ASIAA/CCMS/IAMS/LeCosPA/NTU-Phys/NTNU-Phys Joint Colloquium

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2D Materials for Electronics: Prospects and challenges

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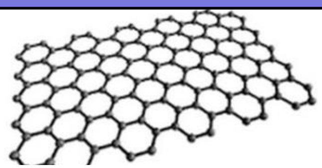
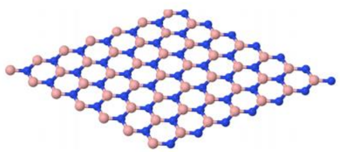
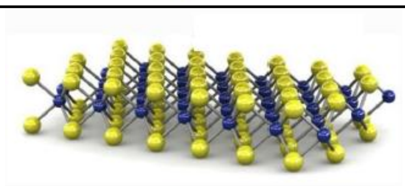
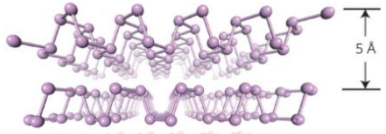
Outline

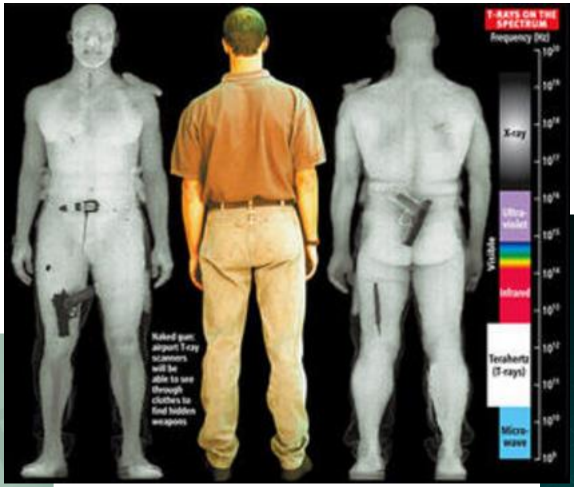
- Introduction – the role of 2D materials for future electronics
- Structure and properties – graphene, transition metal dichalcogenides, and black phosphorus
- Synthesis
- 2D Devices – transistor and tunnel FET
- Conclusion

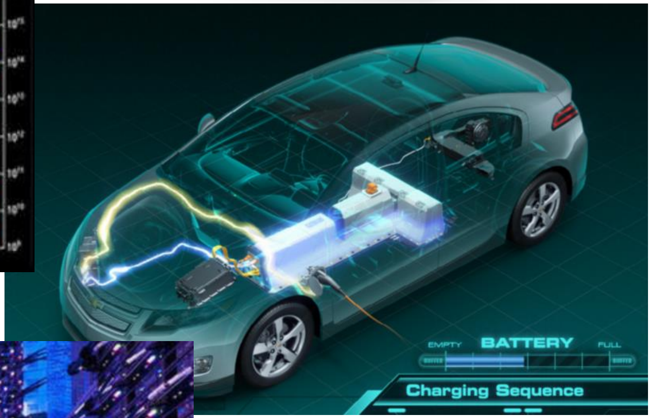
Family of 2-D Crystals

- More than 140 two-dimensional (2-D) materials, and the number is still growing
- Covering insulators, semiconductors, and metals

Material	Structure	Bandgap	Mobility (cm^2/Vs)
Graphene		0	1000-100,000
h-BN		~7.2 eV (indirect)	-
TMD (MX_2) M: W, Mo, Hf, Zr, Ti, Cr, Ta X: S, Se, Te		0.6 – 2.3 eV, and depending on layer #	10~500
Black Phosphorus (BP)		~2 eV (Monolayer) ~0.3eV (few layer)	100~1000

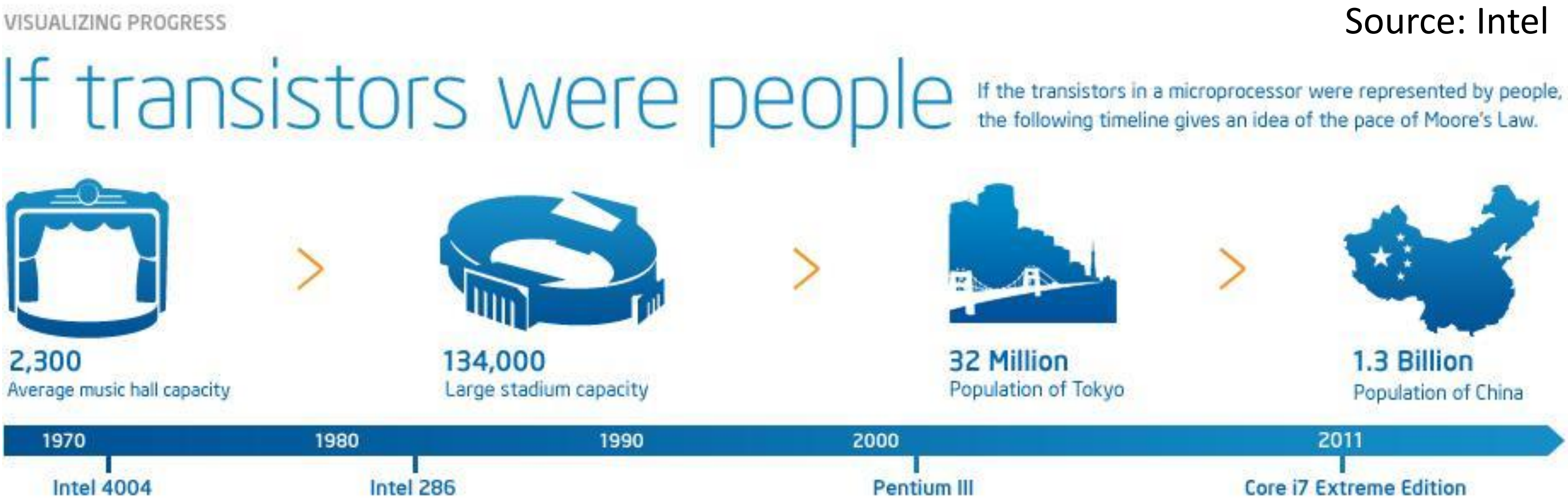
Promises of 2D Materials

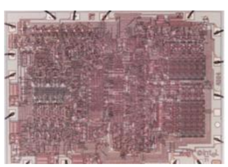




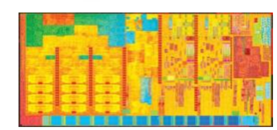
50 Years of Moore's Law

Source: Intel





2.3K Transistors
12 mm^2



1.3B Transistors
122 mm^2

Imagine fitting the entire China population in 10 original music halls –
That's the scale of Moore's Law!

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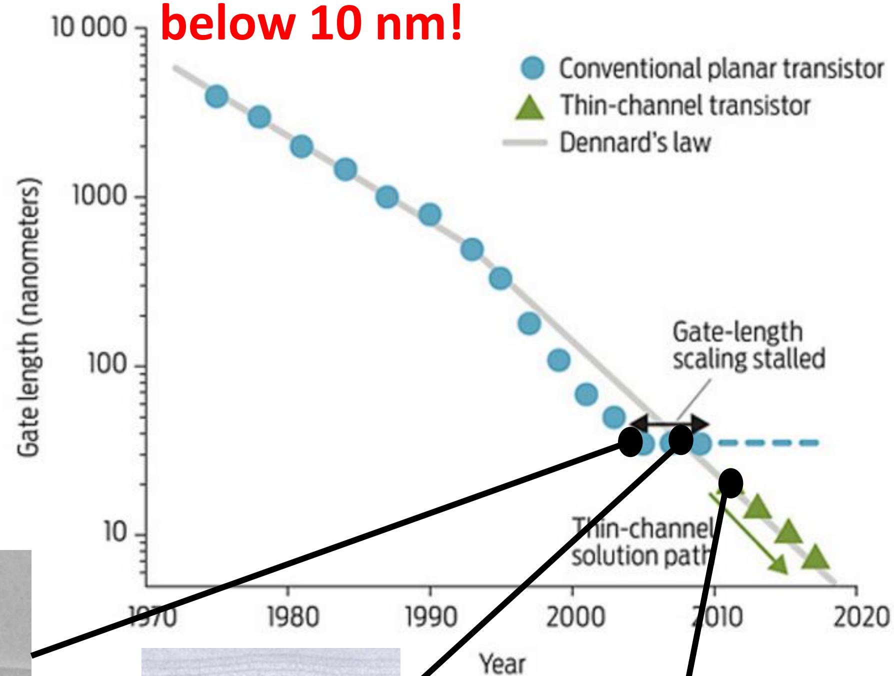
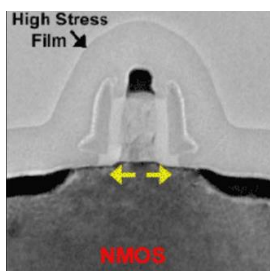
50 Years of Moore's Law: Can it be continued?

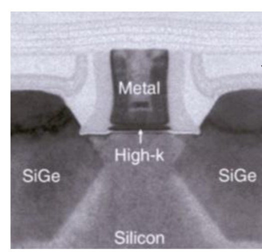
Need innovation for each generation below 10 nm!



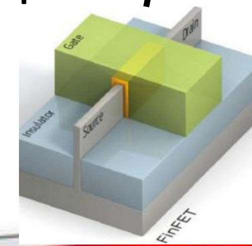
IEEE Spectrum Nov. 2011, p50



Strained Si (2003)

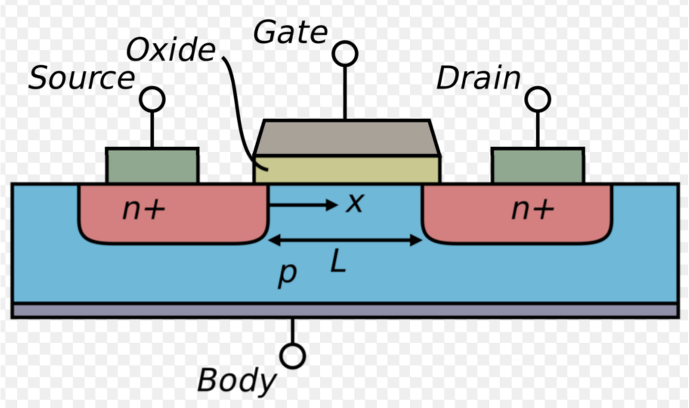


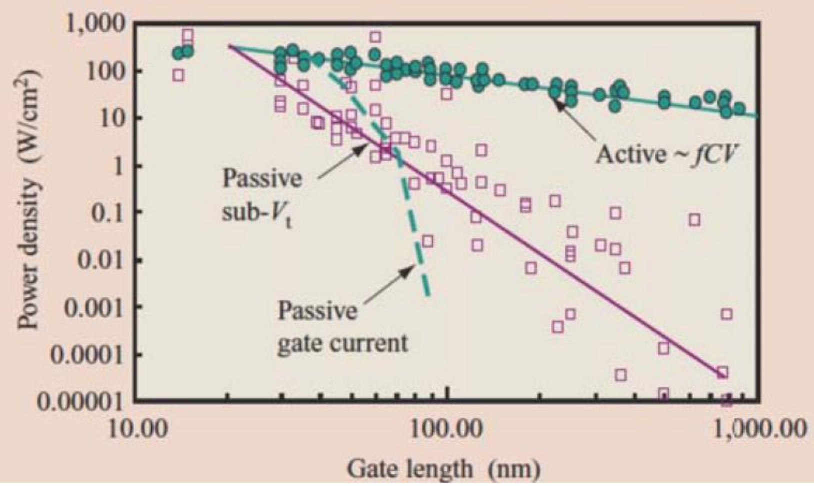
High-k Metal Gate (2008)



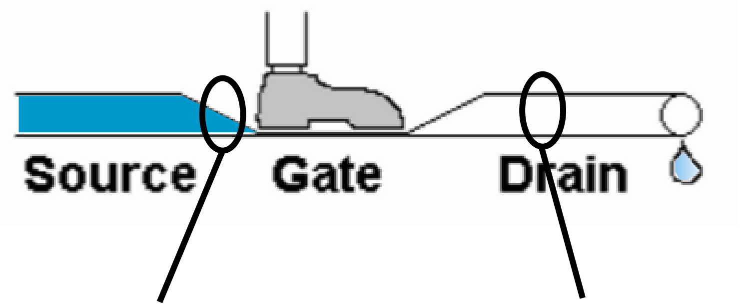
FinFET (2011)

The Major Issue is Leakage





Haensch et al., IBM J. R&D 50, pp. 339-361 (2006)

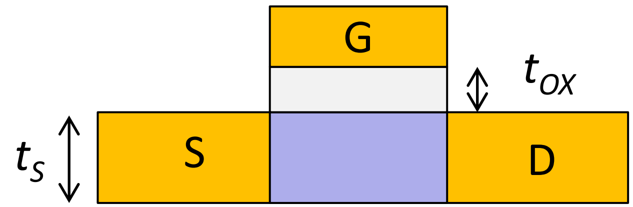


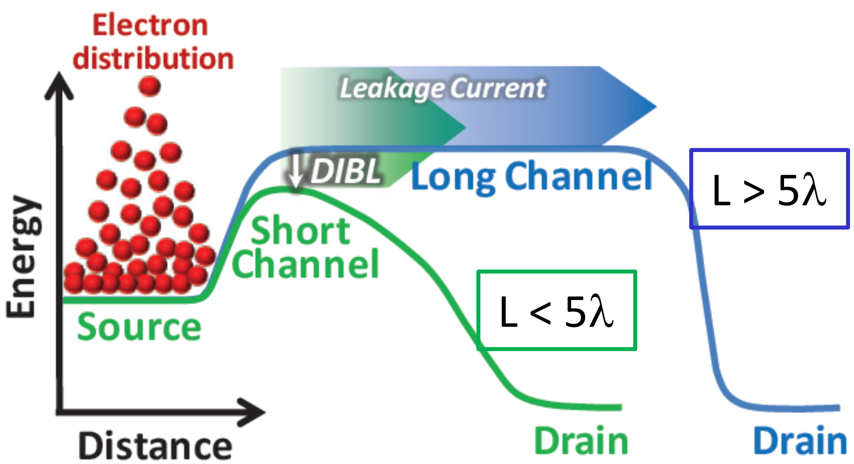
The transistor becomes more difficult to "Turn Off" as the gate dimension shrinks.

No leakage control, no scaling!

Scaling Issue for 3D Materials

- **Electrostatic length** $\lambda = \sqrt{t_S t_{OX} \varepsilon_S / \varepsilon_{OX}}$
- **L ~ 5 λ to suppress short-channel effect (SCE)**
- **Severe mobility degradation for body thickness < 5nm**





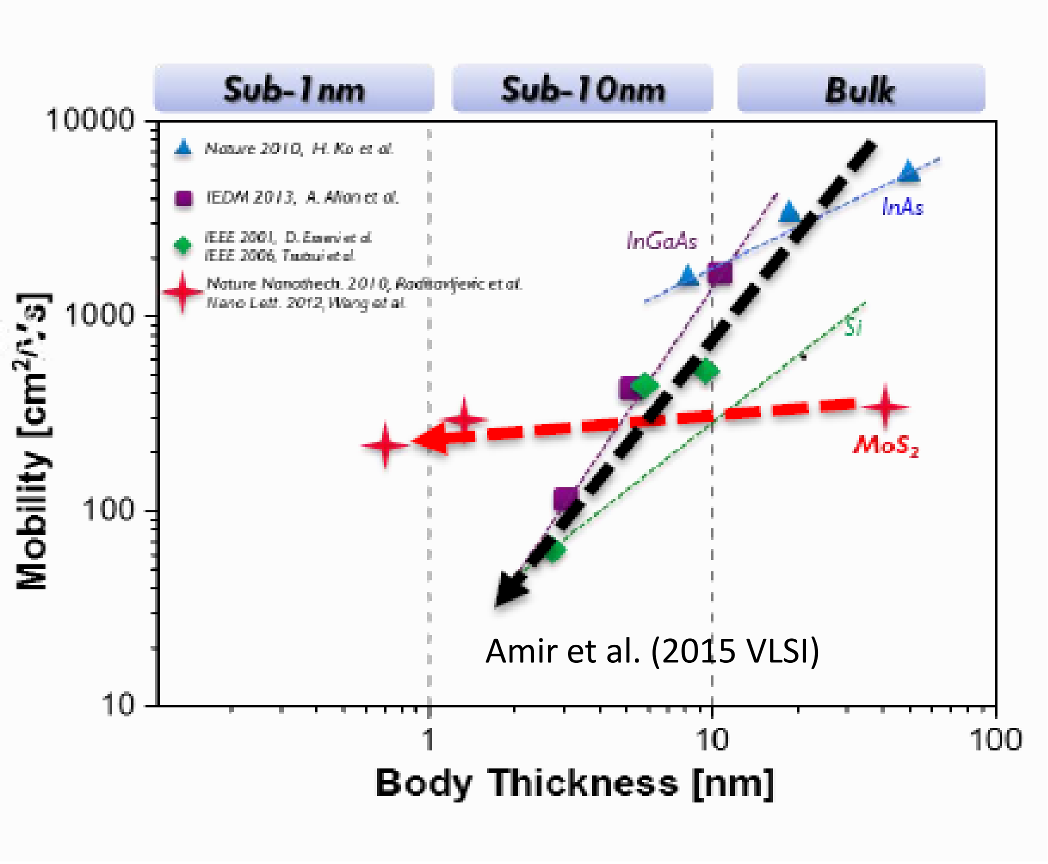
DIBL: Drain-Induced Barrier Lowering

* Double gate with EOT = 0.8 nm, L = 5nm

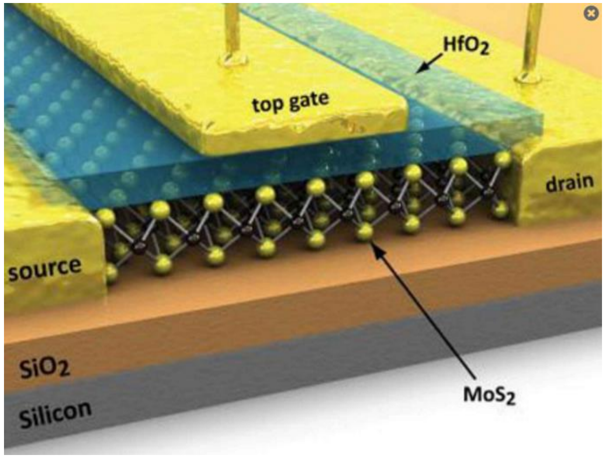
Materials	Dielectric Constant	Body Thickness (nm)
Si	11.7	0.82
Ge	16.2	0.58
GaAs	12.9	0.74

Less than 1nm!!

