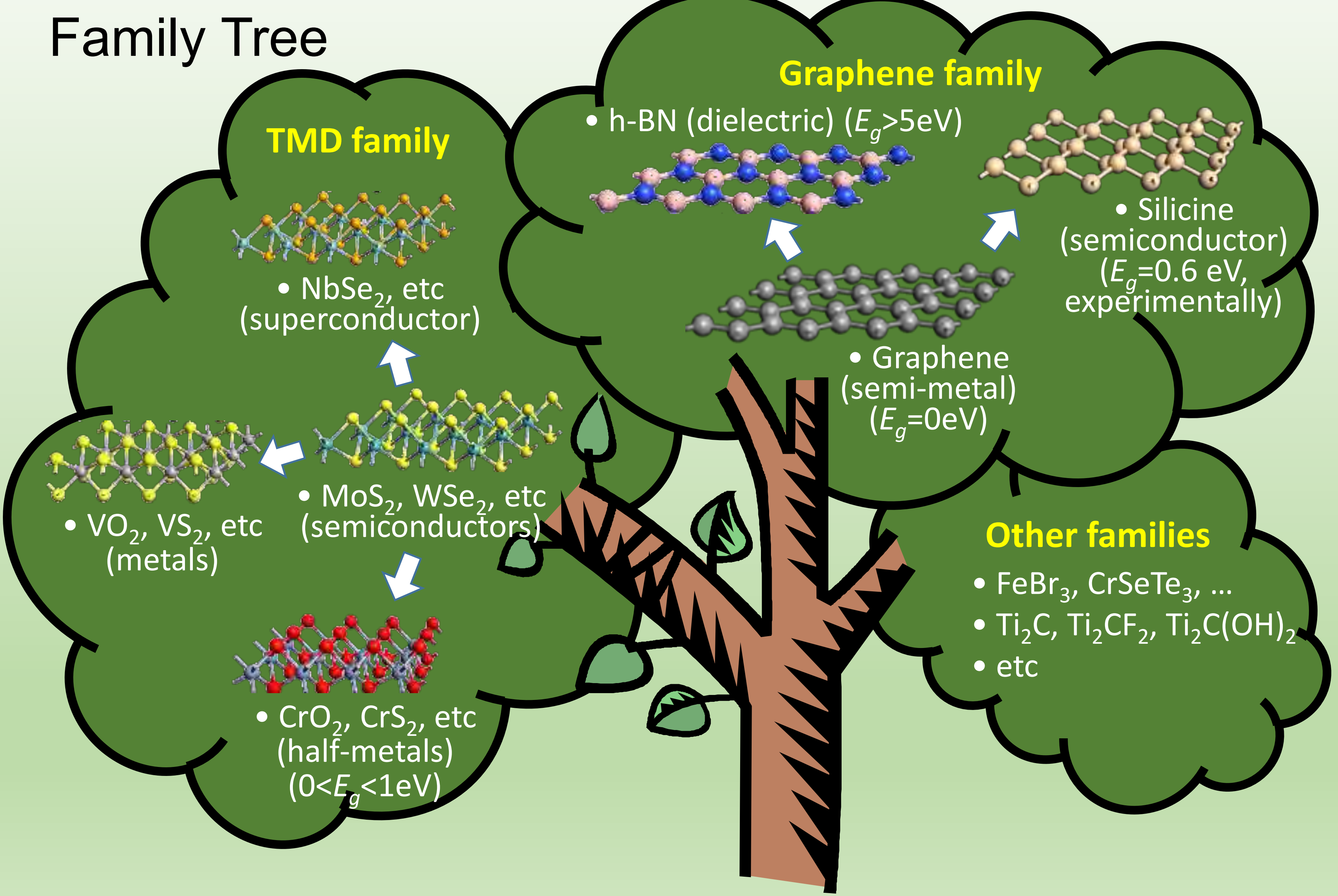
Controllable # of Layers
→ Controllable Band gaps



Pristine Interfaces
(No interface traps)

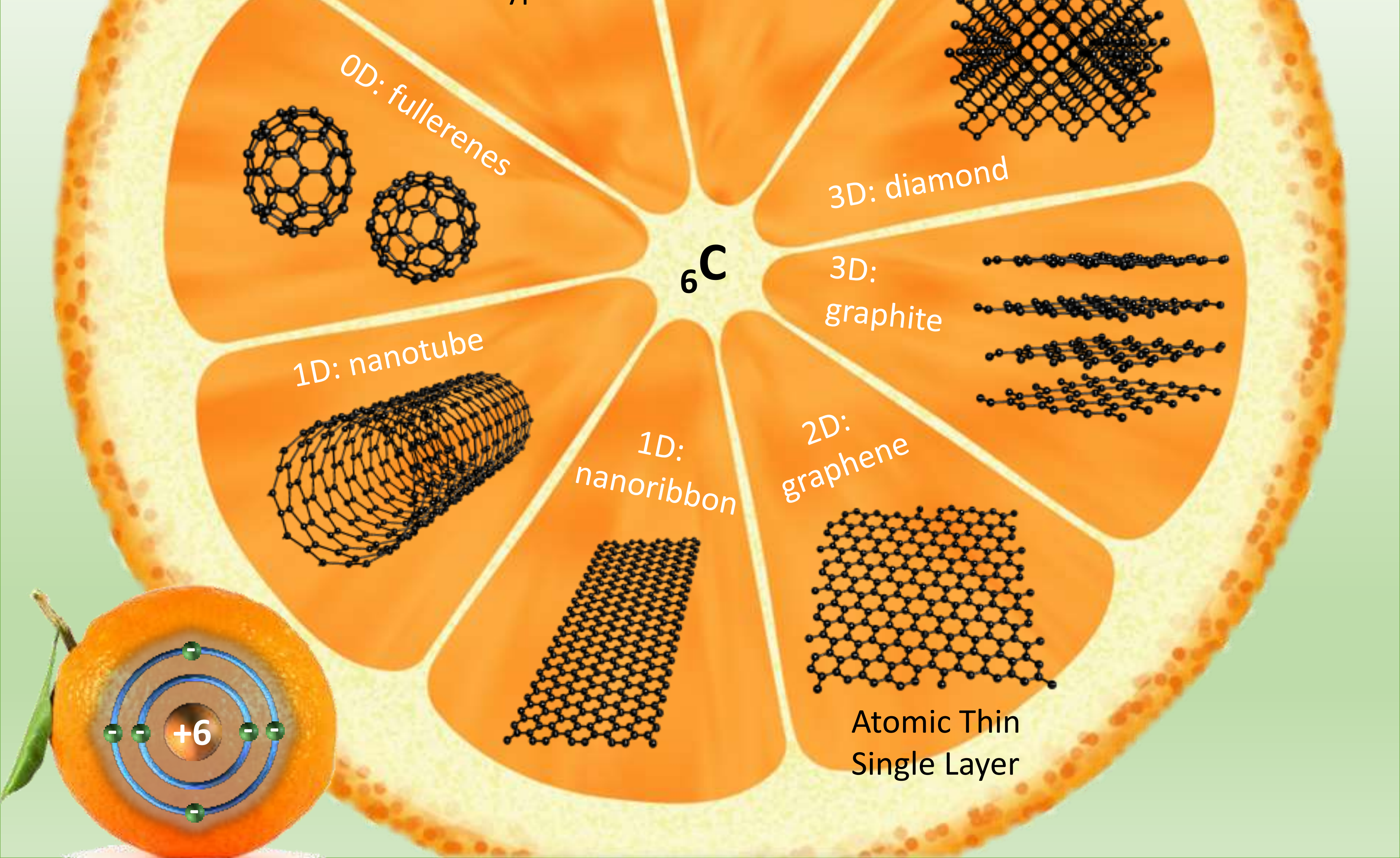


2D Electronic Materials Family Tree

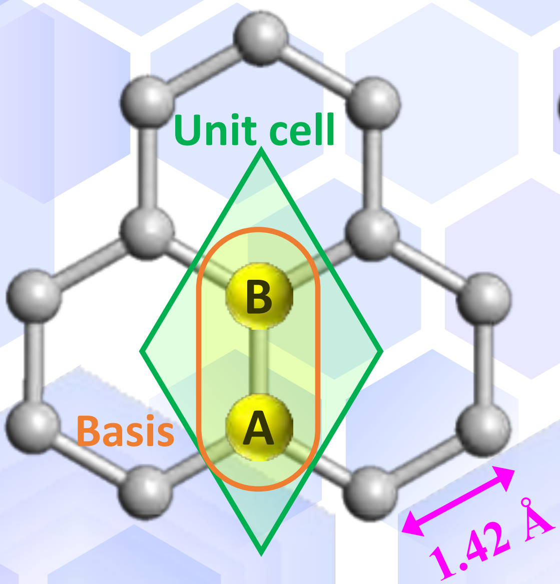


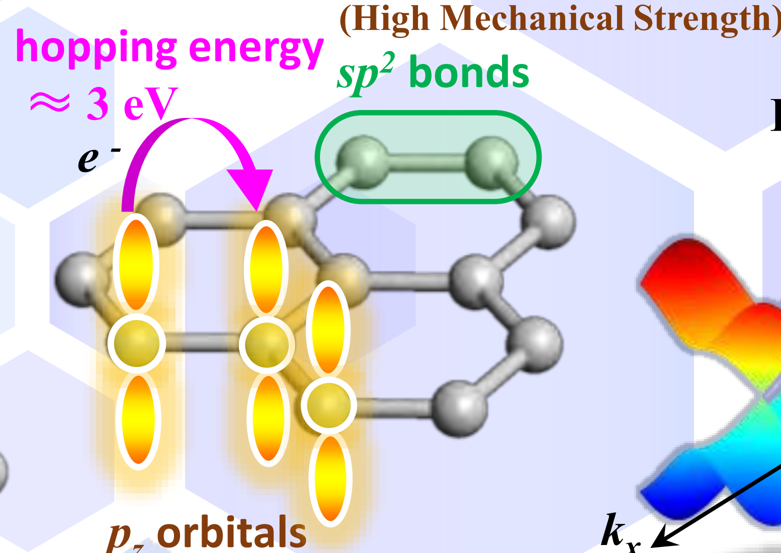
Forms of Carbon…

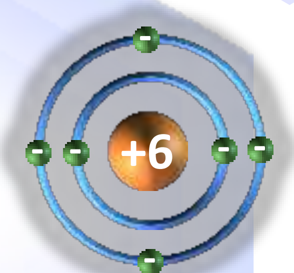
Carbon atoms can form several distinct types of valence bonds….

