Emerging and Non-conventional 2D Materials, Devices & Applications

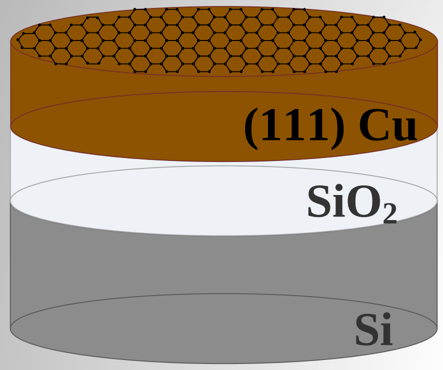
Deji Akinwande,

The University of Texas –Austin

General Research: From Science to Nanotechnology

ACS Nano, 2012, 2014.

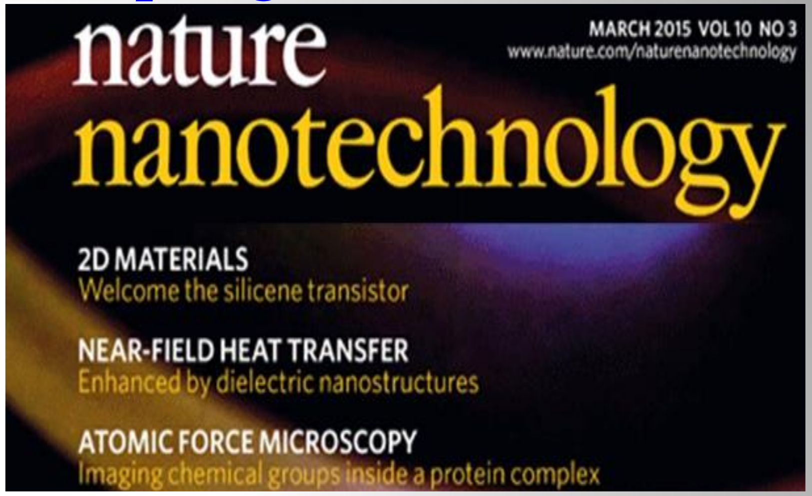
Materials Growth



4in-12in Aixtron Tool
(push-button)

Flexible 2D Electronics

Topological 2D Devices



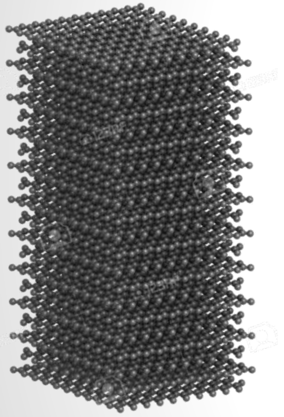
Introduction to 2D Science and Technology

What are Two-dimensional (2D) Layered Nanomaterials?

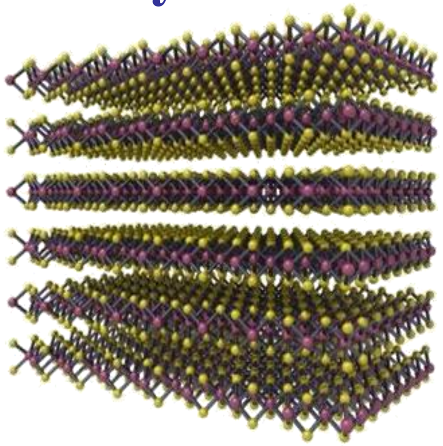
Definition: A layered structure with anisotropic bonding. That is,

- **-strong in-plane (covalent) bonding**
- **-weak out-of-plane (van der Waals) bonding.**

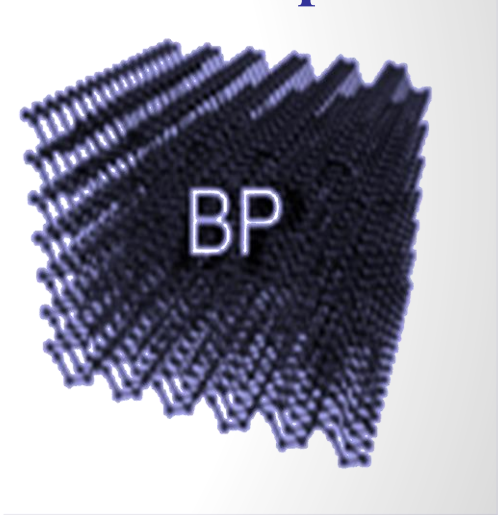
Examples: Graphite

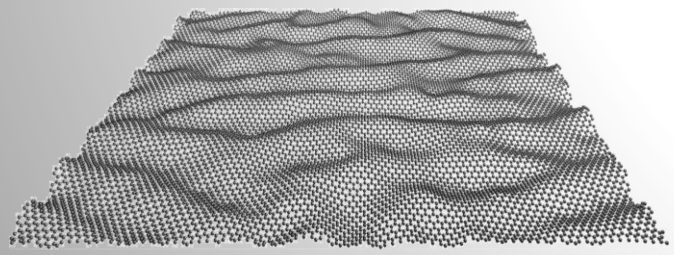


Molybdenite

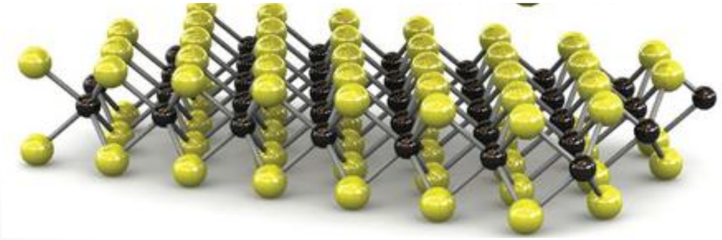


Black Phosphorus

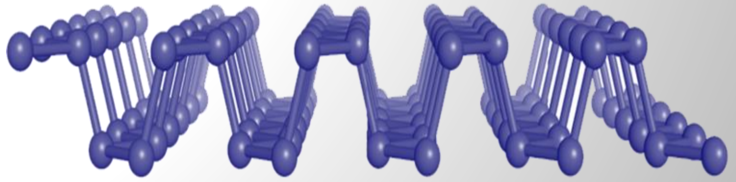




Graphene



MoS_2



Phosphorene

Brief (Incomplete) Timeline to 2D Electron Devices

2004: Graphene

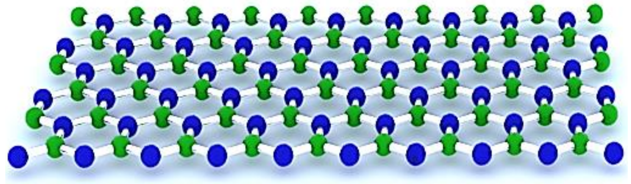
Flat honeycomb
E_g=0eV

Geim & Novoselov, de Heer, etc
Nature 2005, etc

2010 Nobel Physics Prize

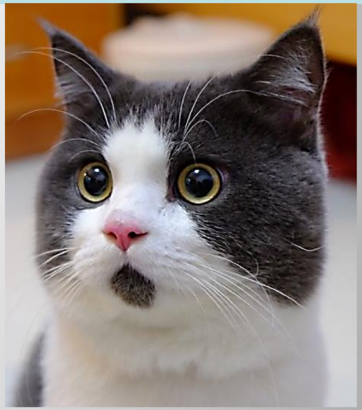
2009: *h*-BN

Diatomic honeycomb
E_g~6eV



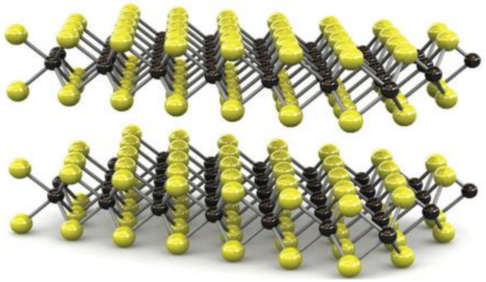
Colombia Univ. group
Nature Nano. 2010, etc

1000s of Layered Materials are known to exist!



2011: TMDs

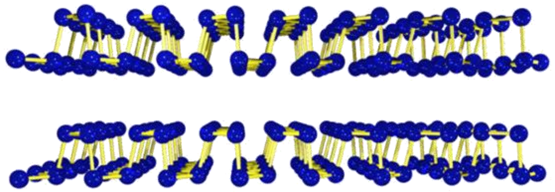
Sandwich honeycomb
E_g~1-2eV



T. Heinz, A. Kis, etc
Nature Nano. 2011, etc

2014: Phosphorene

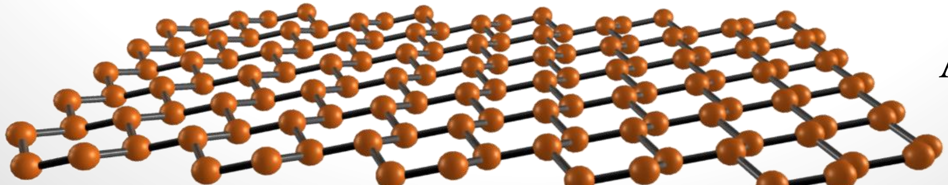
Puckered honeycomb
E_g~0.3-2eV



P. Ye, Y. Zhang, A. C-Gomez, etc
Nature Nano. 2014, etc

2015: Silicene

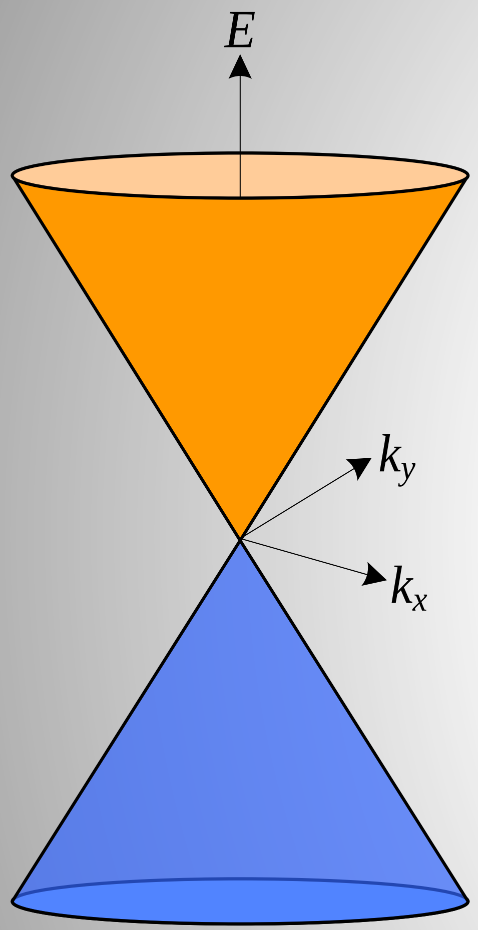
Buckled honeycomb



Akinwande & Molle, etc
Nature Nano. 2015, etc

Graphene Basics & Publication Trends

$$E(\mathbf{k})^{\pm}_{linear} = \pm\eta v_F |\mathbf{k}|$$



Basic Properties

-massless, highest mobility

(~50,000 cm^2/V-s at RT)

-Highest thermal conductivity

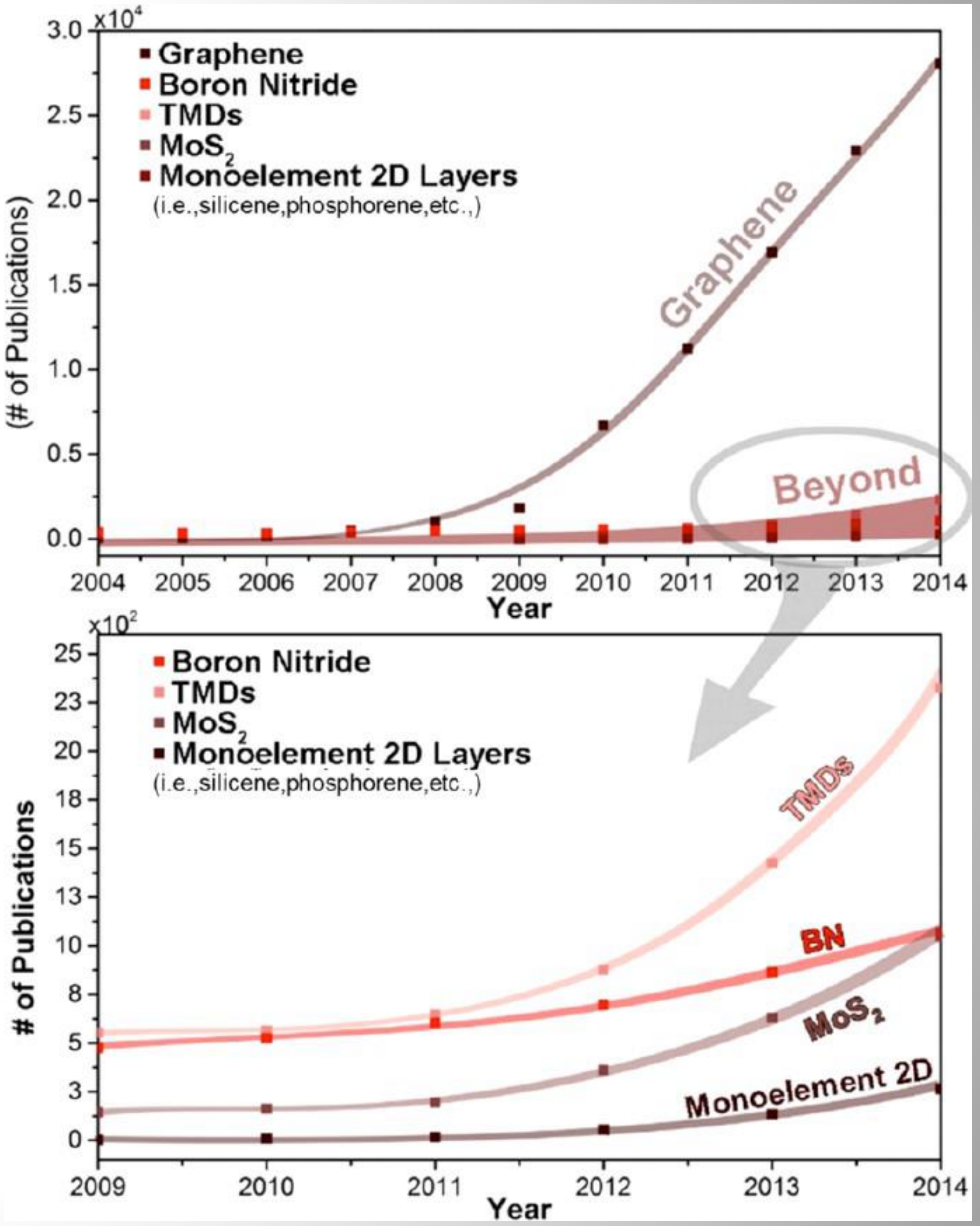
(~5,000 W/m-K near RT)