2D: Ultra-thin Channel with Good Mobility



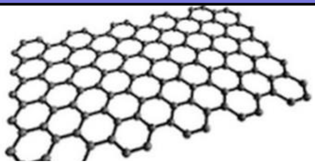
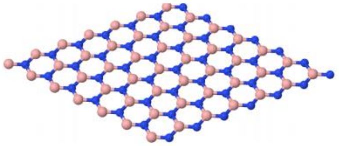
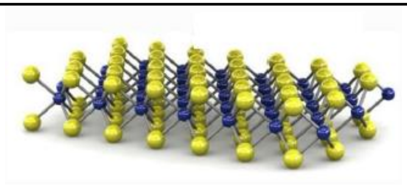
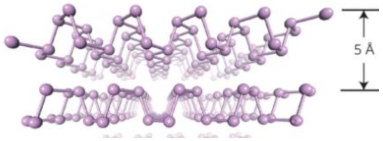
2D Channel FET



2D materials could exhibit high mobility values for sub-nm thickness!

Fundamental Properties of (selected) 2D Materials

Family of 2-D Crystals

Material	Structure	Bandgap	Mobility (cm^2/Vs)
Graphene		0	1000-100,000
h-BN		~7.2 eV (indirect)	-
TMD (MX_2) M: W, Mo, Hf, Zr, Ti, Cr, Ta X: S, Se, Te		0.6 – 2.3 eV, and depending on layer #	10~500
Black Phosphorus (BP)		~2 eV (Monolayer) ~0.3eV (few layer)	100~1000

Graphene: Lattice and Band Structure

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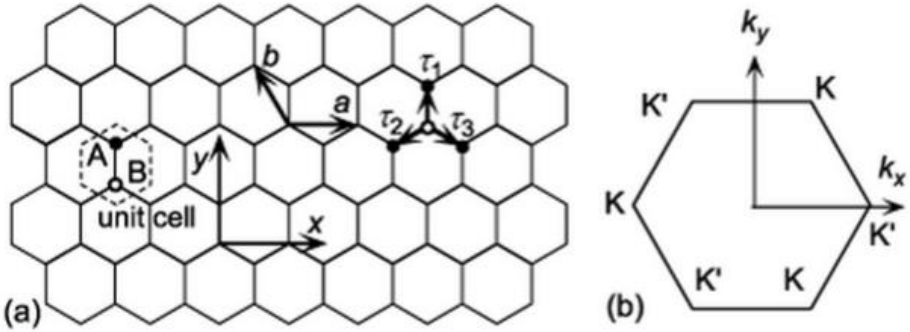
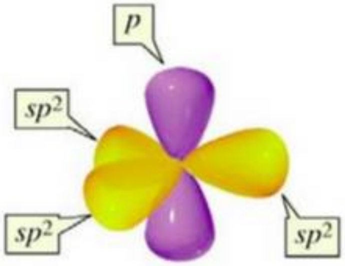
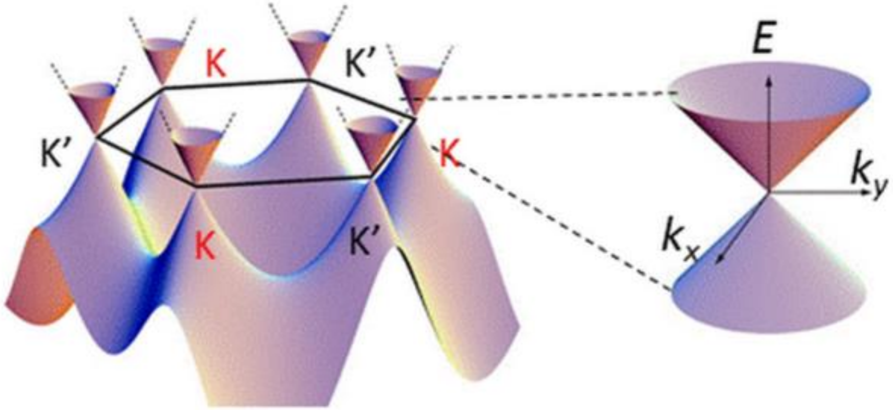
Lattice structure



In-plane sp2 covalent bond



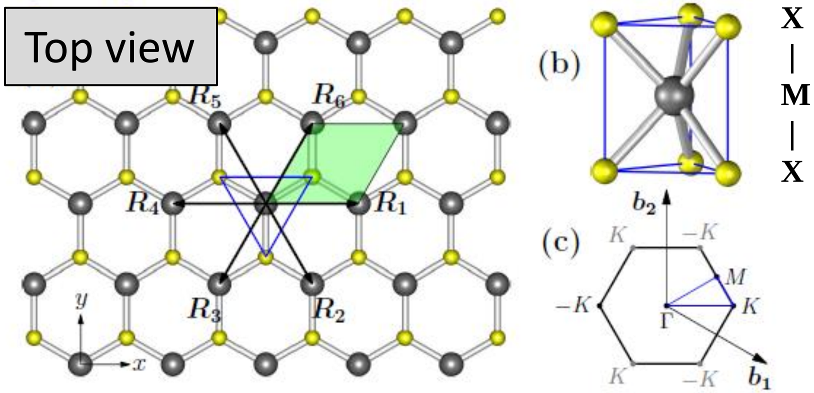
Band structure



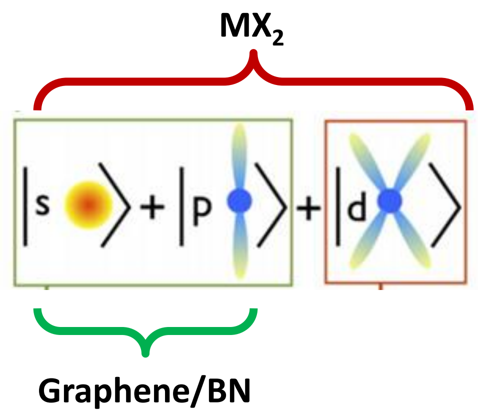
- Two carbon atoms per unit cell
- Massless fermion
- Linear E(k) dispersion
- Zero bandgap due to inversion symmetry

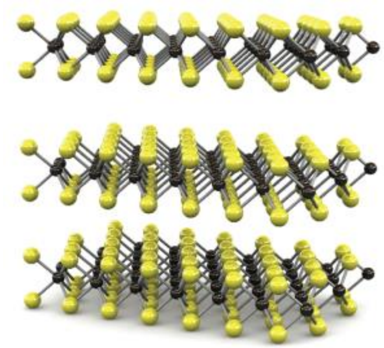
2-D Transition Metal Dichalcogenide

- Lattice structure (1H)

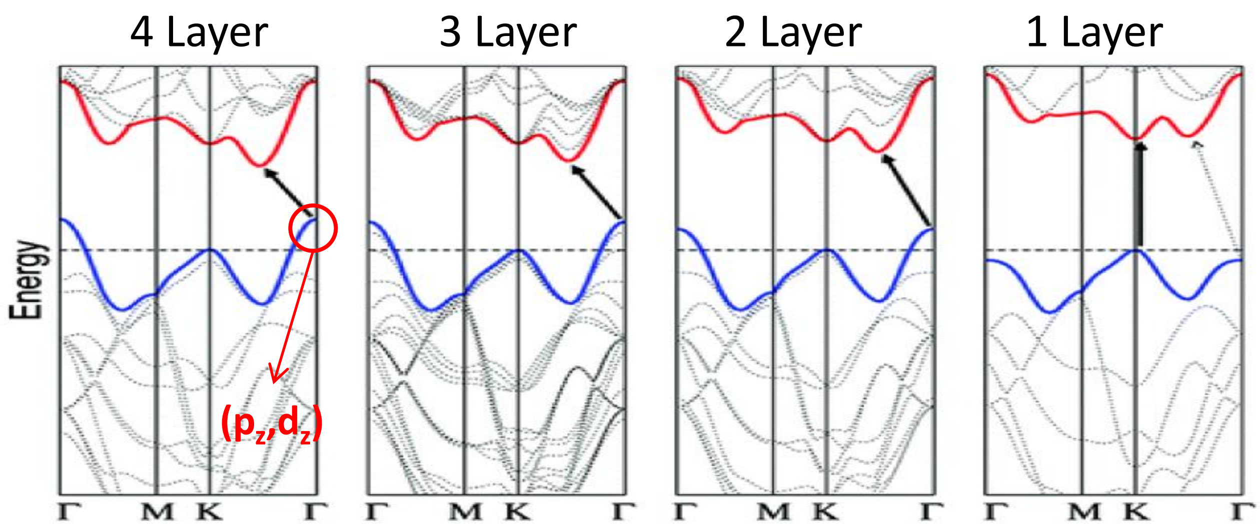


M = Transition metal (Mo, W, etc.)
X = Chalcogen (S, Se, Te)





- Band structure of MoS_2



- Direct gap at monolayer
- Indirect gap with smaller E_G at few layers
- Weak interlayer bonding by van der Waals forces

Splendiani et al.,
Nano Lett. 10, 1271 (2010)

Direct to Indirect Gap in TMD
- Layer dependence

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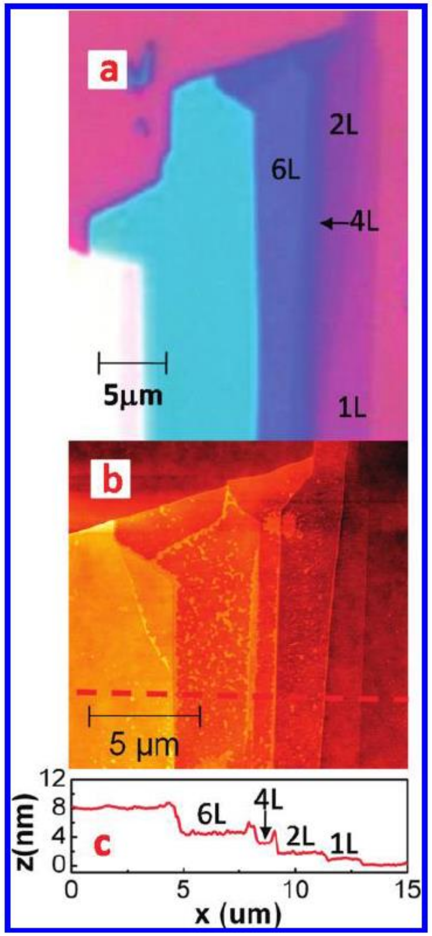
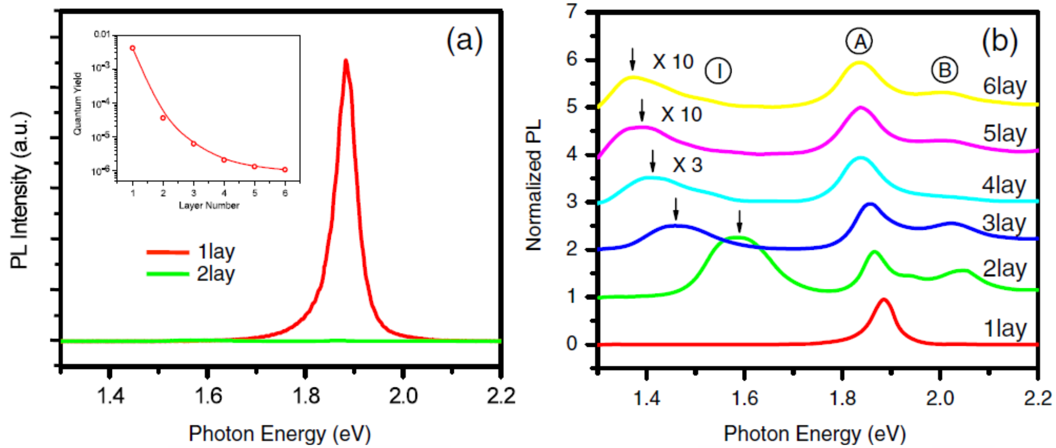
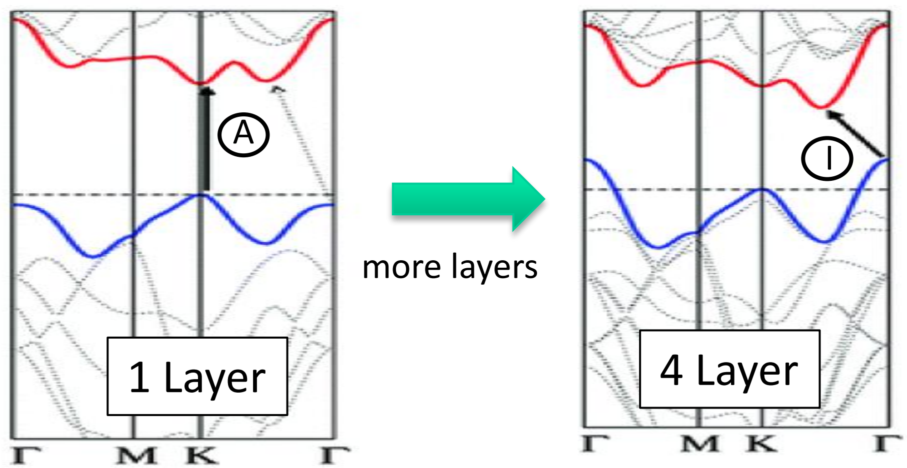
10^4 times stronger photoluminescence (PL) in 1 layer MoS_2