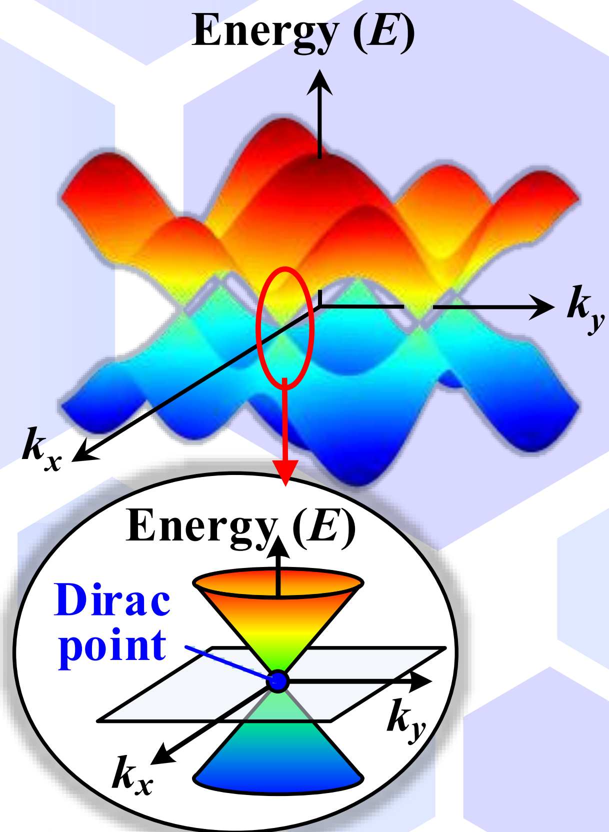


Crystal & Band Structure of Graphene





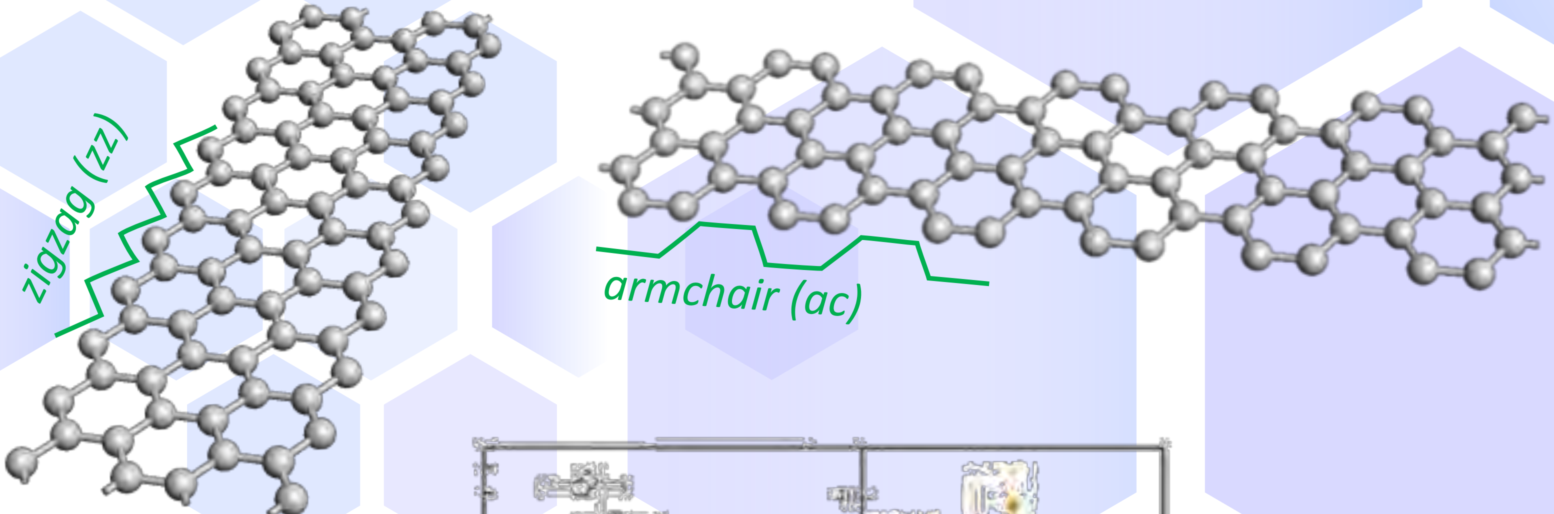


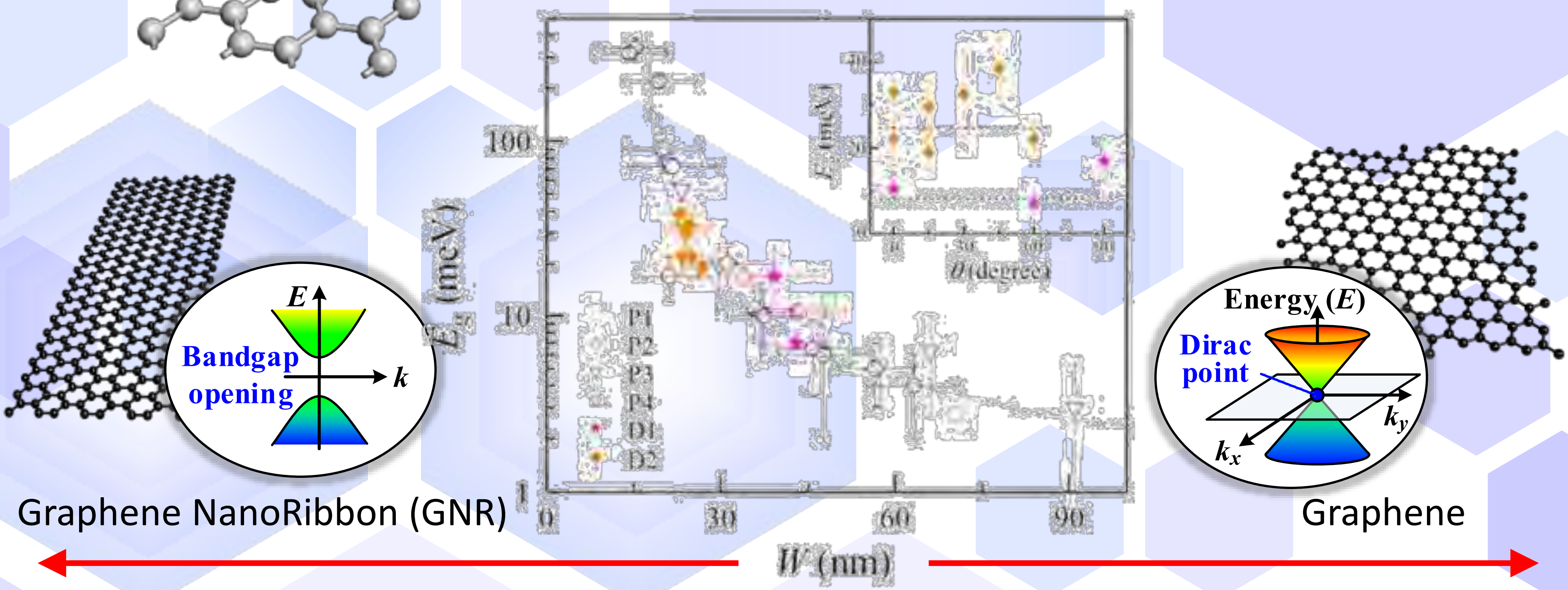


- Zero band gap
- Linear E-k near Dirac point
- Close to zero effective mass
- Symmetric: equal electrons & holes
- High Mobility

