Two-Dimensional van der Waals Heterostructures for Quantum Transport and Ultrafast Optoelectronics

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2018.04.18

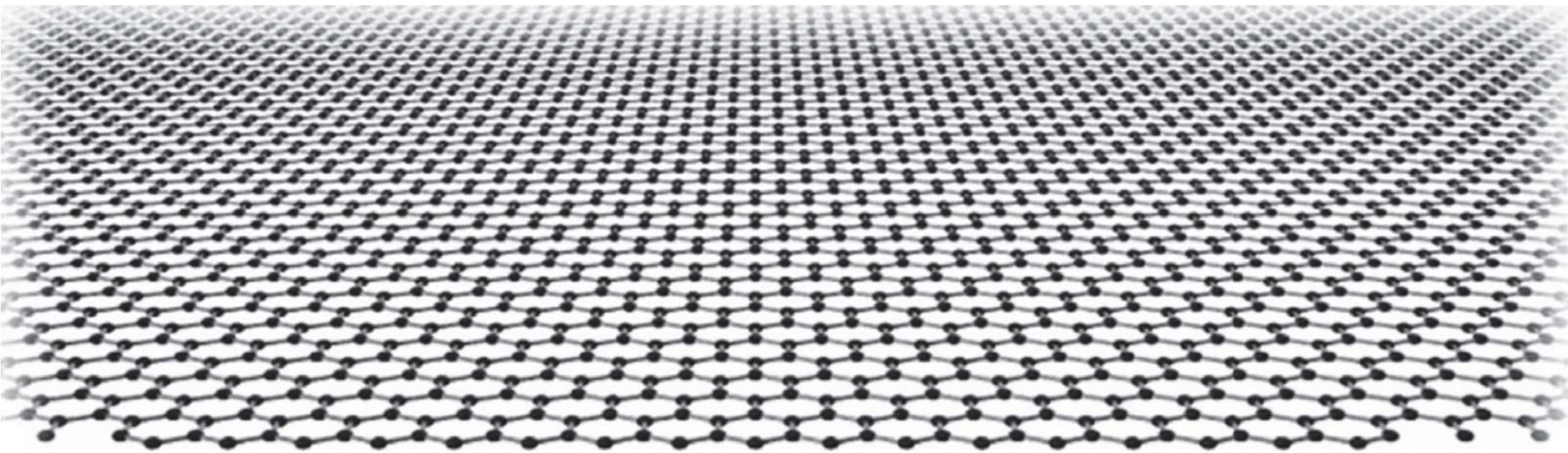
Graphene

One atomic thick carbon film.

First 2D material in human history.

2D = Graphene

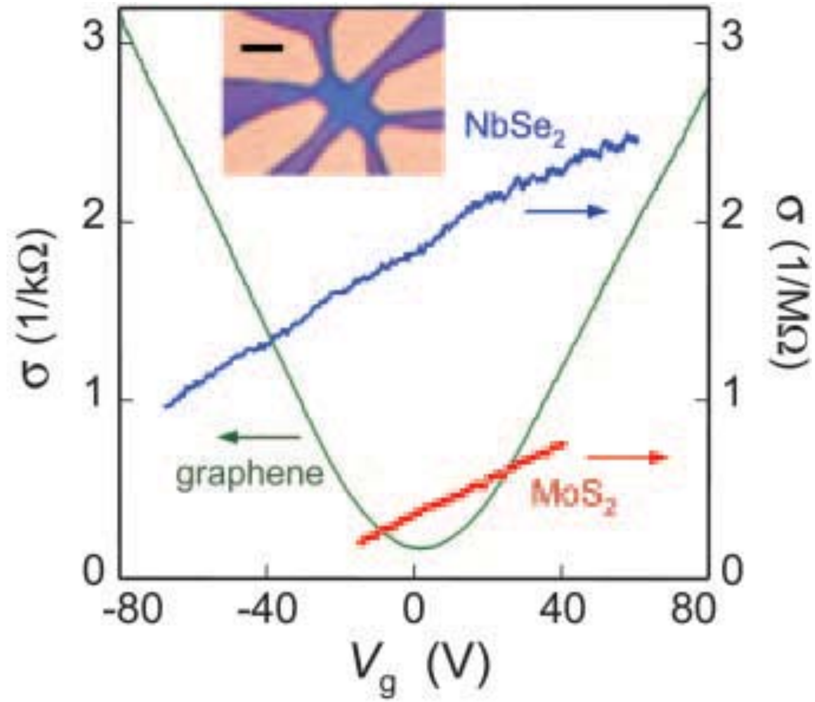
3D = Graphite



Discover of Graphene

Andre Geim

Konstntin Novoselov



Two-dimensional atomic crystals

K. S. Novoselov*, D. Jiang*, F. Schedin*, T. J. Booth*, V. V. Khotkevich*, S. V. Morozov†, and A. K. Geim*‡

*Centre for Mesoscience and Nanotechnology and School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom; and †Institute for Microelectronics Technology, Chernogolovka 142432, Russia