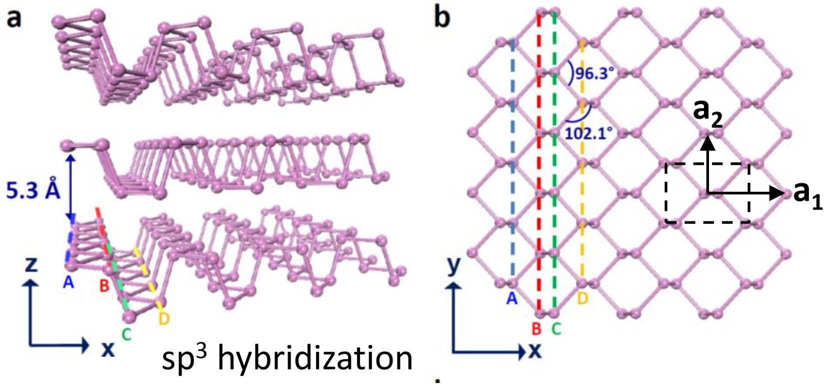


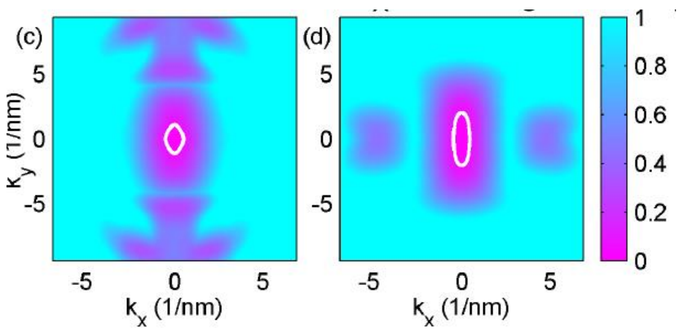


A. Splendiani et al., Nano Lett. 10, 1271 (2010)
K. F. Mak et al., PRL 105, 135805(2010)

Black Phosphorus - Phosphorene

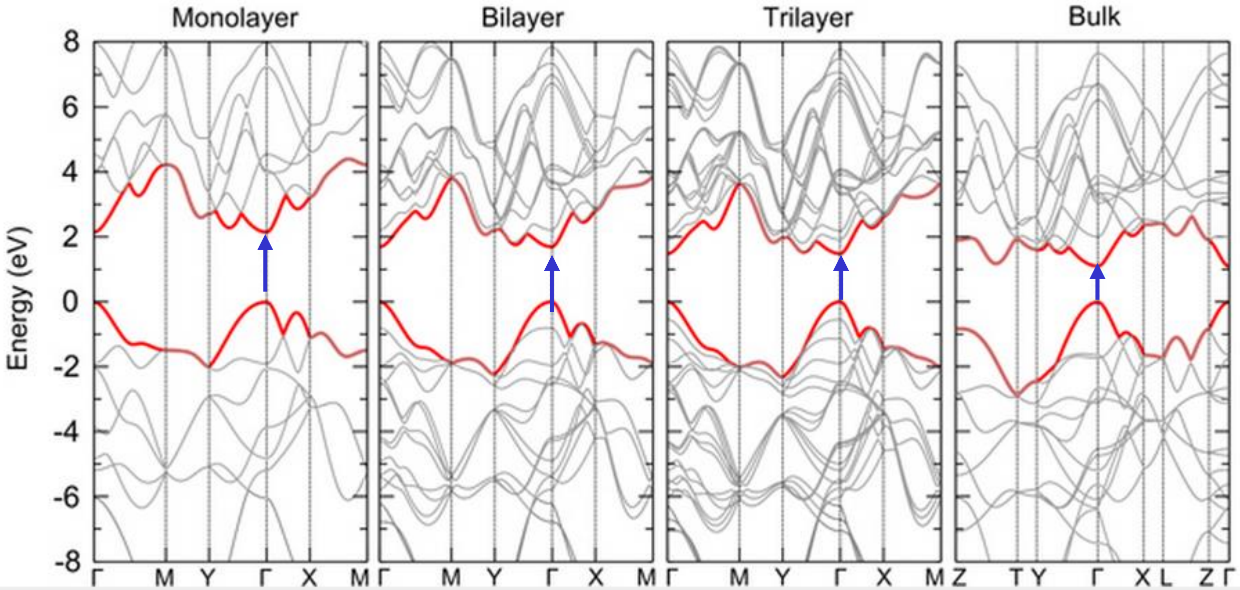
- Lattice structure – puckered honeycomb





Lam et al., EDL 35, 963 (2014)

- Band structure



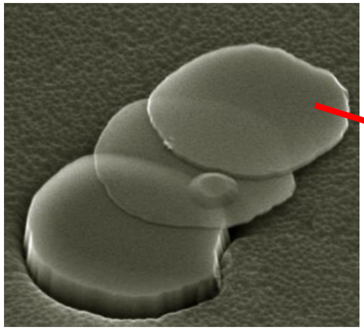
- Direct gap (ML to bulk)
- E_G = 0.3eV for bulk, and 2.0eV for ML
- Highly anisotropic effective mass in *x* (light) and *y* (heavy) for both electron and holes

Castellanos-Gomez et al.,
2D Mater. 1, 025001 (2014)

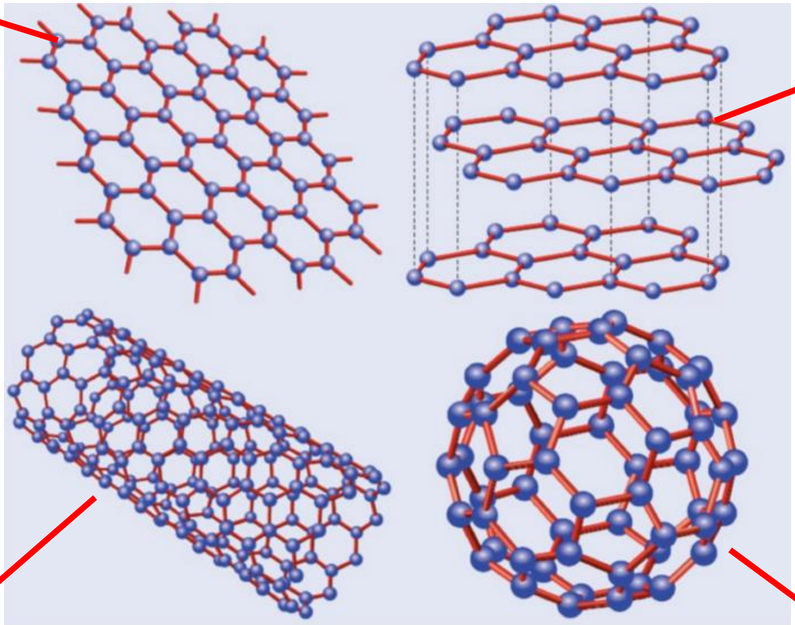
Synthesis of 2D Materials

Carbon in All Dimensionalities

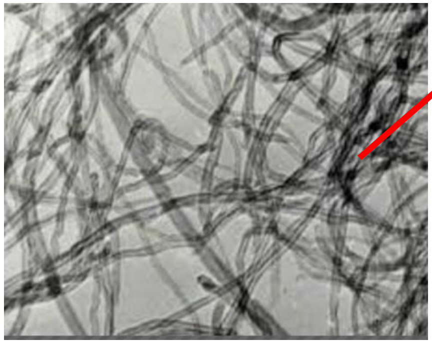
Graphene (2D)



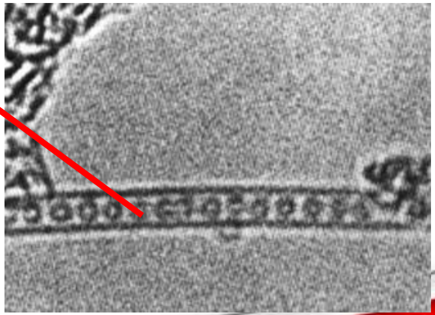
Graphite (3D)



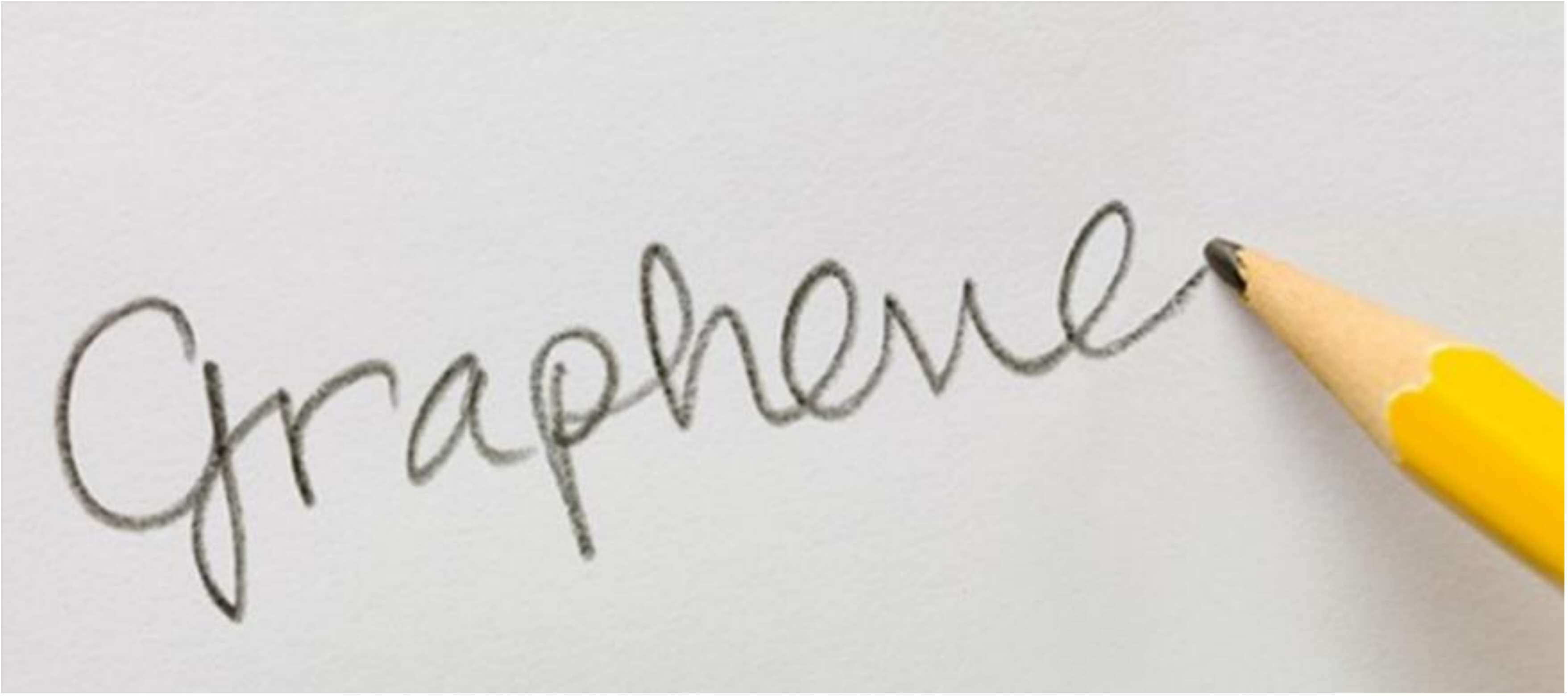
Nanotube (1D)



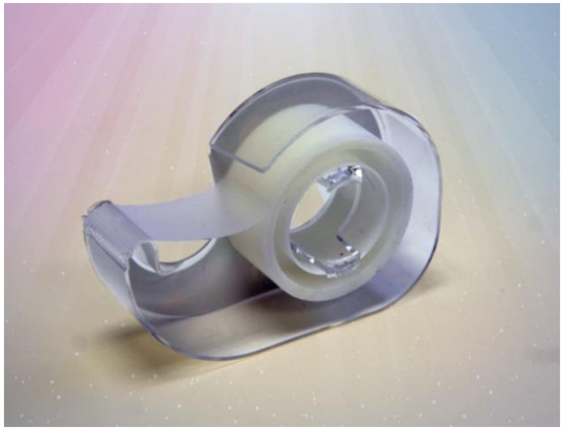
Fullerene (0D)



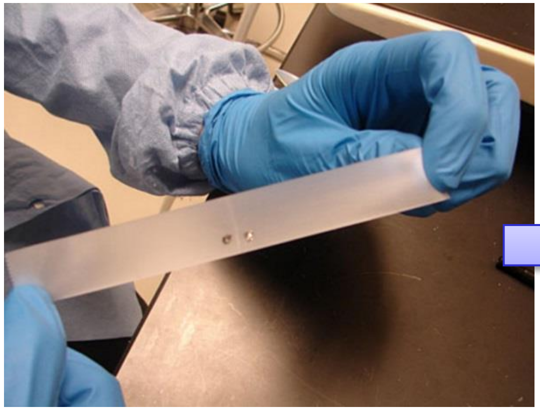
How to Make Graphene?

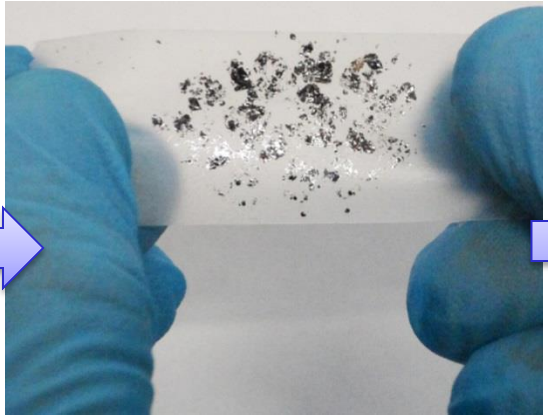


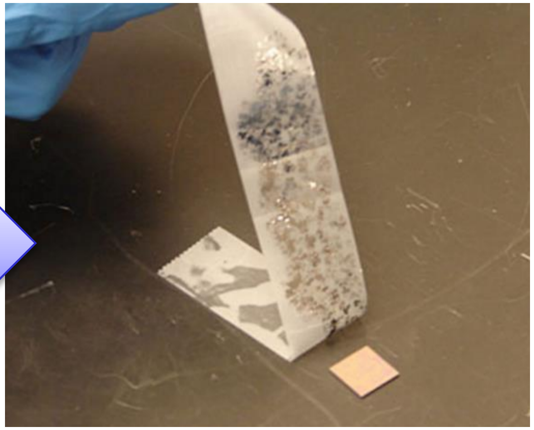
Or, Try This at Home …



You may win one of these ten years ago….

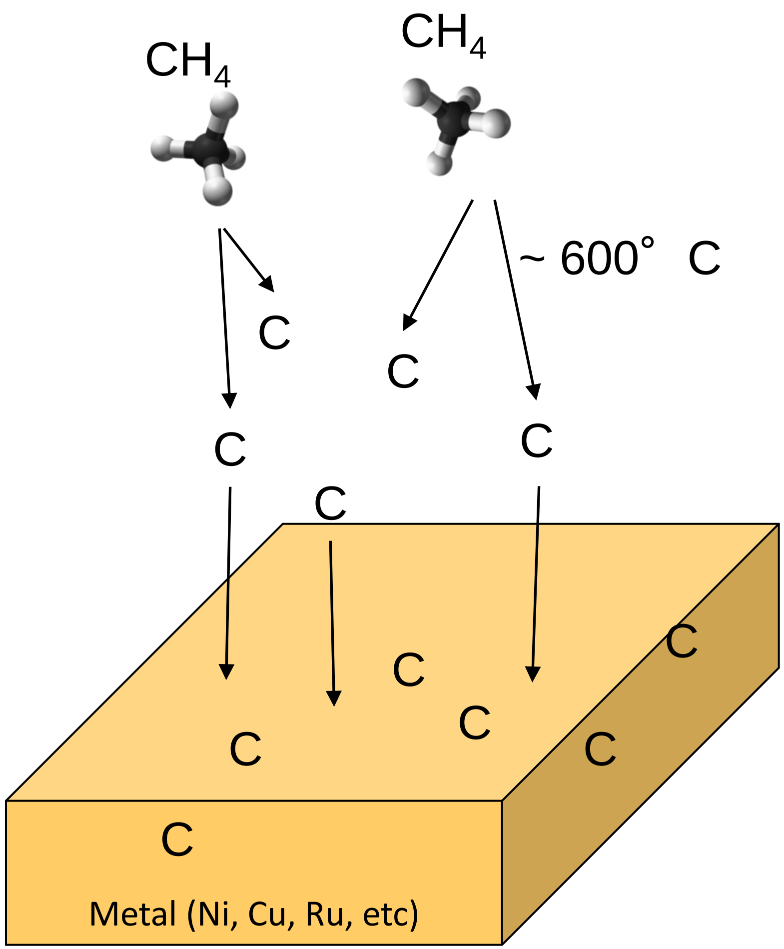




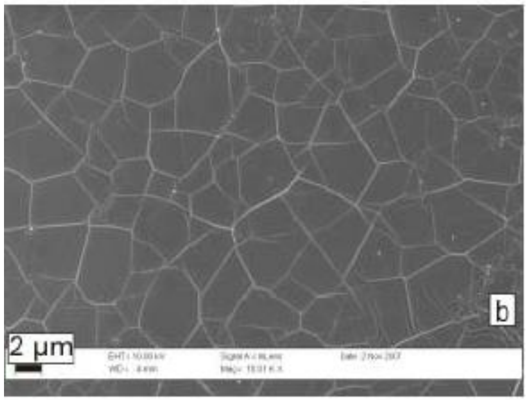


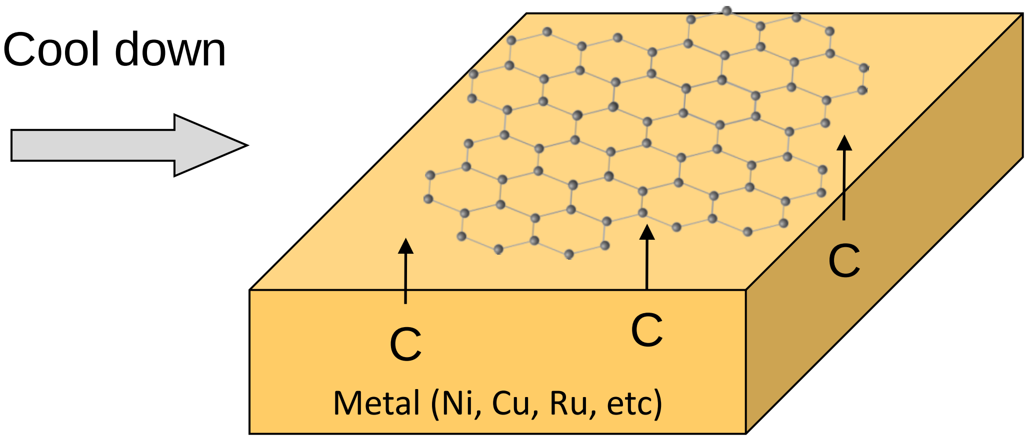
Also works for other 2D Materials!