$$E(k_x, k_y) - E_{Fi} = \pm h v_F \sqrt{{k_x}^2 + {k_y}^2}$$

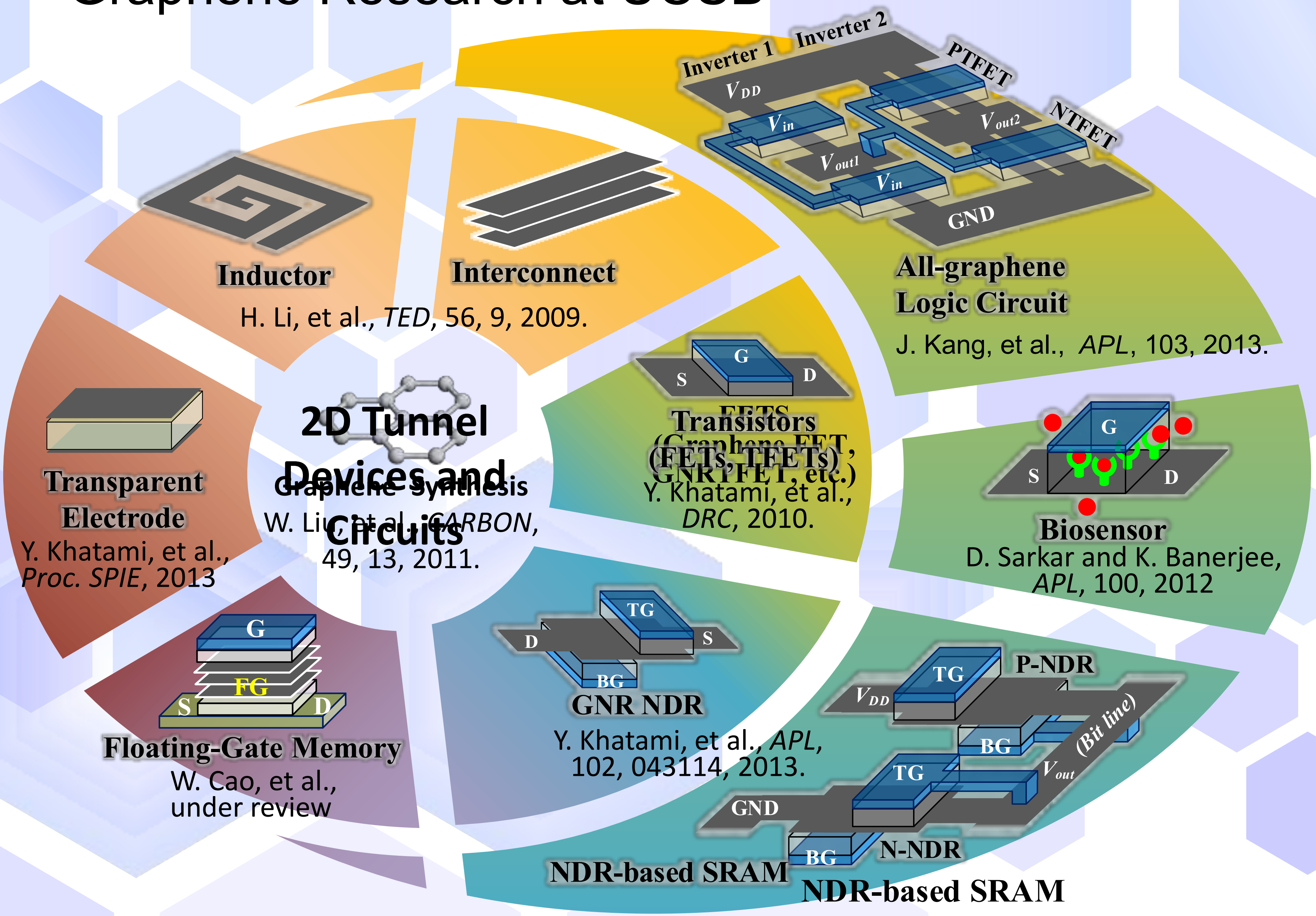
Advantage of Graphene – **Band Gap Tunability**





M. Y. Han, et al., *PRL*, 98, 206805, 2007.

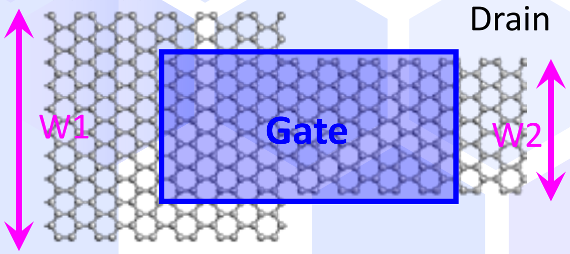
Graphene Research at UCSB

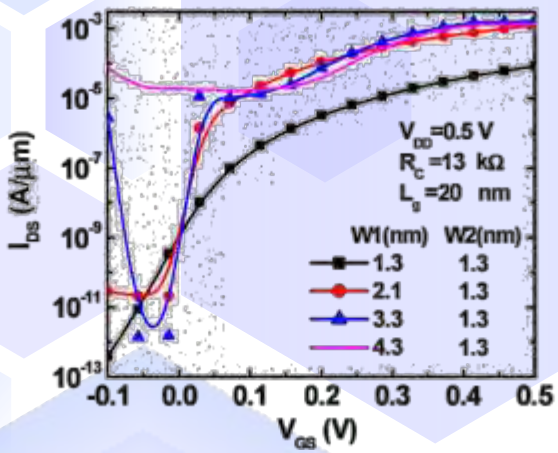


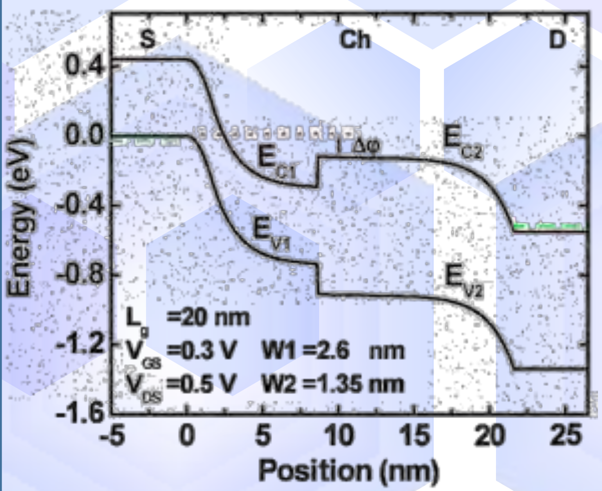
Graphene Nanoribbons Hetero Tunnel-FET

Due to the band gap tunability and few interface traps,
GNR is a great material for Tunnel-FETs.