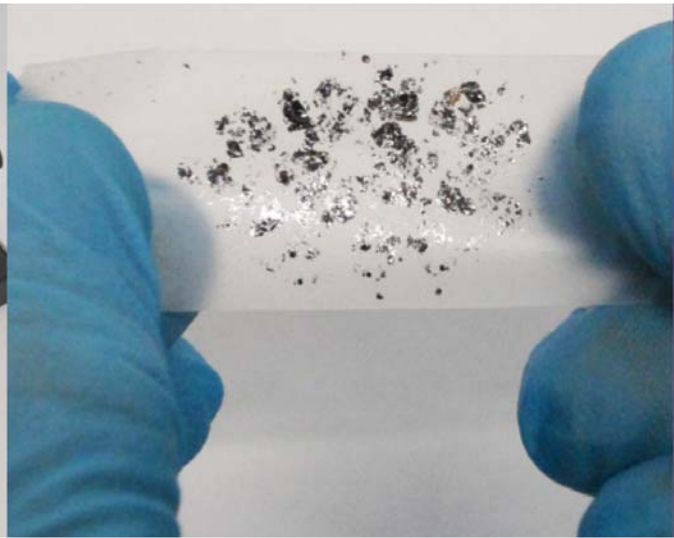
Edited by T. Maurice Rice, Swiss Federal Institute of Technology, Zurich, Switzerland, and approved June 7, 2005 (received for review April 6, 2005)

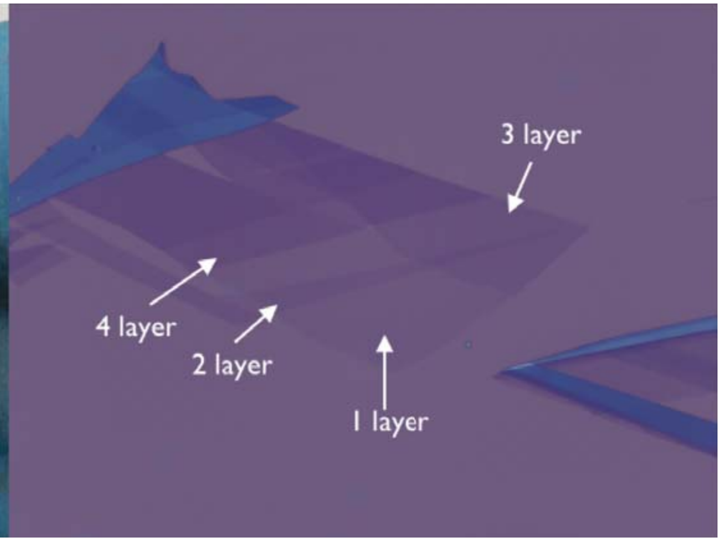
We report free-standing atomic crystals that are strictly 2D and can be viewed as individual atomic planes pulled out of bulk crystals or as unrolled single-wall nanotubes. By using micromechanical cleavage, we have prepared and studied a variety of 2D crystals including single layers of boron nitride, graphite, several dichalcogenides, and complex oxides. These atomically thin sheets (essentially gigantic 2D molecules unprotected from the immediate environment) are stable under ambient conditions, exhibit high crystal quality, and are continuous on a macroscopic scale.

graphene | layered material

wafer (Fig. 1*d*), because even a monolayer adds up sufficiently to the optical path of reflected light so that the interference color changes with respect to the one of an empty substrate (phase contrast). The whole procedure takes literally half an hour to implement and identify probable 2D crystallites. Their further analysis was done by atomic force microscopy (AFM), for which single-layer crystals were selected as those exhibiting an apparent (12) thickness of approximately the interlayer distance in the corresponding 3D crystals.