Large-Area Graphene Growth by CVD

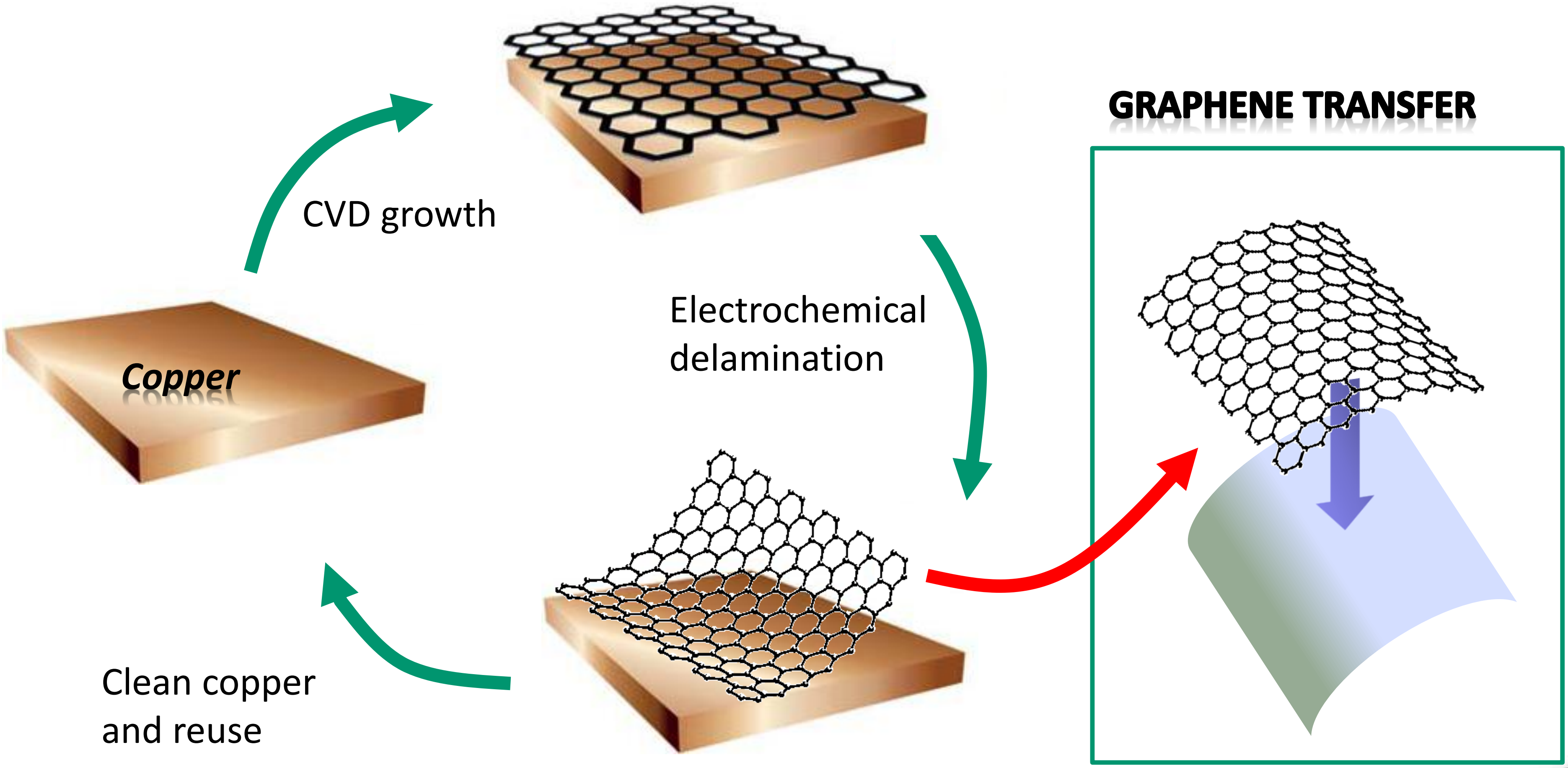


SEM of CVD graphene on Cu



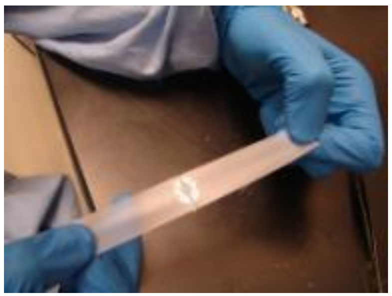


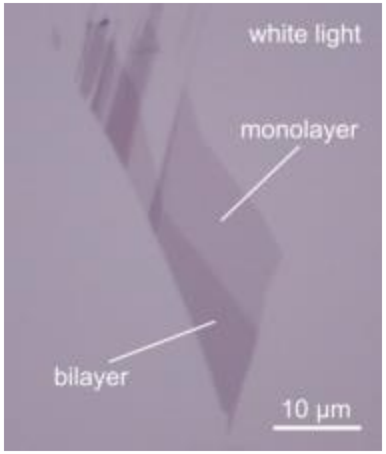
Low-Cost Graphene Production



Large-Area Graphene Production

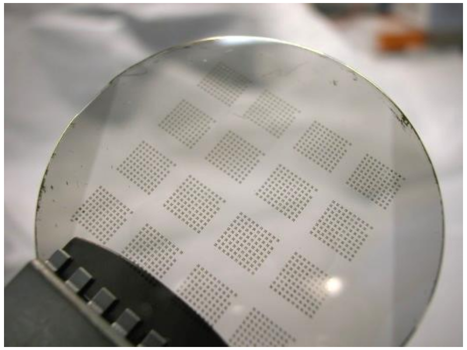
2005

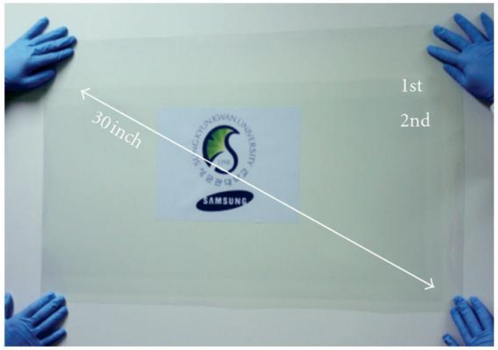




~5 μm

2009 - 2010



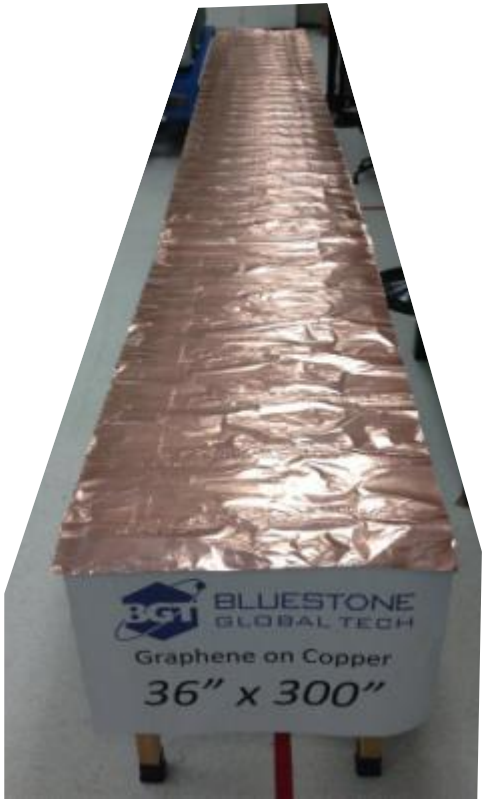


~50 cm

2012

~1 m

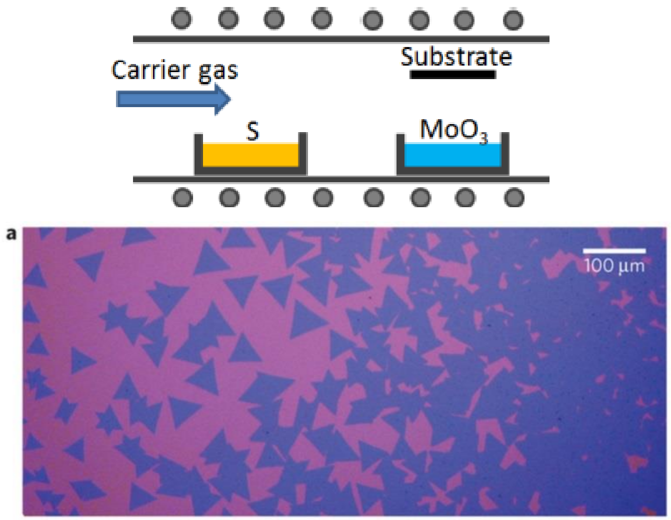
2013 ~



~ 10m

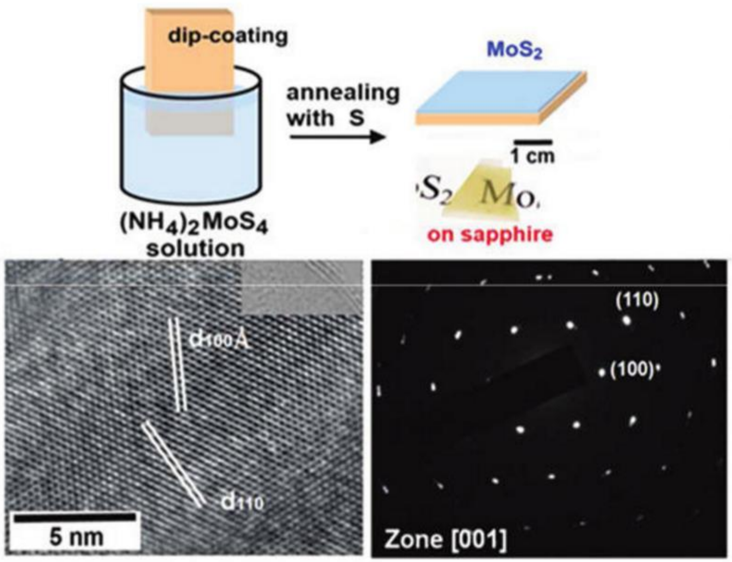
Scalable Synthesis of MX_2

MoS_2 by MoO_3/S CVD at 700°C



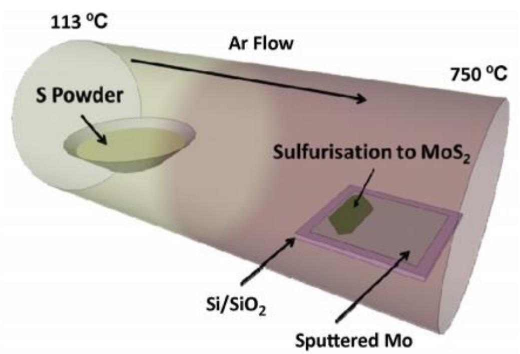
van der Zande et al., Nat. Mater. 12, 554 (2013)

MoS_2 by thermolysis at 1000°C



K. K. Liu et al., Nano Lett. 12, 1538 (2012)

Sulfurization of sputtered metal

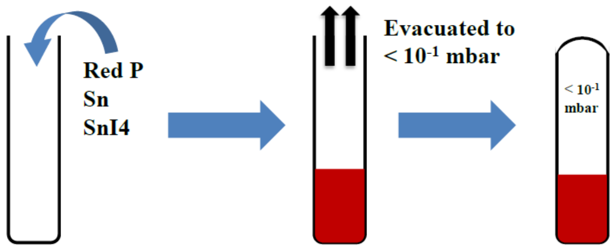


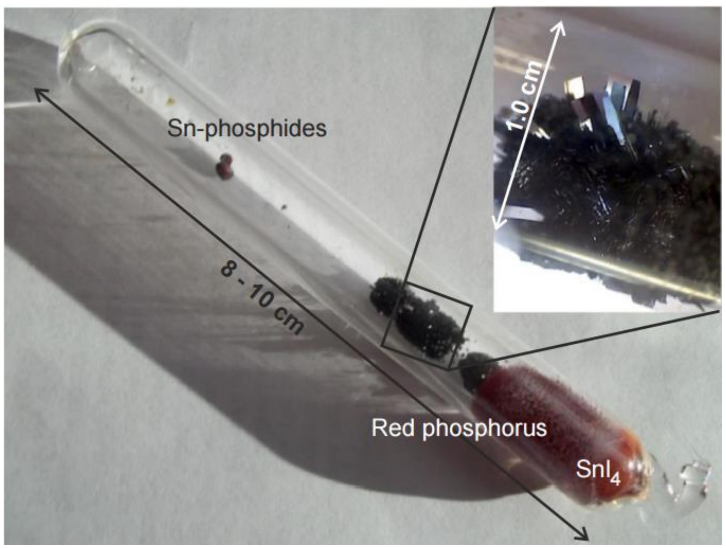
Gatensby et al., Appl. Surf. Sci. 297, 139 (2014)

Challenge – how to maintain Mo:S = 1:2?

Synthesis of Black Phosphorus

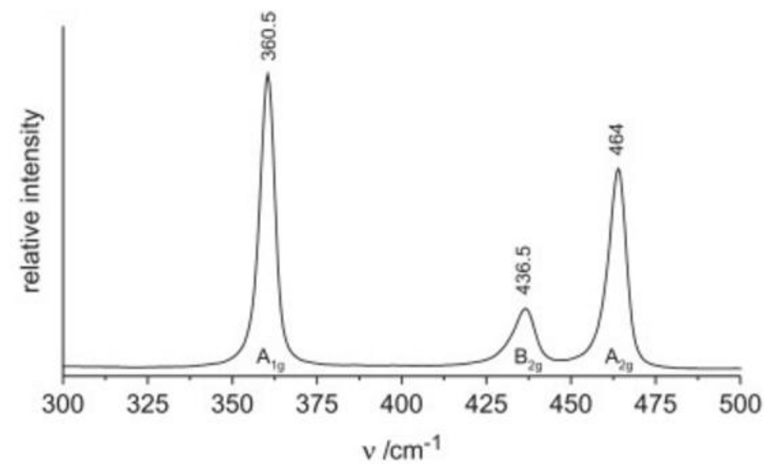
BP by transport reaction at 650°C





M. Kopf et al., J. Cry. Gro. 405, 6 (2014)

Raman Spectra of Synthesized BP

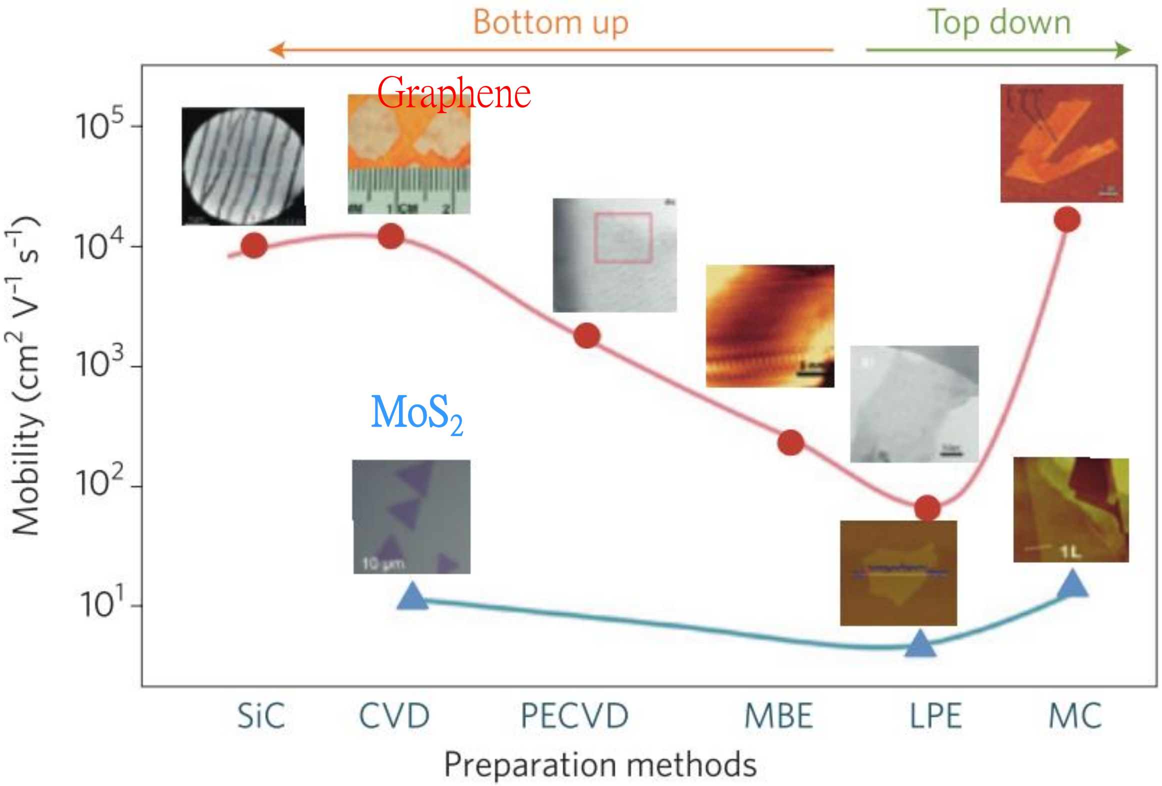


Challenges –
Breakthrough to achieve direct synthesis of thin-film BP on substrate!