E_g Tuned by Width







I_{ON} = 1 mA/μm,

I_{ON}/I_{OFF} = 10^9,

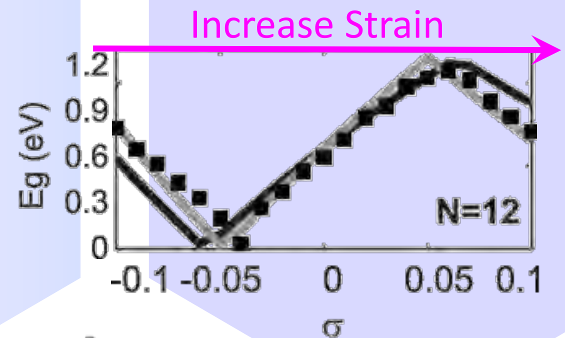
***SS* = *10* mV/dec**

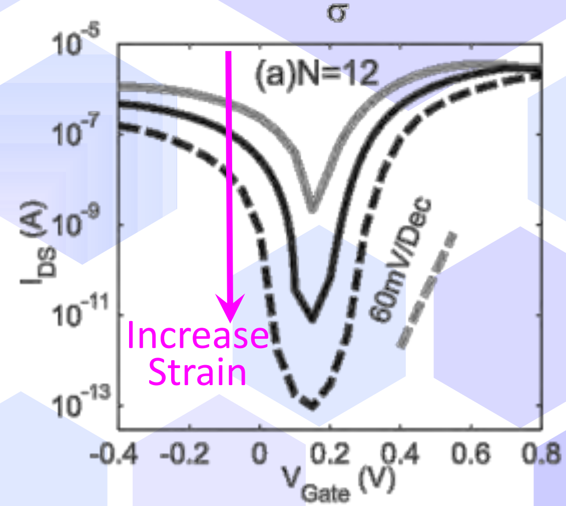
V_{DD} = 0.5 V,

L_{ch} = 20 nm

Y. Khatami, M. Krall, H. Li, C. Xu and K. Banerjee, *Device Research Conference*, 2010.

E_g Tuned by Strain

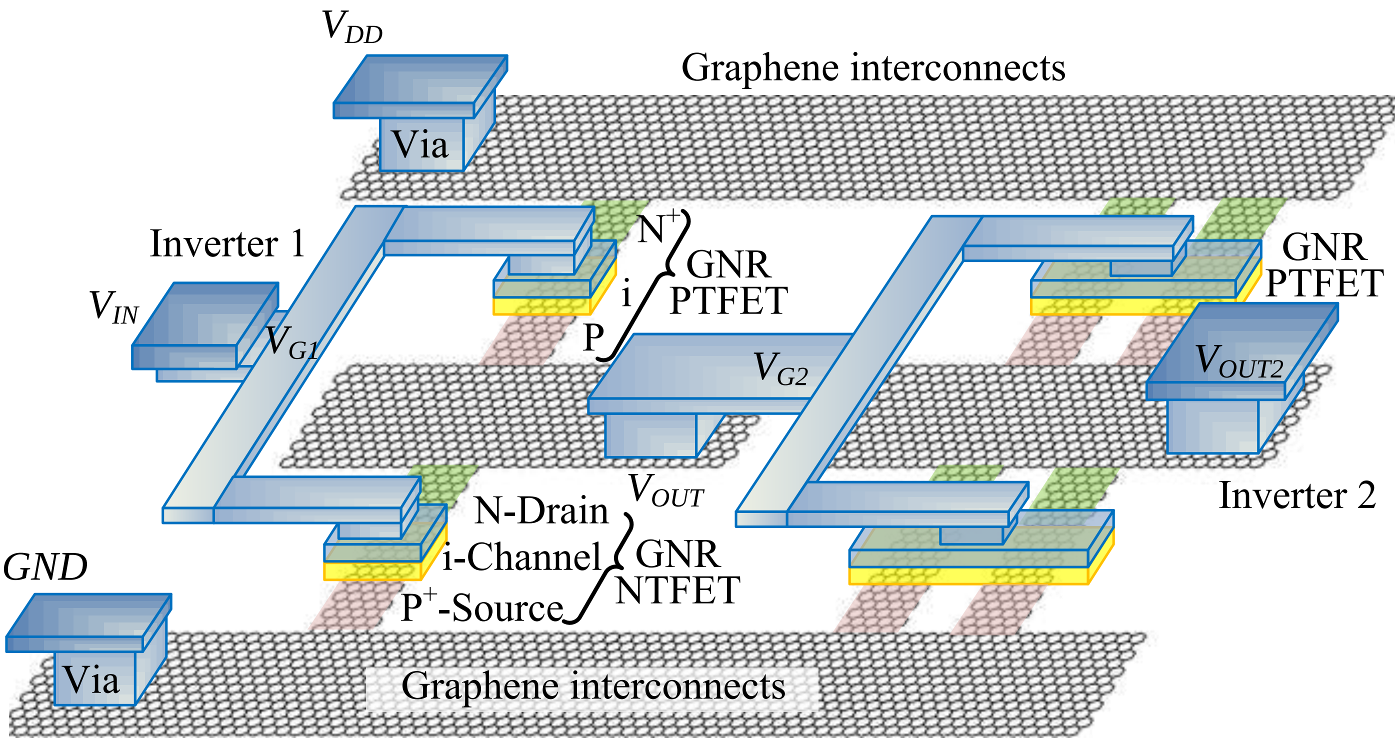


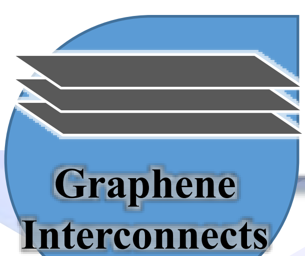


J. Kang, et al., *Appl. Phys. Lett.*, 96, 252105, 2010.

All-Graphene Monolithic Logic Circuits

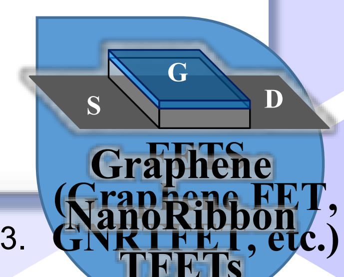
Making Interconnects and Transistors with the Same Materials…