-Highest optical transparency

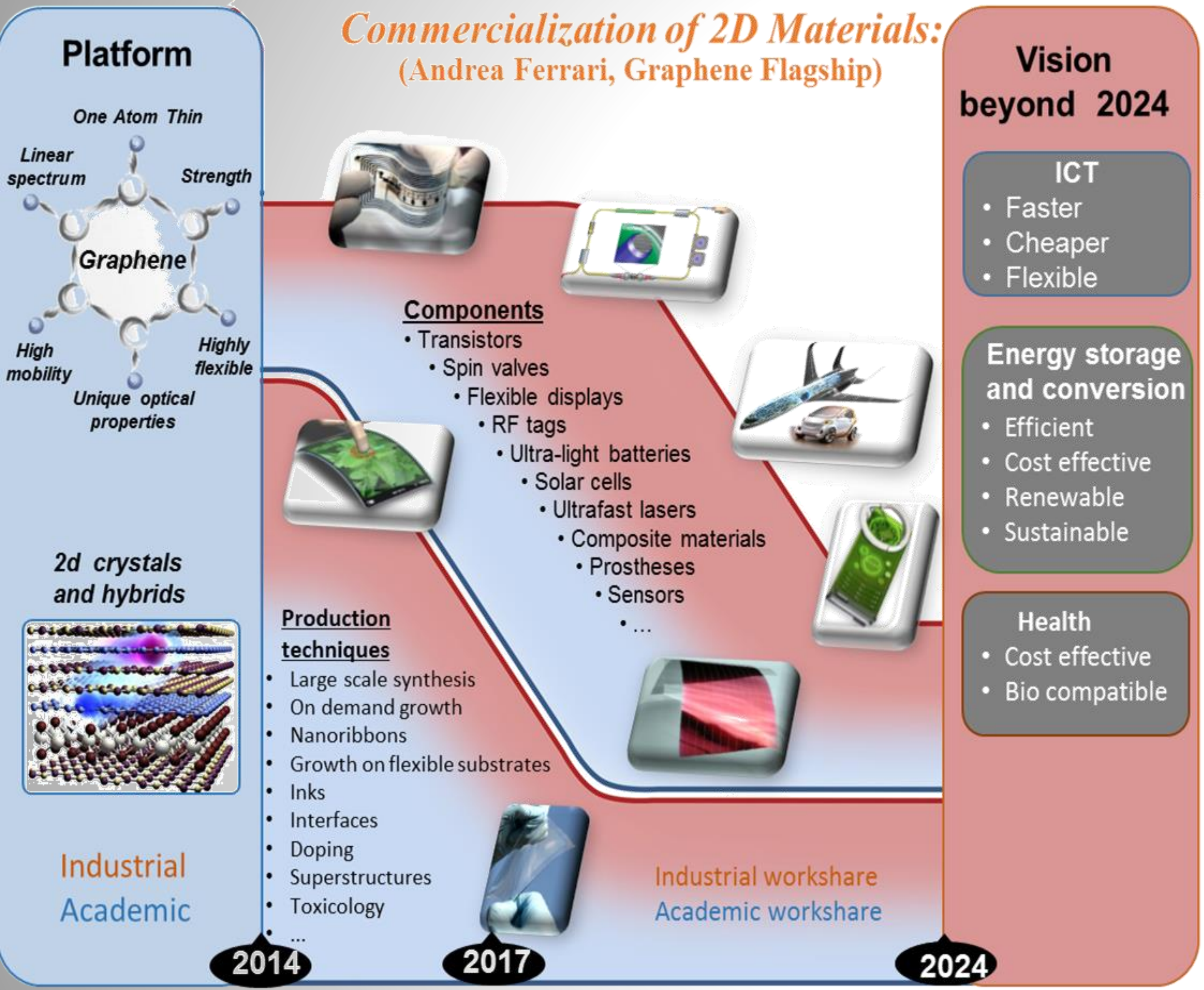
(>97% transparency)

-Largest mechanical strength

(YM~1 TPa, strain limit >25%)



Grand Opportunity: $4B+ International Funding



GRAPHENE CGIA 中国石墨烯产业技术创新战略联盟
China Innovation Alliance of the Graphene Industry

The China National “13-5” Project Goals (2016 – 2020)

100 graphene industry parks to be built *(graphene+2D)*

- ➢ Generate revenues up to 100B RMB ($15B USD) of graphene products
- ➢ Generate revenues up to 1,000B RMB of graphene related products.

Application Areas-1

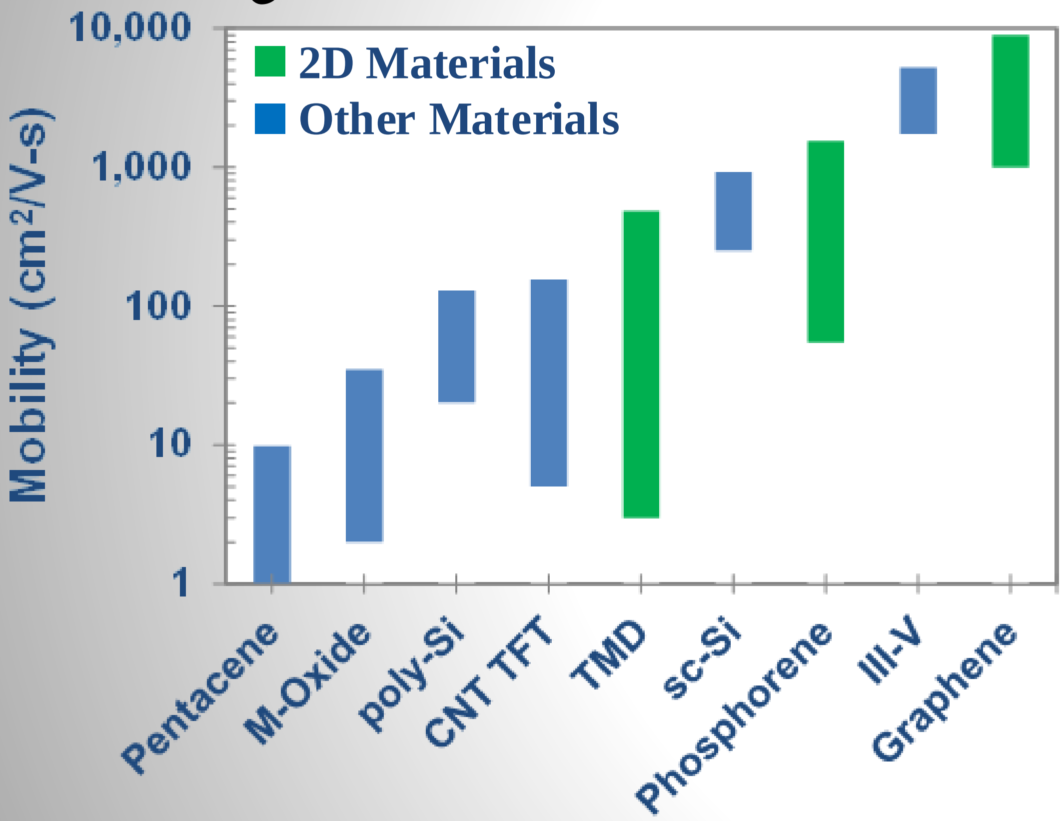
- ➢ Soft and foldable touch display
- ➢ Wearing materials
- ➢ Desalination

http://www.phantomsnet.net/graphin/Files/Keynotes/GraphIn2015_Xiaoyue%20Xiao.pdf

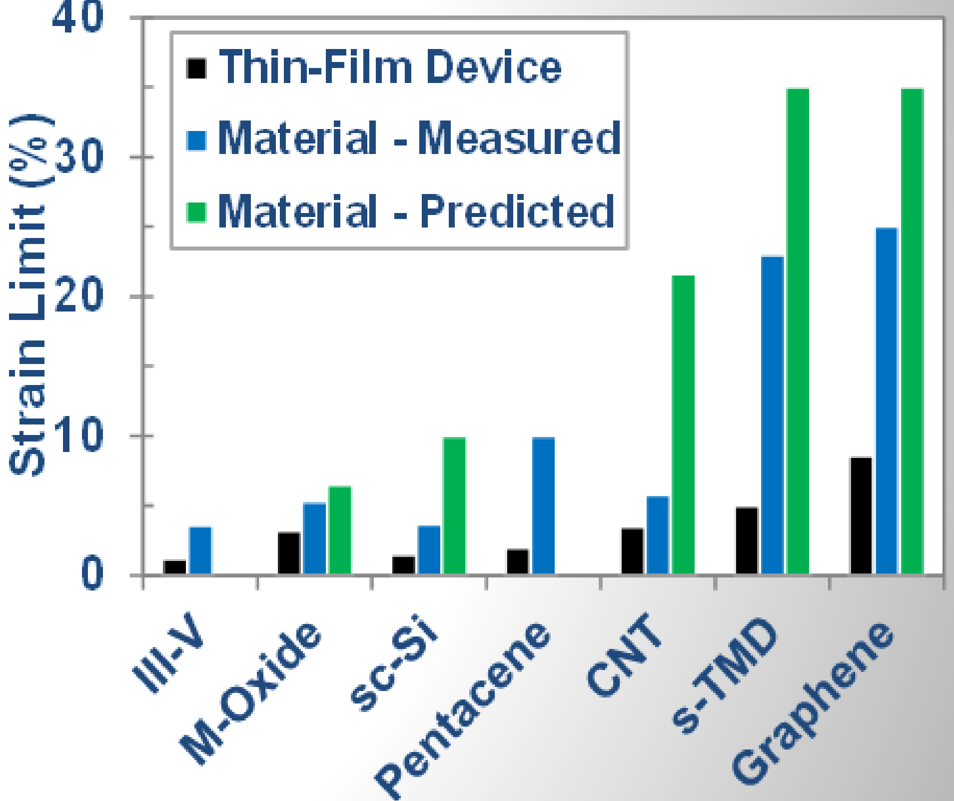
→2D for Performance Flexible Nanotechnology

- Atomic sheets offer maximum flexibility, transparency, electrostatics ..
- Applications are for i) large-area, or ii) high-density integrated nanosystems!

TFT Electronics



Mechanics



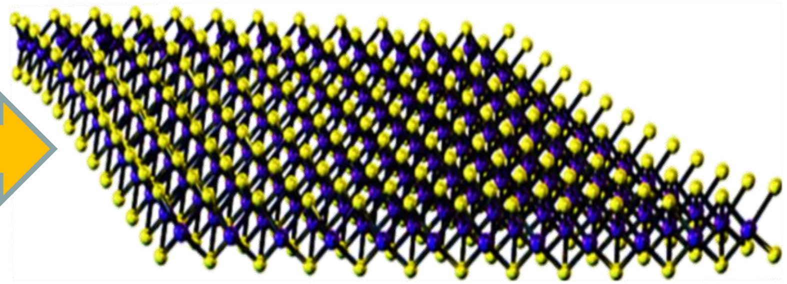
- Graphene/Phosphorene good for RF circuits
- TMDs good for digital circuits and low-power RF

Akinwande, Petrone, Hone et al., *Nature Comm.* invited review (Dec. 2014)

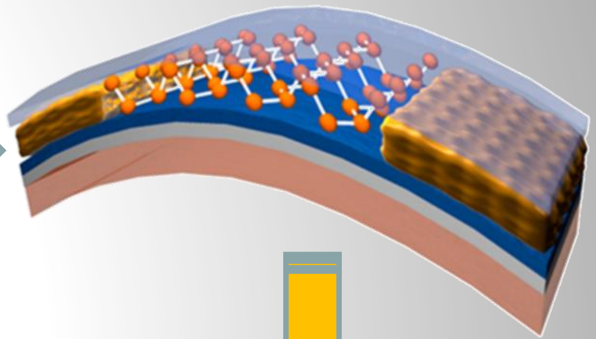
2D Flexible Nanoelectronics: Transdisciplinary R&D

