2D Crystals for Nanoelectronics and Beyond.....

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Need Green Transistors

On-die global interconnect energy scales slower than compute
On-die data movement energy will start to dominate

2D Electronic Materials Family Tree

**TMD family**
- NbSe$_2$, etc (superconductor)
- MoS$_2$, WSe$_2$, etc (semiconductors)
- CrO$_2$, CrS$_2$, etc (half-metals) ($0<E_g<1$ eV)

**Graphene family**
- h-BN (dielectric) ($E_g>5$ eV)
- Graphene (semi-metal) ($E_g=0$ eV)
- Silicene (semiconductor) ($E_g=0.6$ eV, experimentally)

**Other families**
- Ti$_2$C, Ti$_2$CF$_2$
  - Black Phosphorus
  - etc.
Advantages of 2D Materials (1/2)

Potato-like 3D Materials
- Covalent bonds everywhere

Onion-like 2D Materials
- Layered structure
- Can be exfoliated
- Van der Waals force
- Few Å

Increased EOT
- Mobile charges centroid
- 1.2 nm deep

Degraded Channel Potential ($V_{Ch}$)
- $V_{Ch} = \frac{C_G}{C_G + \left(C_{SC} + C_{DC}\right)} V_G$

Advanced Topology & Controllable $V_{Ch}$
- Carrier confined
- Thin Channel: Low $C_{SC}, C_{DC}$
Advantages of 2D Materials (2/2)

Potato-like 3D Materials
- Covalent bonds everywhere
- Unsaturated atoms on surfaces
- Interface Variations (Traps)
  - Dangling bonds (traps)
  - Thickness Roughness
    - Band gap Variation
    - Performance Variation

Onion-like 2D Materials
- Layered structure
- Covalent bonds
- Can be exfoliated
- Van der Waals force
  - few Å
- Controllable # of Layers
  - Controllable Band gaps

Controllable Band gaps
- Graphene
- h-BN
- MoS₂
- WSe₂
- Dirac Point
- $E_C$
- $E_v$
- $E_g$
- $E_c$
- $E_v$

Pristine Interfaces (No interface traps)
- Saturated atoms
- No dangling bonds

Advantages of 2D Materials (2/2)
2D Materials Research @ UCSB – Devices, Interconnects, Circuits

- Key Issues in 2D Device Design
  - Contact
  - Doping
  - Interface

- Explore Green Devices/Circuits and Applications: CMOS and Beyond

- 2D Material Selection and FET Design for ITRS Roadmap
- Novel Heterostructures and Devices (2D Tunnel-FETs)
- Flexible and Transparent 2D Circuits/Sensors
Understanding and Optimizing Metal-TMD Contacts


- Treatment of vdW force in DFT (bulk metal-TMD) for the first time
- Widest diversity of metals and TMDs
- First study of metal-TMD edge contacts
- Fermi level pinning revealed beyond Schottky theory
Contact Engineered TMD FETs – Guided by DFT

First High-Performance Monolayer n-type WSe$_2$ FET


High mobility: 142 cm$^2$/V.s
Record $I_{ON}$: 210 µA/µm

High-Performance MoS$_2$ FET with Mo Contacts

Doping of TMDs using Metallic Nanoparticles


- Back-gate Vth shift up to 137 V (monolayer MoS$_2$ FET)
- Both n- and p-type are available
- First p-type doping of WSe$_2$ FET
- Simple/Effective/Stable way of doping as well as sensing
Understanding TMD-Dielectric Interfaces


- Interfaces hold the key to device performance
- Revealing microscopic physics of 2D-dielectric interfaces
- Dipoles/traps evaluated atomically
- Compared 5 dielectrics
- h-BN buffer layer is preferred
Interface Characterization: Low-Frequency Noise


- Interface vdW gaps induce noise peak in 2D materials
- The first theoretical model explaining the noise peaks in 2D materials
- Annealing process reduces noise

Low-frequency noise in bilayer MoS$_2$ field-effect transistor

Existence and Shift of Noise Peak

![Graph showing noise peak before and after annealing](image)

