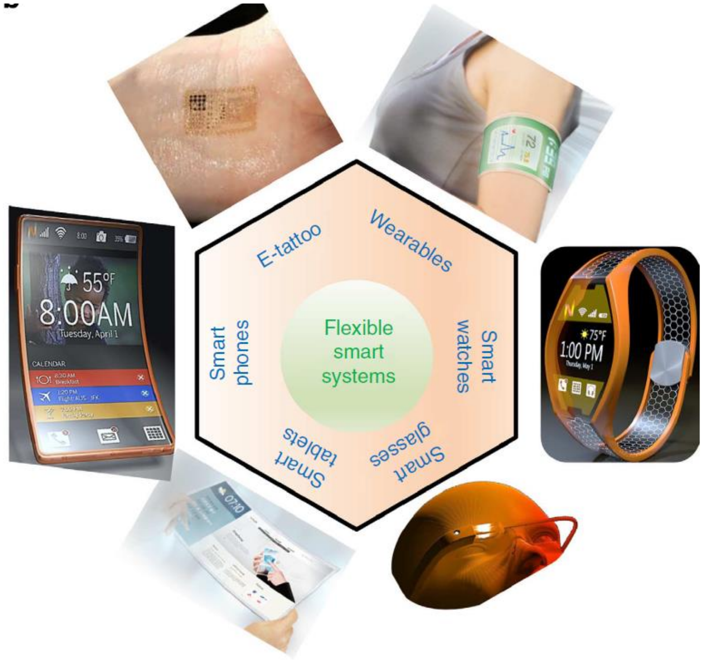
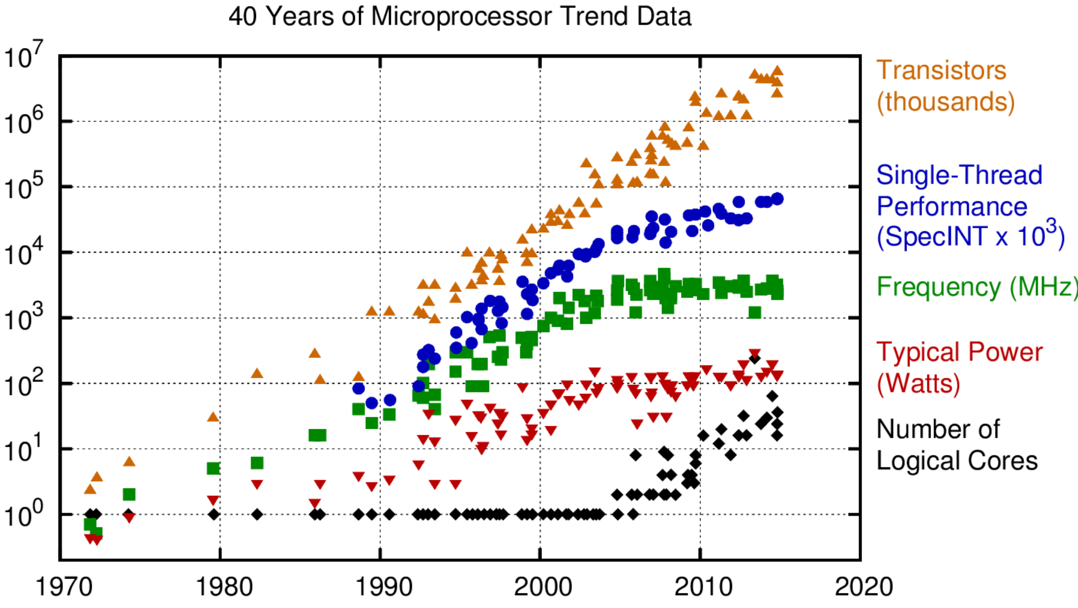
Novel Logic and Memory Devices in Graphene

Sanjay Banerjee
Frank Register, Emanuel Tutuc, Deji Akinwande and Luigi Colombo
Microelectronics Research Center
University of Texas at Austin

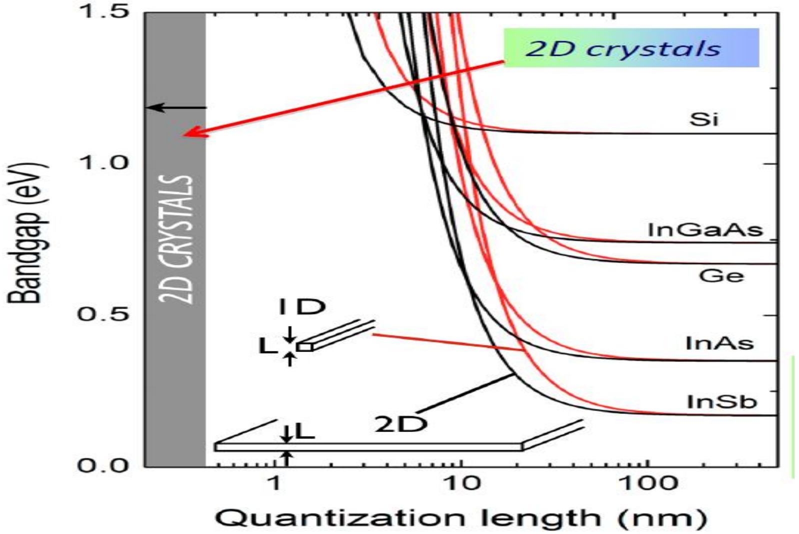




Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2015 by K. Rupp

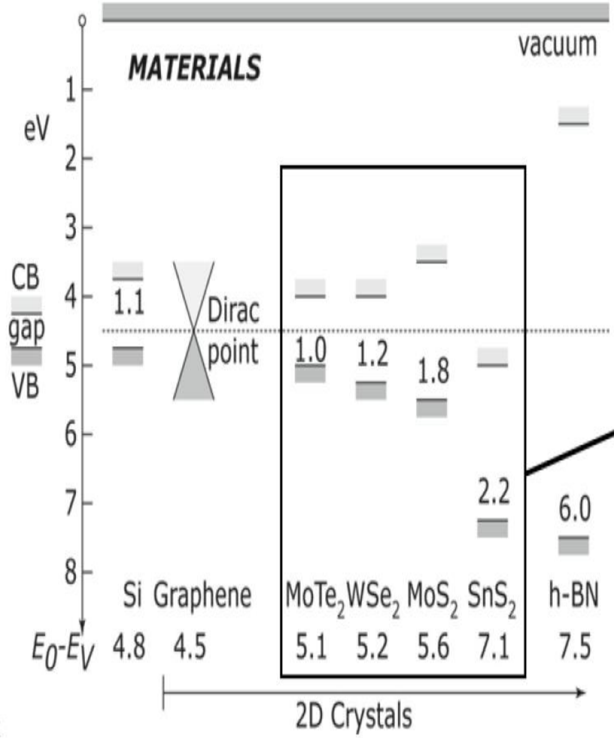
- **Medium Frequency, Low Power IoT Devices**
- **Beyond-CMOS Low Power Transistors**

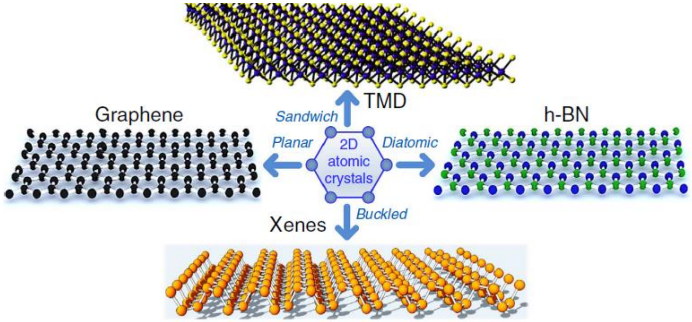
Acknowledgments: NRI SWAN, NSF NASCENT ERC, NNCI, DOE BAPVC, Army STTR