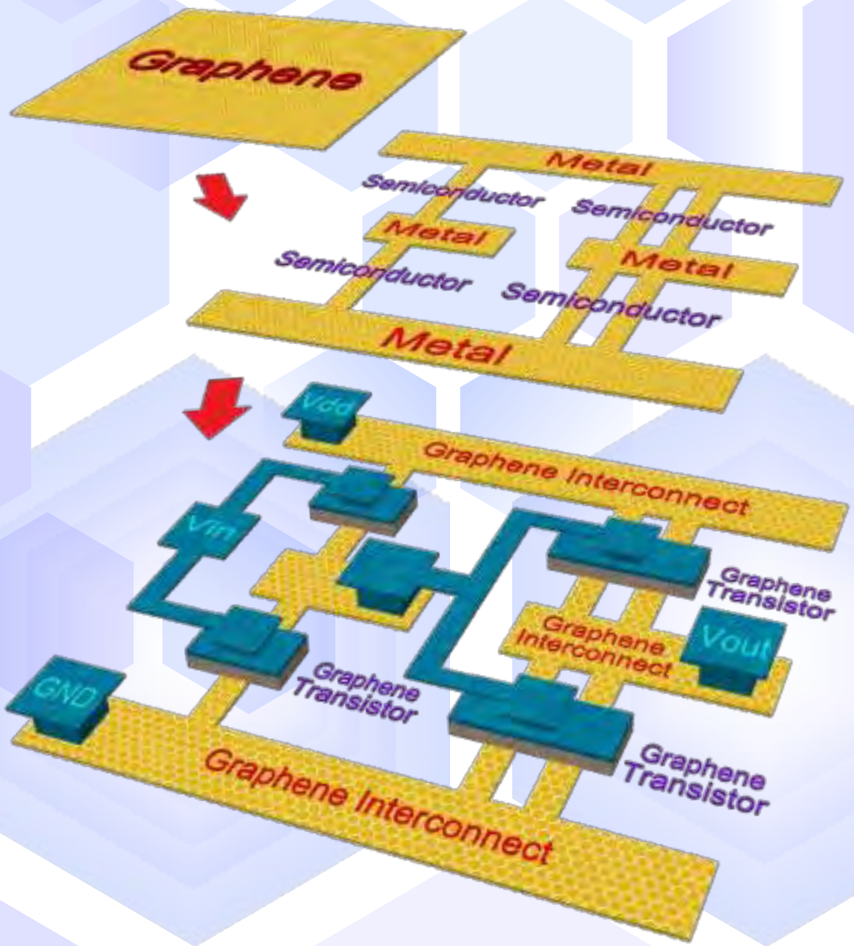
High Current Carrying

J. Kang, D. Sarkar, Y. Khatami and K. Banerjee, *App. Phys. Lett.*, 103, 2013.

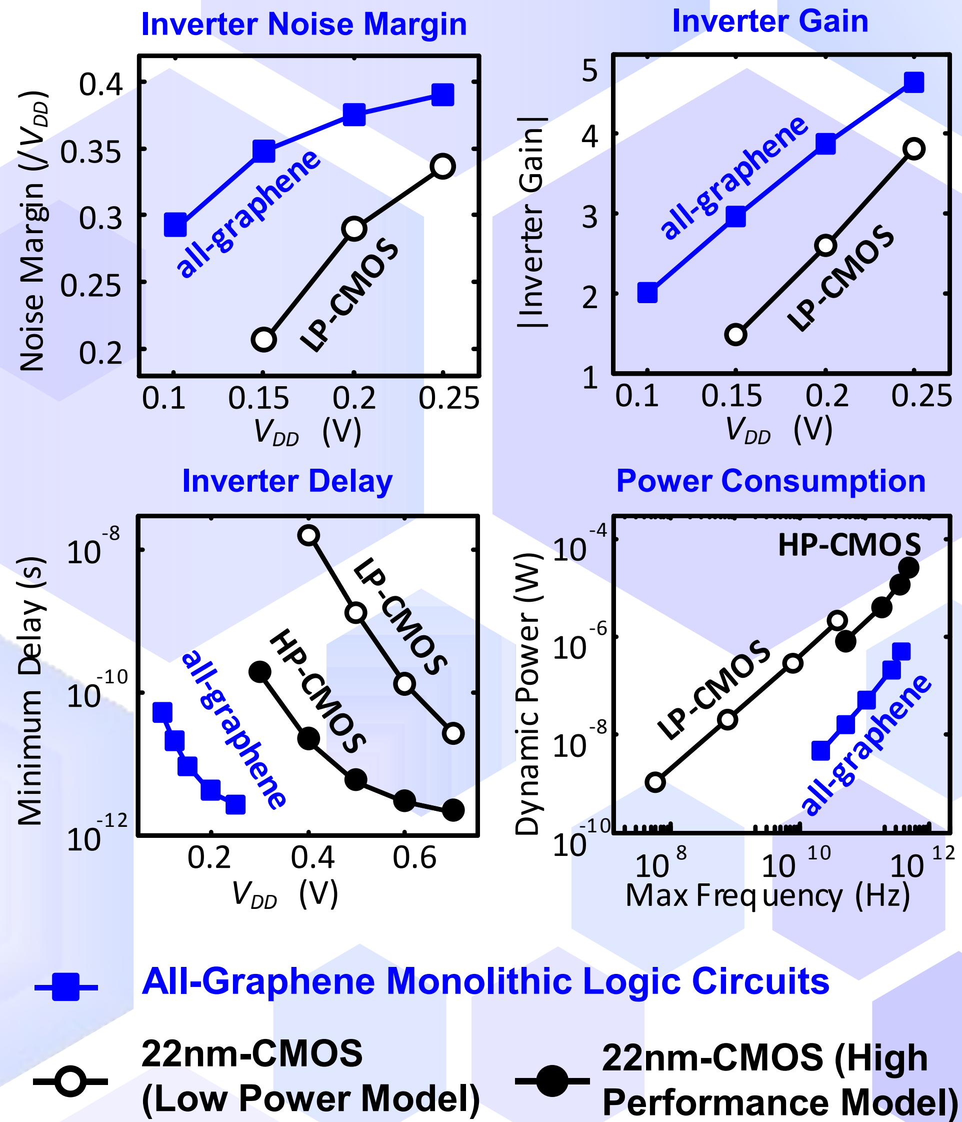


High Ion/Ioff, Low SS

- Few Fabrication Steps
- Low Contact Resistance
- High Performances

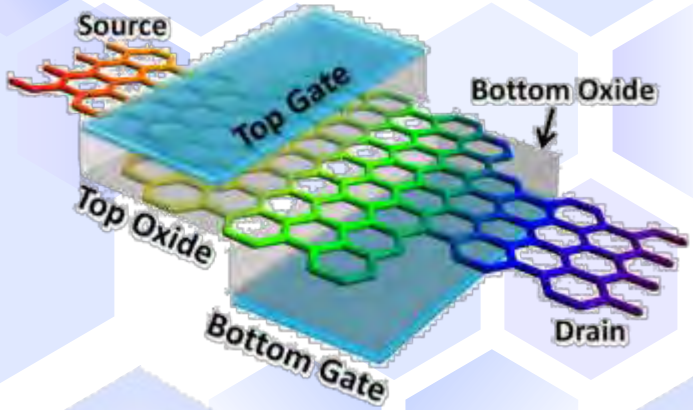


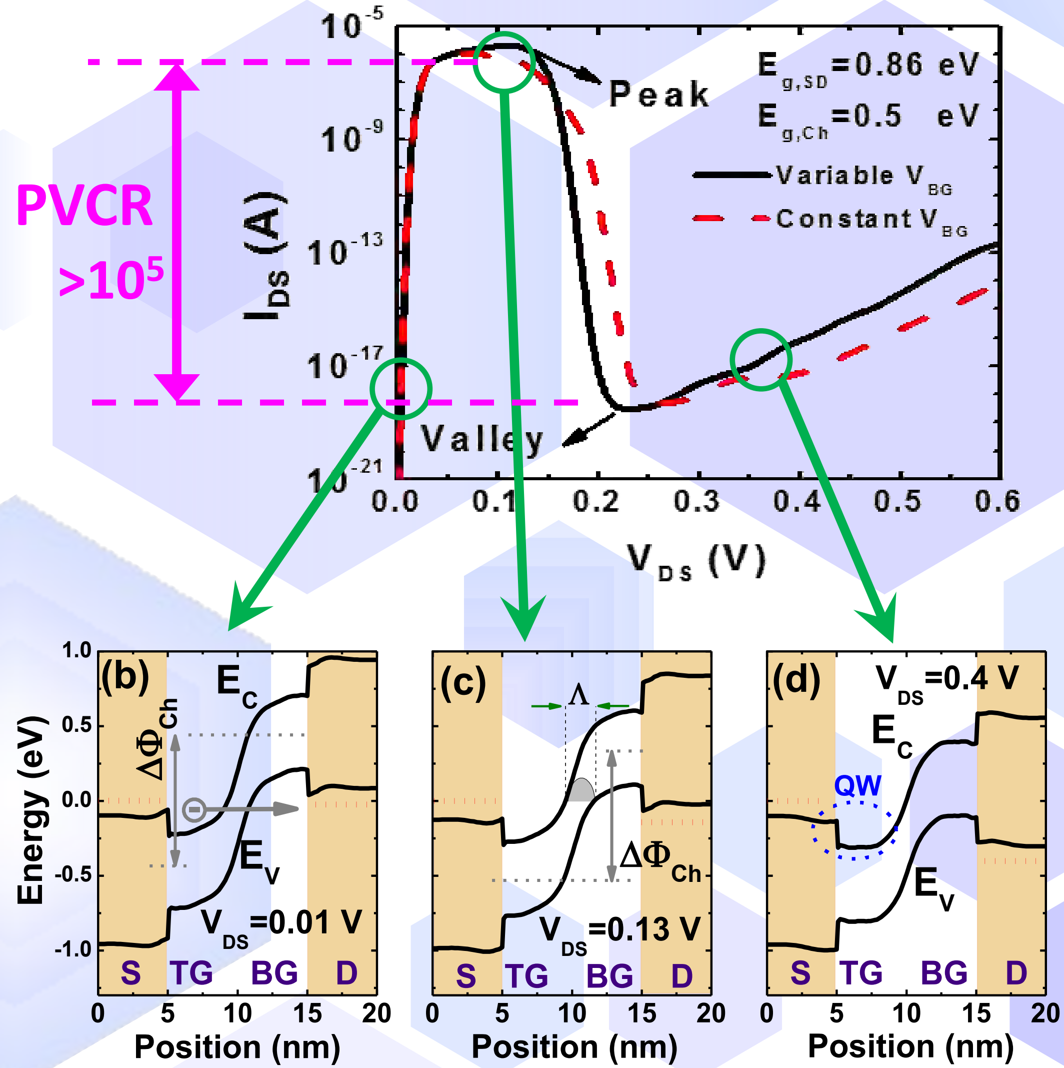
Performance Evaluation



GNR based Negative Differential Resistance (NDR) Device

Re-inventing the Esaki Diode…

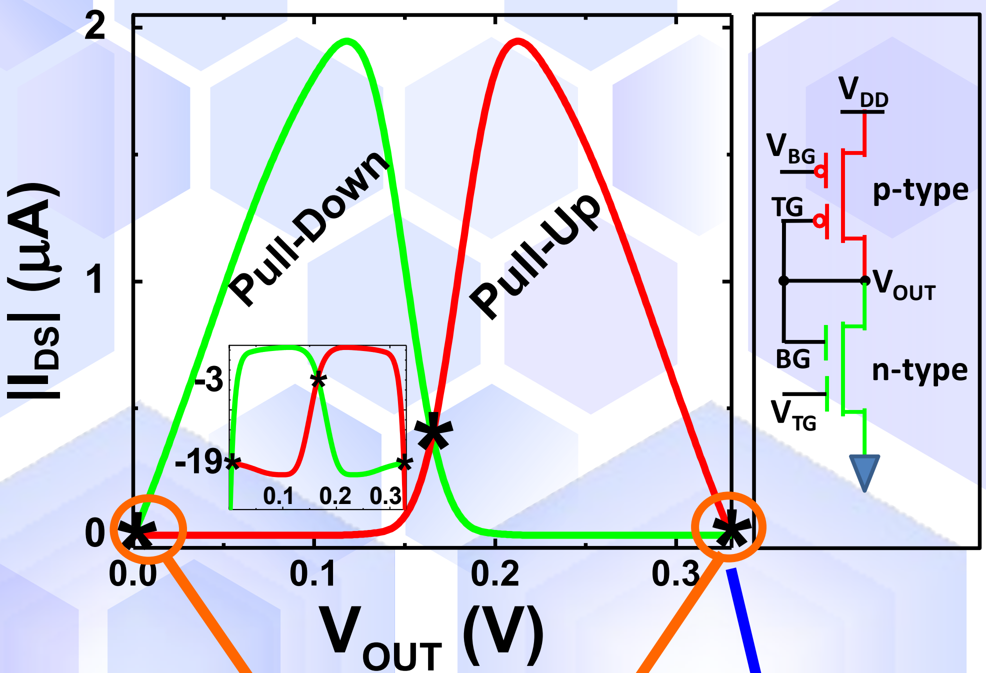


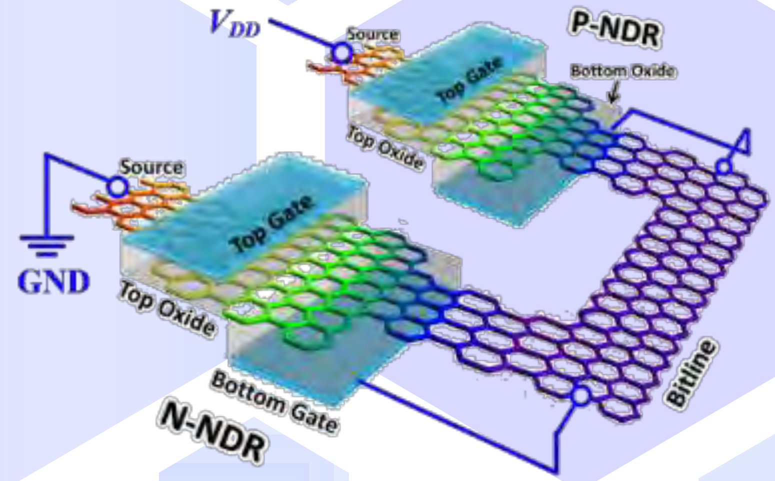


- **Low trap states**
- **High PVCR (>10^5)**
- **High current density: 700μA/μm**

Y. Khatami, J. Kang, K. Banerjee, *APL*, 102, 043114, 2013.

Compact SRAM Cell based on GNR NDR Devices





Stable points
Data Storage of 0/1

Low voltage operation

- **Complimentary devices**
- **Compact**
  GNR: 2T+1T(access)
  CMOS: 4T+2T(access)
- **Low V_{DD}: V_{valley}**

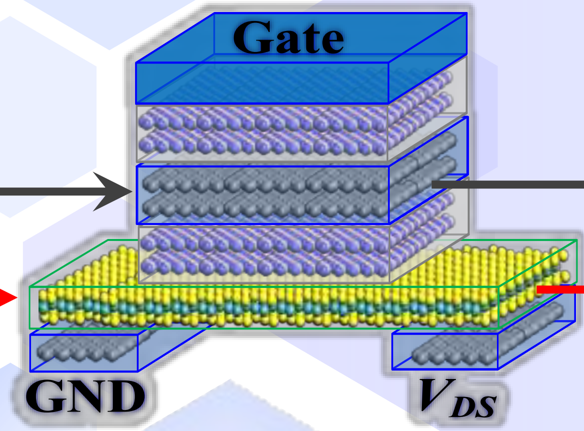
Y. Khatami, J. Kang, K. Banerjee, *APL*, 102, 043114, 2013.