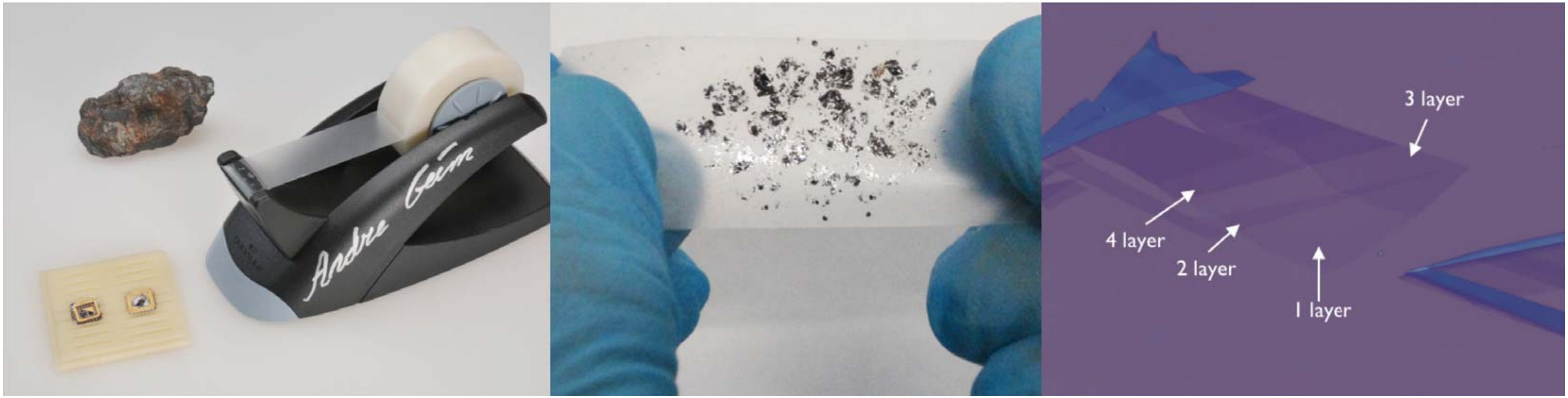
Despite its simplicity, the described cleavage technique has several nonobvious features that are instructive to analyze,