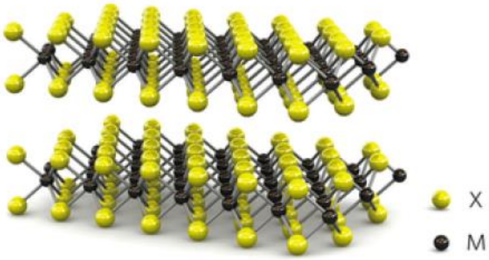


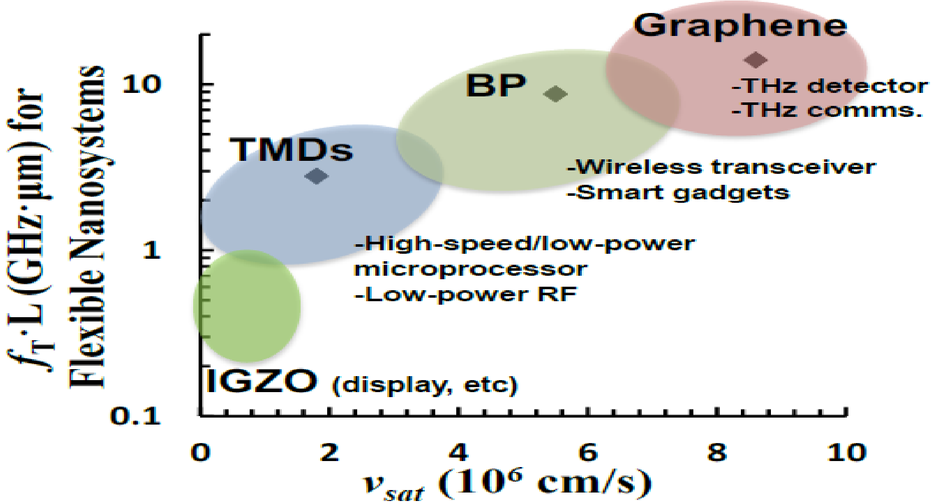
Mo [Kr]$4d^5 5s$

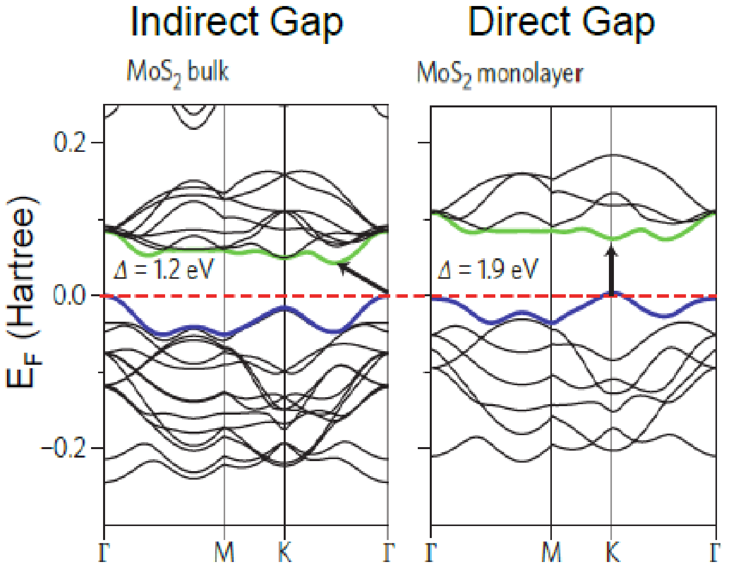
S [Ne]$3s^2 3p^4$



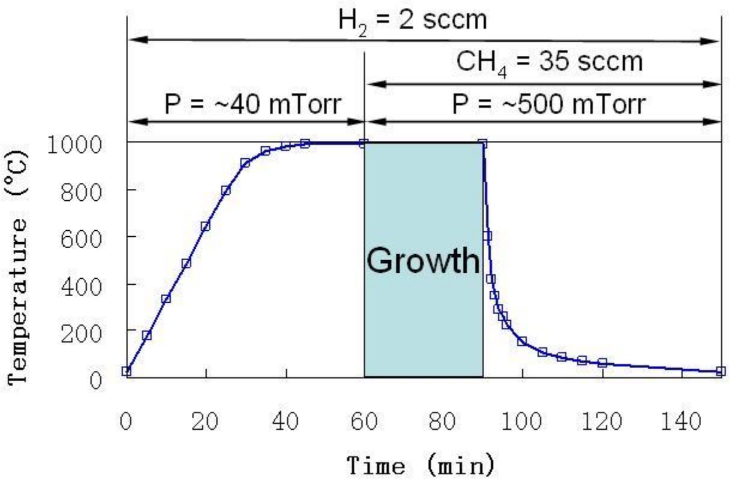


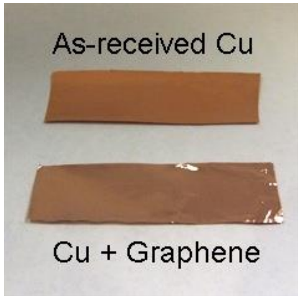


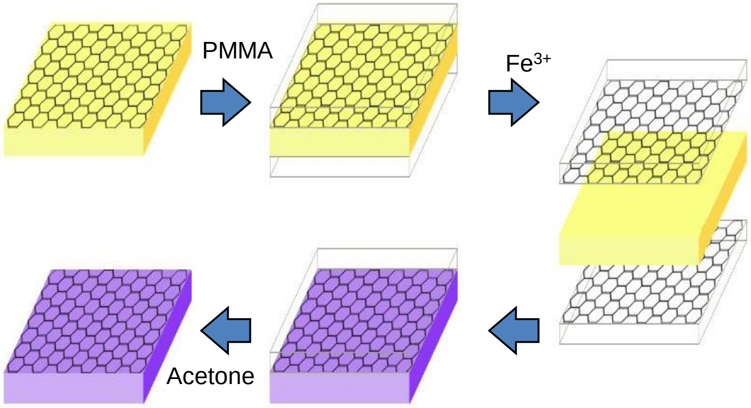


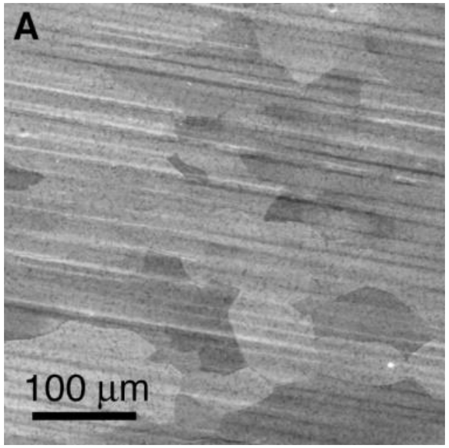


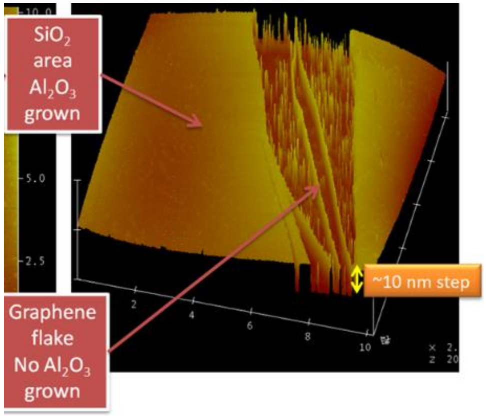
Large-Area Graphene Grown on Cu Foils and FETs with high-k