Substrates

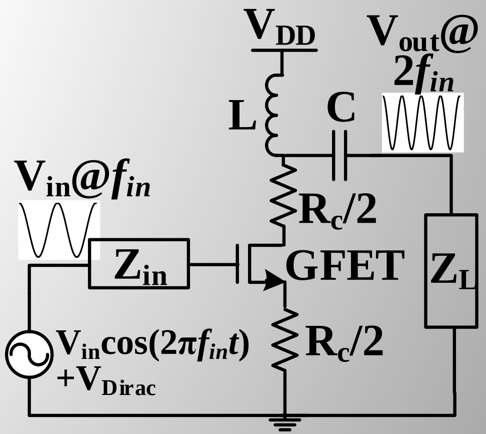
Materials



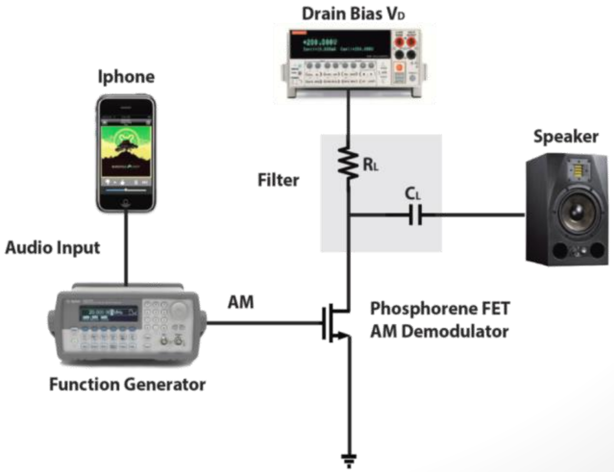
Devices



Circuits



Systems



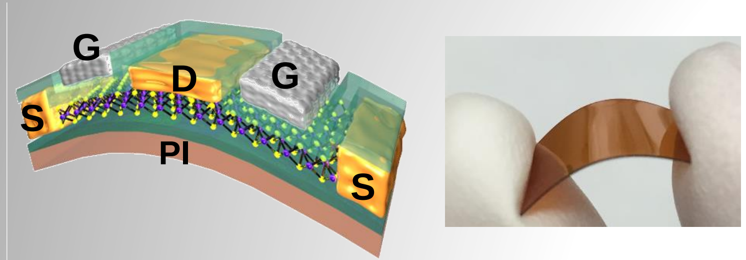
nanomanufacturing

Demo of High-Performance 2D High-Frequency TFTs

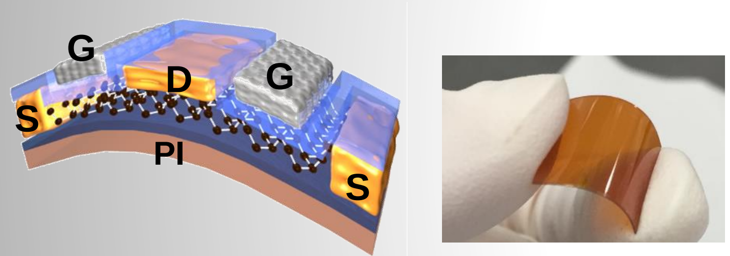
IEDM 2012, 2013, 2015, 2017, etc

$$f_T L = \frac{v_{sat}}{2\pi}$$

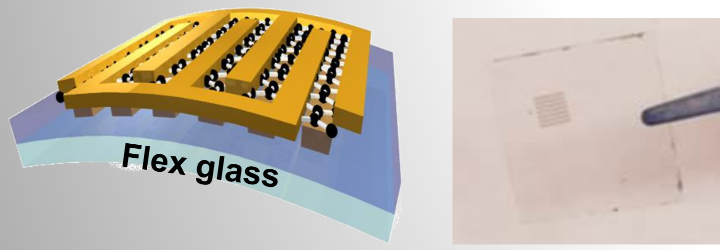
Transfer Integrated 2D Devices



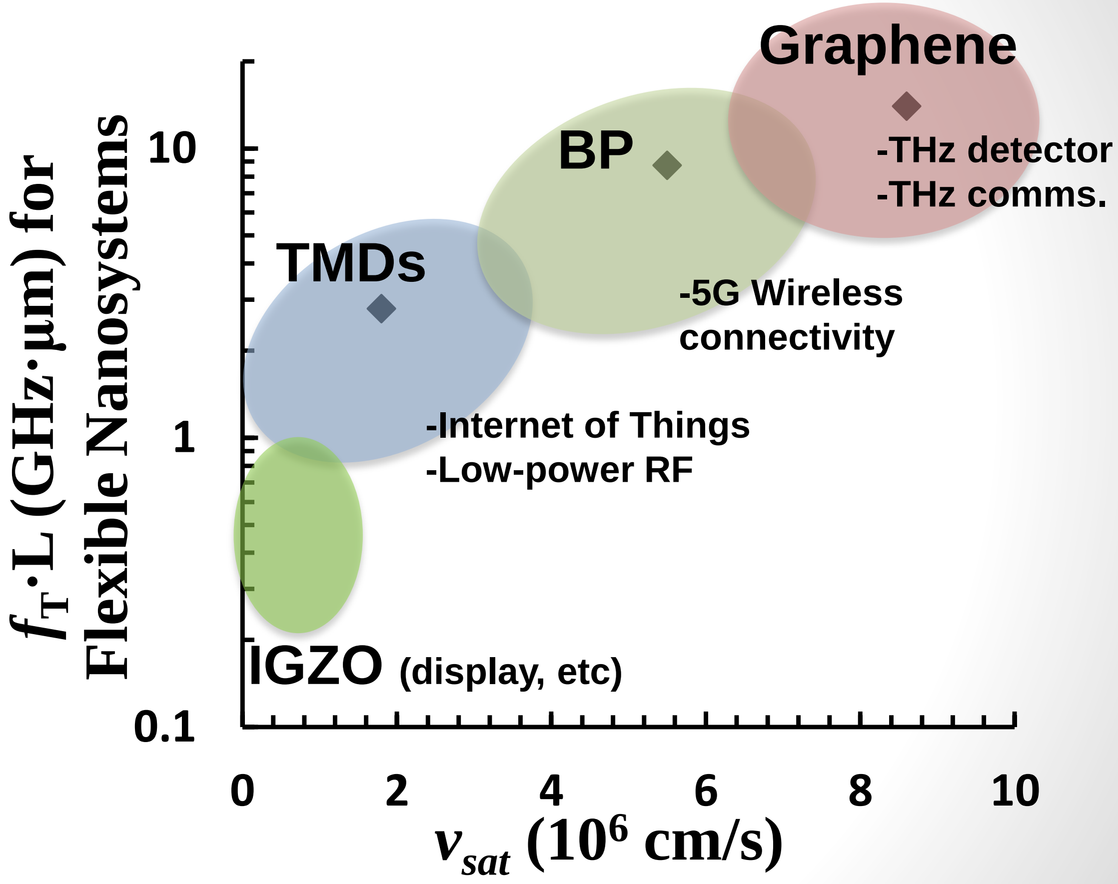
Flexible CVD-MoS_2 (6GHz)



Flexible BP (20GHz)



Flexible CVD-Graphene (100GHz)



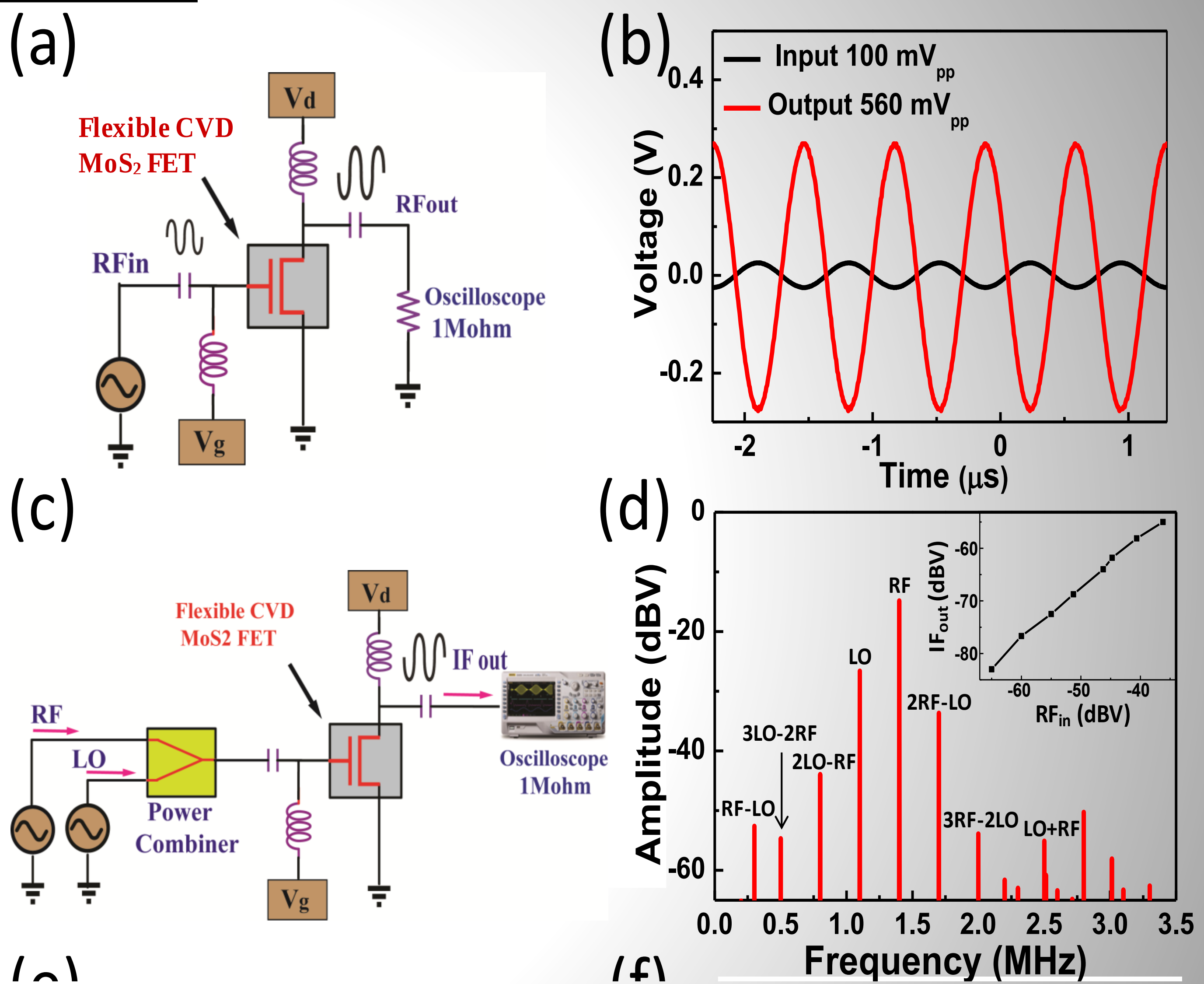
Also other groups
- -Hone (Columbia)
- -Happy (Lille)
- -Northwestern
- -Cambridge
- -AMO/RWTH
- -EPFL
- -ARL
- -SKKU
- -KAIST
- -Tsinghua
- -etc

For reviews, see Akinwande, *Nature Comm.* (Dec. 2014); *Materials Today* (2017)

