2D Materials for Ubiquitous Electronics

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2DCC-MIP Webinar September 7, 2017
Traditional Electronics
Transistor Evolution

Scaling Ends – Doomsday?

4 decades–4 orders of magnitude length scaling

<table>
<thead>
<tr>
<th>Length</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>100µm</td>
<td>1975</td>
</tr>
<tr>
<td>10nm</td>
<td>2015</td>
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</tbody>
</table>

22 nm 1st Generation Tri-gate Transistor

14 nm 2nd Generation Tri-gate Transistor

\[
\lambda_S = \lambda_{geo} = \sqrt{\frac{\varepsilon_{body-x}}{\varepsilon_{ox}}} \cdot t_{body} \cdot t_{ox}
\]

Si FinFET \( t_{body} \approx 6\text{nm} \quad \lambda_S \approx 4.2\text{nm} \)

Short Channel Limit

\( L_{CH} > 3\lambda_S \)
Transistor Evolution

2D Materials can rescue!!

Short Channel Limit

\[ L_{CH} > 3\lambda_S \]

\[ \lambda_S = \lambda_{geo} = \sqrt{\frac{\varepsilon_{body-x}}{\varepsilon_{ox}}} t_{body} t_{ox} \]

Si FinFET
\[ t_{body} \approx 6\text{nm} \quad \lambda_S \approx 4.2\text{nm} \]

Monolayer MoS\(_2\)
\[ t_{body} \approx 0.65\text{nm} \quad \lambda_S \approx 1.4\text{nm} \]

22 nm 1\text{st} Generation Tri-gate Transistor

14 nm 2\text{nd} Generation Tri-gate Transistor

\[ t_{MoS2} = 0.65 \text{ nm} \]
Transistor Evolution
Monolayers are Essential

Monolayer Mobility is poor

Ballistic Limit
No Concerns

Quasi Ballistic
Low mobility – No problem
h-BN buffer layer

Large Bandgap (1.8eV)

Schottky Barrier Contact
1T-phase contact (200Ω-µm)

Bandgap Engineering
Straintronics

![Graph showing bandgap engineering](image)

- MoS$_2$
- MoSe$_2$
- MoTe$_2$
- WS$_2$
- WSe$_2$
- WTe$_2$
Transistor Evolution

Future looks promising


Current State of Affairs
CVD, MOCVD, MBE Growth

Power Dissipation

Boltzmann Tyranny

\[ SS = \frac{k_B T}{q} \ln 10 \]

Voltage Scaling Almost Stopped

Fundamental Limitations at \textbf{Device Level}

\textbf{Innovation in Device Physics}
Power Dissipation

Boltzmann Tyranny

\[ SS = \frac{k_B T}{q} \ln 10 \]

Voltage Scaling Almost Stopped

Fundamental Limitations at **Device Level**

Innovation in Device Physics
Two Dimensional (2D) - Electrostrictive Field Effect Transistor


Monolayer MoS$_2$ undergoes SMT at 3GPa

Das. S; Two Dimensional Electrostrictive Field Effect Transistor (2D-EFET). Scientific Reports, 6, 34811, 2016.
A Novel Concept: 2D EFET

Ultra Low Power FET

\[ \Psi_S = r V_{GS} \quad r \leq 1 \]

\[ \Psi_E = -\frac{\alpha}{2} P \]

\[ P_{2D} = \eta C_{33,2D} \frac{1}{t_{2D}} d_{33} V_{GS} \]

\[ \psi_T = V_{GS}(1 + \eta \beta d_{33}) \]
A Novel Concept: 2D EFET

Ultra Low Power FET

\[ \psi_T = V_{GS}(1 + \eta \beta d_{33}) \]


\( \perp \) MoS\(_2\) Compliance:
\[ C_{33} = 60 \text{ GPa} \]

Piezoelectric Coefficient:
\[ d_{33} = 850 \text{ pm/V} \]