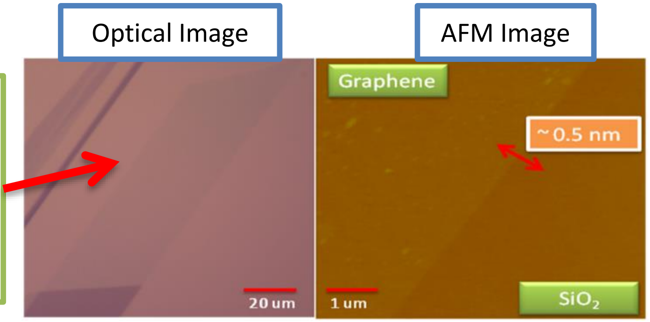






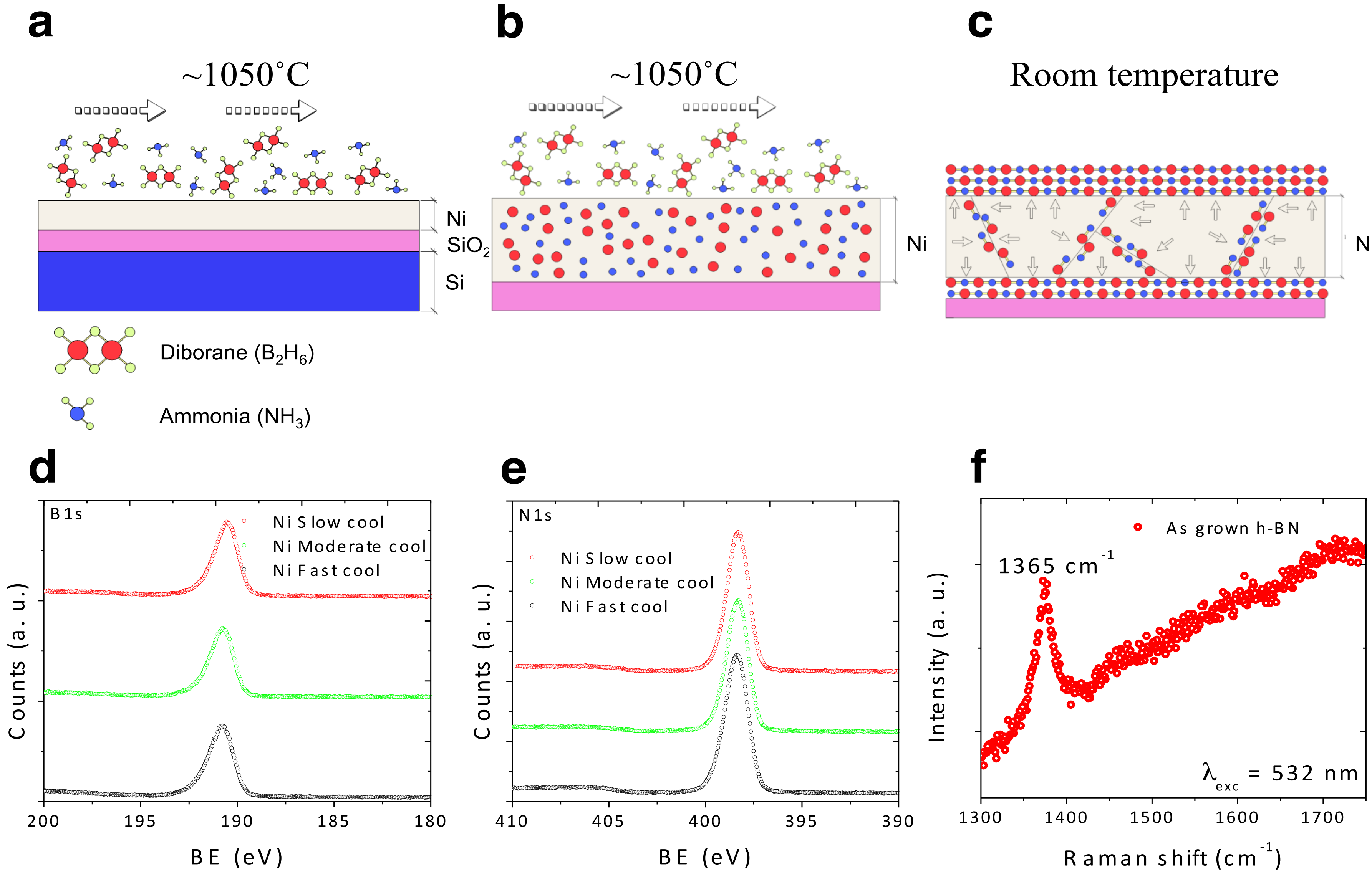


Al seeding allows ALD



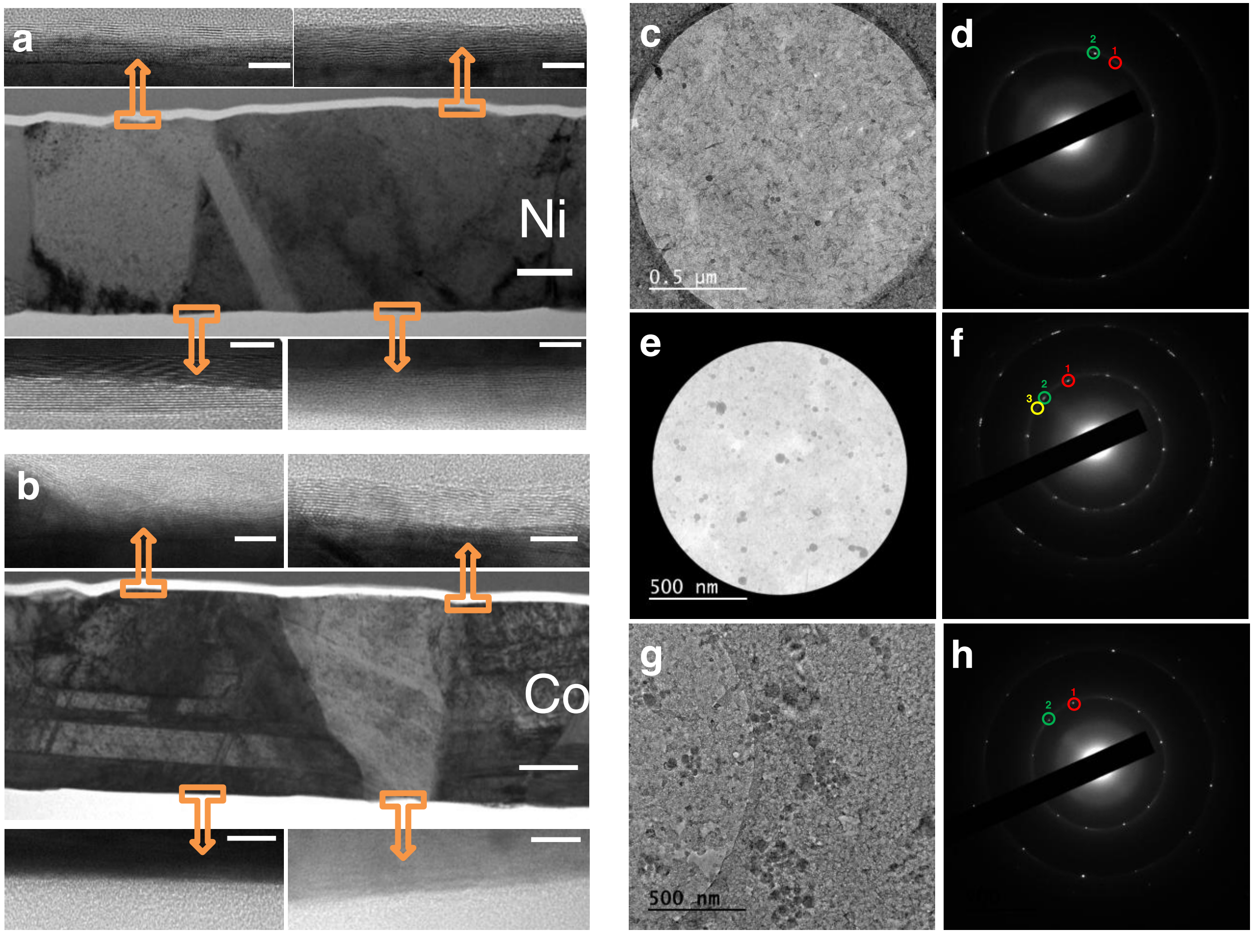
Large-Area Synthesis of High-Quality and Uniform Graphene Films on Copper Foils
Xuesong Li, Weiwei Cai, Jinho An, Seyoung Kim, Junghyo Nah, Dongxing Yang, Richard Piner, Aruna Velamakanni, Inhwa Jung, Emanuel Tutuc, Sanjay K. Banerjee, **Luigi Colombo, Rodney S. Ruoff**, *Science*, 2009