Security C – TSMC Secret

Status of 2D Materials Synthesis

- A number of growth methods to produce large-area TMD films on various substrates (oxide, metal) are available
- Top-down growth of phospherene is yet to be demonstrated



Fiori *et al.*, Nat. Nano. 9, 768 (2014)

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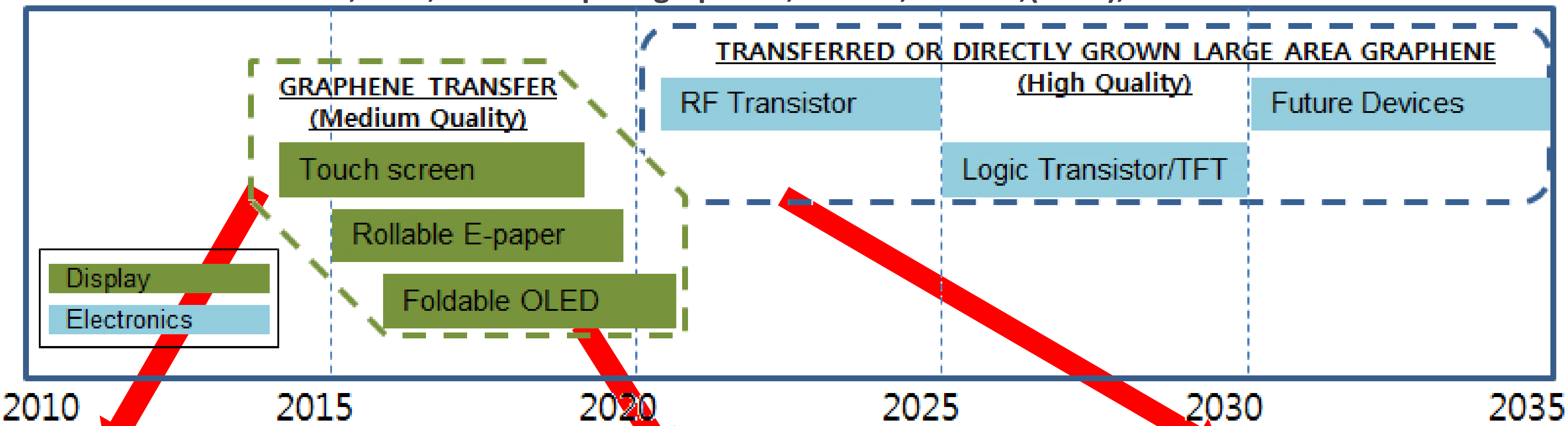
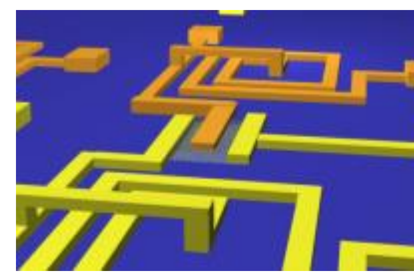
Graphene Technology Roadmap

K.S.Novoselov, et.al; A roadmap for graphene; Nature, Vol 490,(2012),192



Flexible and Rigid
Graphene touch panel

Rollable Display



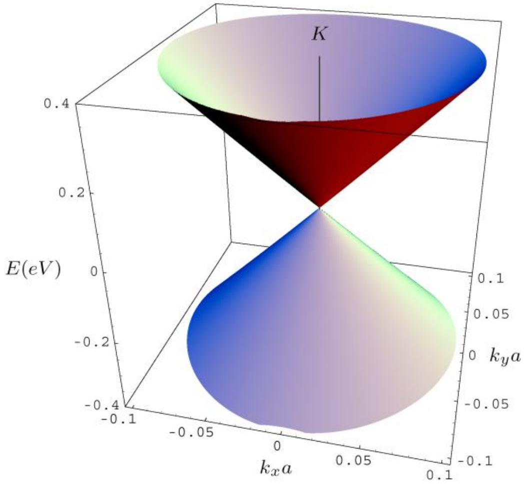
Graphene FET and
Circuits

Graphene vs. bulk Semiconductors

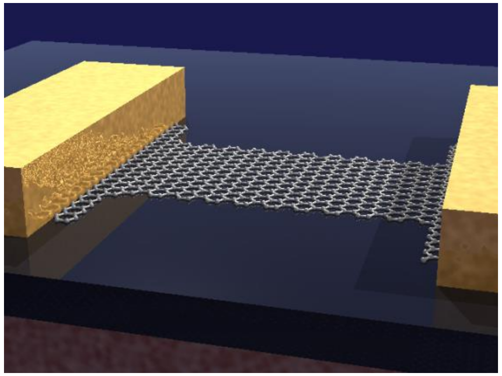
	Si	GaAs	$In_{.53}Ga_{.47}As$	InAs	InSb	Graphene
Electron mobility (cm^2/Vs) at $n = 10^{12}\ cm^{-2}$	600	4,600	7,800	20,000	30,000	25,000 (flake) ~3000 (Epieaxial) ~2000 (CVD)
Electron saturation velocity (10^7 cm/s)	1	1.2	0.8	3.5	5	8
Ballistic mean free path (nm)	28	80	106	194	226	400
Band-gap (eV)	1.12	1.42	0.72	0.36	0.18	0

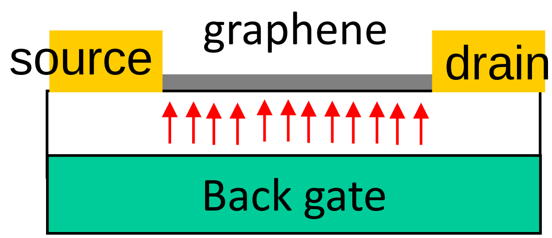
Key features

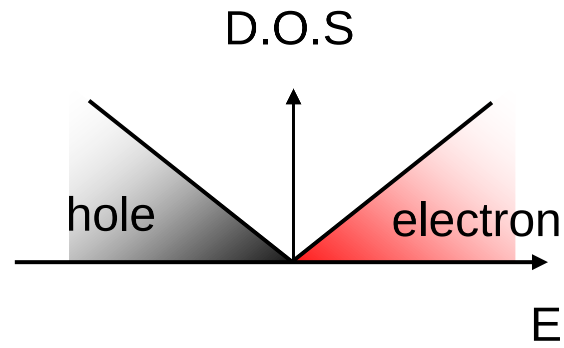
- A true two-dimensional system
- Ambipolar transport
- Optically transparent
- **Flexible with high mechanical strength**
- **Zero bandgap**

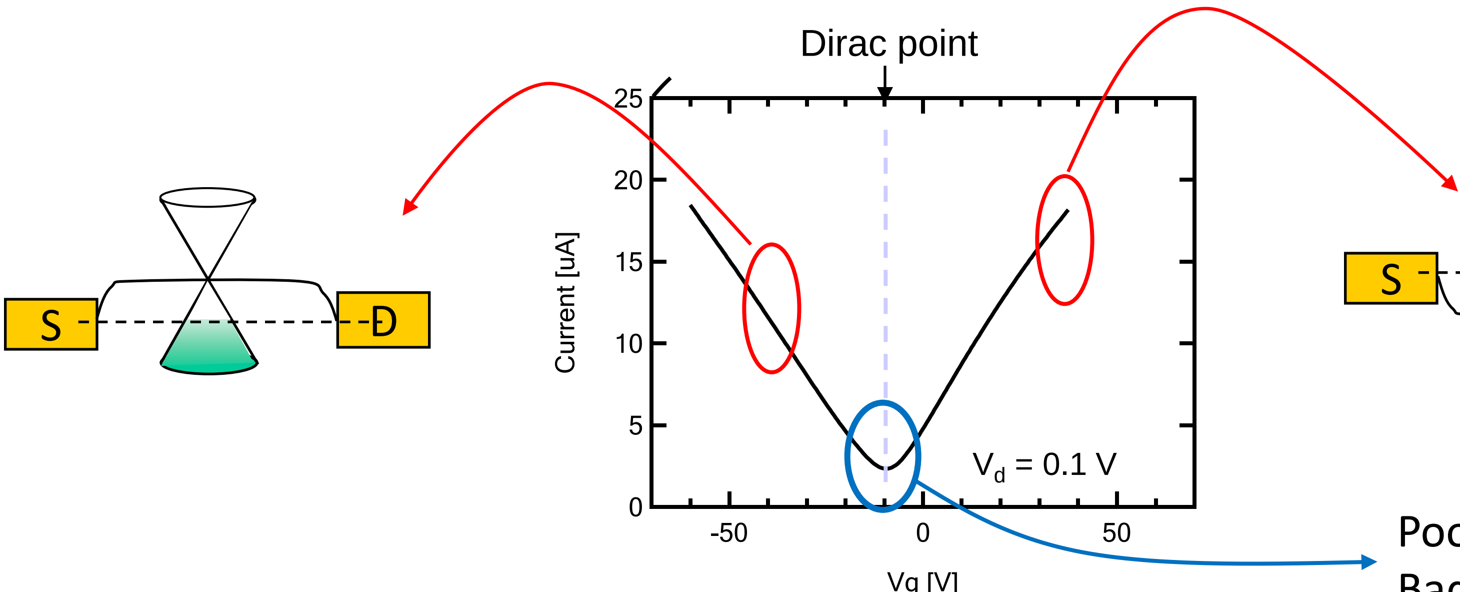


Graphene Field-Effect Transistor (FET)





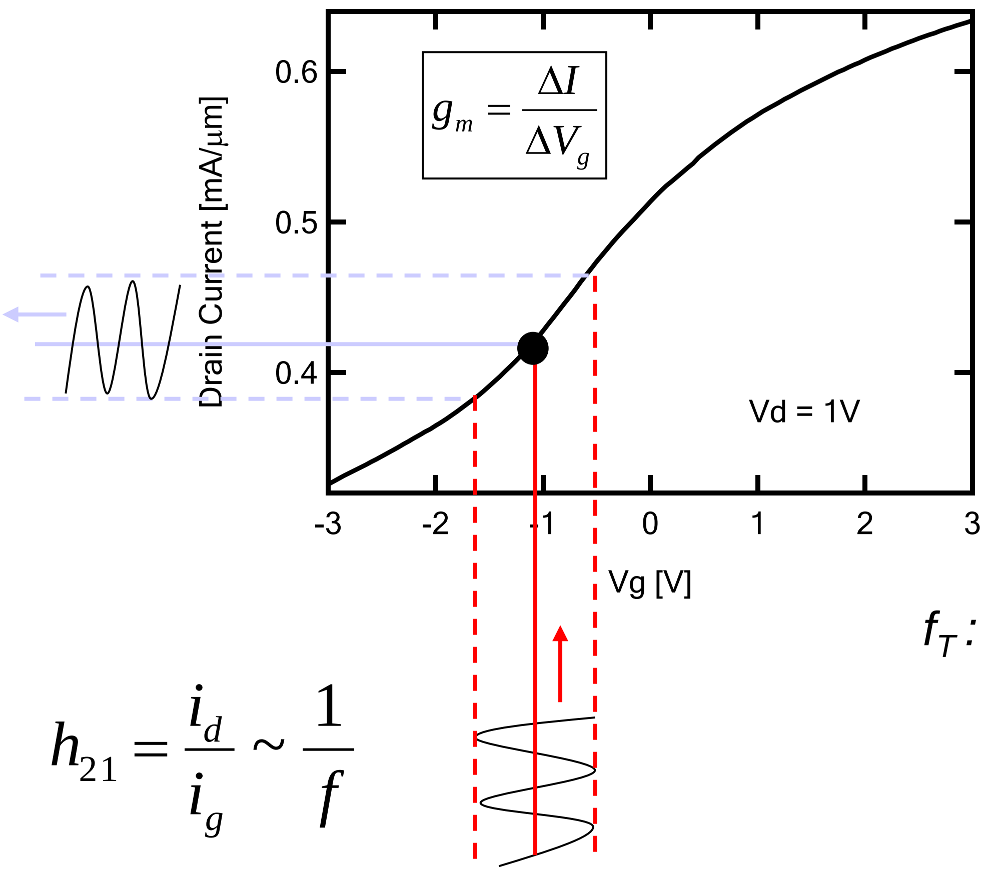


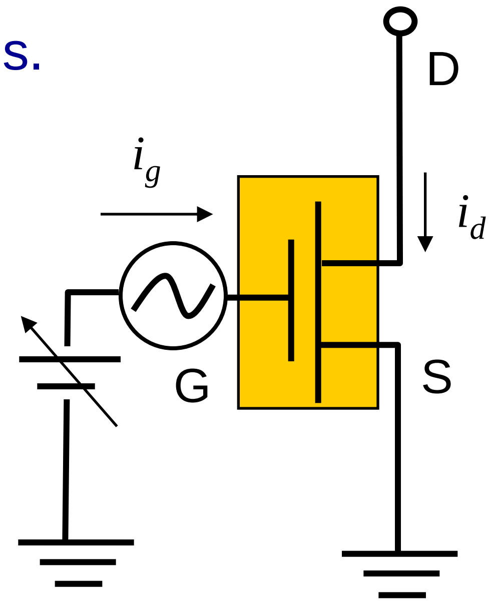


Poor on/off ratio
Bad for digital switches

Graphene for RF electronics

High on/off ratio is not required for RF applications.





f_T: cut-off frequency where current gain is 1

$$h_{21} = \frac{i_d}{i_g} \sim \frac{1}{f}$$

$$f_T = \frac{g_m}{2\pi C_g}$$

GHz Graphene Device and Circuit

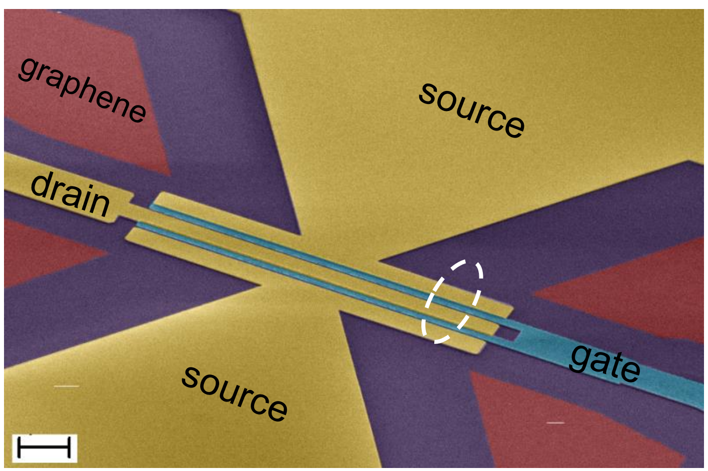
Proprietary
& Confidential

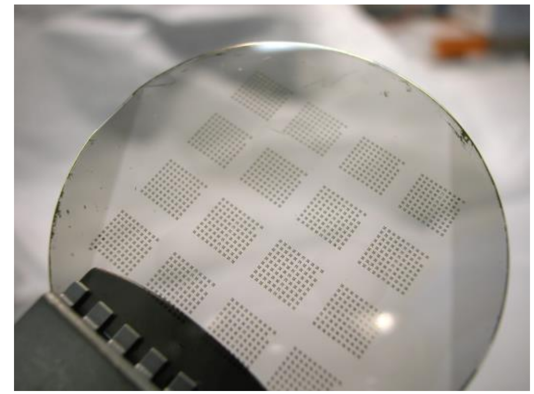
BREVIA

Lin et al., Science 327, p. 662 (2009)