MoS\(_2\) E\(_g\) Coefficient:
\[ \alpha = -80 \text{ meV/GPa} \]
**Motivation**

Trimming the high energy Fermi tail results in sub-60mV/decade SS

**Band to Band Tunneling**

\[ SS = \frac{k_B T}{q} \ln 10 \]

\[ I_{ON} \propto T_{WKB} = \exp(-\frac{4}{3\hbar} \sqrt{2m_eE_G \lambda}) \]

\[ T_{WKB} = \exp\left(-\frac{4}{3\hbar} \sqrt{2m_eE_G d_{OX}d_{BODY}}\right) \]

Excitonic Device

Formation of excitonic condensate in spatially separated nanosheets (n-type and p-type) controlled by gate voltage

ON State: Superconductor
OFF State: Normal Semiconductor

ON State: Normal Semiconductor
OFF State: Perfect Insulator
Sensor Electronics
Internet of Things

Sensors

- Electrical
- Mechanical
- Optical
- Thermal
- Chemical
- Biomedical

- High Performance – No
- Low Power/Self Power – Yes
- Low Cost – Yes
- Flexible – Yes
- Light Weight – Yes
- Transparent – Yes
Flextronics

Das, S. et al. All Two Dimensional, Flexible, Transparent and Thinnest Thin Film Transistor. *Nano Letters* 14 (5), 2014

Thinnest Transistor

Metal: Graphene

Insulator: h-BN

Semiconductor: WSe$_2$

Electron Branch
Mobility: 24 cm$^2$/V.s
ON/OFF : 2x10$^7$

Hole Branch
Mobility: 45 cm$^2$/V.s
ON/OFF : 7x10$^7$

Displays
Glasstronics

Source/Drain Contacts Ni/Au

EXG Glass

MoS$_2$

Al 65nm

HSQ 150nm

HSQ

MoS$_2$
Piezotronics


Self Powered Electronics
Optoelectronics


EQE of up to 15%  Photoresponsivity of $5 \times 10^8$ A/W

**Photodetectors**

**Solar Cells**

**LEDs**

**Photodetector**

\[ I_{ph} \]

**Photovoltaic (solar cells)**

\[ I_{sc}, V_{oc} \]

**Electroluminescence (LEDs)**

\[ h\nu \]

Electrostatically doped WSe$_2$ p-n diodes
All Purpose Electronics

Integrated circuit based on MoS$_2$

Memory transistor with MoS$_2$

MoS$_2$ FET based bio-sensor
Late, D. J. et al. *ACS Nano* 7(6), 2013

MoS$_2$ FET based gas-sensor
Harsh Environment Electronics
Van Allen Belts

Cosmic Rays

Van Allen Belts
- Protons
- Electrons

Cosmic Rays
- Protons (90%)
- Helium Nuclei (9%)
- Electrons (<1%)
- Heavier Ions (<1%)

2 MeV proton: $10^{14}$ protons/cm²

390 keV He: $2 \times 10^{15}$ ions/cm²

390 keV He: $10^{16}$ ions/cm²


Radiation Exposure Courtesy: Prof. Jovanovic Group (UMich)
Anticorrosion Electronics

Electrochem Magic


Extreme Stability/Corrosion Resistance of Monolayer TMDs
Electro-ablated MoS$_2$ Monolayers

As Exfoliated Multilayer MoS$_2$ flakes

Electro-ablated Monolayer MoS$_2$ flakes

**Raman**

- Electro-ablated Monolayer MoS$_2$: 20.6 cm$^{-1}$
- As Exfoliated MoS$_2$: 26.7 cm$^{-1}$

**Photoluminescence**

- Electro-ablated Monolayer MoS$_2$: $E_g = 1.86$ eV
- As Exfoliated MoS$_2$

**SAED**

**TEM**

*in-situ spectroscopy In progress: Prof. Emilie Ringe (Rice)*
Anticorrosion Monolayer FETs