hBN CVD on Ni and XPS, Raman



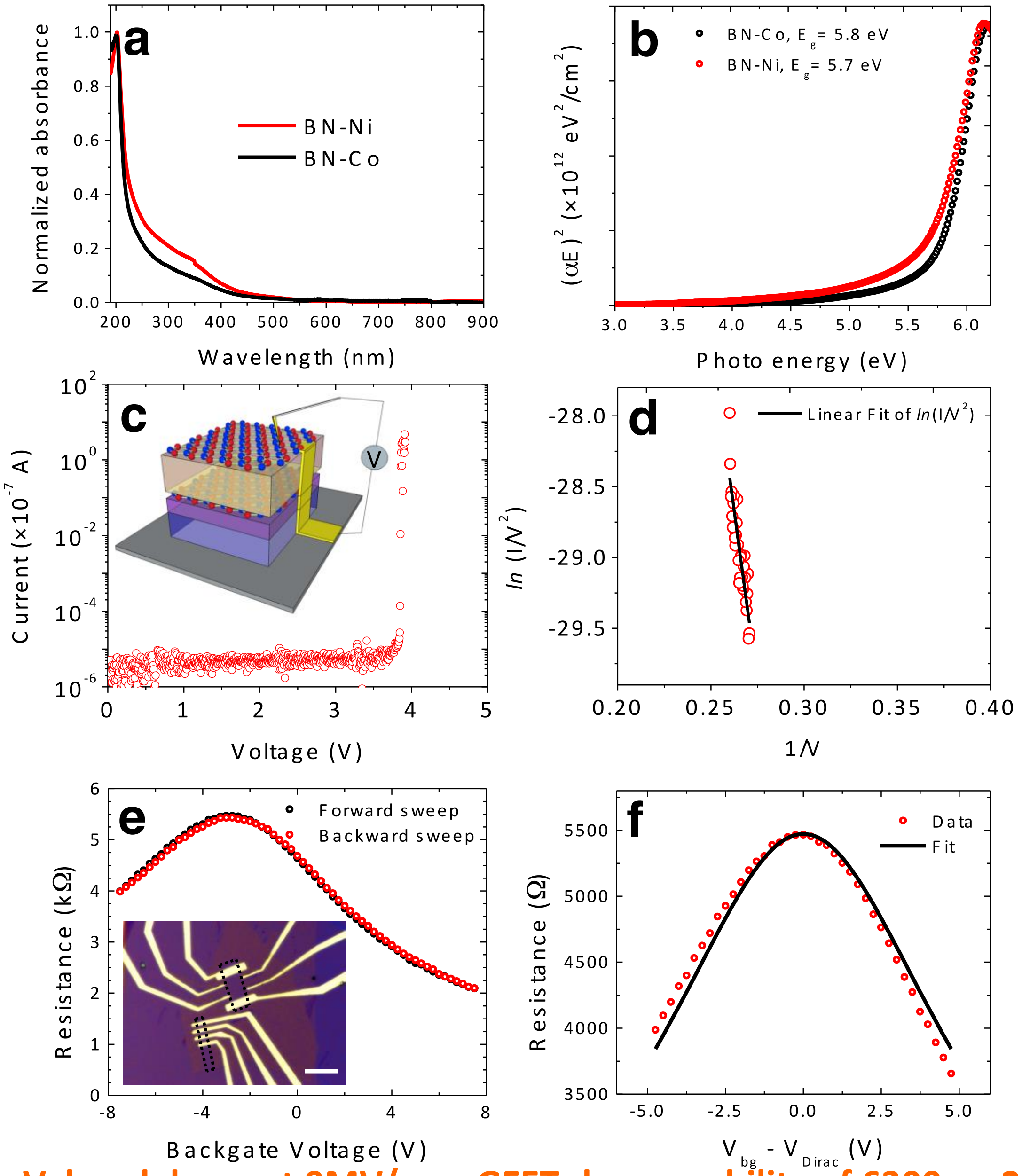
Diborane and Ammonia precusrors for B and N dissolution and segregation on top and bottom of Ni

hBN on Ni and Co



For Ni, hBN segregates on top and bottom; for Co, there is segregation only on top

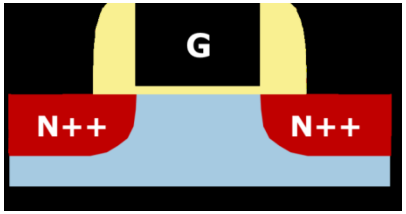
hBN GFET Electrical Characteristics

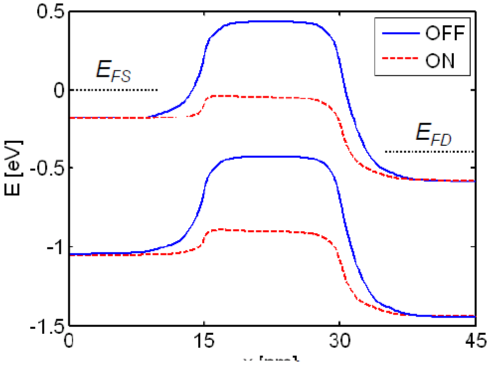


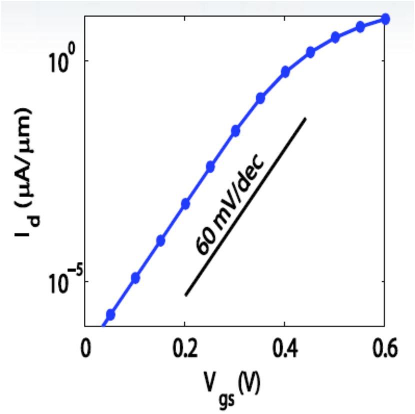
hBN bandgap of 5.7 eV; breakdown at 9MV/cm. GFETs have mobility of 6300 cm2/V.s; no= 3E11 cm-2

MOSFETs vs. Steep Slope TFETs & Resonant TFETs

- MOSFETs

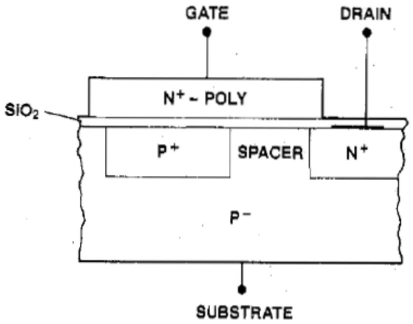


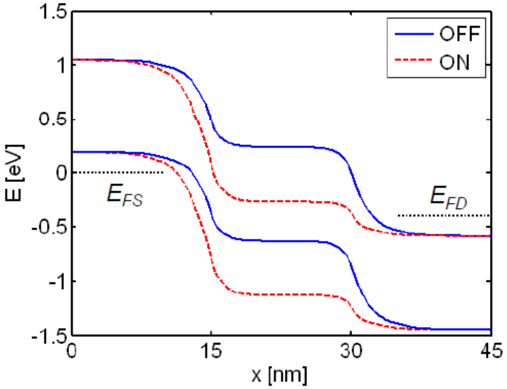


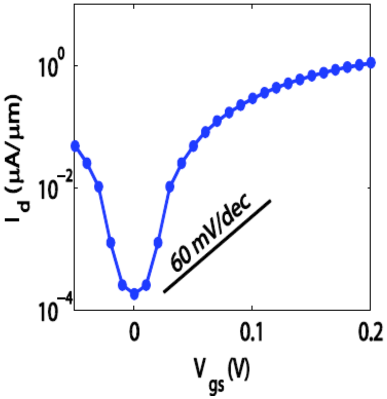


- Steep slope TFETs

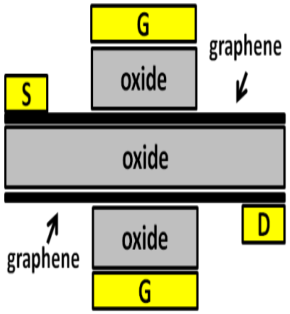
(Banerjee, ..EDL 1987)