Layered Material

Discover of Graphene



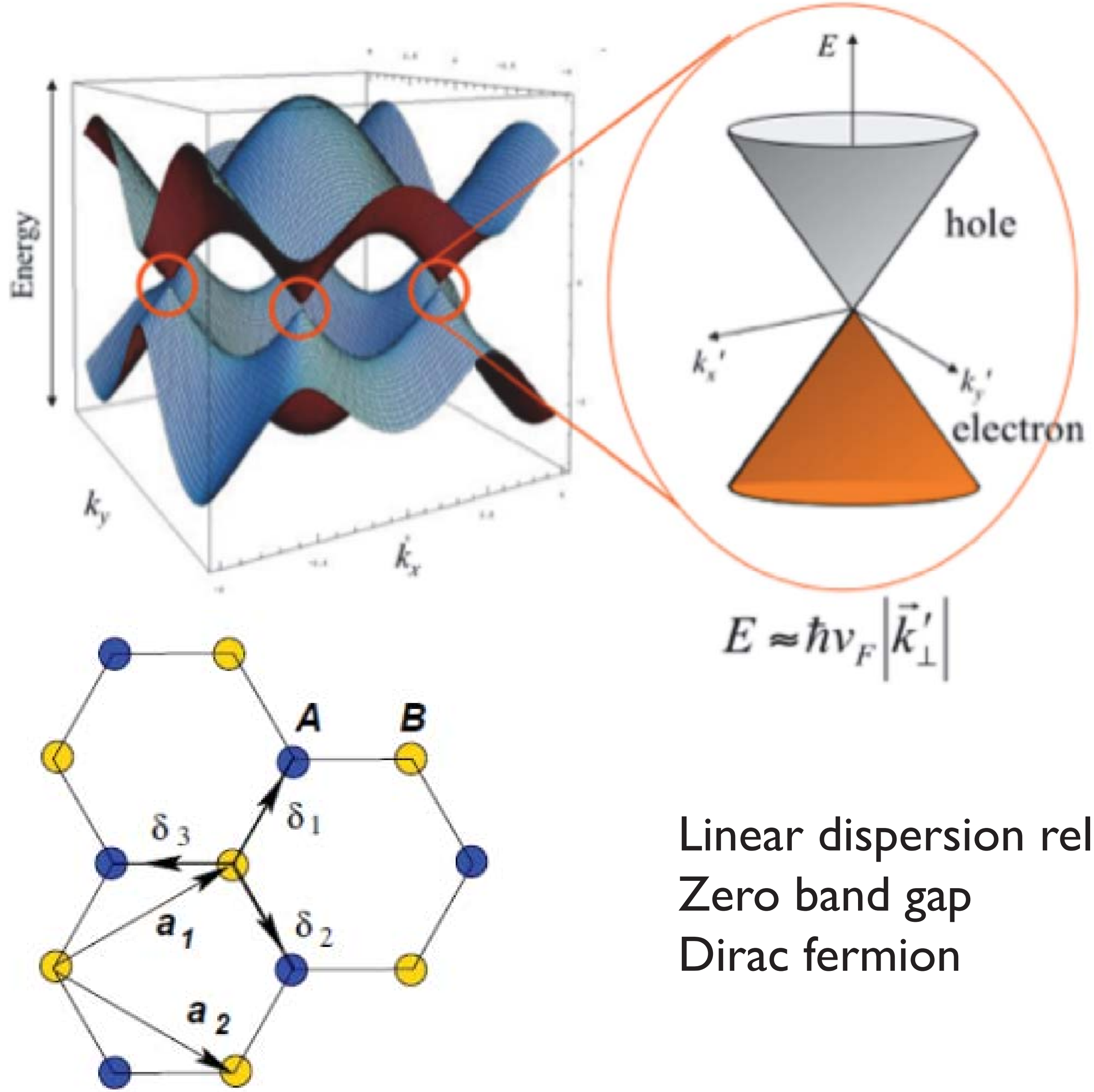
The Nobel Prize in Physics 2010

"for groundbreaking experiments regarding the two-dimensional material graphene"