Flexible (Hybrid) RF Radio Devices and Receivers

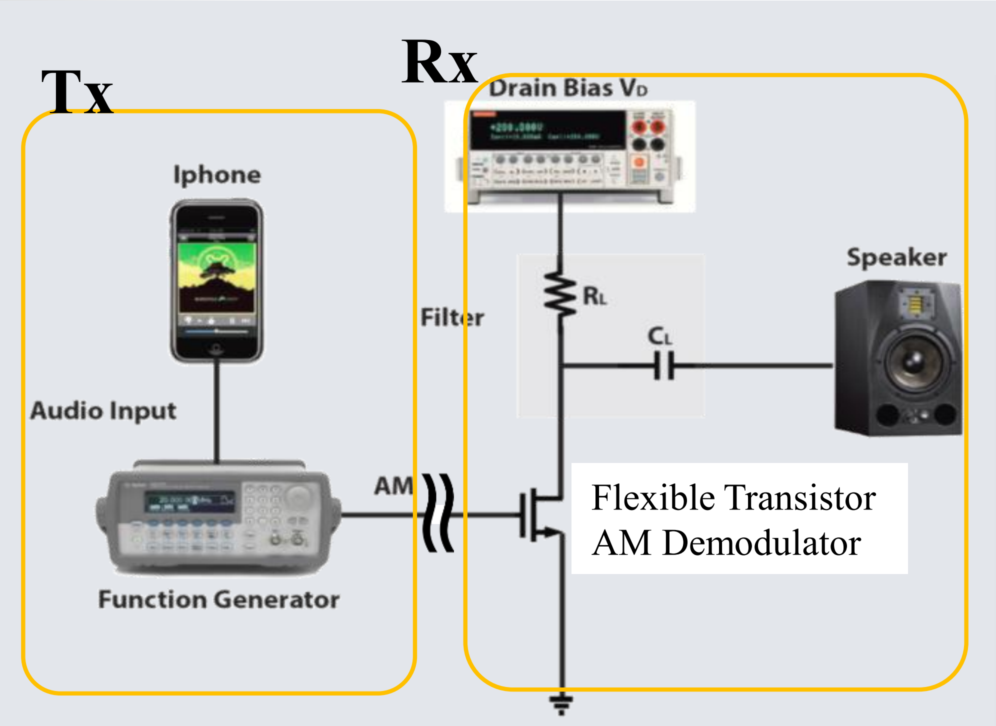
Amplifier

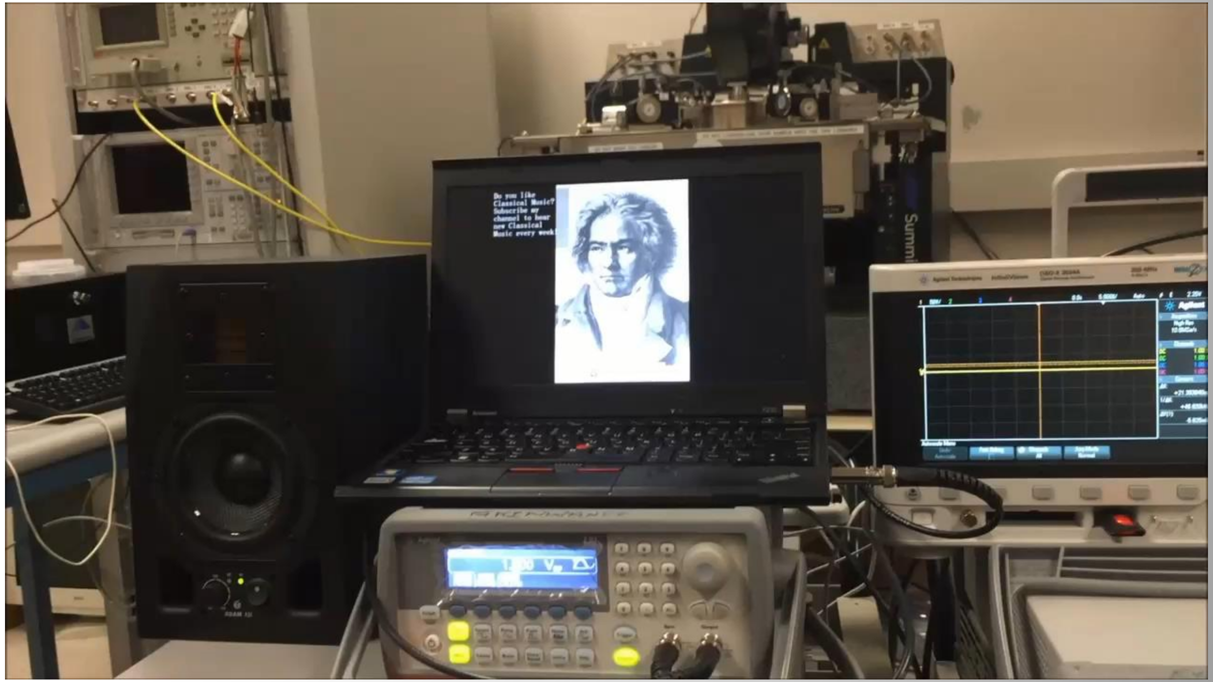
Demodulator



Flexible (Hybrid) RF Radio Devices and Receivers

Wireless Radio Receiver





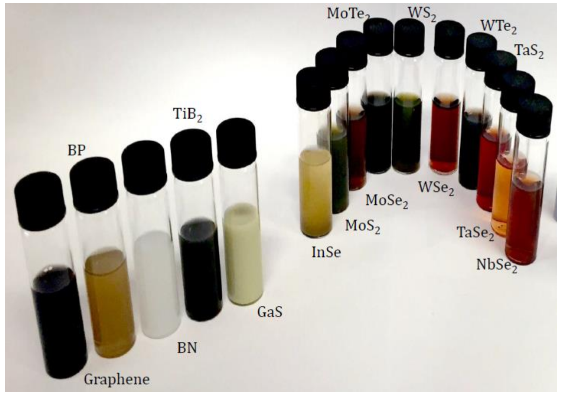
Wireless

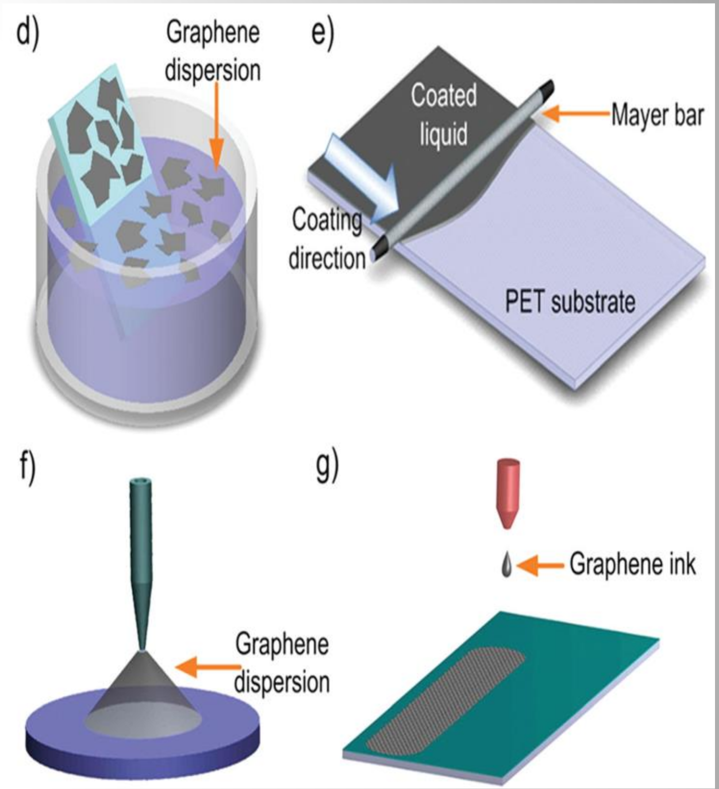
2D Inks For Printed Electronics and 3D Printing

Scale up (Gallons) of 2D Functional Inks

(semiconductors, metals, insulators, sensors, etc)

Groups
- Casiraghi (Manchester)
-Hersam (Northwestern)
- Coleman (Trinity)
- Estrada (Boise)
- Ferrari (Cambridge)
- etc

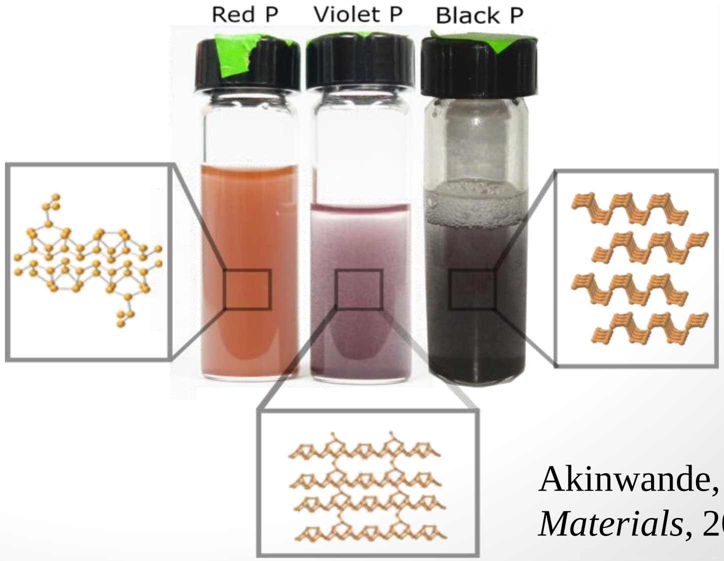




Ferrari et al, *Nanoscale*, 2015

Phosphorus Inks

Groups
-Coleman (Trinity)
-Hersam (Northwestern)
-O'Brien (Manchester)
-Warren (UNC)
- etc



Akinwande, *2D Materials*, 2016

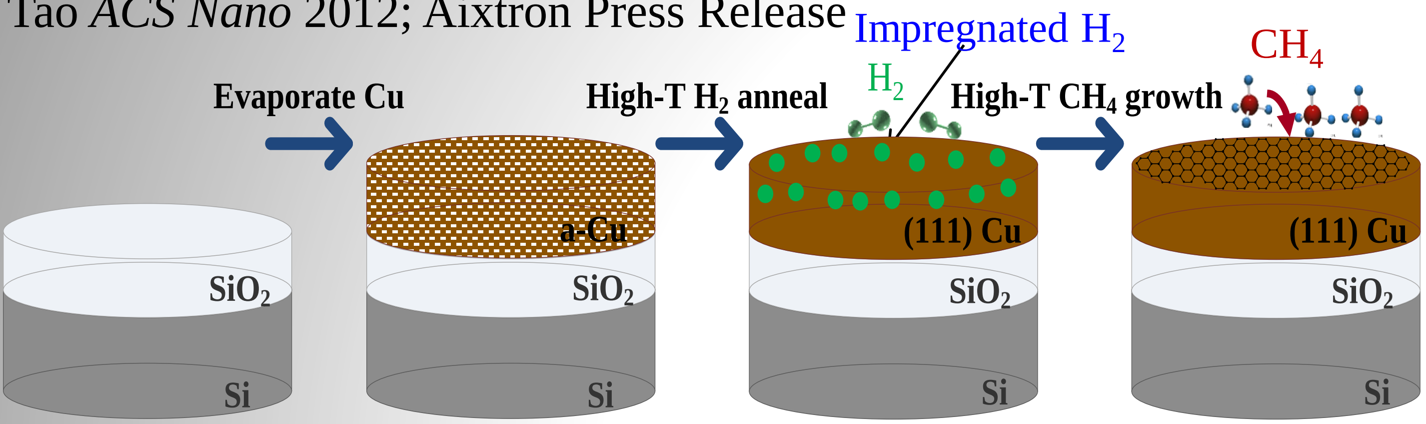
Great Expectations

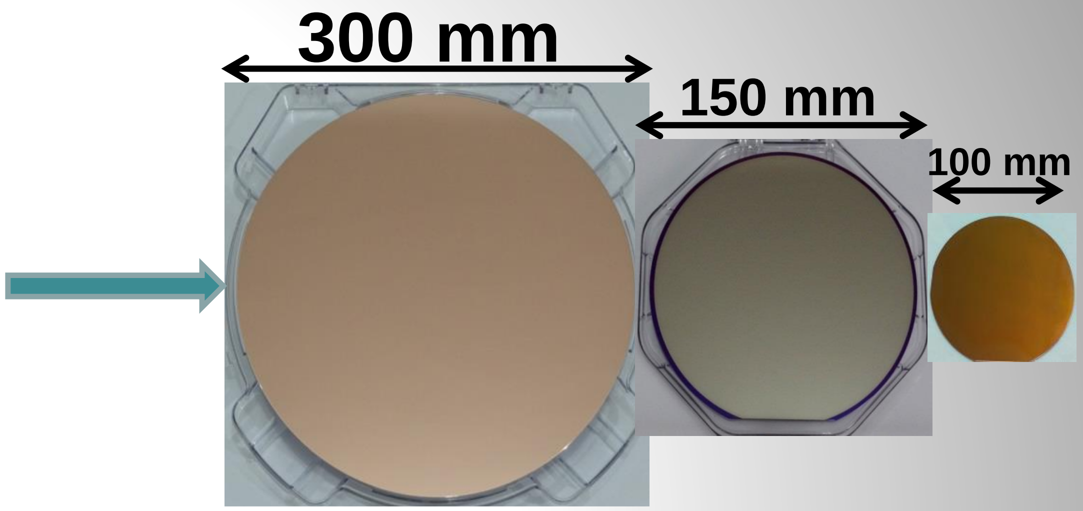
Convert Science to Technology (S&T)

2D materials are the new silicon

S&T Example1:Graphene Growth&Commercialization w/Aixtron

Rahimi et al., *ACS Nano*, 2014, *DRC* 2014
Tao *ACS Nano* 2012; Aixtron Press Release

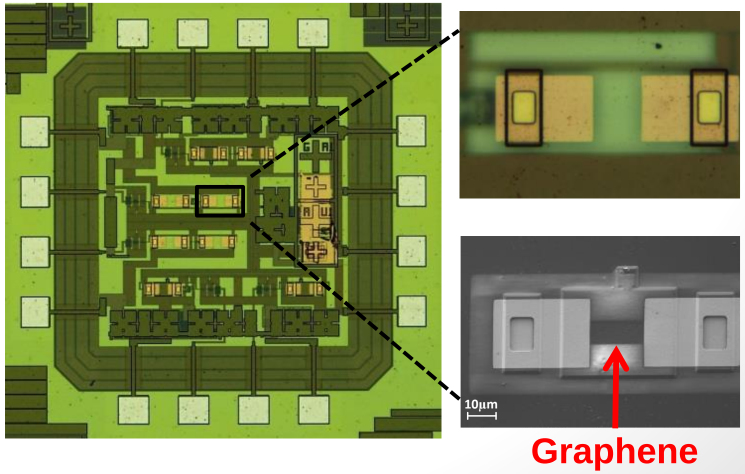




Control of microstructure: grain, phase, roughness, interface

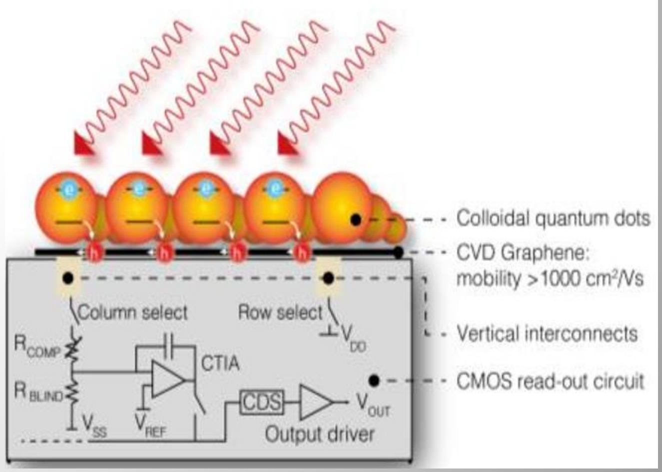
100-300 mm Aixtron Tool

G-CMOS Integrated Sensor Chip (UT-Austin)



nature 2D materials, 2017

G-CMOS Camera (F. Koppens, ICFO)

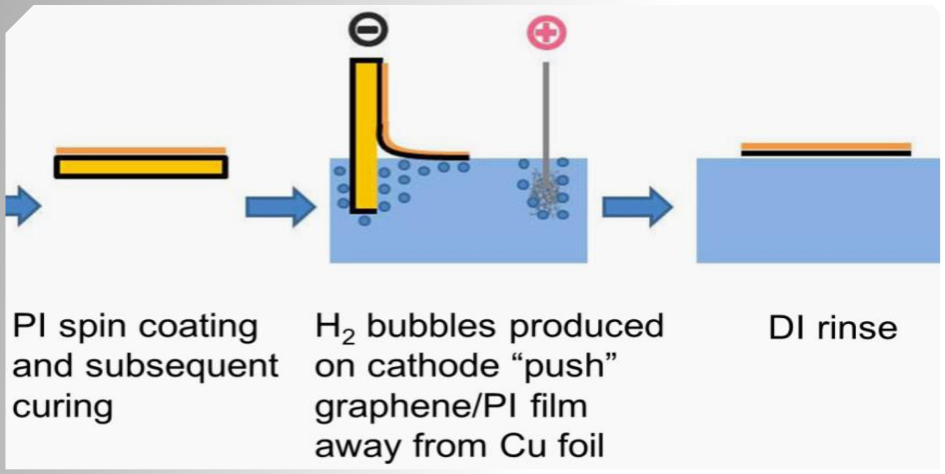


nature photonics, 2017

S&T Example 2: Graphene Transfer & Commercialization

Gen 2 Method: X. Wang, et al. *Small*, 2014.