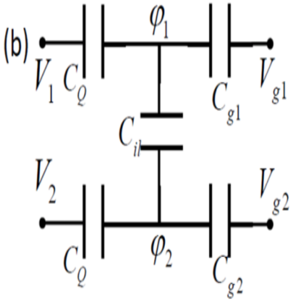


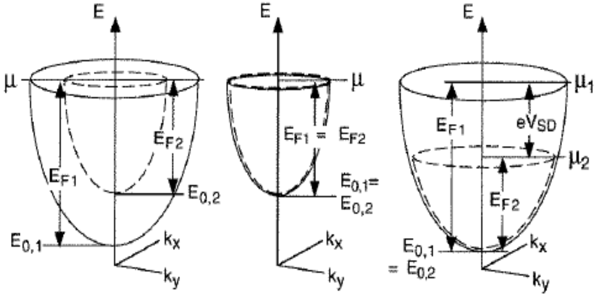


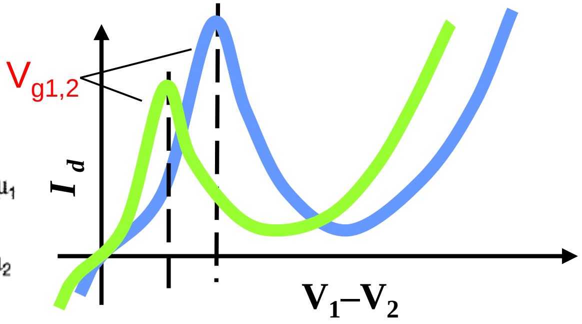


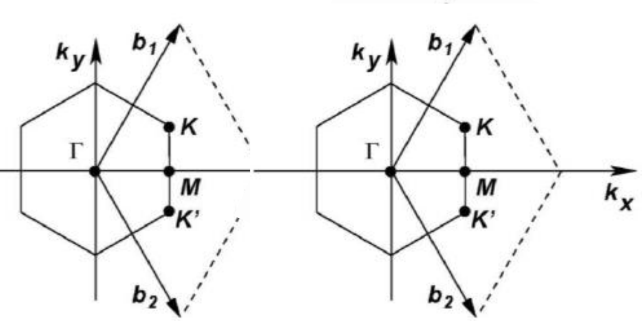
- Resonant ITFETs

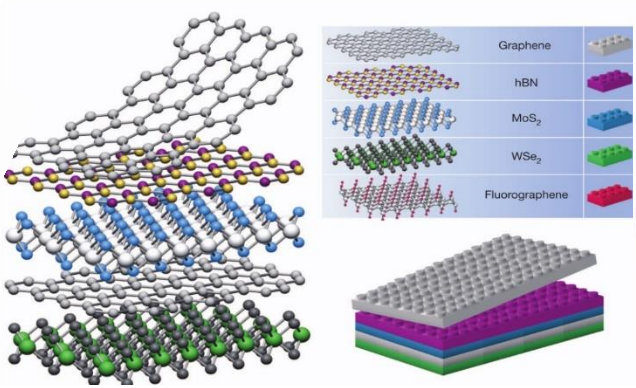


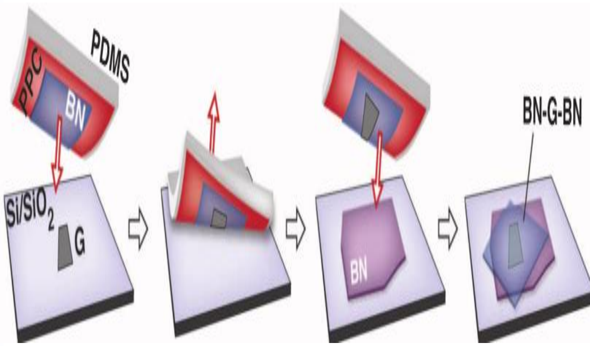


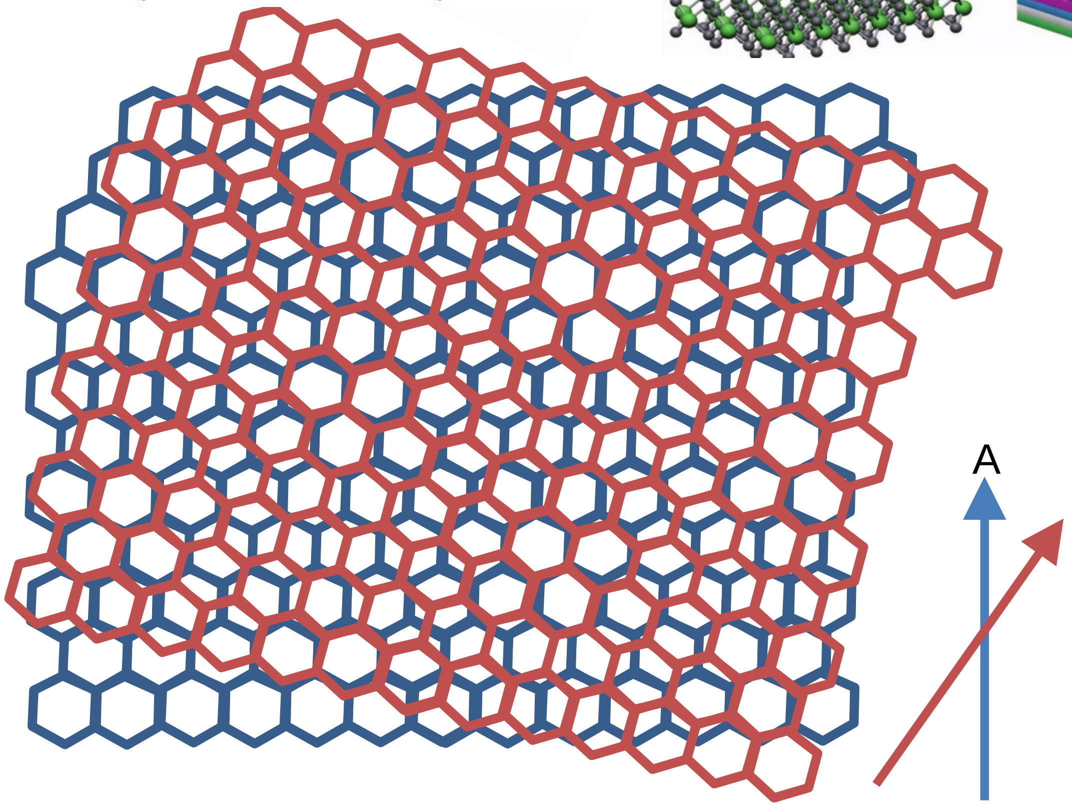


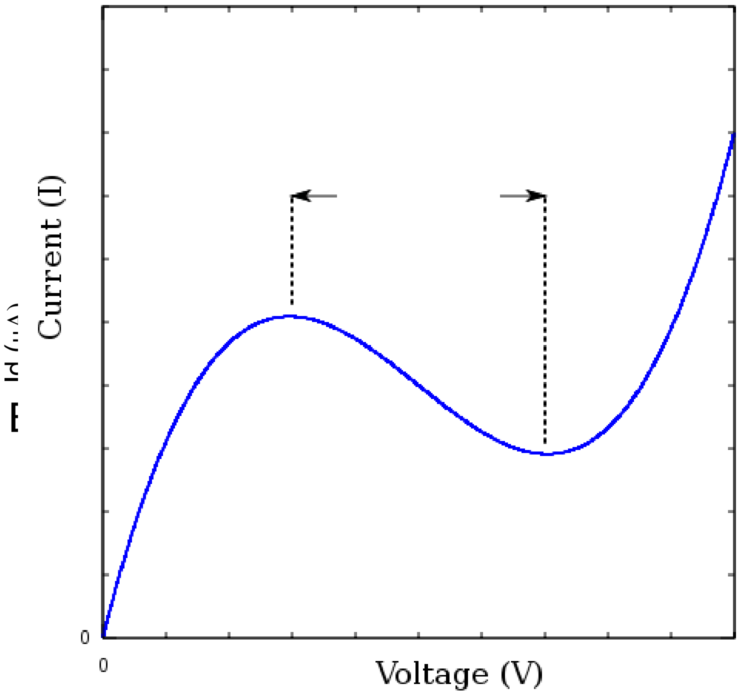












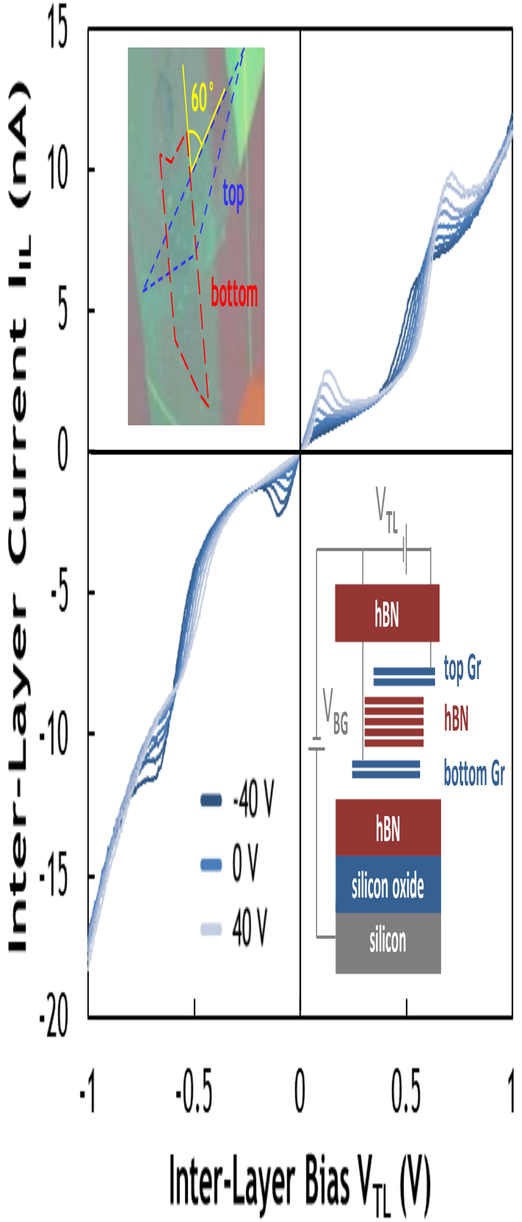