Andre Geim

Konstntin Noveselov

Graphene: Dirac Particles in 2D

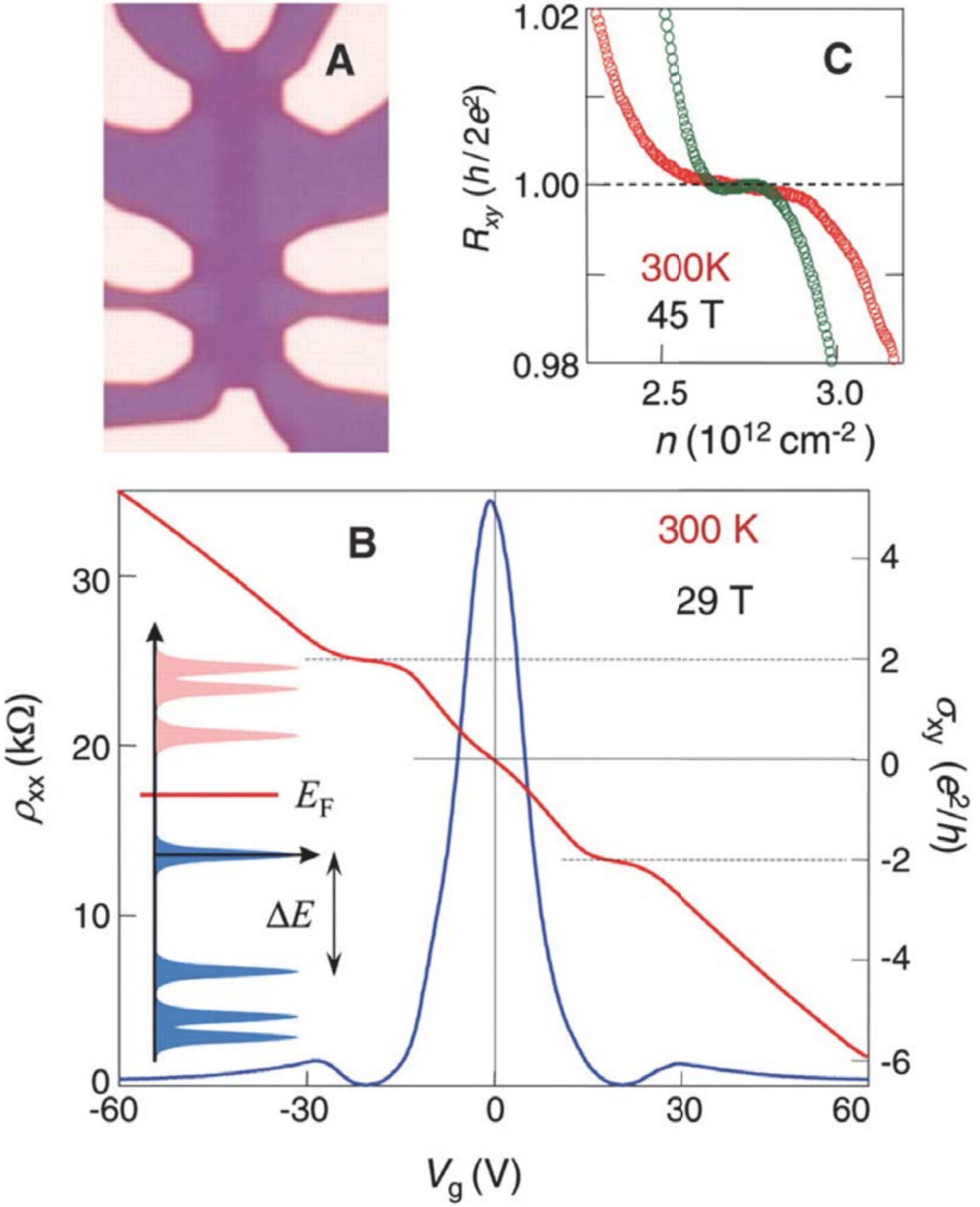


$$E \approx \hbar v_F \left|\vec{k}'_\perp\right|$$

Linear dispersion relation
Zero band gap
Dirac fermion

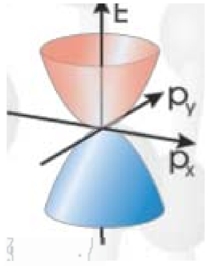
Room Temperature Quantum Hall Effect

T= 300 K, High magnetic field



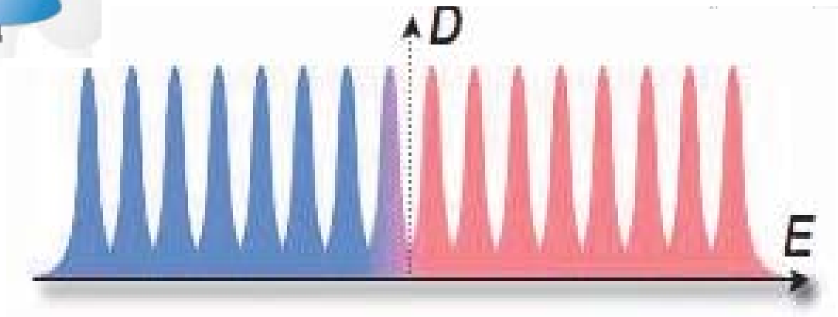
K.S. Novoselov et al, Science 315, 1379 (2007)