Electrochemical delamination



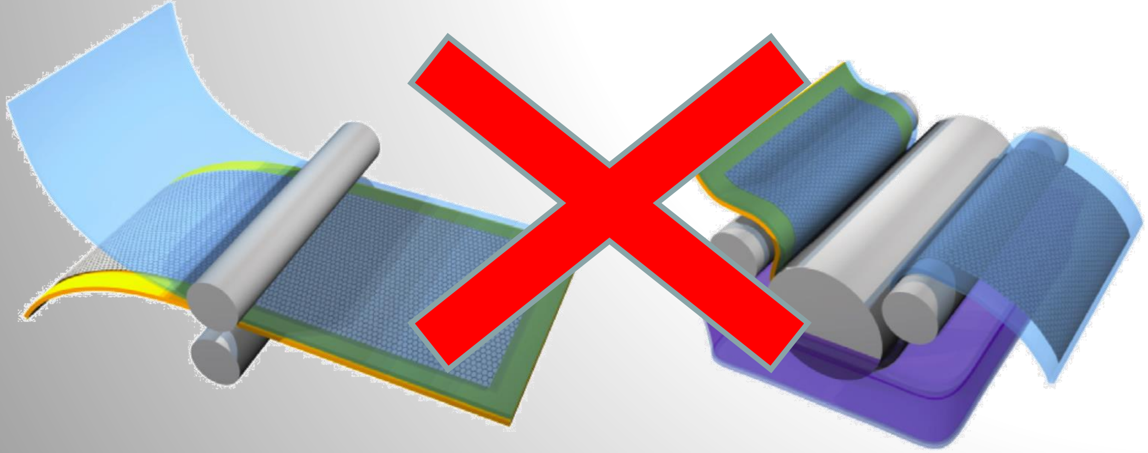
With R. Ruoff & Q. Yu

Graphene Smartphone by '2D Carbon'; *>50K units sold*

Akinwande, et al.
IEEE Nano Magazine, 2015.

'Moxi/Galapad'
~30K sold

Gen 1 Method Bae, et al. *Nat Nano*, 2010. (SKKU Group)



New Emerging Science & Applications

i. Wearable Sensors and Human Interfaces

ii. 2D Memory Effect & Atomic Tunneling

iii. Some Recent Directions

Conventional Epidermal vs Wearable Tattoo Sensors

Conventional

- Bulky
- Size ~mm
- Non portable
- Non stretchable

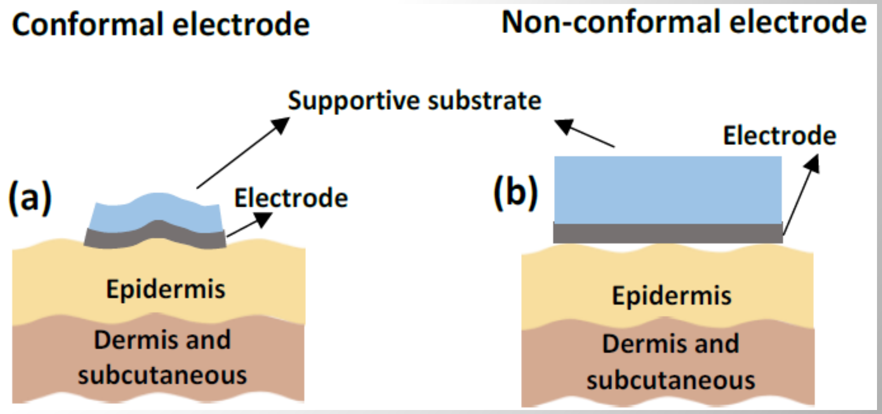
Metal Tattoo

- Light
- Size ~um
- Portable/wearable
- Stretchable

Graphene 'tattoo' sensor

IEDM 2016

- Ultra Light
- Transparent & Imperceptible
- +all metal tattoo benefits



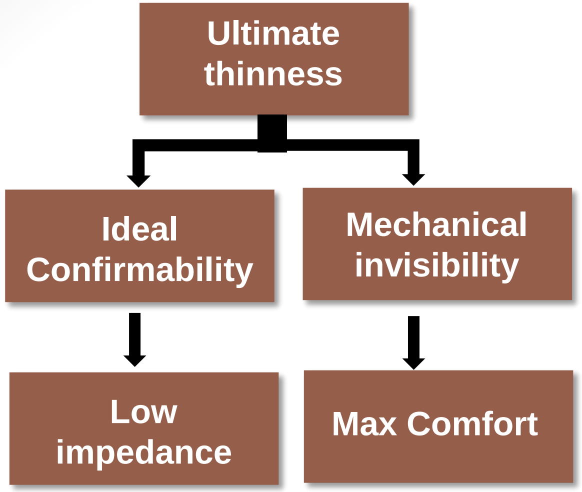
Thinner (electrode) is better

Applications of Tattoo Sensors

→Wearable Multi-functional G. Tattoo Sensors

with Nanshu Lu

Kabiri et al, ACS Nano 17
IEEE Spectrum
BBC News
+ a dozen news media



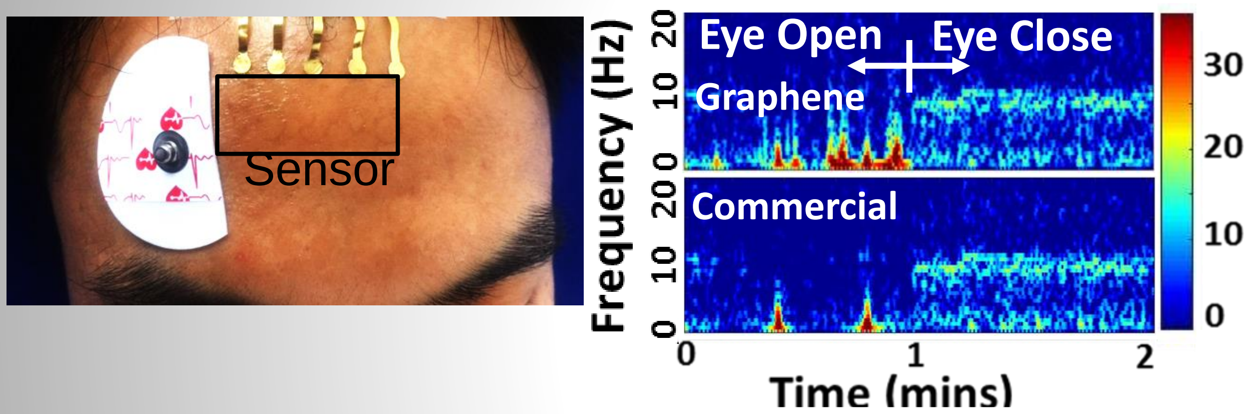
Integration

Flexibility

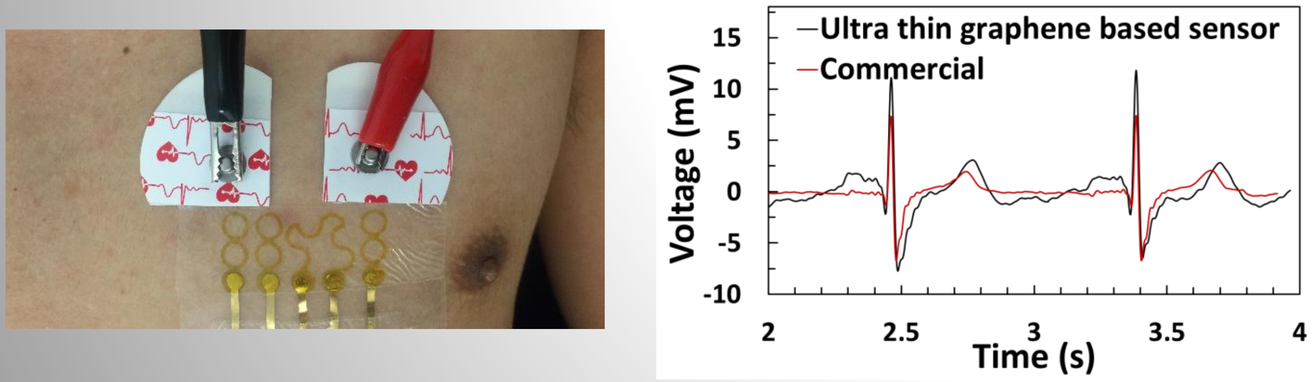
→Graphene E-tattoo Physiological Recordings:

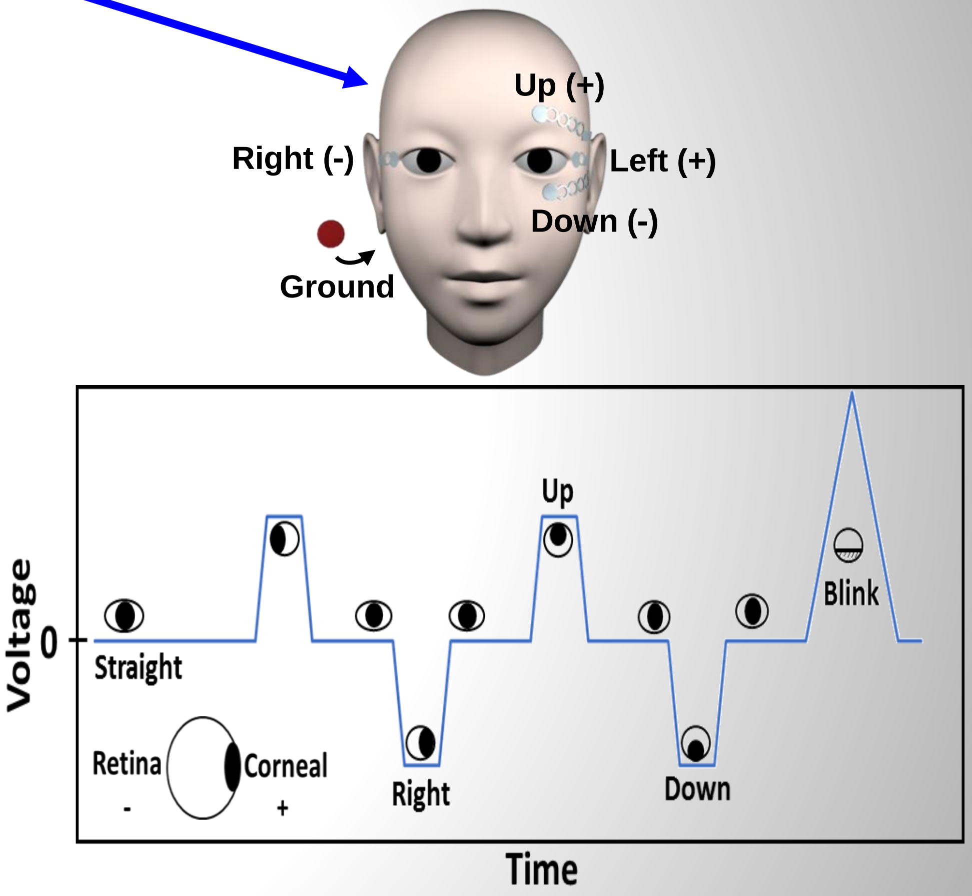
i) EEG, ii) ECG, iii) EMG, iv) EOG, v) Temperature, vi) Hydration

EEG



ECG





What Next for R&D?