Rotationally misaligned 2D materials

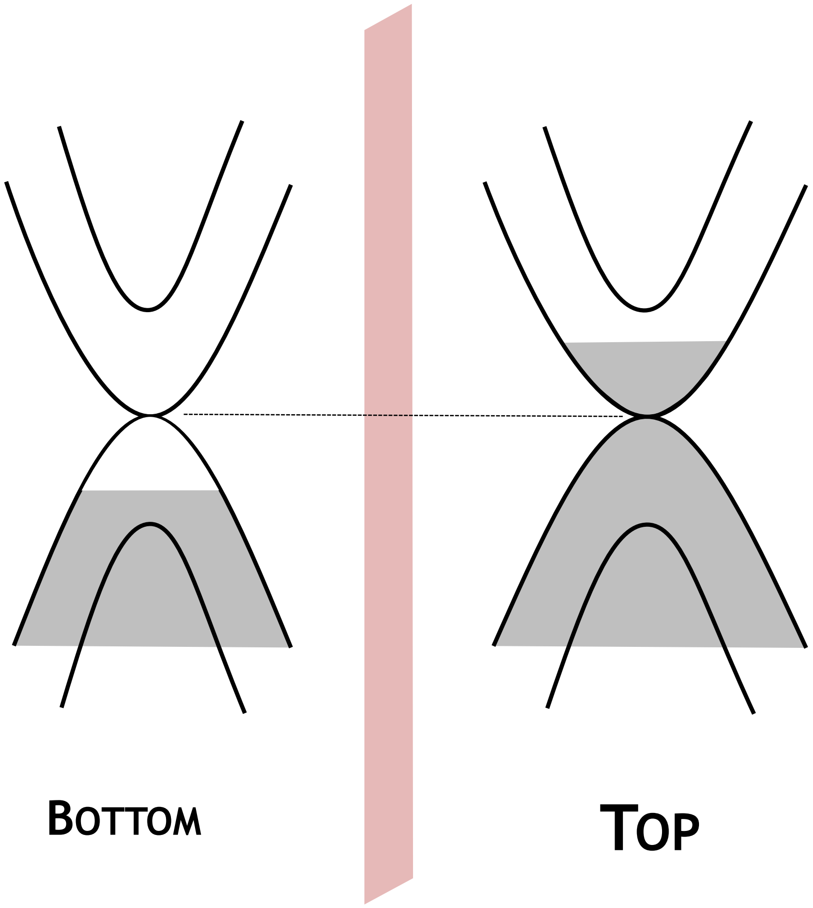
Rotationally **ALIGNED** 2D materials

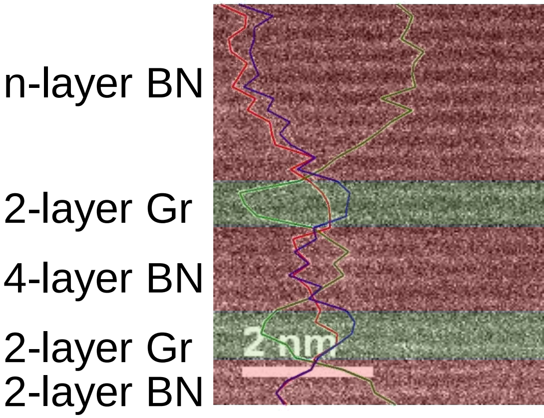
Negative differential resistance

Tunneling behavior

Origin of the First and Second NDR?





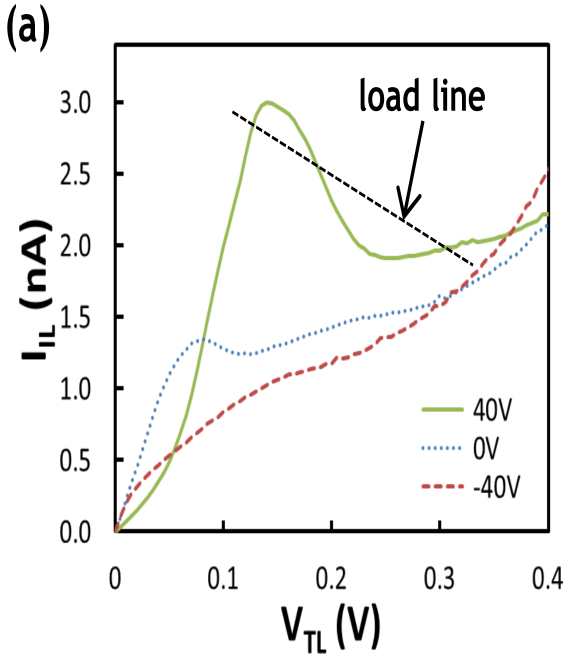


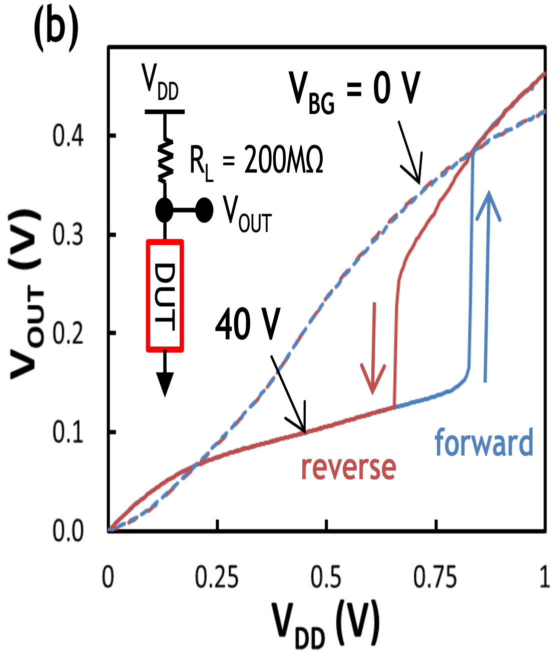
HRTEM AND EELS OF ITFET
(*COURTESY, M.KIM*)