Extend the Lifetime of Floating-Gate Transistor Memory by Using 2D Materials

S Bertolazzi, D. Krasnozhon , and A. Kis, ACS Nano, 7, 4 2013.

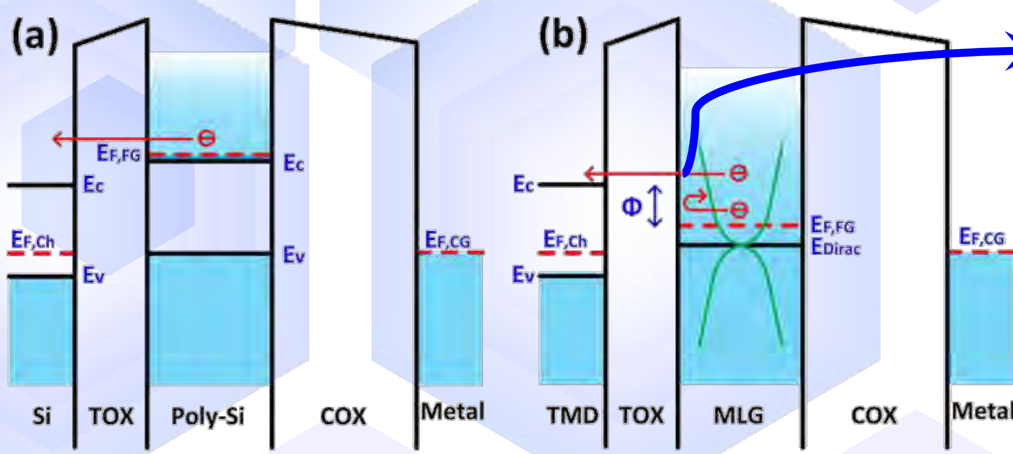
Multi-Layer Graphene (MLG) Floating Gate

TMD Channel



Advantages:

- **Immune to cell-to-cell interference**
- **Small Vth roll-off**
- **Small *SS***
- **Additional Barrier Suppress Leakage (enable further vertical scaling)**



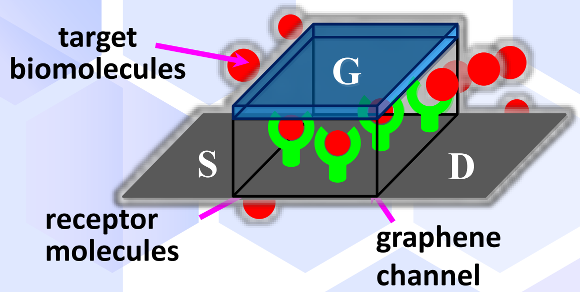
Si/poly-Si based FG transistor

TMD/MLG based FG transistor

W. Cao, J. Kang, S. Bertolazzi, A. Kis and K. Banerjee (under review).

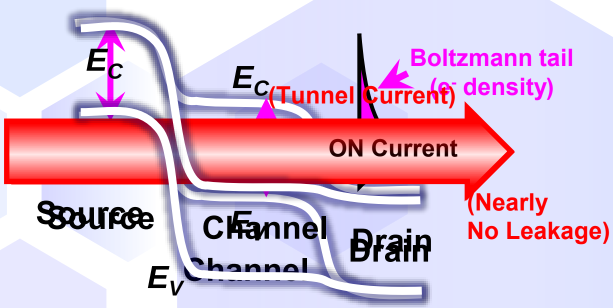
First Proposal for Tunnel-FET Biosensors

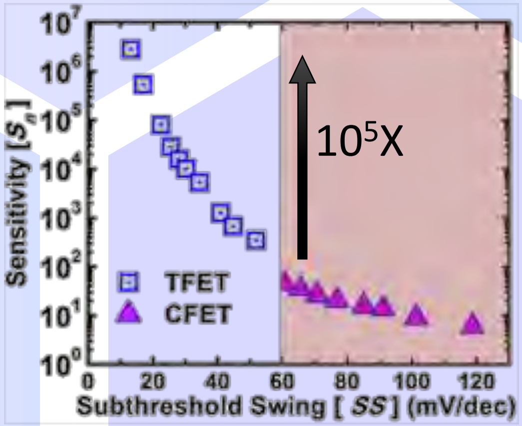
Ultra-Low Power and Ultra-Sensitive



Before conjunction

After conjunction





D. Sarkar and K. Banerjee, *APL*, 100, (2012)

TFET Biosensor in Research Highlights of Nature Nanotechnology

FIELD-EFFECT TRANSISTORS

Biomolecular turn-ons

D. Sarkar and K. Banerjee

Appl. Phys. Lett. **100**, 143108 (2012)

Transistors can make good biosensors. The usual approach is to functionalize the gate oxide of a field-effect transistor with receptors for specific, charged biomolecules. When these are captured, they modulate the conductance of the channel, which can be measured. Deblina Sarkar and Kaustav Banerjee of the University of California, Santa Barbara have now predicted that tunnel field-effect transistors could be used to make biosensors that are even better.

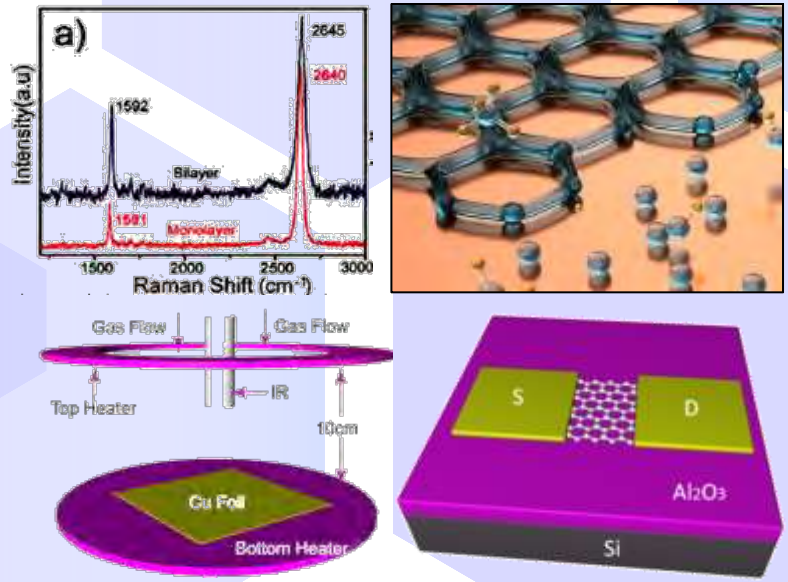
NATURE NANOTECHNOLOGY | VOL 7 | MAY 2012 | www.nature.com/naturenanotechnology

Challenges of 2D Materials: 1. Synthesis (scalable, high quality)

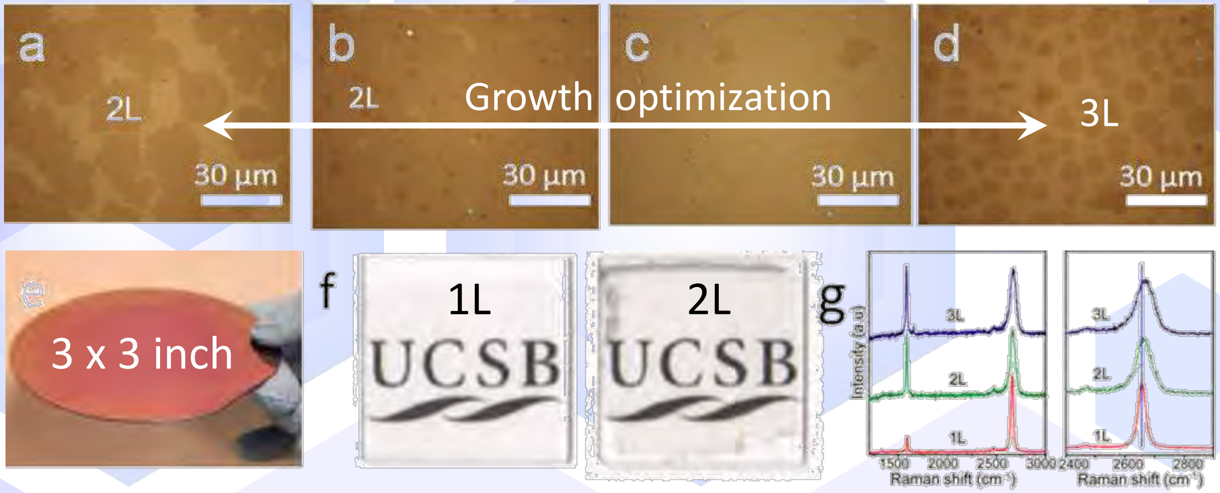
Graphene Growth in UCSB

- Synthesized using CVD
- Record Mobility
- Controlled synthesis of monolayer and bilayer graphene