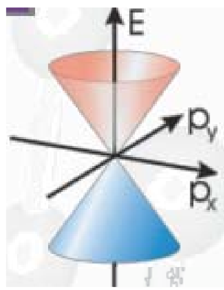
Landau level splitting



Standard 2DEG

$$E_n = E + \hbar eB/m^*(n + 1/2)$$

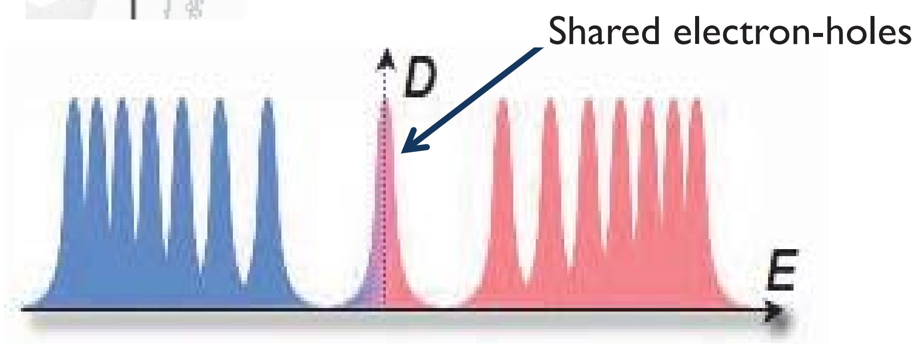




Relativistic

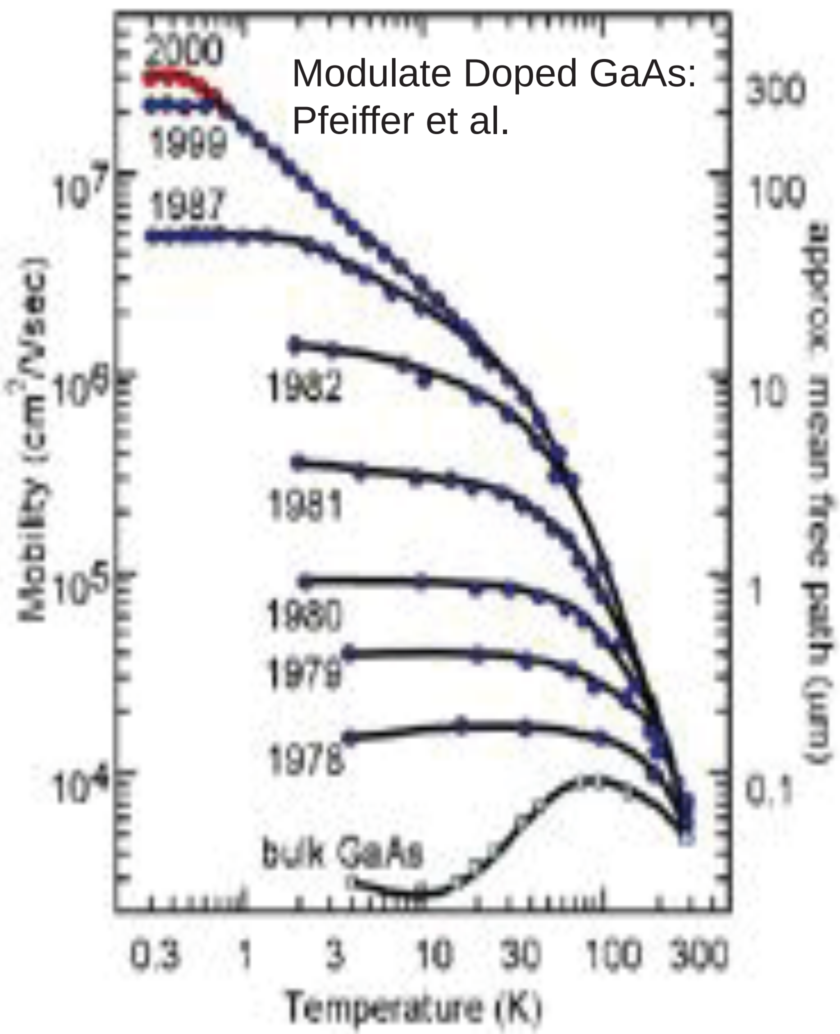
$$E_n = \pm\sqrt{2e\hbar v_F^2|n|B}$$

$E_1 \sim 100\ meV$ at 5 T