**OFF State Stressing**

- Negative $V_T$ shift
- Quick device recovery
- $V_D = 2V$
- $V_D = 4V$
- $V_D = 6V$
- $V_D = 8V$
- $V_D = 10V$
- $V_G = -50V$

**ON State Stressing**

- Negative $V_T$ shift
- Abrupt changes at $V_D = 10V$
- Slow device recovery
- $V_D = 2V$
- $V_D = 4V$
- $V_D = 6V$
- $V_D = 8V$
- $V_D = 10V$

**Curiosity Driven Stressing**

- Positive $V_T$ shift
- Abrupt changes at $V_D = 18V$
- Permanent device damage
- $V_D = 10V$
- $V_D = 12V$
- $V_D = 14V$
- $V_D = 16V$
- $V_D = 18V$

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**Reliable Electronics**

**Hot Electron Transistor**


- Positive $V_T$ shift
- Abrupt changes at $V_D = 18V$
- Permanent device damage
Hot Carrier Transport

Electron becomes HOT

- Impact Ionization e-h pair generation
- "Lucky" hole
- hole trapping in the gate oxide
- negative $V_{TH}$ shift

- "Lucky" electron
- electron trapping in the gate oxide
- positive $V_{TH}$ shift

- momentum randomizing collision

$V_T = V_{FB} - \frac{Q_{IT}}{C_{ox}} - \frac{Q_F}{C_{ox}} - \frac{Q_M}{C_{ox}}$

$\Delta V_T = -\frac{\Delta Q}{C_{ox}}$
Brain Inspired Electronics
Neuron

Immediate Action: Muscle Movement, Chemical Secretion
Long-term Action: Memory, Learning
Neurotransmitter Release


Quantal

\[ PSC \propto n_T f(n_{AP}) \]

Stochastic

\[ PSC \propto p_r n_T f(n_{AP}) \]

Bipolar

Excitatory: Glutamate
Inhibitory: GABA
Neuromorphic Transistor

Source

Drain

MoS$_2$

2µm

Low DIBL

$\mu_n = 20 \text{cm}^2/V\cdot\text{s}$

$V_{\text{TH}}$

$V_{DS} = 1.0V$
$V_{DS} = 0.8V$
$V_{DS} = 0.6V$
$V_{DS} = 0.4V$

$I_{DS}$ [µA]

$10^0$

$10^{-6}$

$10^{-3}$

$10^{-6}$

$V_{GS}$ [V]

$V_{DS}$ [V]

$I_{DS}$ [µA]

$10^0$

$10^{-6}$

$10^{-3}$

$10^{-6}$

$V_{GS}$ = 10V:10V:60V

Back Gate Oxide

P-Doped Si

$V_{GS}$ (Synaptic Input)

$I_{DS}$ (PSC)

$V_{DS}$
Origin of Hysteresis
Neuromorphic Transistor

Inhibitory Response

Excitatory Response

Quantal Stochastic Bipolar
Neuromorphic Transistor


Quantal: Pulse Frequency
Stochastic: Pulse Magnitude
Bipolar: Pulse Polarity
Summary

✓ 2D materials can reinstate transistor scaling

✓ 2D Materials support novel low power device concepts like EFET, TFET and ExFET

✓ 2D Materials are promising for all purpose sensors

✓ 2D Materials can be used for harsh environment electronics

✓ 2D Materials can be used for brain inspired electronics
Acknowledgement

Graduate Students
Daniel Schulman
Andrew Arnold
Joseph Nasr
Yu Ting Huang (visiting)
Amritanand Sebastian
Drew Buzzell

Faculty Collaborator
Dr. Mauricio Terrones (PSU)
Dr. Nasim Alem (PSU)
Dr. Joshua Robinson (PSU)
Dr. Susan Trolier-McKinstry
Dr. Sumeet Gupta
Dr. Sukwon Choi (PSU)
Dr. Emilie Ringe (Rice)
Thank You