W. Liu, H. Li, C. Xu, Y. Khatami and K. Banerjee, *CARBON*, Vol. 49, No. 13, pp. 4122-4130, 2011.



Controllable Synthesis of AB Stacked Bilayer Graphene in UCSB

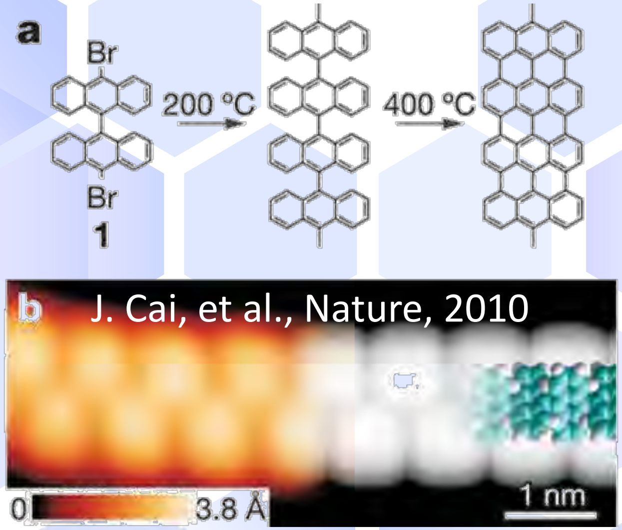


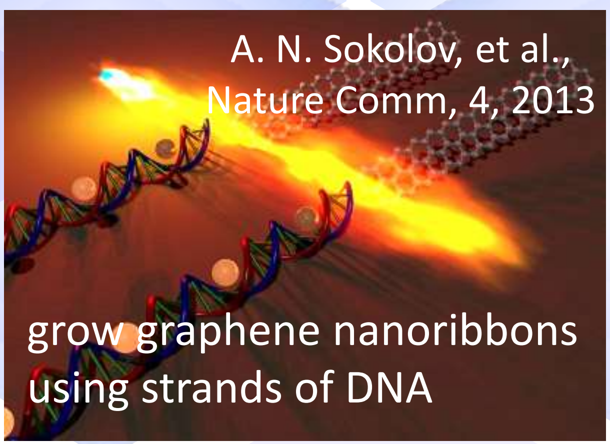
- Wafer scale
- High quality
- >98% AB stacking
- Most reliable method

W. Liu et al., UCSB/Rice, (2013) (under review)

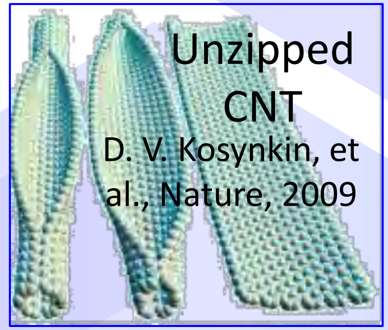
Challenges of 2D Materials: 2. Patterning (Graphene as an example)

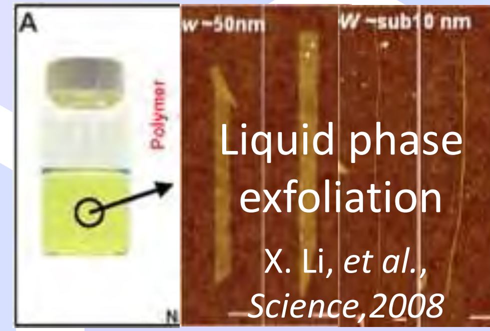
Bottom-up



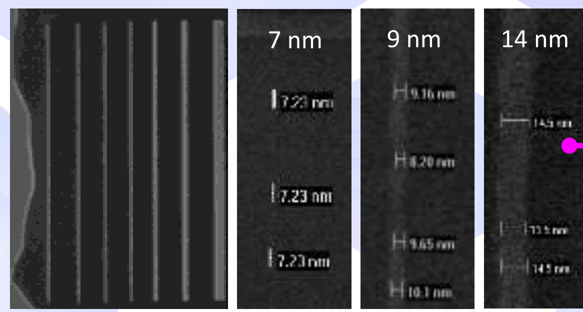


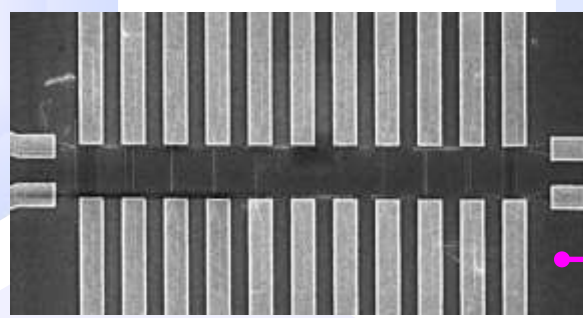
Top-down

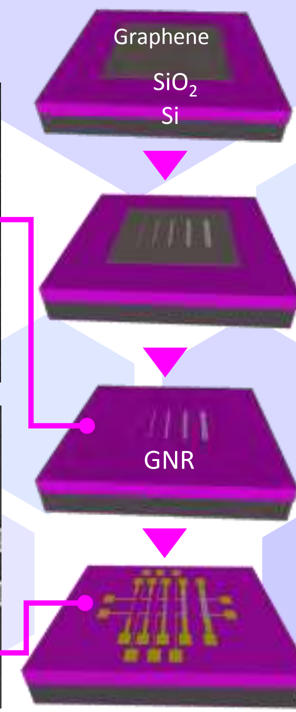




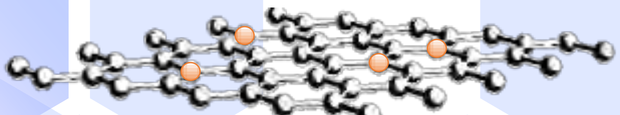
Sub-10 nm width GNR patterned by E-beam Lithography at UCSB





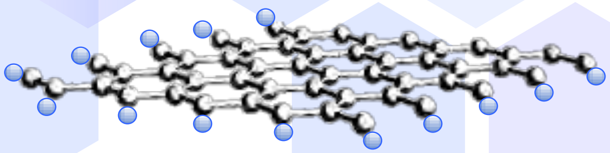


Challenges of 2D Materials: 3. Doping (Graphene as an example)



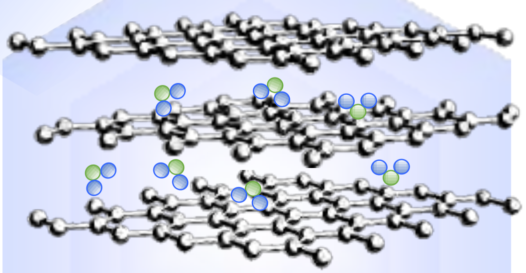
Substitution Doping

Wei et. al., Nano Lett., p.1752, 2009



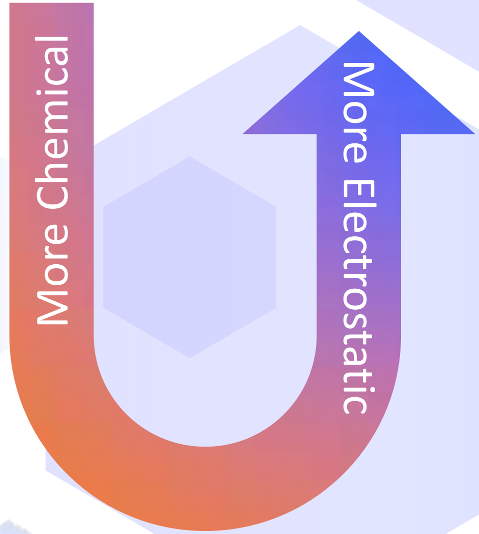
Edge Doping

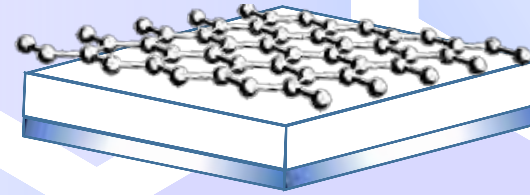
Brenner, K., et al., CARBON.2012



Intercalation Doping

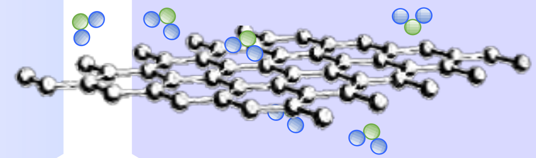
Ohno et.al., J. Phys. Soc. Japan, 1125, 1979