100-GHz Transistors from Wafer-Scale Epitaxial Graphene

Y.-M. Lin,* C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H.-Y. Chiu, A. Grill, Ph. Avouris*





Gate length: 240 nm
f_T : 60 – 100 GHz

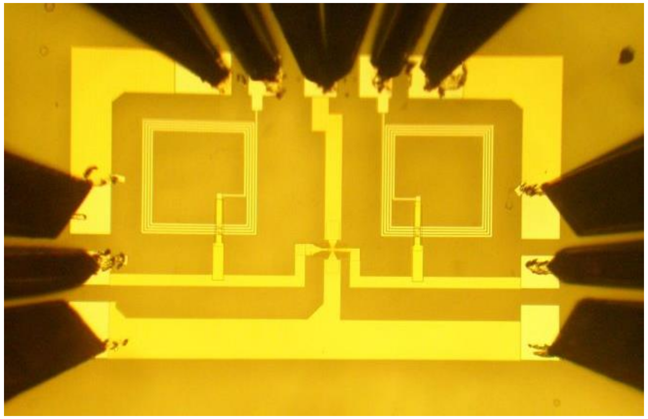
Gate length: 550 nm
f_T : 25 – 50 GHz

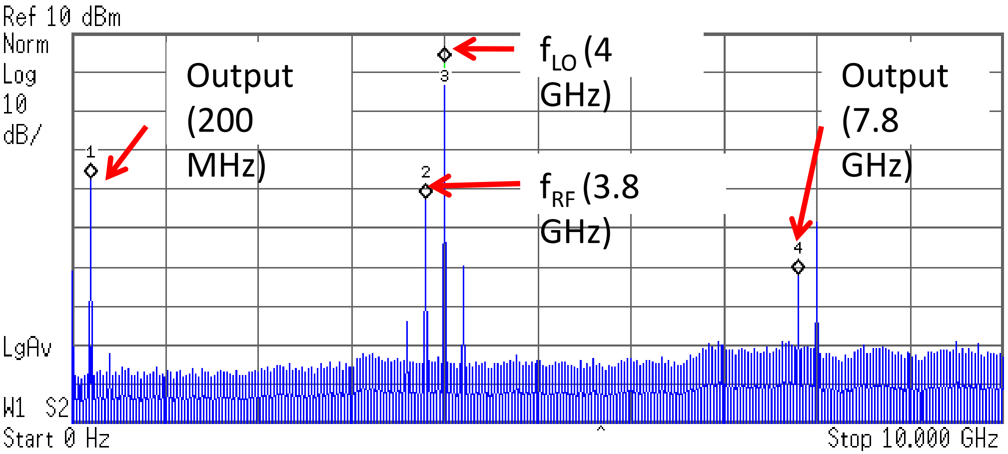
GHz Graphene Device and Circuit

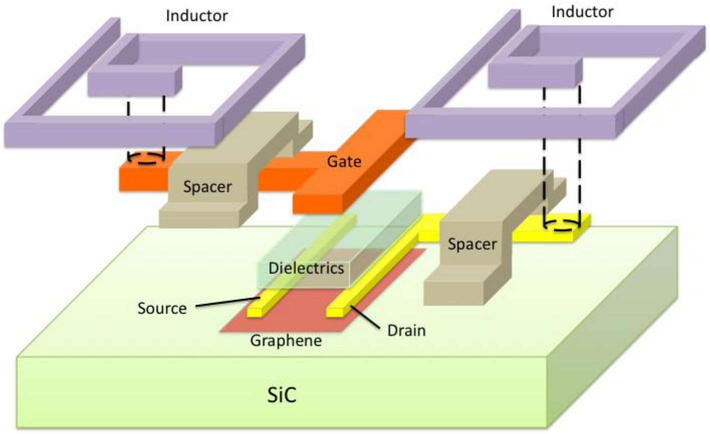
Lin et al., Science 332, 1294 (2011)

Wafer-Scale Graphene Integrated Circuit

Yu-Ming Lin,* Alberto Valdes-Garcia, Shu-Jen Han, Damon B. Farmer, Inanc Meric,†
Yanning Sun, Yanqing Wu, Christos Dimitrakopoulos, Alfred Grill,
Phaedon Avouris,* Keith A. Jenkins







Beyond 400 GHz Operation

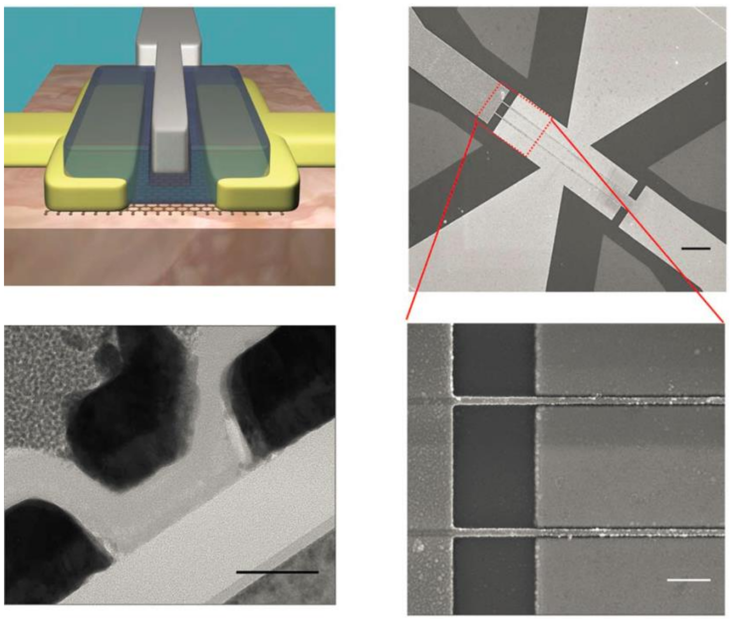
LETTER

Nature 472, 74 (2011)

doi:10.1038/nature09979

High-frequency, scaled graphene transistors on diamond-like carbon

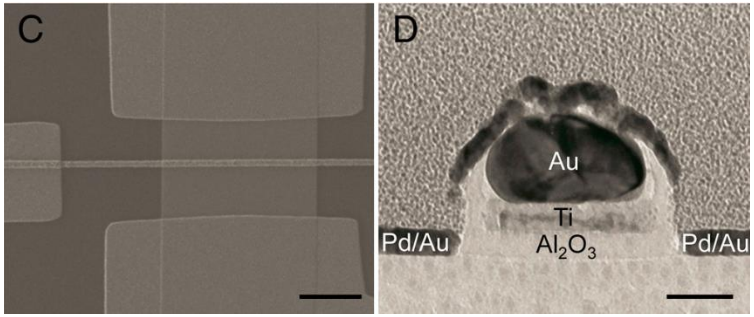
Yanqing Wu[1], Yu-ming Lin[1], Ageeth A. Bol[1], Keith A. Jenkins[1], Fengnian Xia[1], Damon B. Farmer[1], Yu Zhu[1] & Phaedon Avouris[1]



Lg = 40nm
350 GHz (IBM)

PNAS 109, 11588 (2012)

Nanowire Gate ~ 40 nm
427 GHz (UCLA)



High-frequency self-aligned graphene transistors with transferred gate stacks

Rui Cheng[a,1], Jingwei Bai[a,1], Lei Liao[b], Hailong Zhou[b], Yu Chen[a], Lixin Liu[b], Yung-Chen Lin[a], Shan Jiang[b], Yu Huang[a,c], and Xiangfeng Duan[b,c,2]

[a]Departments of Materials Science and Engineering, and [b]Chemistry and Biochemistry, and [c]California Nanosystems Institute, University of California, Los Angeles, CA 90095

Creating a Bandgap in Graphene

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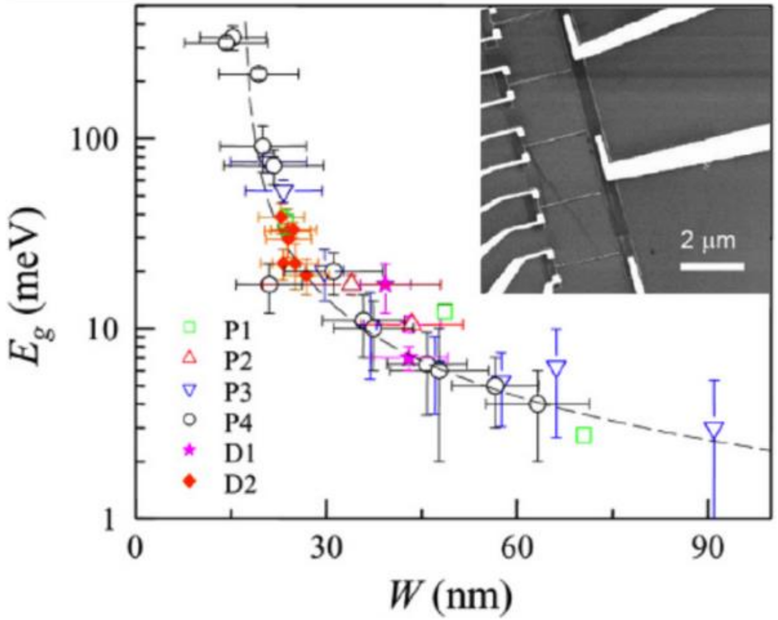
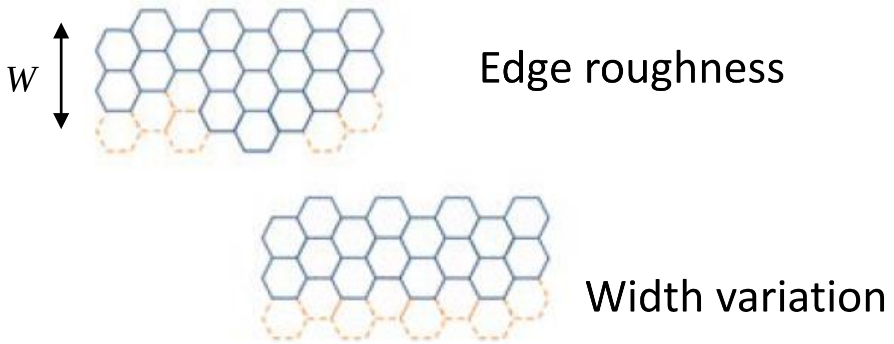
$E_g \sim 1.4$eV/W, (Width in nm)



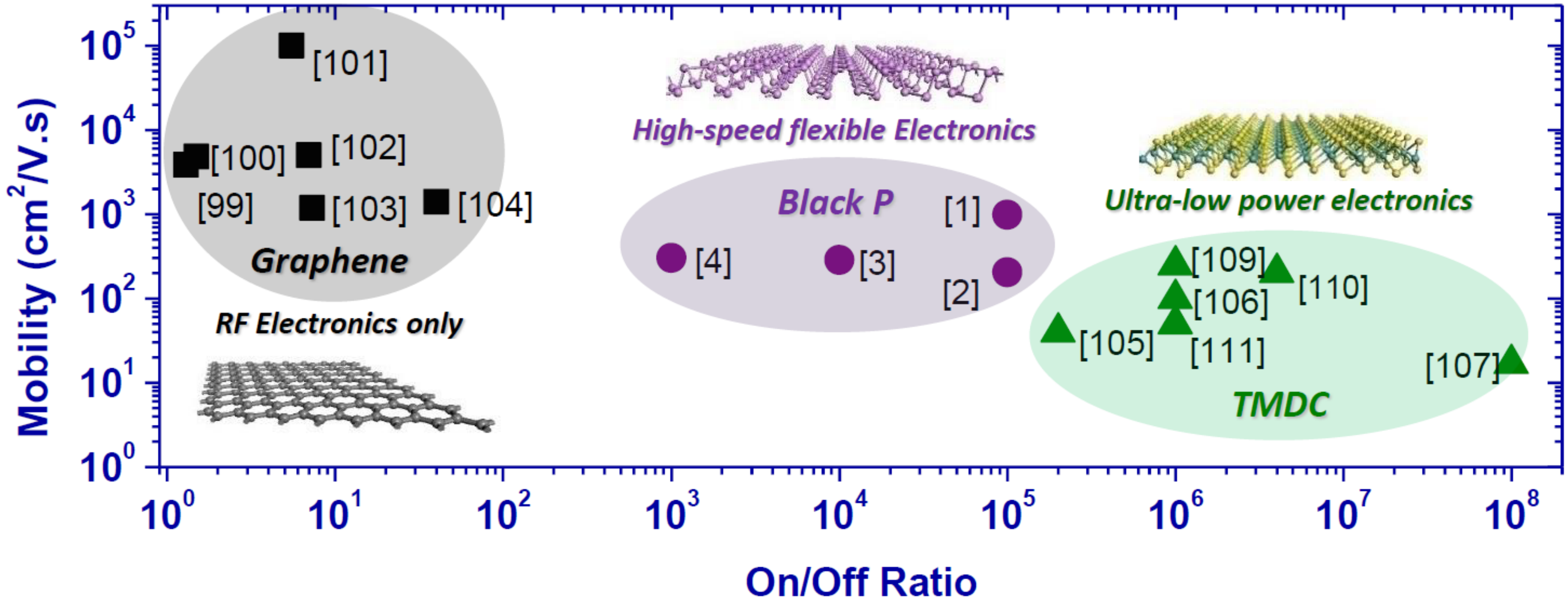
Han et al, Phys. Rev. Lett. 98, 206805

Graphene Nanoribbon



Challenge-
Atomically smooth edge with a precise width control

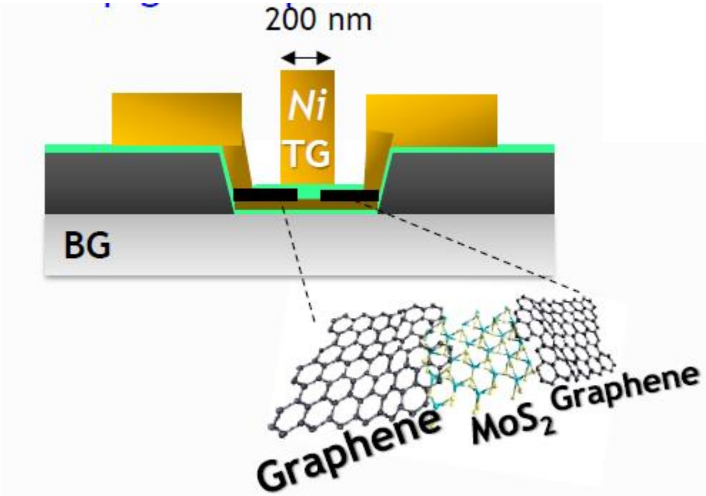
Choice of 2D Material for CMOS

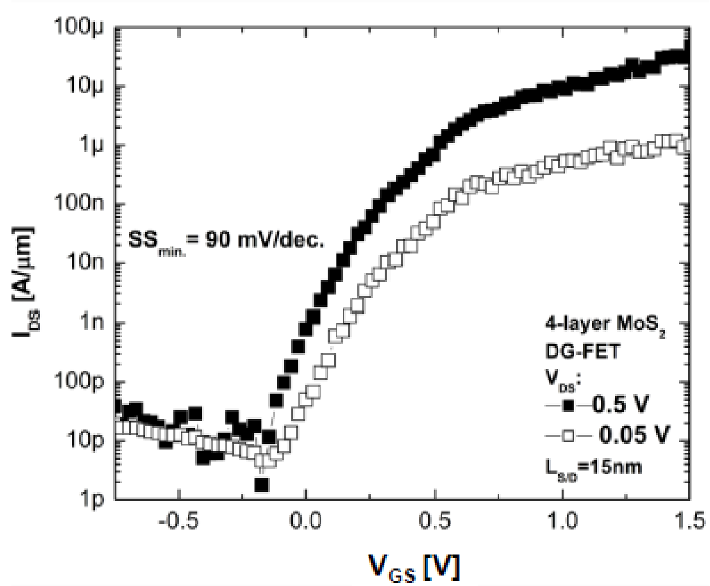


Ling et al., PNAS 112, 4523 (2014)