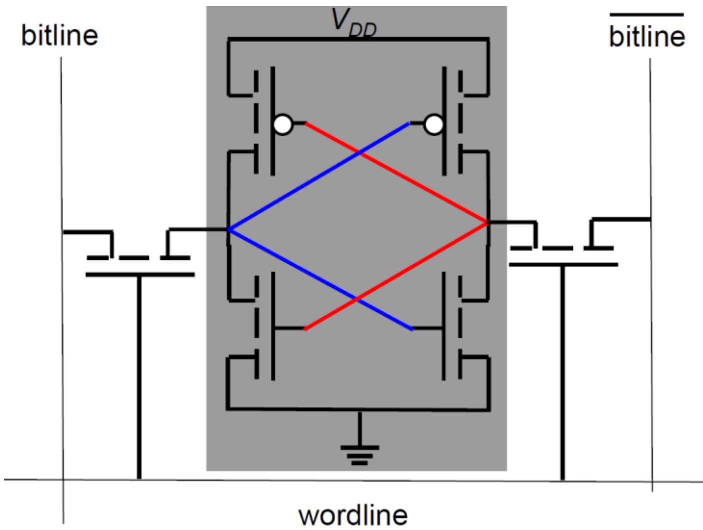
Fallahazad... Register, Banerjee, Tutuc Nano. Lett (2015)

Kang.... Register, Tutuc, Banerjee, EDL (2015)

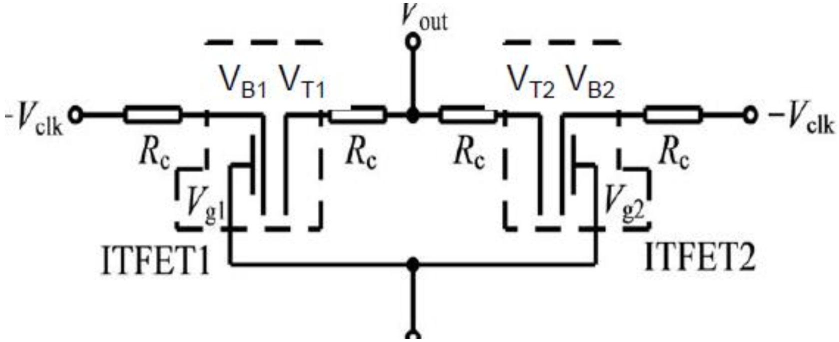
ITFET SRAM and Inverter







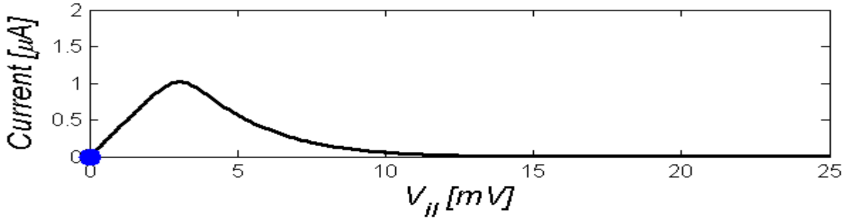
Kang.... Register, Tutuc, Banerjee, EDL (2015)