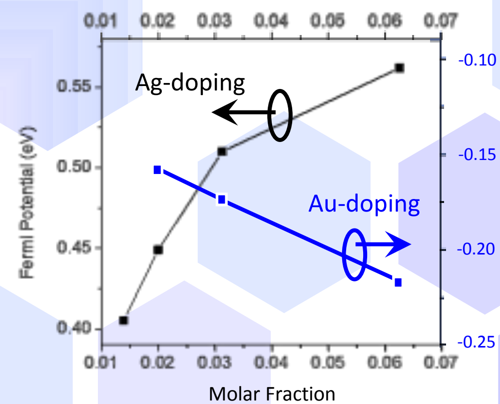
Gate Doping

Giovannetti, et al., PRL. 2008



Surface Doping

J. Kang, W. Liu and K. Banerjee, (under review)

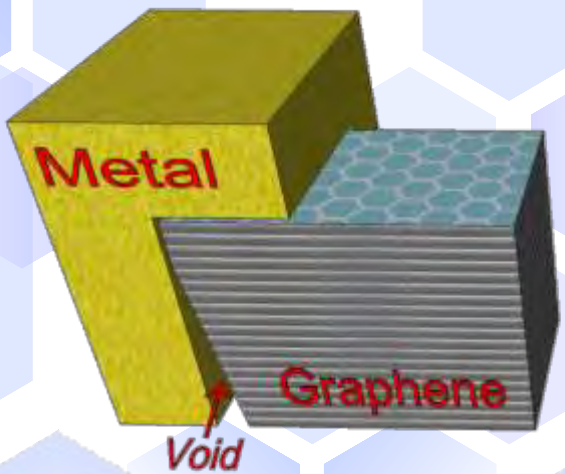


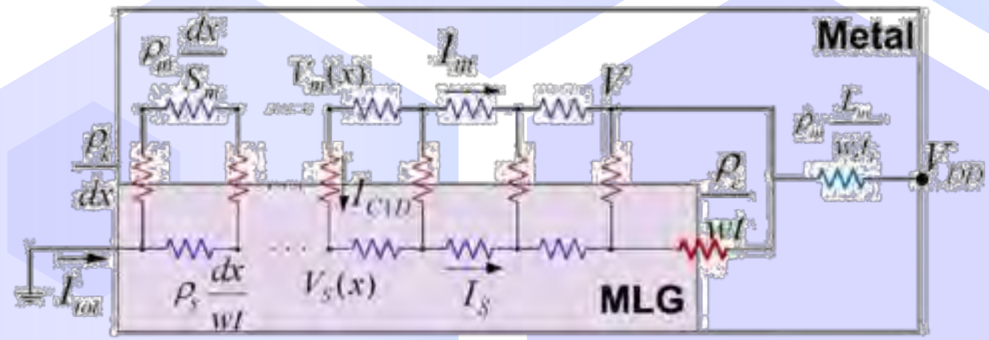
A stable, controllable method for small regions is still missing…

Challenges of 2D Materials: 4. Contact

(A key factor in device/circuit applications)

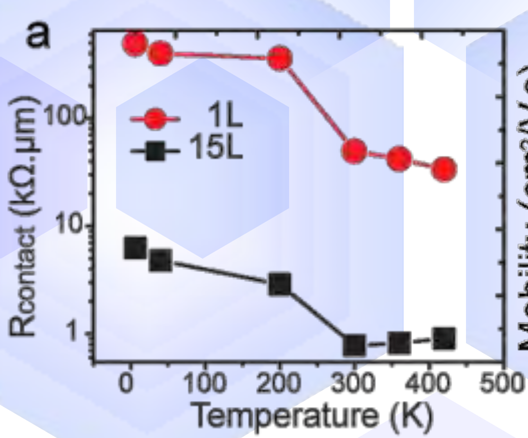
Issue 1: Contact Geometry

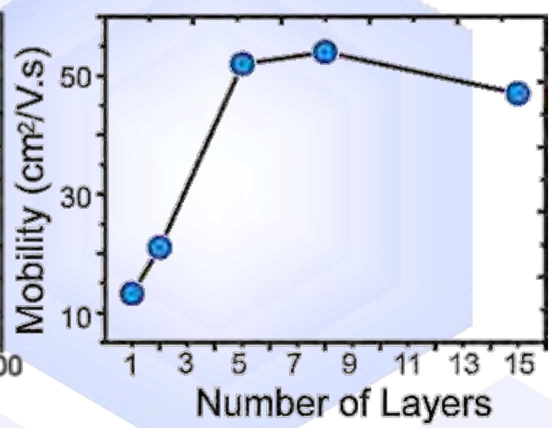




Contacts to multilayer graphene

Y. Khatami, et al., *IEEE Trans. on Electron Devices*, 59, 9, 2444-2452, 2012.

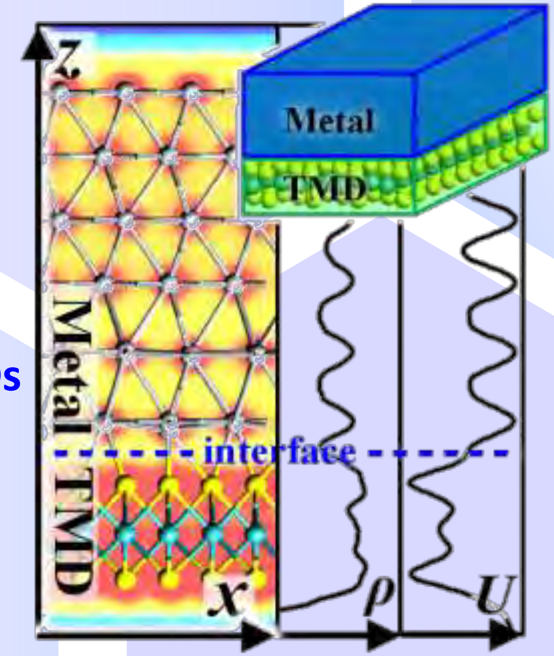




Contacts to multilayer MoS_2

W. Liu, J. Kang, W. Cao, D. Sarkar, Y. Khatami, D. Jena and K. Banerjee, *IEDM,* 2013, to appear.

Challenges of 2D Materials: 4. Contact



Issue 1: Contact Geometry

Issue 2: Interface Properties

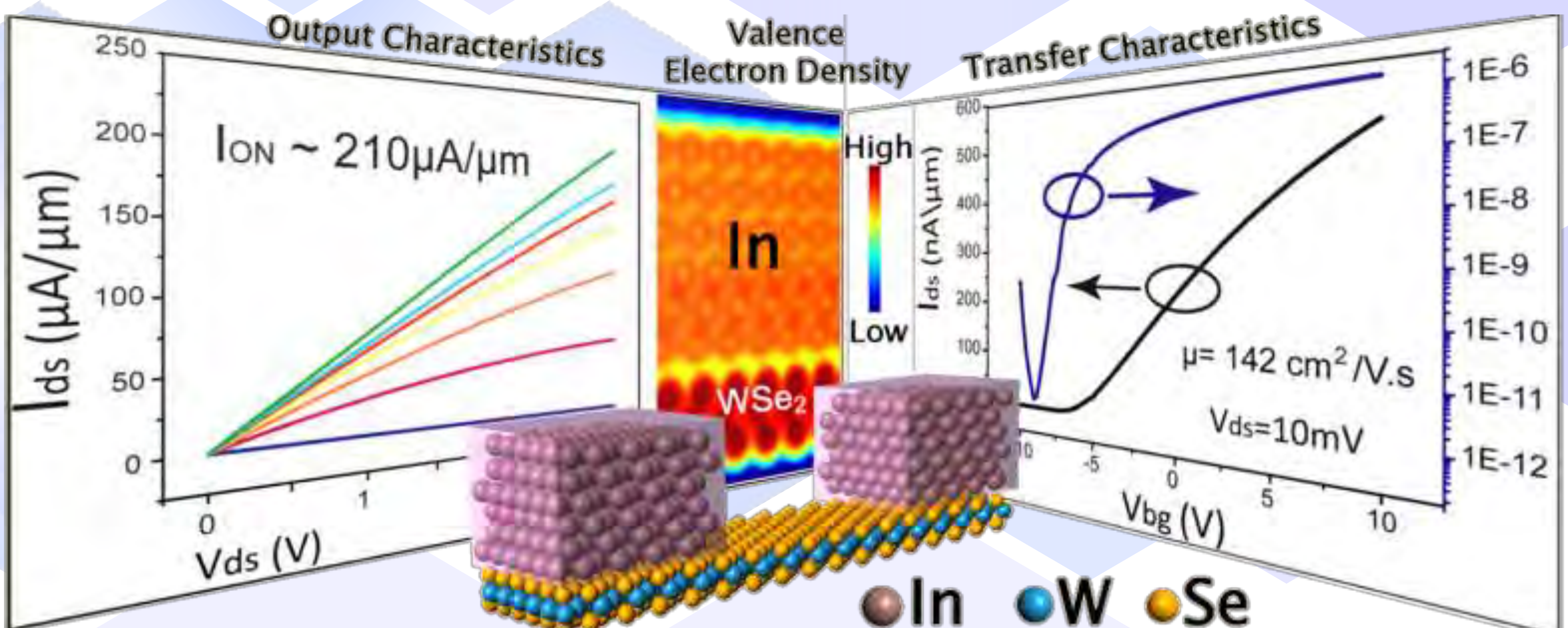
- **Orbital Overlap**
- **Schottky Barrier**
- **Tunnel Barrier**

Contacts to monolayer TMDs

J. Kang, D. Sarkar, W. Liu, D. Jena and K. Banerjee, *IEDM,* 2012, pp. 407-410.

Contacts to monolayer WSe_2

W. Liu, J. Kang, D. Sarkar, Y. Khatami, D. Jena and K. Banerjee, *Nano Lett.*, 2013.



Summary

- Advantages of 2D Materials for Tunnel Devices
  - Better Electrostatics
  - Suppressed Variations
  - Band gap Tunability of Graphene
- Opportunities of 2D Tunnel Devices on Graphene
  - Hetero GNRTFETs
  - All-Graphene Monolithic Logic Circuits
  - GNR NDR Devices (Esaki Diodes)
  - Floating-Gate Transistors
  - TFET Biosensors
- Challenges of 2D Materials
  - Synthesis
  - Doping
  - Patterning
  - Contact

Thank you!