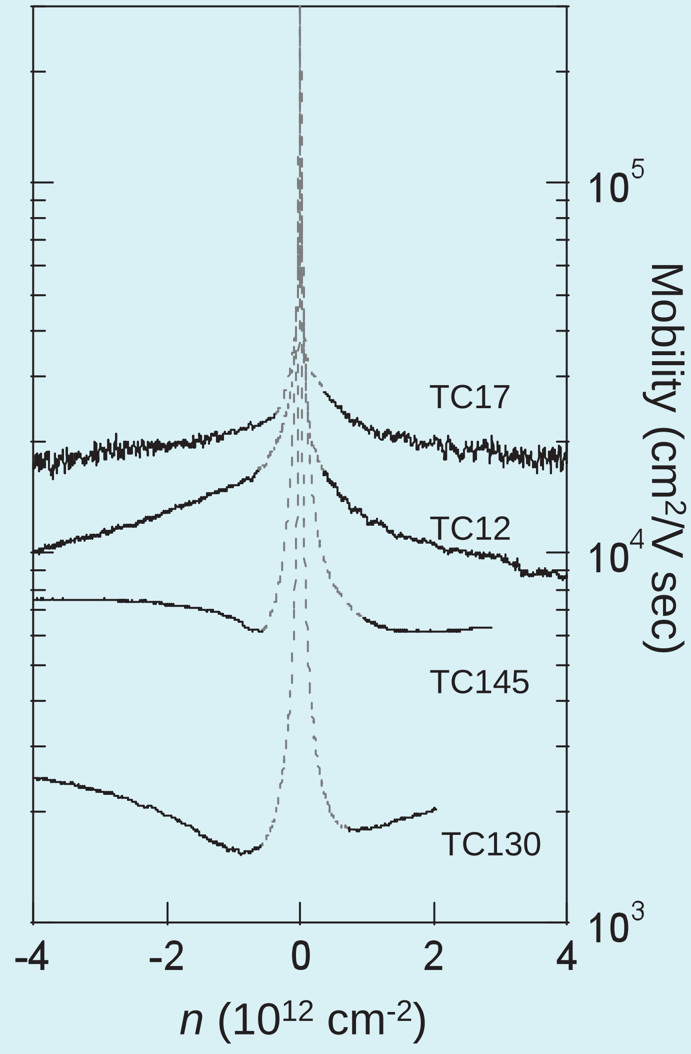


Graphene Mobility

GaAs HEMT



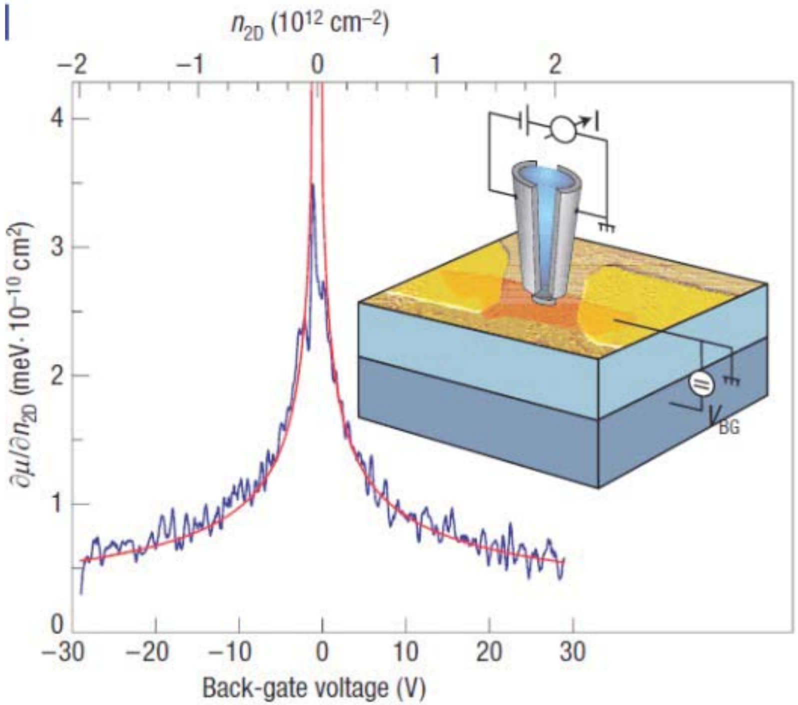
Graphene Mobility



Tan et al. PLR (2007)

Graphene on SiO_2 mobility (<20,000 cm^2/V.s) is smaller than theoretical expectation.
Material intrinsic disorder or extrinsic effect?