- Full wireless capability with NFC or optical comms
- Integration of 2D semiconductors for in-sensor amplification/processing
- Machine learning for in-sensor decision (e.g. health, distraction, etc)
- Applications?
  - Human-machine interfaces
  - 'wear and forget' sensors,
  - Remote monitoring
  - Electromagnetic interference/security

New Emerging Applications

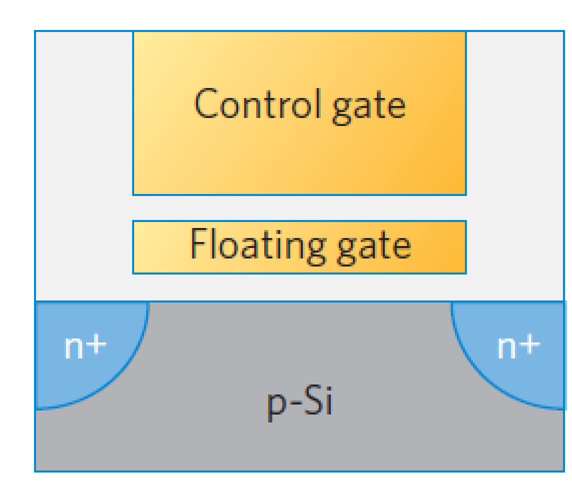
i. Wearable Sensors and Human Interfaces

ii. 2D Memory Effect & Atomic Tunneling

iii. Some Recent Directions

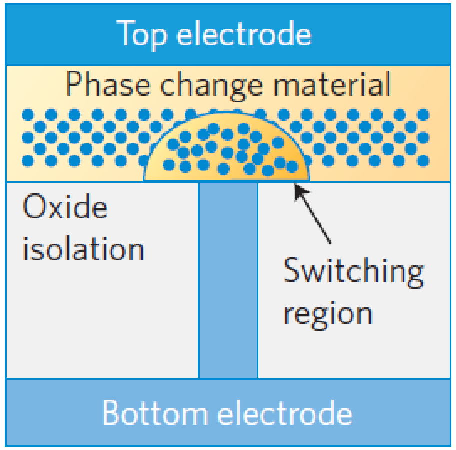
Conventional Non-Volatile Switching (Memory) Devices

Flash: electronic

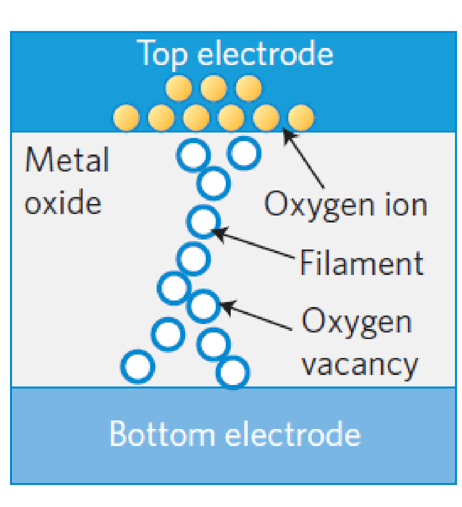


Phase change (PCM): thermal

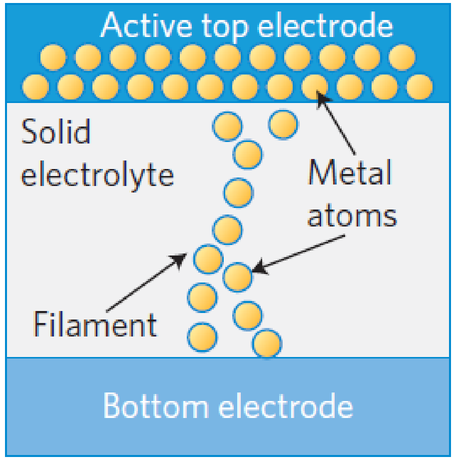
f



Resistance change (RRAM): ionic



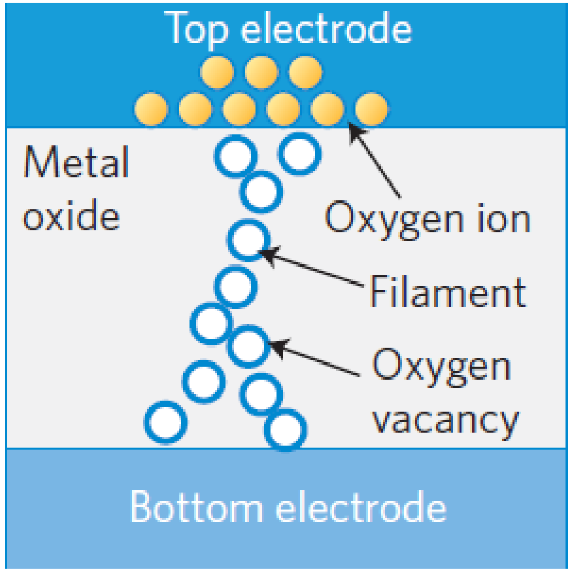
h

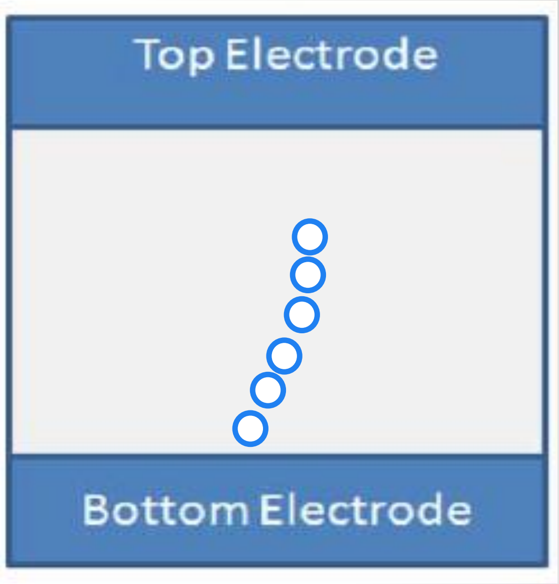


H. S. P. Wong and S. Salahuddin, "Memory leads the way to better computing," Nature Nano, 2015.

Basic Physics of Non-volatile Switching in Metal Oxides

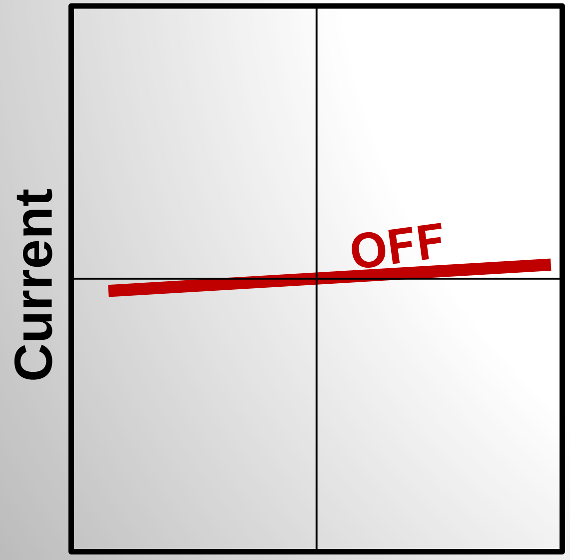
'Fresh' Oxide | **'ON' State (LRS)** | **'OFF' State (HRS)**

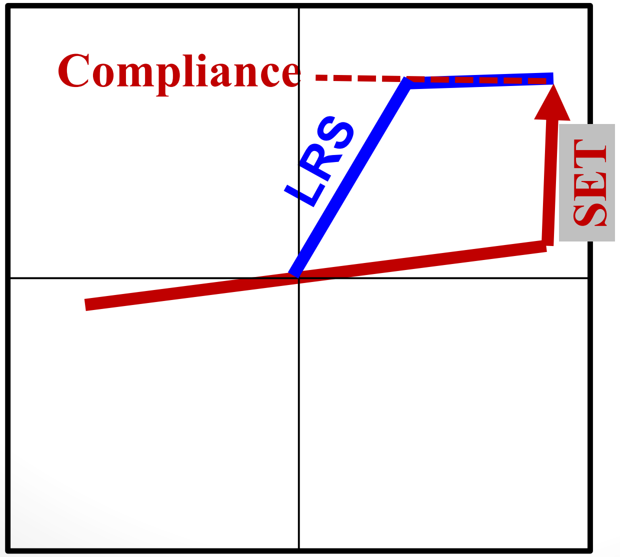


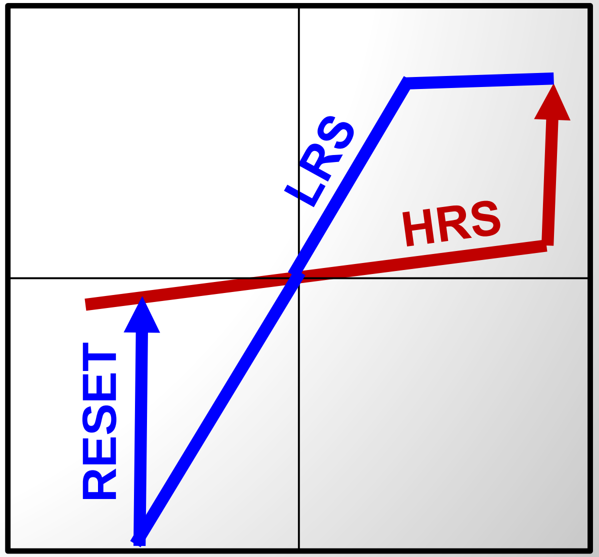


Application of Defects

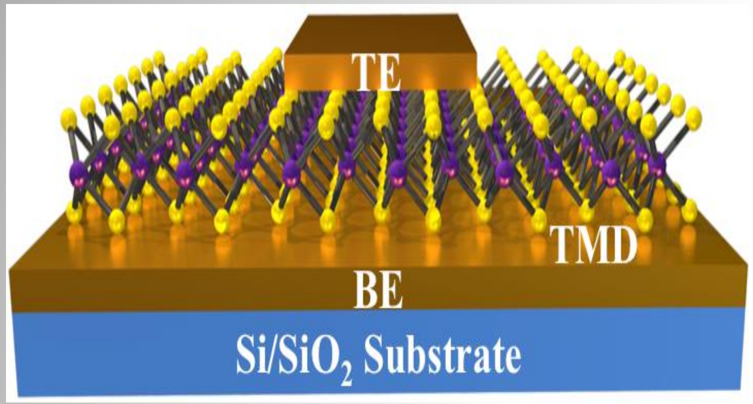
Typical I-V curves







Are Atomic Monolayer Non-Volatile Switches Possible?



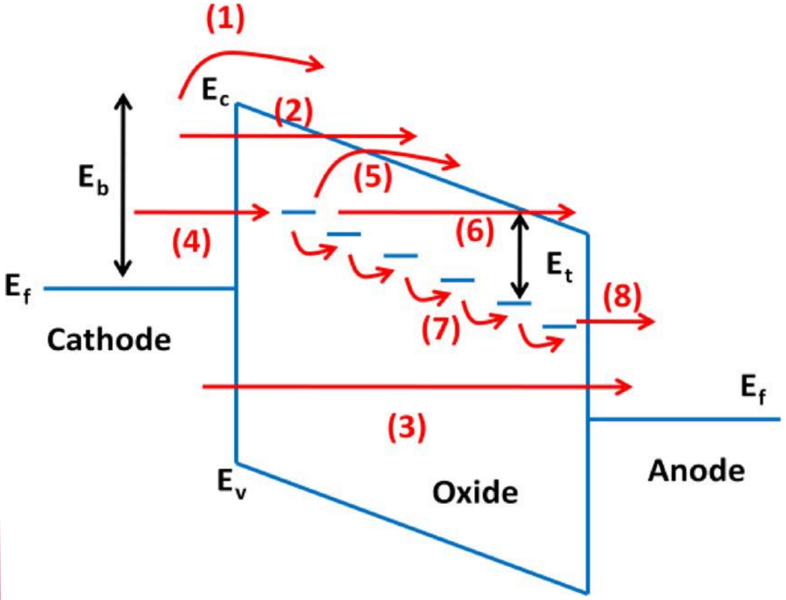
Concerns

i-Not TMO

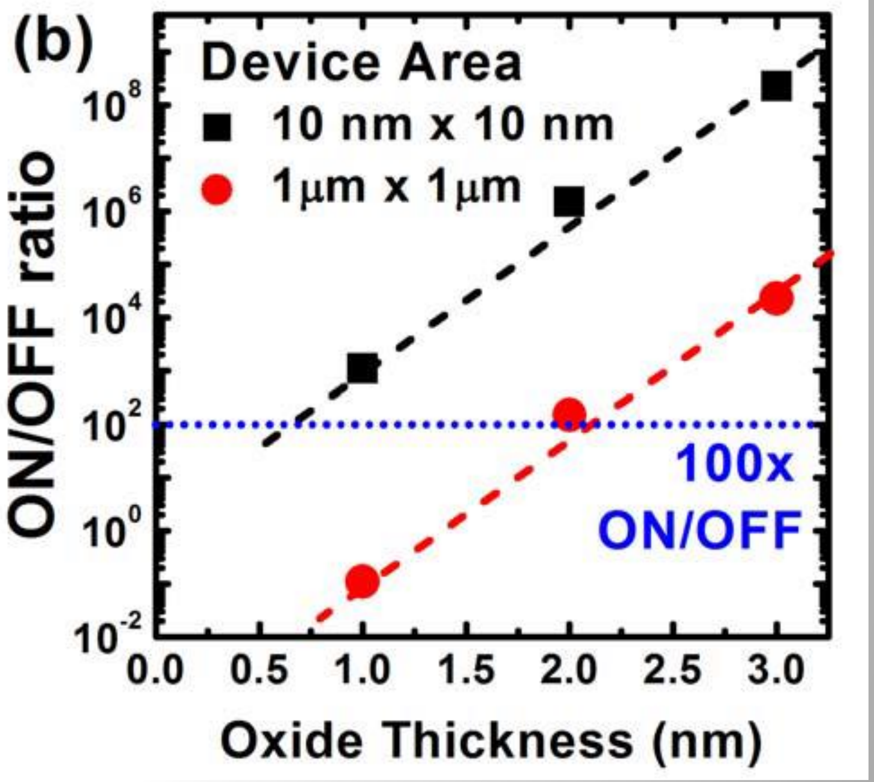
ii-TMD Thickness <1nm

Ultrathin (~2nm) HfO_x as the Fundamental Resistive Switching Element: Thickness Scaling Limit, Stack Engineering and 3D Integration