- Noise Peak before annealing
- Noise Peak after annealing

- $S_0$ - 10$^5$
- $10^6$
- $V_{GS}$ (V)
- -20 -10 0 10 20 30 40
2D FET Material Selection for ITRS 2026 (5.9 nm)


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**HP**

**LSTP**

Direct Tunneling

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Tunnel Leakage

\[ T \propto e^{-a\sqrt{m}} \]

Low m degrades SS

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Effective mass should be in suitable region

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\[ \nu = \frac{\hbar k}{m} \]

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**Improving mobility only does not work for 5.9 nm node!**
Advantages of 2D TFET:

- Heterojunctions with low band overlap
- Better electrostatics
- Small tunneling barrier width
- Pristine interfaces


First Physics based Compact Model for 2D TMD FET


Model available on: https://nanohub.org/groups/needs

I. Start from fundamental: Gauss’s law

II. Develop a modified Poisson’s equation specifically for 2D channel

III. Use Drift-Diffusion equation for current transport

IV. Explicit intrinsic drain current expression obtained
V. Model important extrinsic issues existing in 2D TMD FETs:

1. Interface trap
2. Mobility degradation
3. Insufficient S/D doping

- Inclusion of Interface trap effect can recover experimental data better
- Mobility degradation reduces transconductance after device turn-on
- S/D series resistance degrades $I_{ON}$
  - can be compensated with bottom gate

Model available on: https://nanohub.org/groups/needs


First Physics based Compact Model for 2D FET
First Demonstration of 2D TMD FET Biosensor


- Label Free
- Fast
- Low-Cost
Ultra-Low Power and Ultra-Sensitive Tunnel-FET Biosensors


TFET Biosensor in Research Highlights of Nature Nanotechnology

FIELD-EFFECT TRANSISTORS

**Biomolecular turn-ons**

D. Sarkar and K. Banerjee

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
• **Nano-carbon on-chip inductors**
  - large momentum relaxation time
  - low-loss

**Graphene interconnects:**
Xu et al., *IEDM* 2008, pp. 201-204.
Xu et al., *TED* 56, 8, 1567-1578, 2009.

**First Demonstration of Horizontal CNT Interconnects & Inductors**
H. Li, et al., *TED* 60, 9 (2013)

**Design Analysis of CNT Inductors**
H. Li, et al., *TED* 56, 10 (2009)

**Design Analysis of Graphene Inductors**
D. Sarkar, et al., *TED* 58, 3 (2011)

**First Demonstration of Graphene Inductors**
X. Li/J. Kang et al., *IEDM* 2014

2009

2011

2013

2014
All-2D Circuits for Flexible Electronics – First Demonstration of Graphene Inductors


Voltage Controlled Oscillator (VCO) designed based on Graphene Inductors

Oscillation Frequency Range: 40-47 GHz
Future Perspectives- 2D Crystals for Smart Life

- Flexible Electronics
- Smart Screens
- Graphene Inductors
- Transparent Electrode

2D Materials
- Ultra-thin body
- Smooth surfaces
- Range of materials
- Materials by design
  - new layered materials

- 2D Insulator
  - h-BN, etc
- 2D Metal
  - VO₂, Ti₂C, etc
- 2D Semiconductors
  - MoS₂, WSe₂, etc
- 2D Semi-Metal
  - Graphene, etc

- High-Performance
  - 2D Transistors
- 2D Tunnel-FETs
- Ultra-thin NV Memory
  - IEEE TED 2014 (UCSB)
- 3D ICs with 2D

Future Perspectives
- Point-of-Care
- Homeland Security
- Mobile Health
- Ultra-Sensitive MoS₂ Biosensors

- Graphene Inductors
- Chem. Mat. 2014 (UCSB)
- IEDM 2014 (UCSB)
- ACS Nano 2014 (UCSB)

- Energy-Efficient ICs
- High-Density Memory
- High-Power
- Smart Screens
- Homeland Security
- Mobile Health
- Smart Screens

- Ultra high-density
  - low-power hardware...
- to enable “Big Data”
- Internet of Things
- Social Media

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