Short-Channel MoS_2 FET
- Good switching down to 11nm

4L MoS_2 FET:
Double gate: L_{min}~11nm < $L_{S/D}$=15 nm

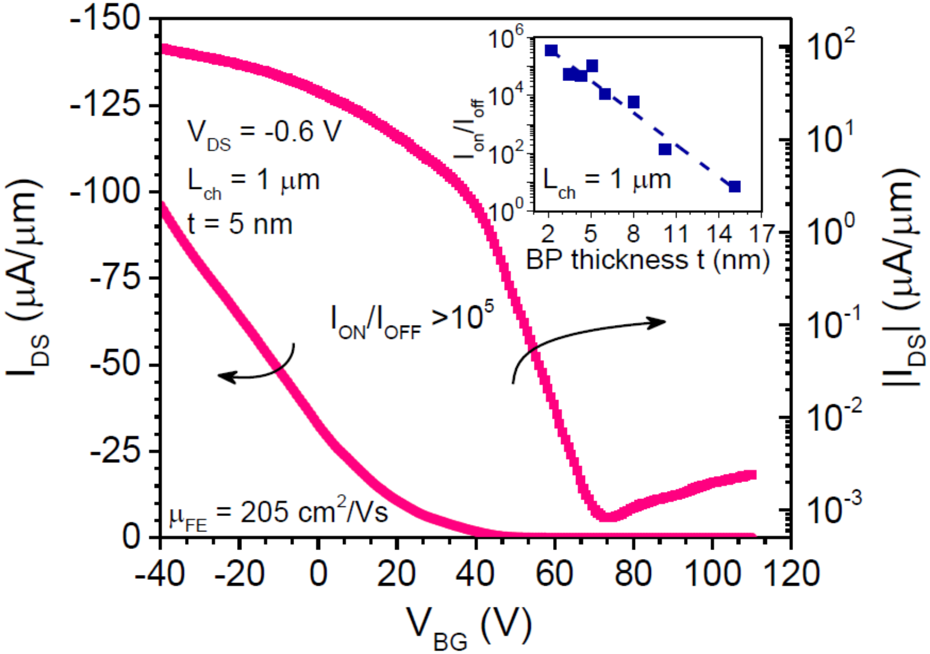


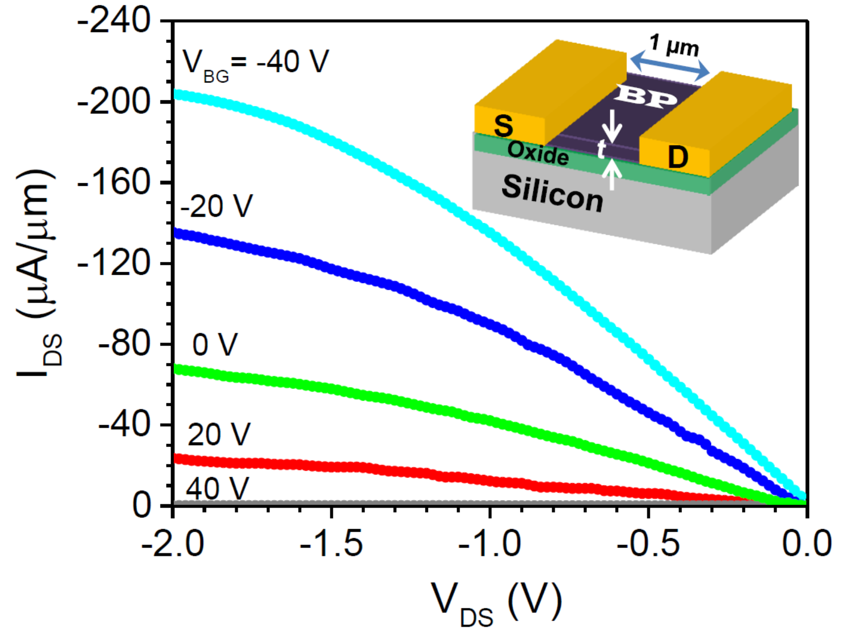


Nourbakhsh et al. (2015 VLSI Symp.)

$$\lambda = \sqrt{\frac{1}{N}\varepsilon_S t_S \frac{t_{OX}}{\varepsilon_{OX}}}$$, N=2 for double gate

Phospherene p-FET

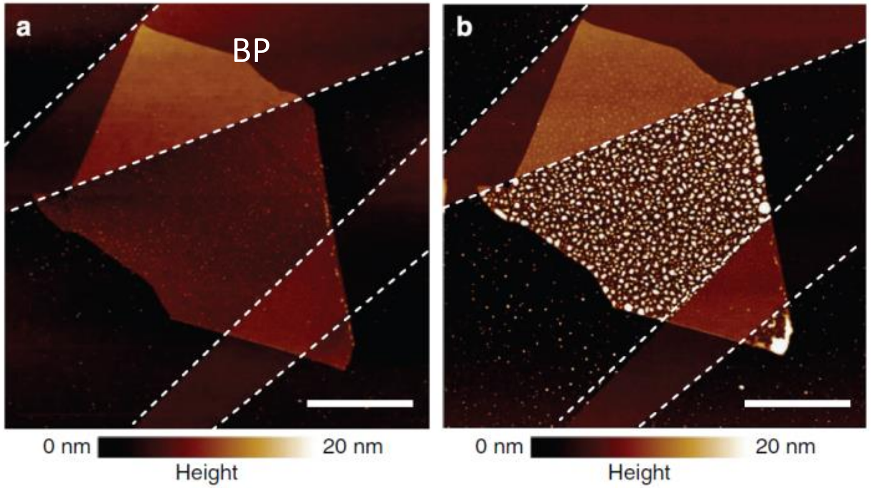




Xia et al., Nature Comm. 5, 4458 (2014)

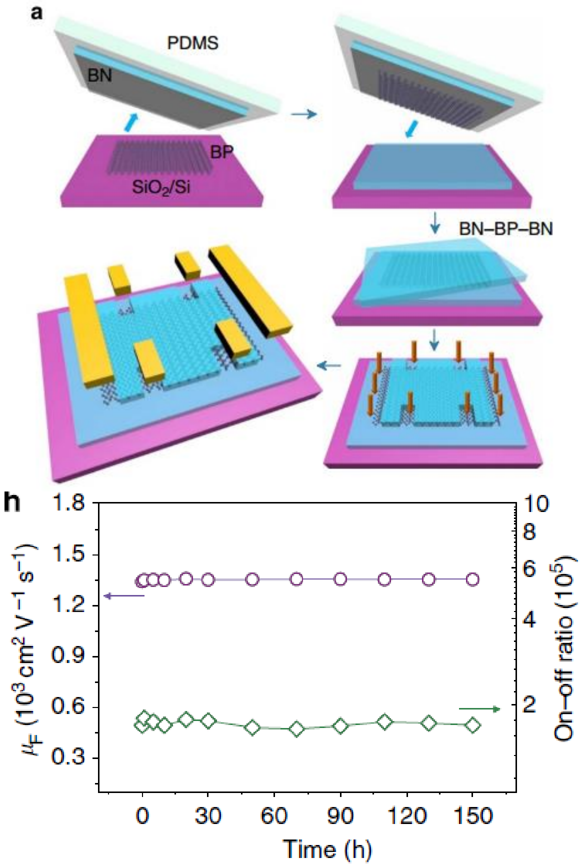
Stability of Phosphorene in Air

10 mins 24 hours



BP disintegrates in ambient.

B. Ozyilmaz et al.,
Nature Comm. 6, 6647 (2015)



Passivation with BN

Chen et al., Nature Comm. 6, 7315 (2015)

Issues of Contacts in 2D Materials

- Schottky barrier and Fermi-level pinning
- Currently achievable Rc for TMDs and BP are still two orders of magnitude higher than Si and ITRS requirement

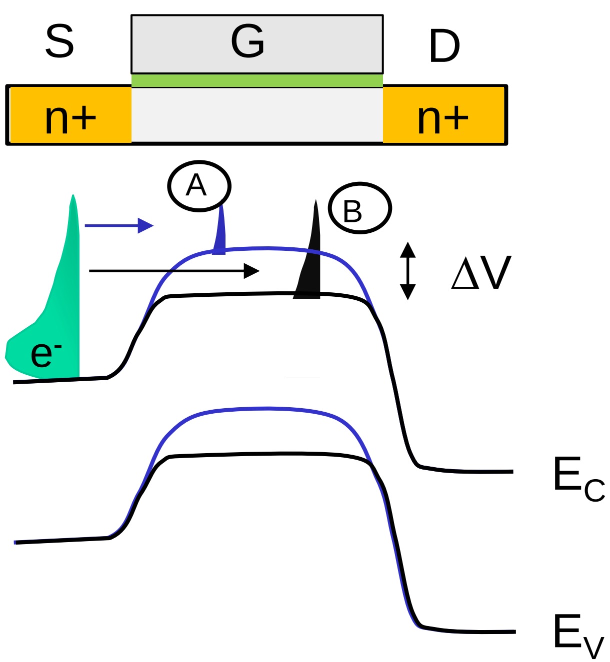
Transistor type	R_{co} (Ω mm)	Metal	Comment
Graphene MOSFET	0.011–0.08	Ni, Ti	BL
	0.1–0.2	Ti, Ni, Pd/Au, Cr/Au	SL
MoS_2 MOSFET	0.2–1.6	Ni/Au, Ti/Au, Au	FL
	2	Au	SL
WSe_2 MOSFET	1.4	Graphene	BL
	2	Graphene	FL
Phosphorene MOSFET	1.75	Ni/Au, PdAu	FL
Si MOSFET	<0.01		
InP HEMT	0.03		
GaAs mHEMT	0.02		

ITRS 2024 requirement: Rc = 0.065 Ω.mm

F. Schwierz et al., Nanoscale 7, 8261 (2015)

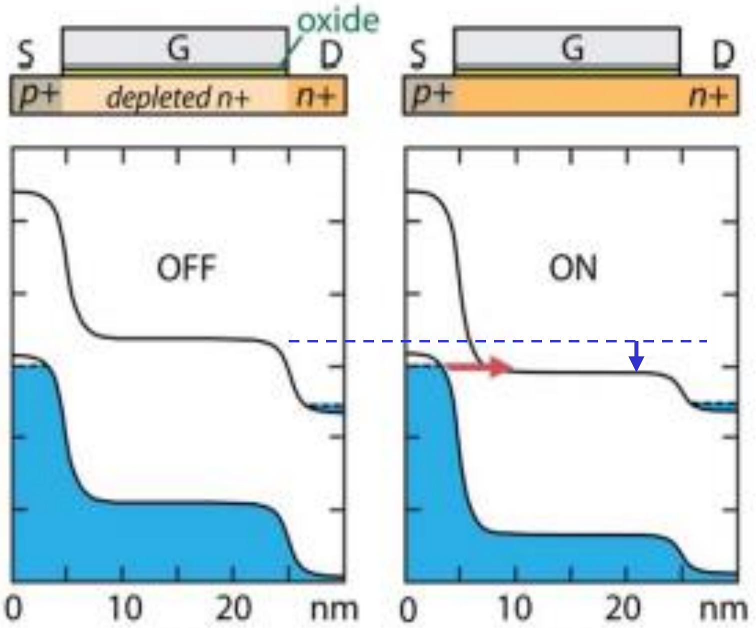
Tunnel FET: Low voltage operation

MOSFET with n/i/n junction



I_A/I_B ~ exp (-$\Delta V/kT$)
ΔV = 60mV, I_A/I_B = 1/10

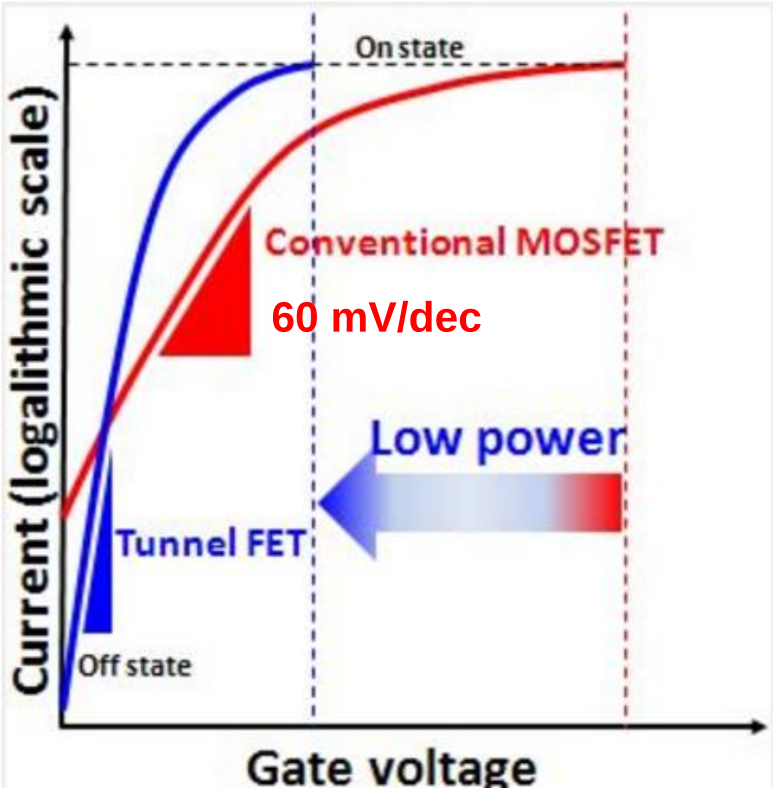
Tunnel FET with n/i/p junction



Thermal tail is filtered by bandgap and thus is not limited to 60mV/dec as in MOSFET

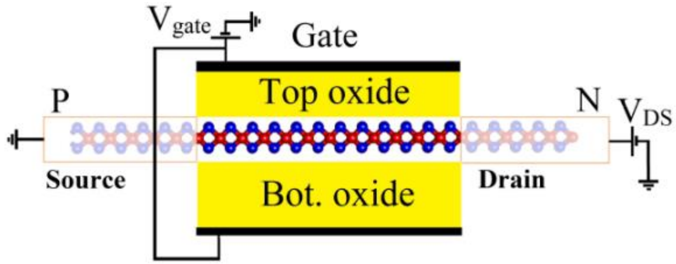
Tunnel FET vs. MOSFET

Proprietary & Confidential

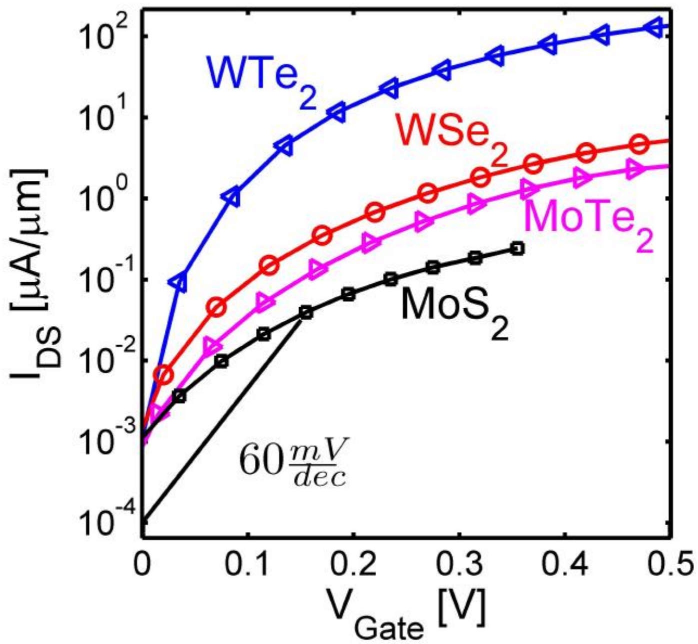


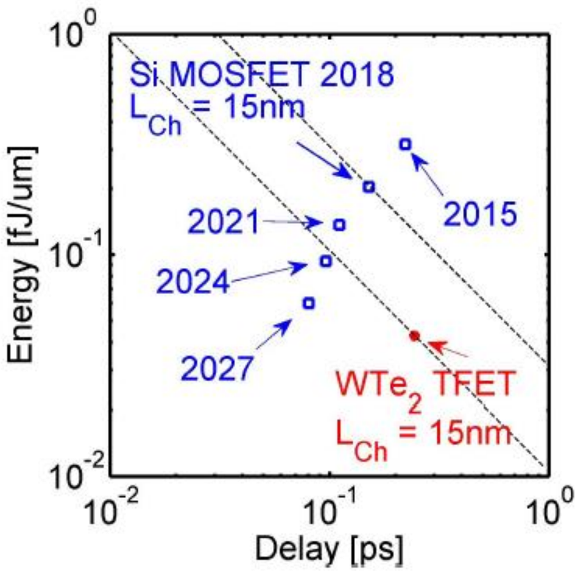
Lower operating voltage → lower power comsumption!