Liang Zhao*, Zizhen Jiang, Hong-Yu Chen, Joon Sohn, Kye Okabe, Blanka Magyari-Köpe, H.-S. Philip Wong, Yoshio Nishi
Department of Electrical Engineering, Stanford University, Stanford, CA 94305-4070, USA; *Email: lzhao10@stanford.edu

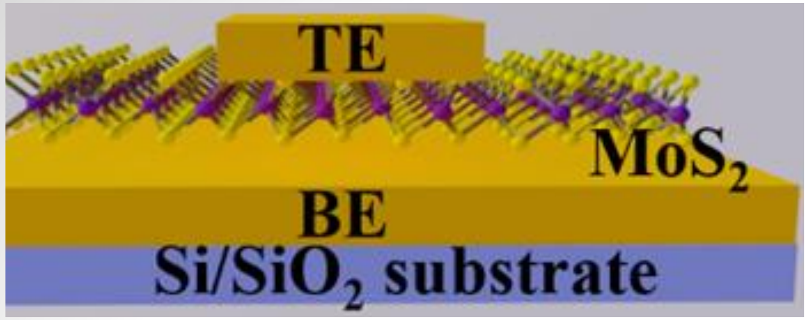


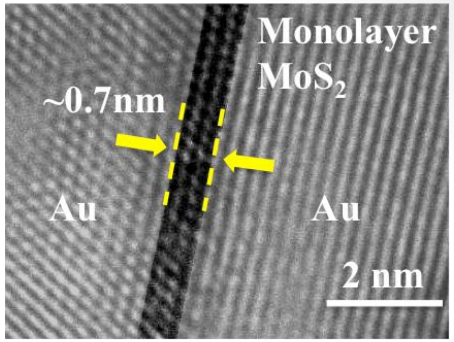
Yu et al., *APL,* 2011.



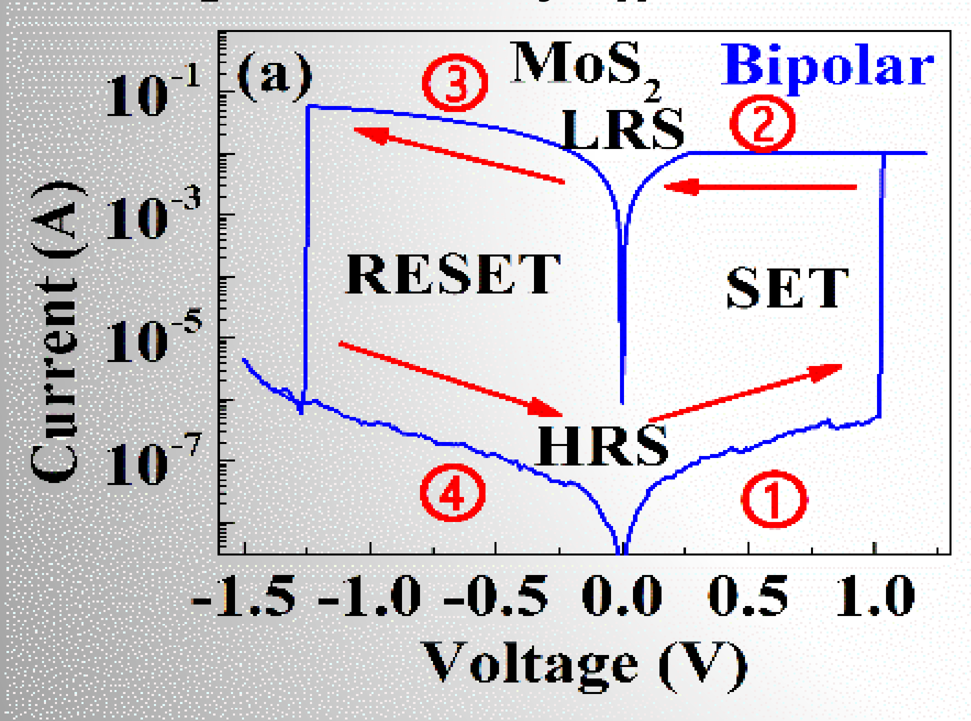
Zhao, ..Wong, Nishi, *IEDM,* 2014.

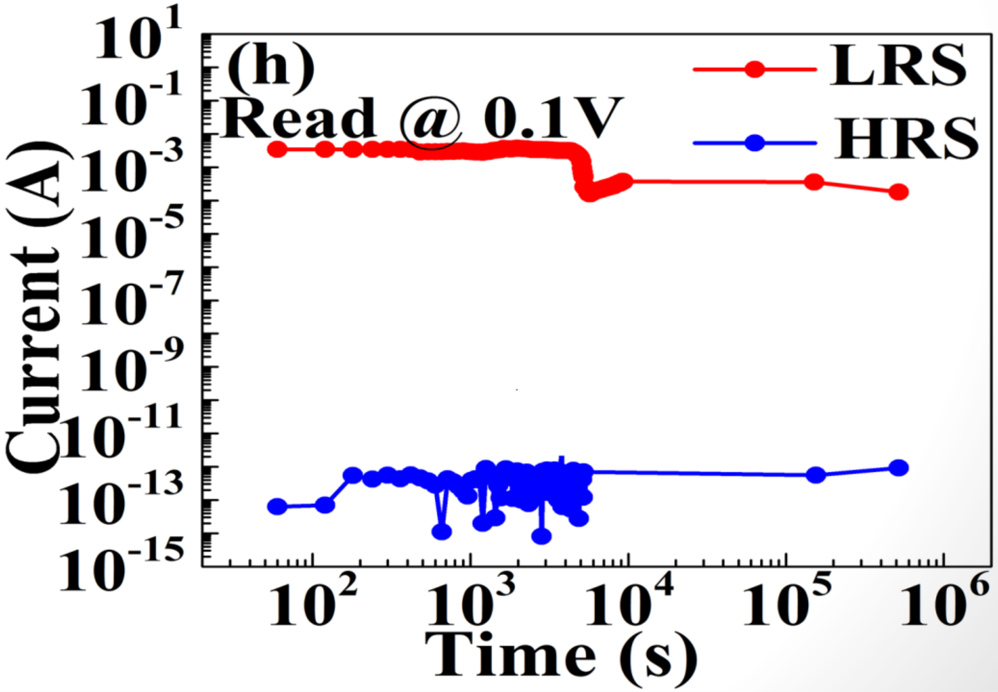
YES: Atomic-Scale Monolayer Switches Are Possible





- Bipolar memory effect



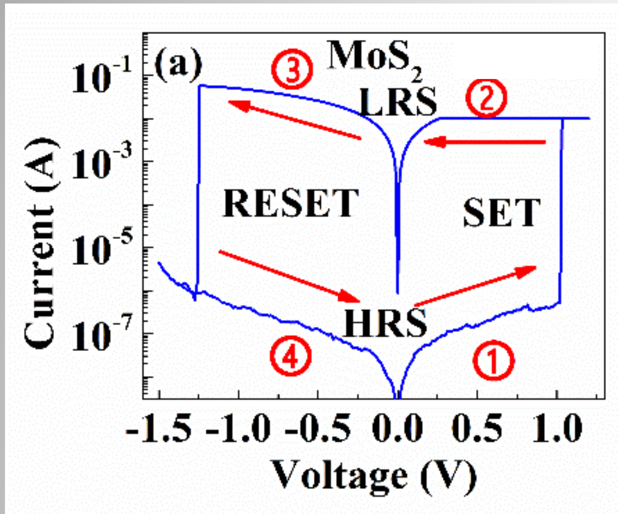


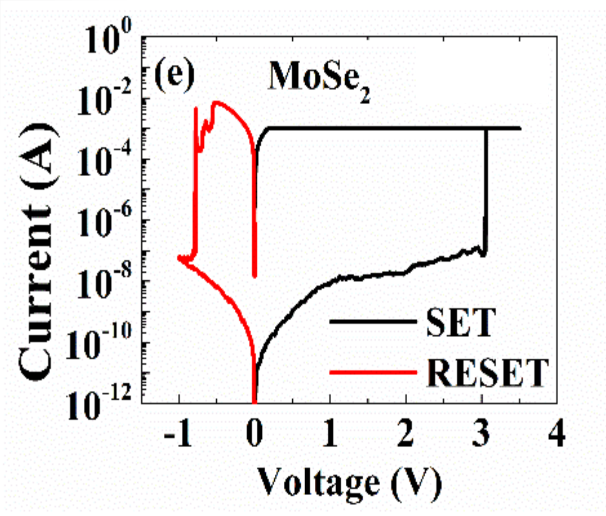
Observable in

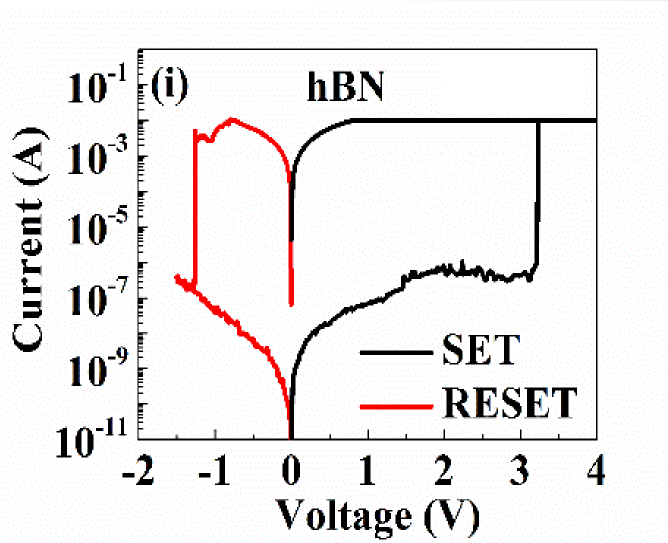
- -CVD MoS2
- -MOCVD MoS2
- -MoOx precursor
- -MoCl3 precursor (L.C)
- -CVD on SiO2
- -CVD on Au
- -1-4 layers (L.C)

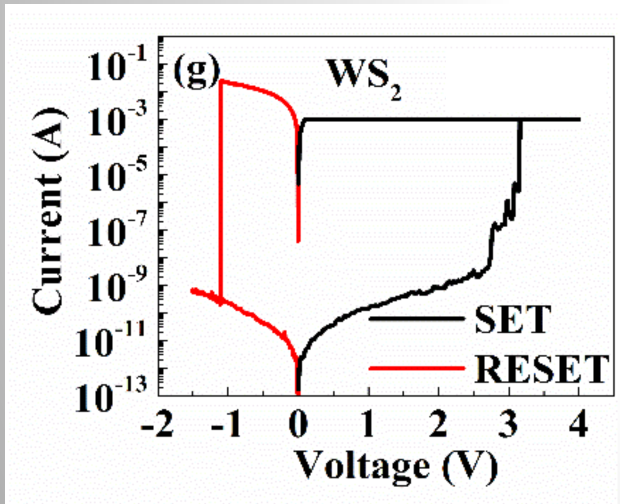
Nanoletters, 2018 (Editors Choice); IEEE Spectrum, nature nano news, etc

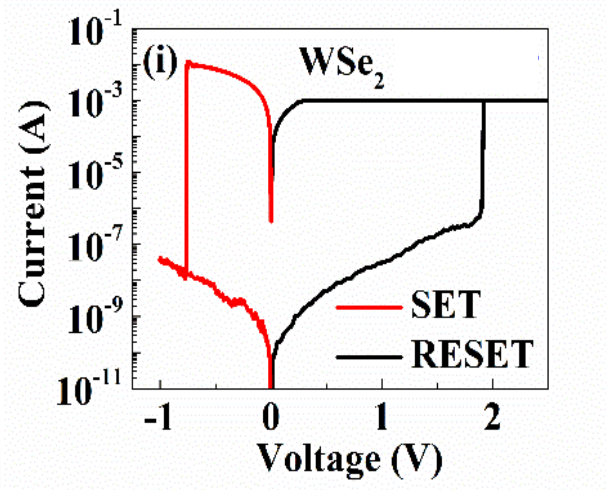
Atomristors: Universal Behavior in TMDs & hBN