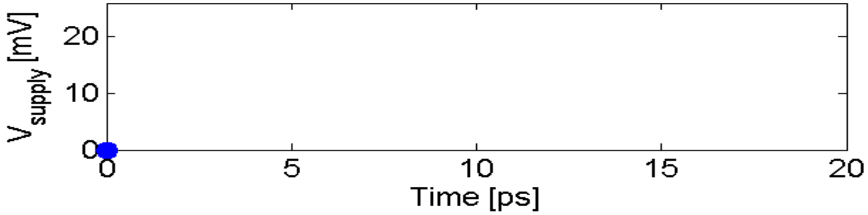
V_{in} = 0, 1

V_{out} = 1, 0

Load Line Plot for Inverter

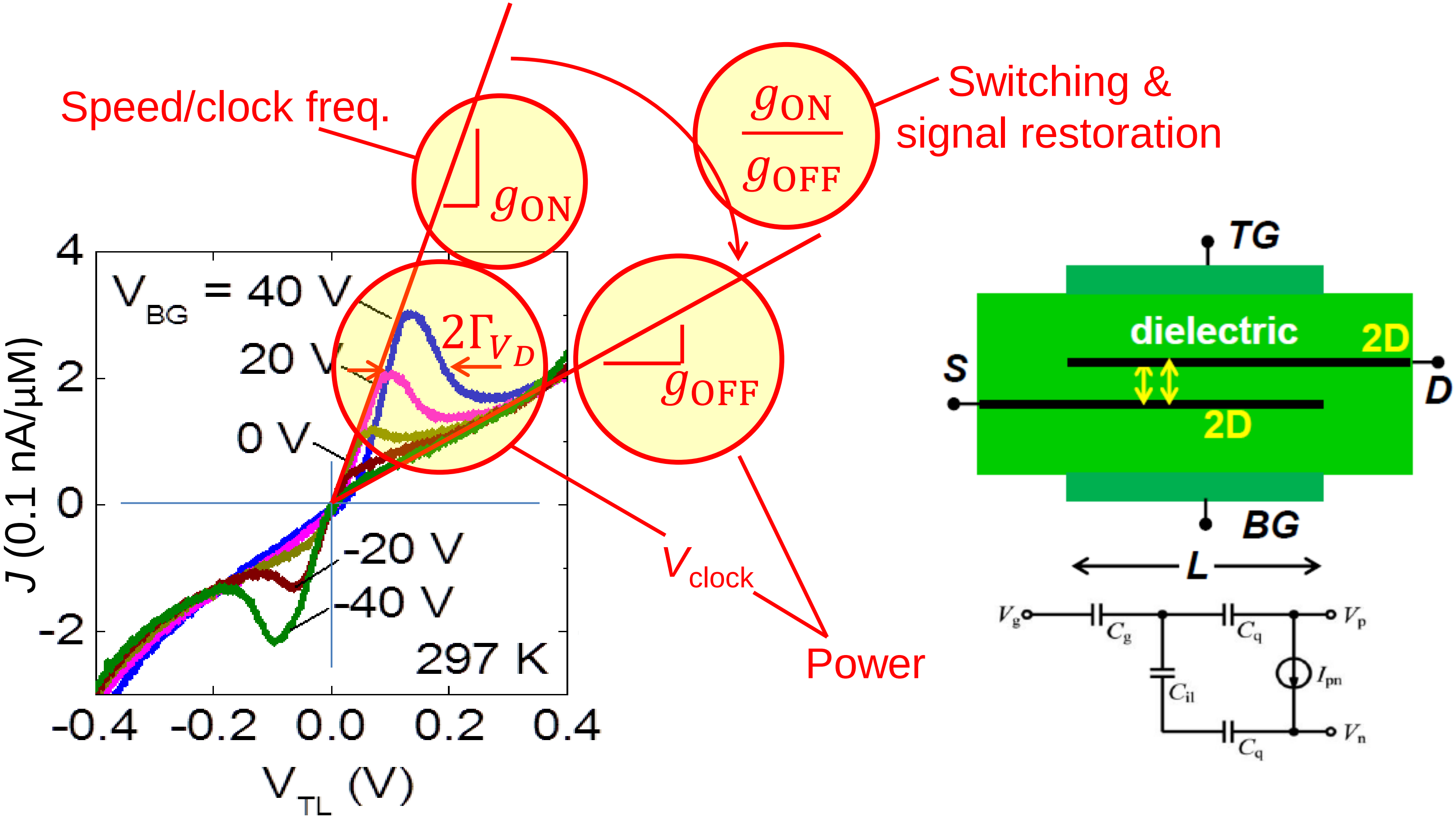


Transient Simulation of a Inverter



Effects of device characteristics on ITFET circuit performance

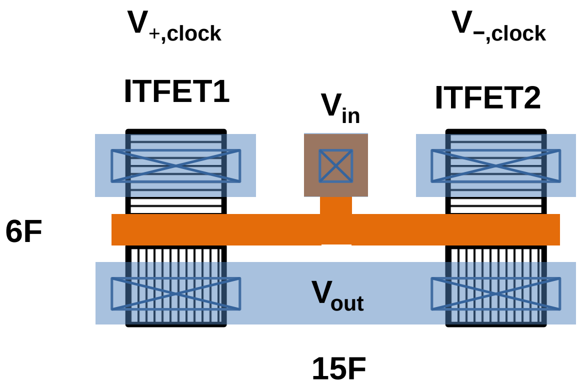
$$I_{\mathrm{tun}} = \frac{A\Gamma\left(V_{\mathrm{p}} - V_{\mathrm{n}}\right)}{\Gamma^2 + \left(\phi_{\mathrm{il}} - \phi_0\right)^2}$$

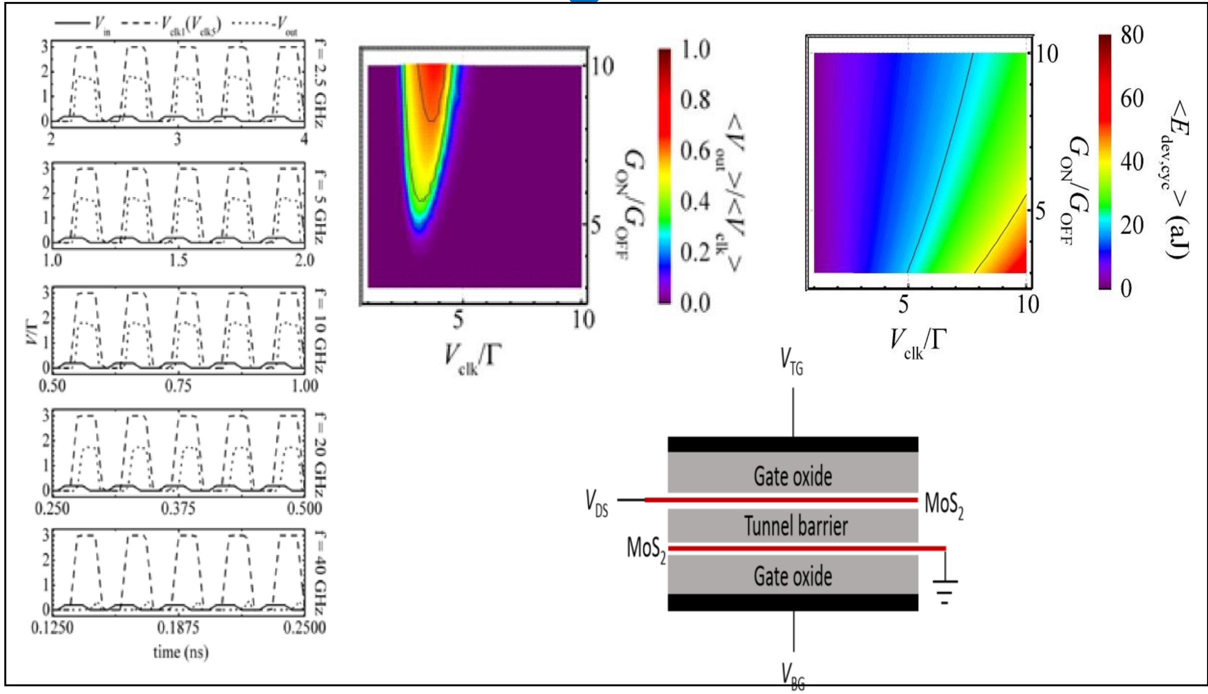


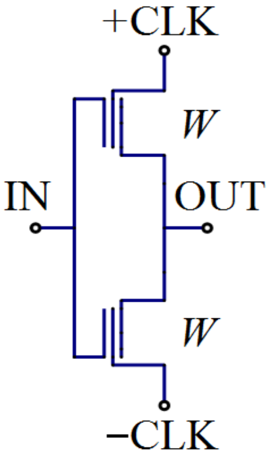
Short L
Fast carriers
Scattering
→ **Large energy broadening** → **High voltage, power**

Need *low defect* electrodes with *high* effective mass to reduce broadening Γ, power
Need vdWE with *clean* interfaces and rotational *alignment* to reduce OFF current

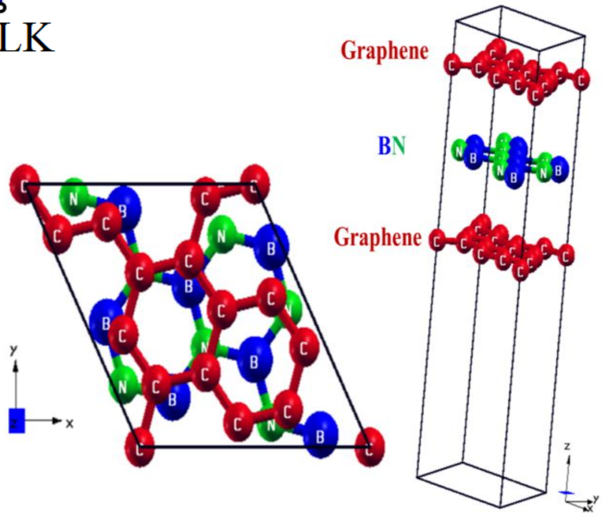
ITFET Circuit Modeling

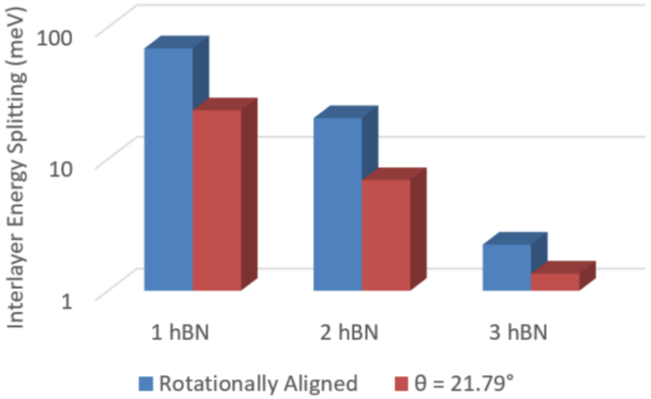






Rotation Angle (degrees)	Band Splitting (meV)	atoms per Supercell	Relative Current Drop
Aligned	69.1	6	--
21.79°	23.4	42	8.72
13.17°	13.8	114	25.1
9.43°	9.51	222	52.8





Conclusions and Challenges

- Electronics in Flatland good for more-than-Moore

- Opportunities in sensors, RF, IoT, and ultra-low power beyond-CMOS devices

- Need progress in large area van der Waals heteroepitaxy for commercial viability