Tunnel FET based on TMDs



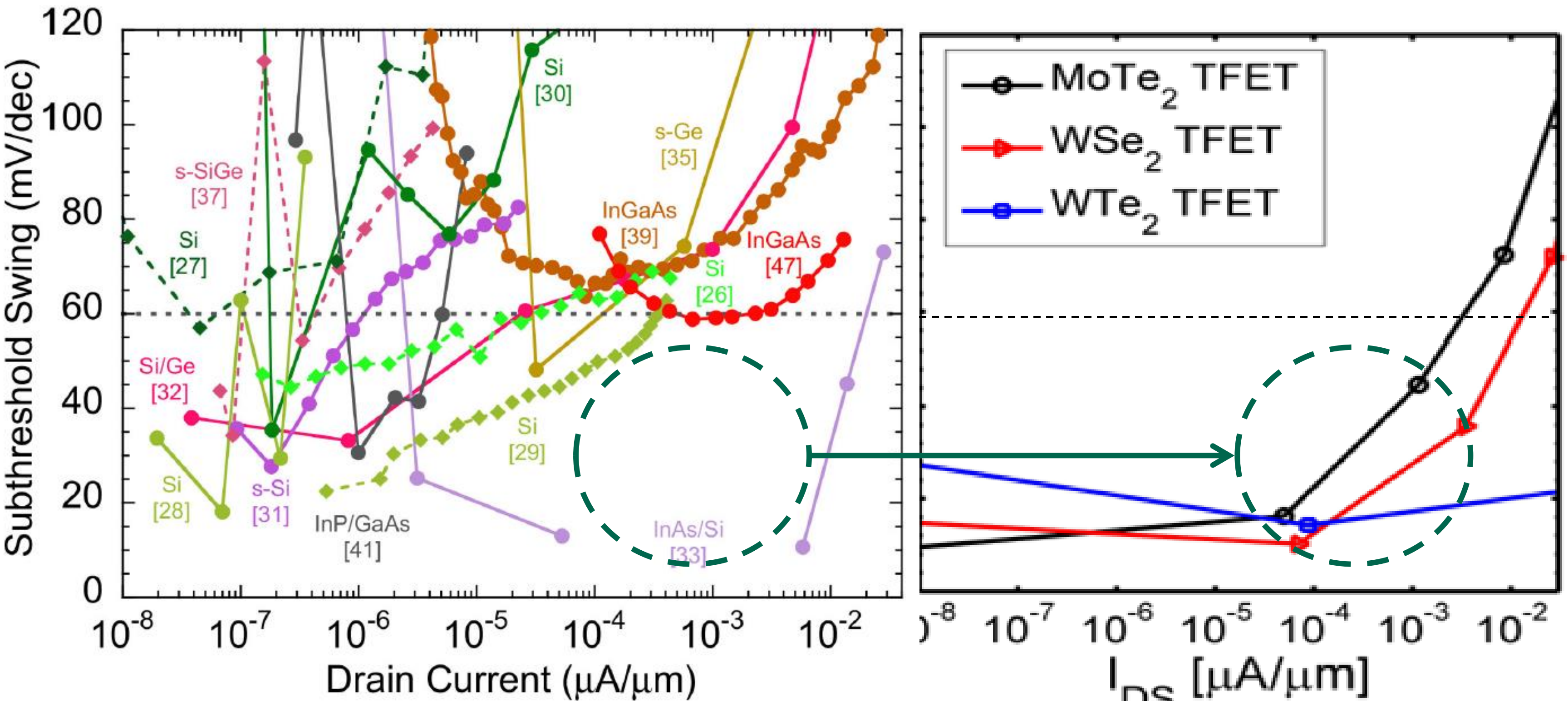
From tunneling consideration:
1. **Direct bandgap**
2. **Small mass in transport direction**
3. **Bandgap ~ 0.6eV**





Appenzeller et al., IEEE XCDC (2015)

Comparison of TFET Performance



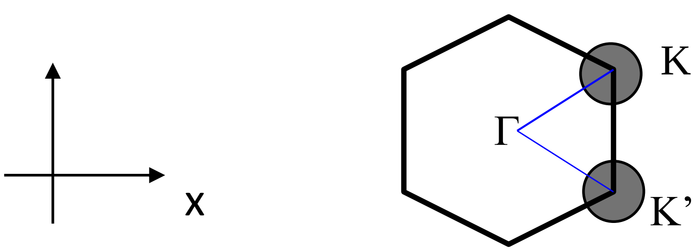
A. Seabaugh et al., J. EDS 2, 44(2014)

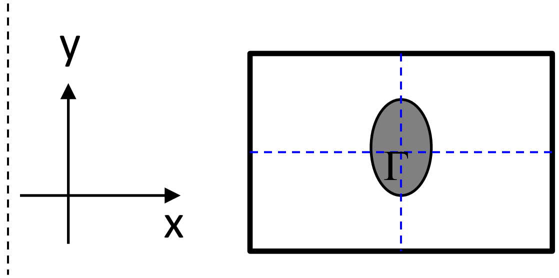
2D Candidates for TFET

Multilayer BP is also promising:

- **Bandgap < 1eV**
- **Highly anisotropic carrier mass ($m_x << m_y$)**
- **Direct bangdap**

	MoS_2	$MoSe_2$	$MoTe_2$	WS_2	WSe_2	WTe_2	BP 1L	BP 3L	BP 5L
m_{hx}/m_o	0.64	0.72	0.75	0.43	0.5	0.3	0.15	0.15	0.14
m_{hy}/m_o							6.35	1.12	0.89
Eg (eV)	1.68	1.51	1.085	1.93	1.56	0.75	1.53	0.73	0.52





Vertical Tunnel FET with 2-D Materials

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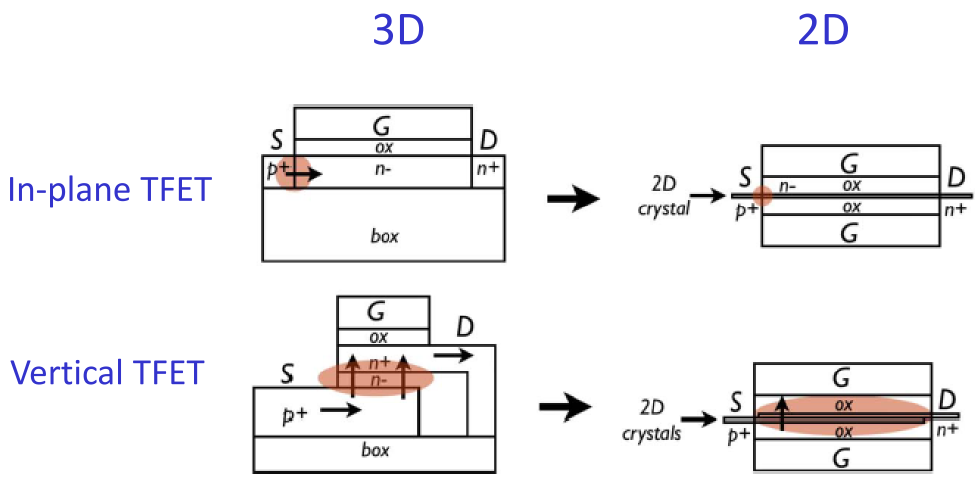
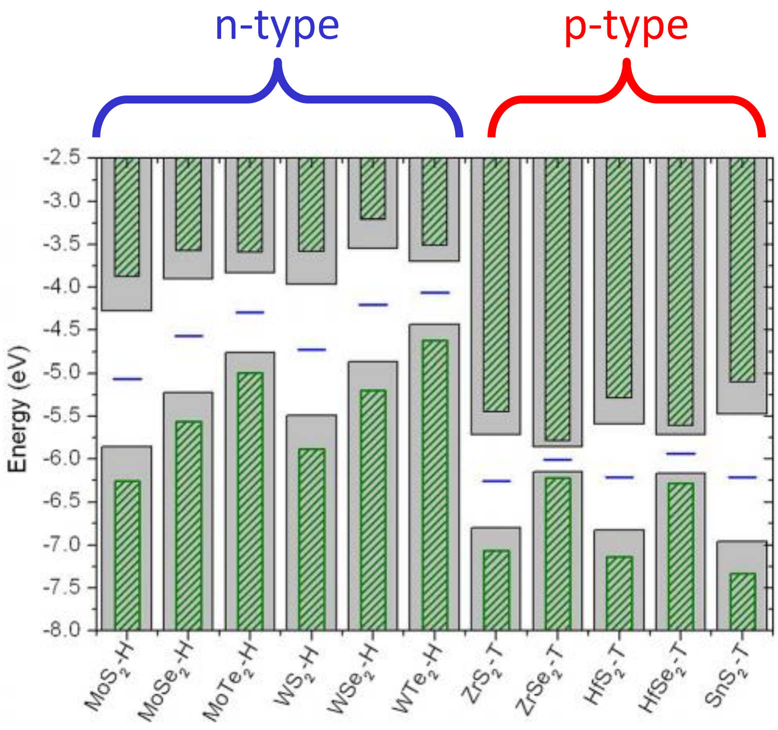
- **Stacking of n- and p-type 2D crystals**
  - **Enhanced tunnel area**
  - **Ultra-short junction**

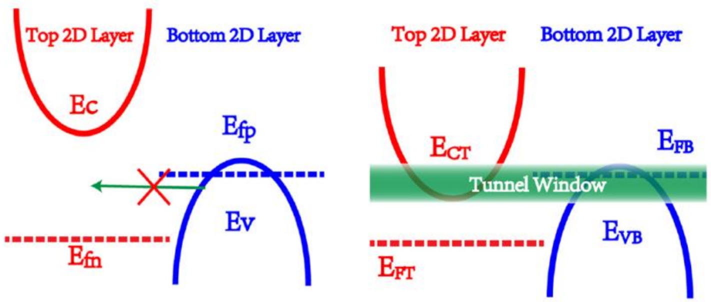


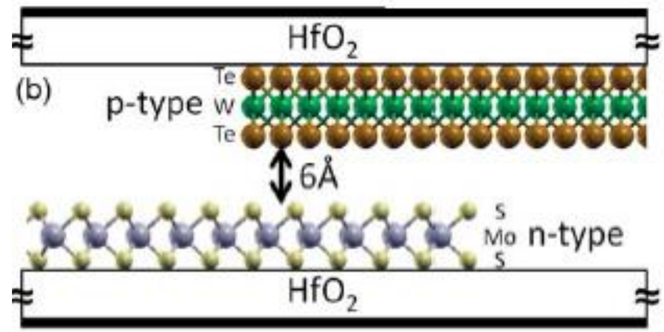


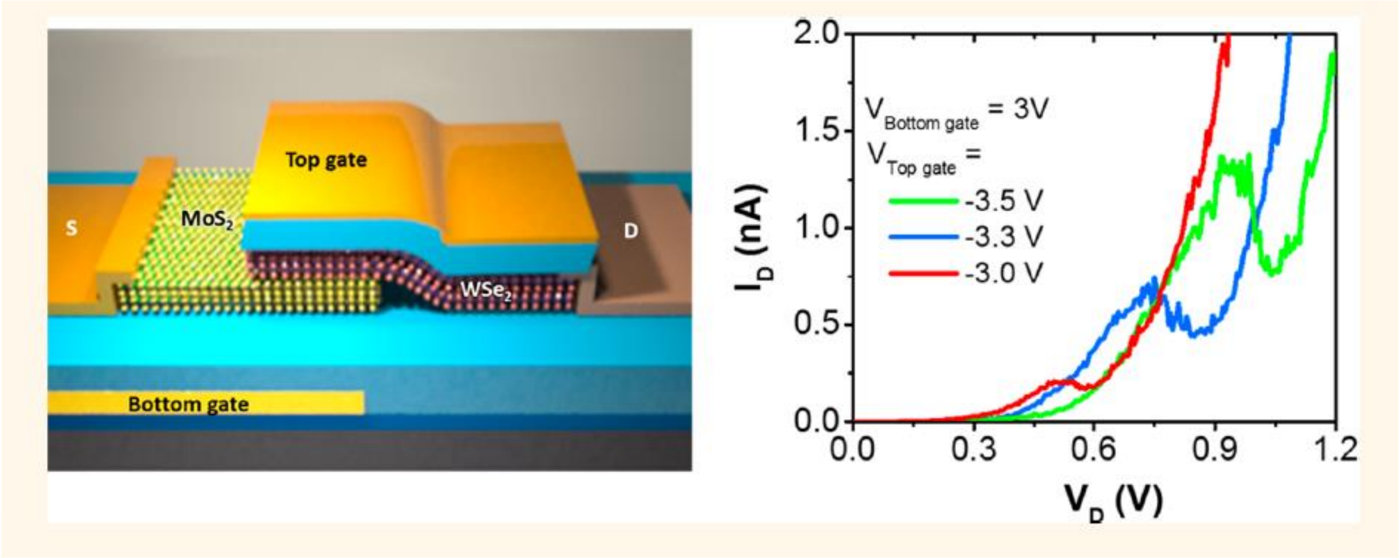
Gong et al., Appl. Phys. Lett. 103, 053513 (2013)

Security C – TSMC Secret

2D Heterojunction Vertical TFET







T. Roy et al., ACS Nano 9, 2071 (2015)

Benchmarking of Beyond-CMOS Exploratory Devices for Logic Integrated Circuits

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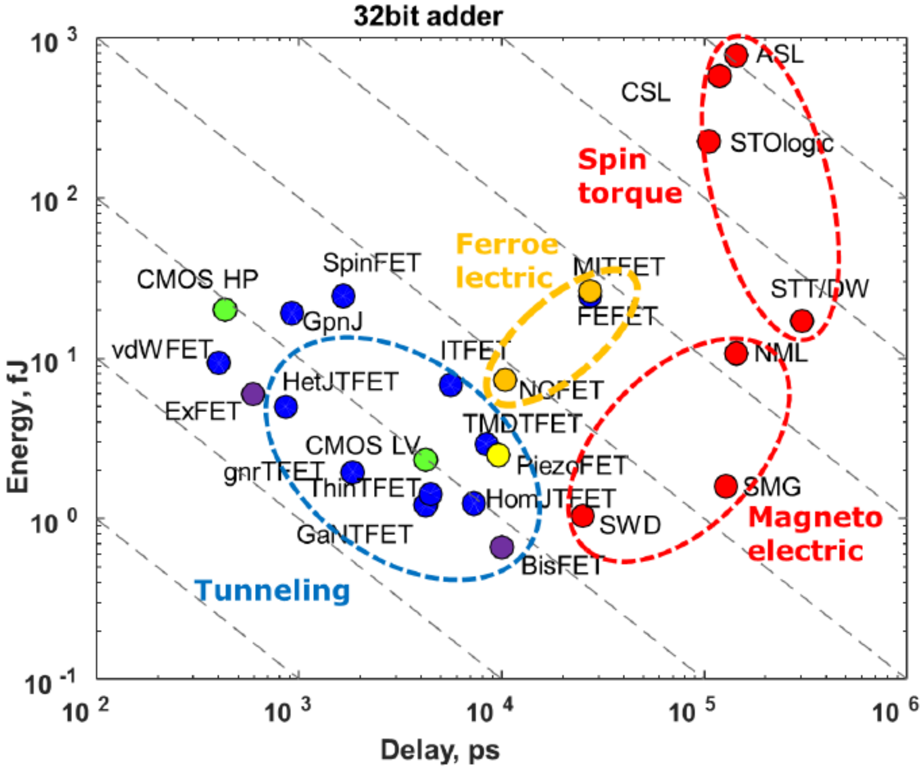

Device name	acronym	material
Si MOSFET high perf.	CMOS HP	silicon
Si MOSFET low voltage	CMOS LV	InAs
van der Walls FET	vdWFET	MoS_2
Homojunction III-V TFET	HomJTFET	InAs
Heterojunction III-V TFET	HetJTFET	GaSb/InAs
Graphene nanoribbon TFET	gnrFTET	graphene
Interlayer tunneling FET	ITFET	graphene
Two D Heterojunction Interlayer TFET	ThinFET	$WTe_2/SnSe_2$
GaN TFET	GaNFET	GaN
Transition Metal Dichalchogenide TFET	TMDTFET	WTe_2
Graphene pn-junction	GpnJ	graphene

D. E. Nikonov and I. A. Young
IEEE J. XCDC 1 (2015)

Tunnel FETs are promising for better EDP than Si MOSFETs.

Conclusion

Proprietary & Confidential

- 2D materials have potential for future electronics
  - The real and unique benefits is the atomically thin body
- So far, experimental studies have yet to demonstrate the full advantage and potential of 2D materials for electronic devices
  - Short history of only ~4 year for TMDs and ~1 year for BP
- Materials synthesis will be one deterministic factor
  - Most 2D materials in their bulk form has been extensively used in industrial applications
  - Defect density?
- Other fundamental challenges
  - Contact resistance
  - Doping scheme
  - Gate stack options

Thank you