The Fundamental Question

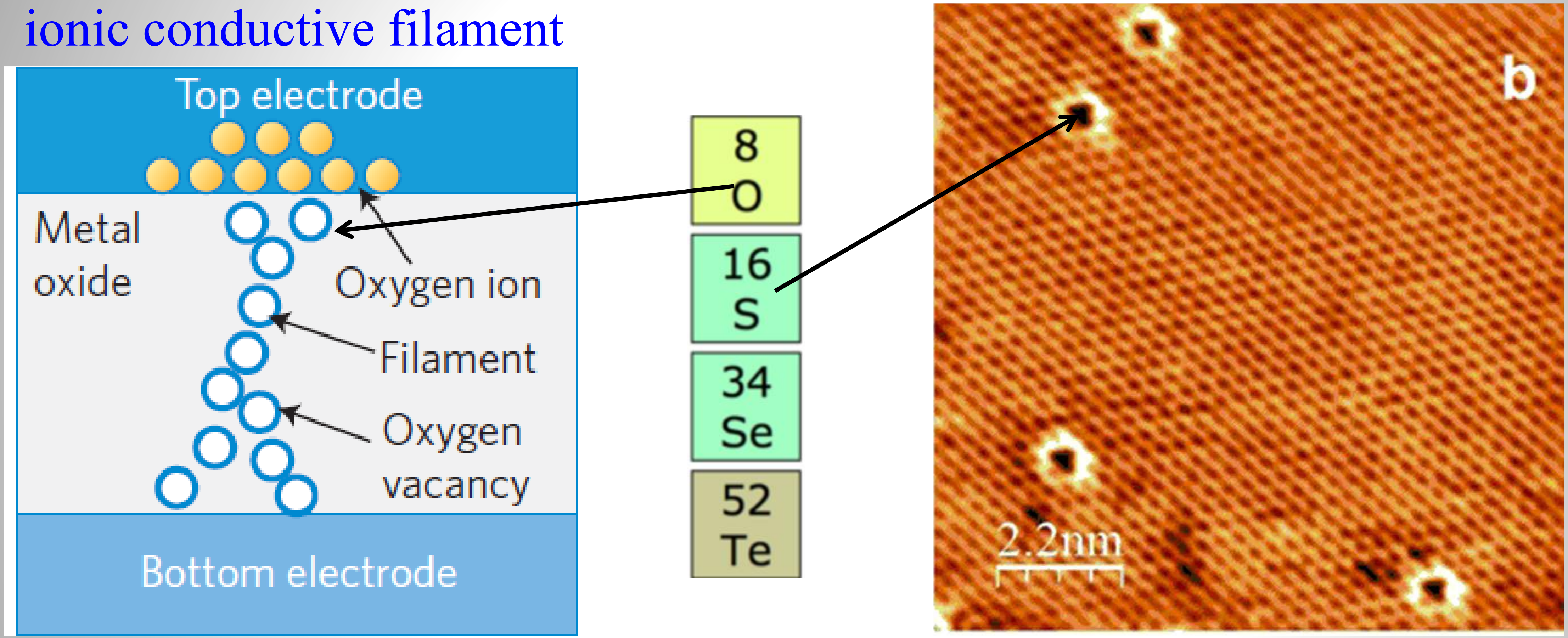
-is this resistive switching present in the hundreds or thousands of 2D non-metallic monolayers?

Nanoletters, 2018 (Editors Choice); IEEE Spectrum, nature nano news, etc

(Mechanism) Sulfur Vacancies forming Ionic Path?

TMO; O vacancies form ionic conductive filament

TMD; S vacancies~10^{12}-10^{13}/cm^2

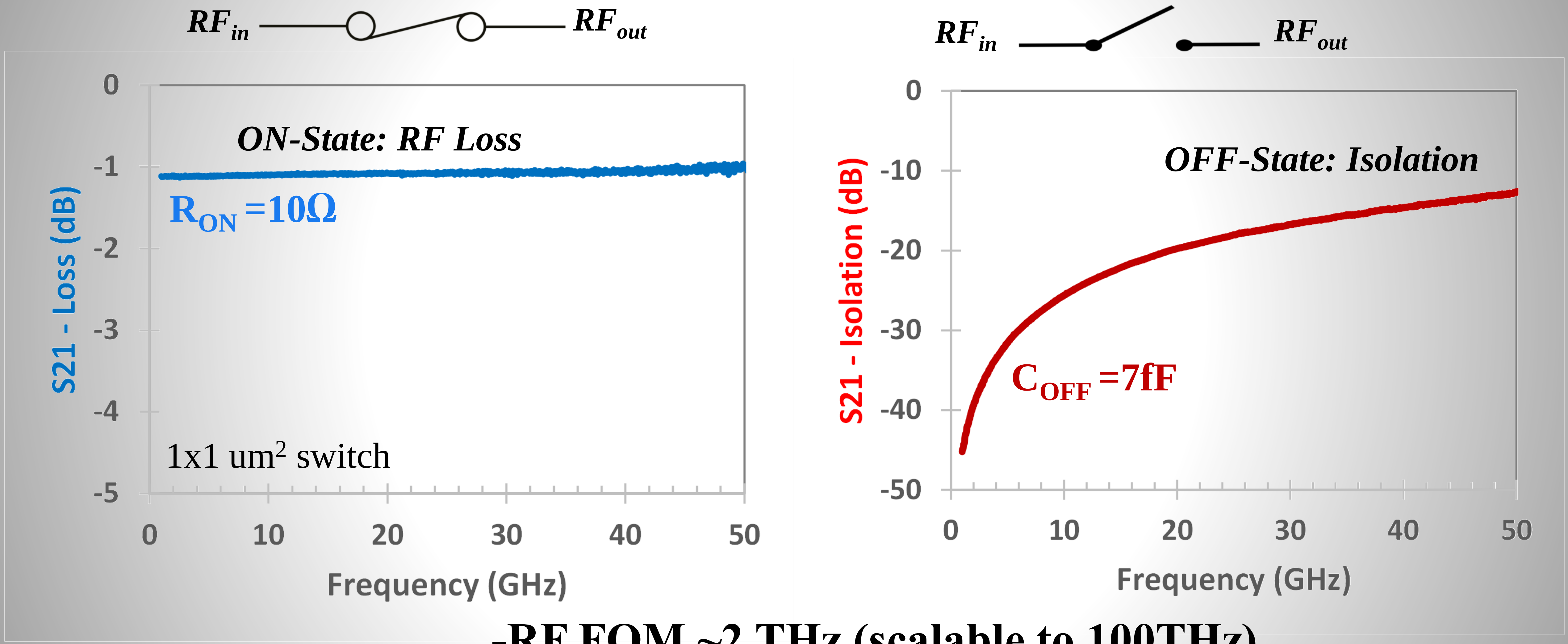


Cluster (triangular, circular) and defects (useful application of defects)

Tapasztó group (Hungary), *Scientific reports*, 2016.

New Application: Non-volatile (zero-power) RF Switches

S-Parameter RF measurements in ON and OFF states



-RF FOM ~2 THz (scalable to 100THz)

in-review, nature communications, 2018

Basic Research Questions:

a) Fundamental mechanisms?

b) Theoretical computation?

c) Role and energetics of defects, e.g sulfur/oxygen?

Schottky tunneling results suggest temperature-dependent refractive index

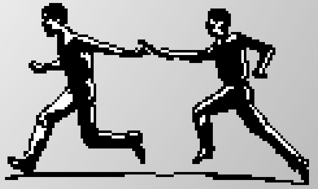
d) Advanced experimental techniques (working with Oak Ridge)

4-probe STM STEM for individual defect imaging and in-situ transport

HRTEM for cross-sectional monolayer/interface imaging?

e) Fundamental switching energy?

-Seeking collaborators on these topics



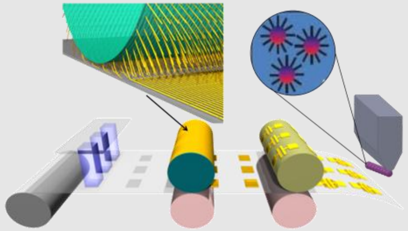
New Emerging Applications

i. Wearable Sensors and Human Interfaces

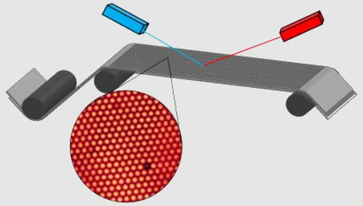
ii. 2D Memory Effect & Atomic Tunneling

iii. Some Recent Directions

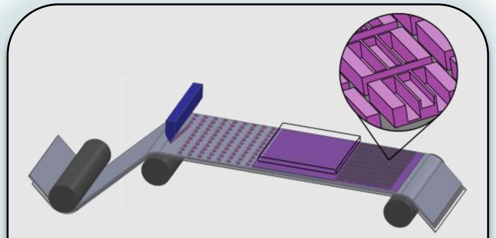
$50M NSF NASCENT ERC Center at UT-Austin (5+yr old):
A R2R Nanomanufacturing Facility For Flexible Nanoelectronics



Nanomaterials Dep

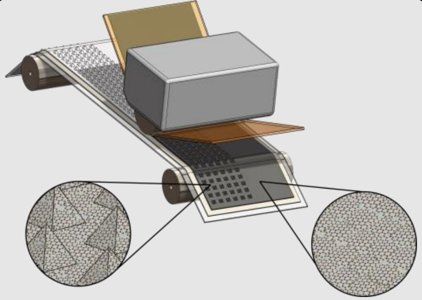


High Speed Process & Functional Metrology



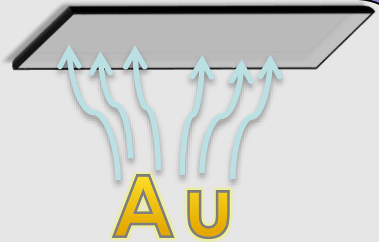
Nanoshape Imprint

NEXTFLEX
America's Flexible Hybrid Electronics Manufacturing Institute

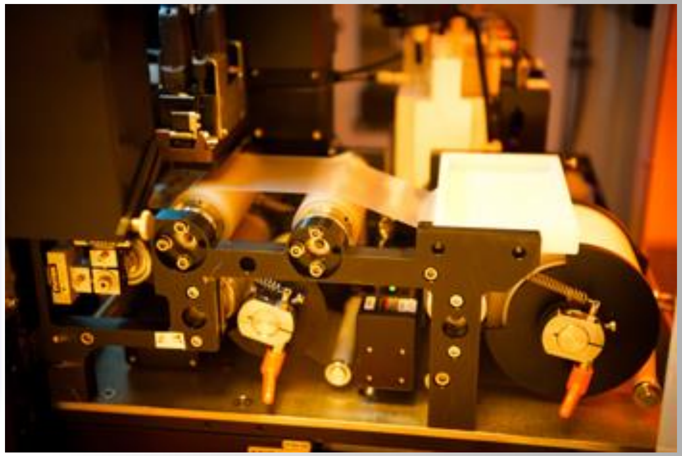


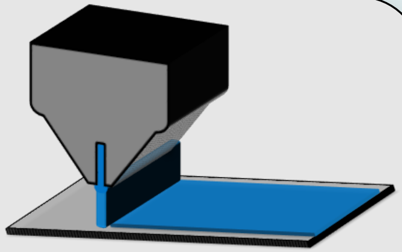
Graphene Transfer

Exemplar Mobile Devices to Validate R2R Manufacturing Capability: THz Graphene Transceivers, Display Polarizers, Plasmonic OLED Cameras , Etc.

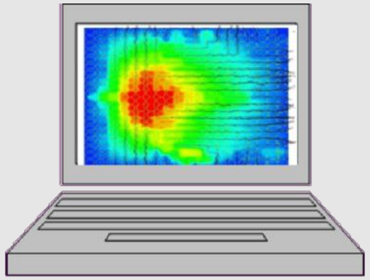


Metal/Dielectric Deposition

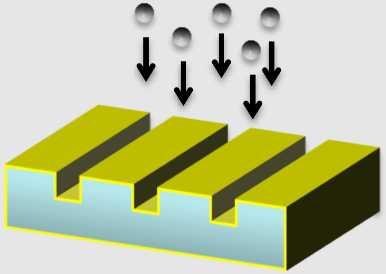




NanoScale Encapsulation



Multiscale Modeling



Plasma/Wet Etch

NASCENT In-House Technologies

Support Technologies

2D Topological Insulators: Completely New Frontier

Light-driven 2D Topological Insulators – (new NSF MRSEC)

Group 4B

C	6
Si	14
Ge	32
Sn	50
Pb	82

Strong SOC

nature materials

PERSPECTIVE

PUBLISHED ONLINE: 16 JANUARY 2017 | DOI: 10.1038/NMAT4802

Buckled two-dimensional Xene sheets

Alessandro Molle[1]*, Joshua Goldberger[2], Michel Houssa[3], Yong Xu[4,5,6], Shou-Cheng Zhang[7,8,9] and Deji Akinwande[10]*

Silicene, germanene and stanene are part of a monoelemental class of two-dimensional (2D) crystals termed 2D-Xenes (X = Si, Ge, Sn and so on) which, together with their ligand-functionalized derivatives referred to as Xanes, are comprised

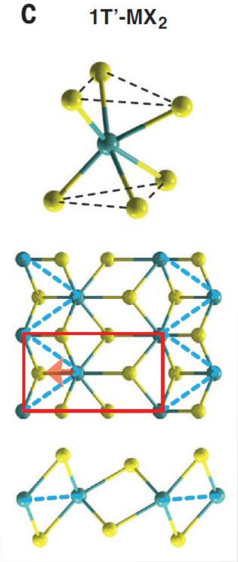
1T’ TMDs

SOLID STATE THEORY

Quantum spin Hall effect in two-dimensional transition metal dichalcogenides

Xiaofeng Qian,[1]* Junwei Liu,[2]* Liang Fu,[2]† Ju Li[1]†

Quantum spin Hall (QSH) effect materials feature edge states that are topologically protected from backscattering. However, the small band gap in materials that have been identified as QSH insulators limits applications. We use first-principles calculations to predict a class of large-gap QSH insulators in two-dimensional transition metal dichalcogenides with 1T′ structure, namely, 1T′-MX_2 with M = (tungsten or molybdenum) and X = (tellurium, selenium, or sulfur). A structural distortion causes an intrinsic band inversion between chalcogenide-*p* and metal-*d* bands. Additionally, spin-orbit coupling opens a gap that is tunable by vertical electric field and strain. We propose a topological field effect transistor made of van der Waals heterostructures of 1T′-MX_2 and two-dimensional dielectric layers that can be rapidly switched off by electric field through a topological phase transition instead of carrier depletion.



Thank You

Collaborators welcomed