Graphene Mobility

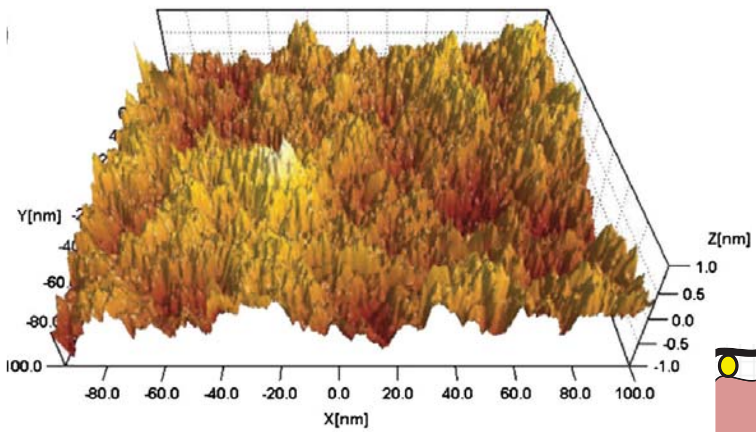


Bulk

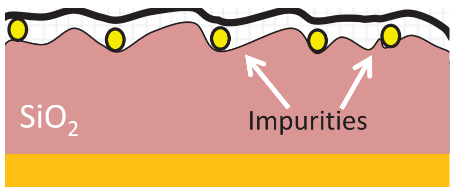
VS

2D

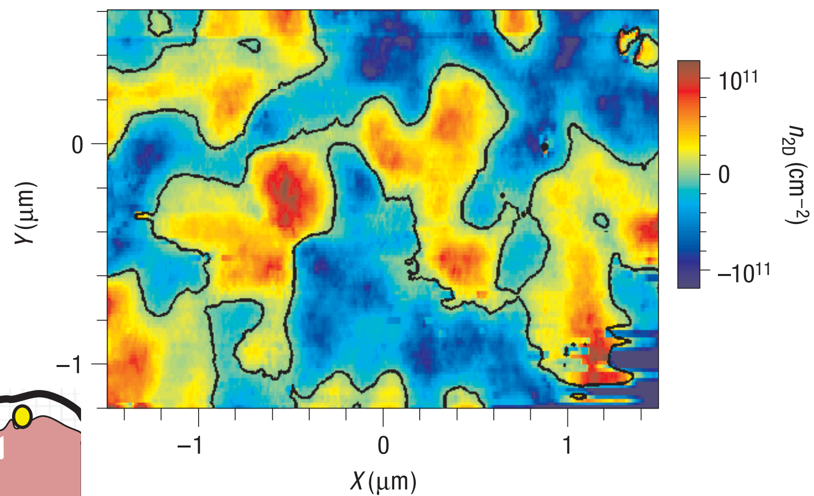
Surface roughness



J. Martin et al, Nature Physics, (2008)



e-h puddles

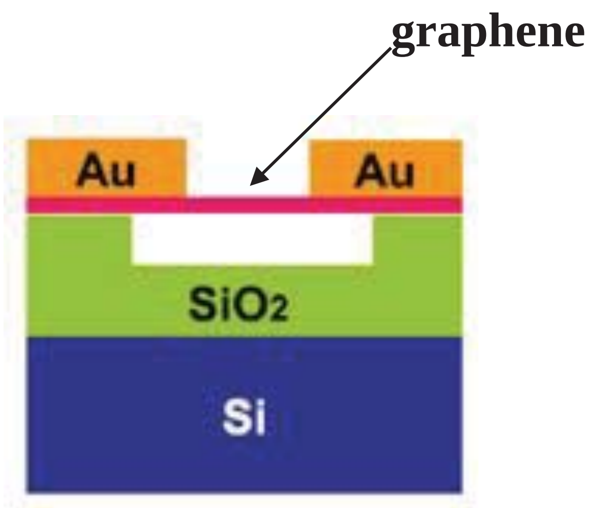


W. G. Cullen et al, Phys. Rev. Lett. (2010)

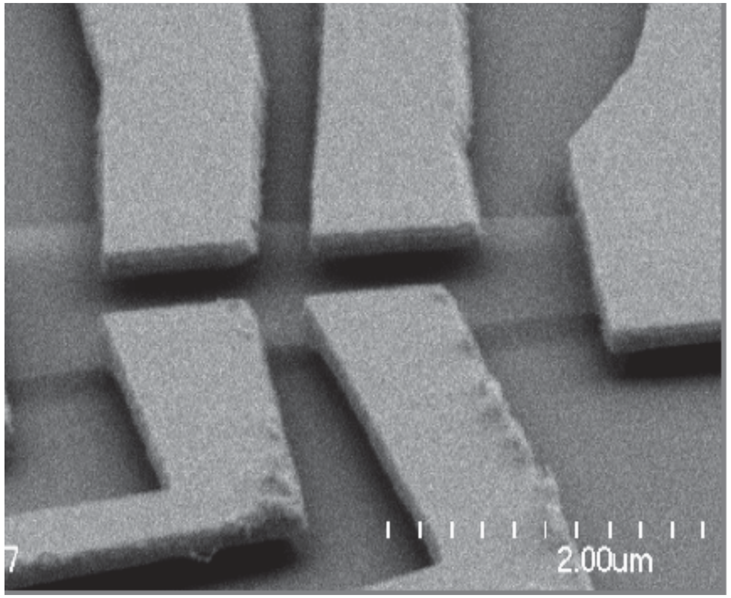
Problem: 3D substrates are not a good match for 2D materials! (Disorder, Scattering, Doping…)

Suspended Graphene

Toward high moblity device



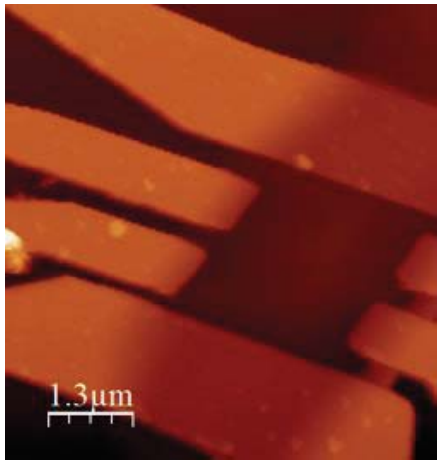
HF etching
-> critical pointing drying

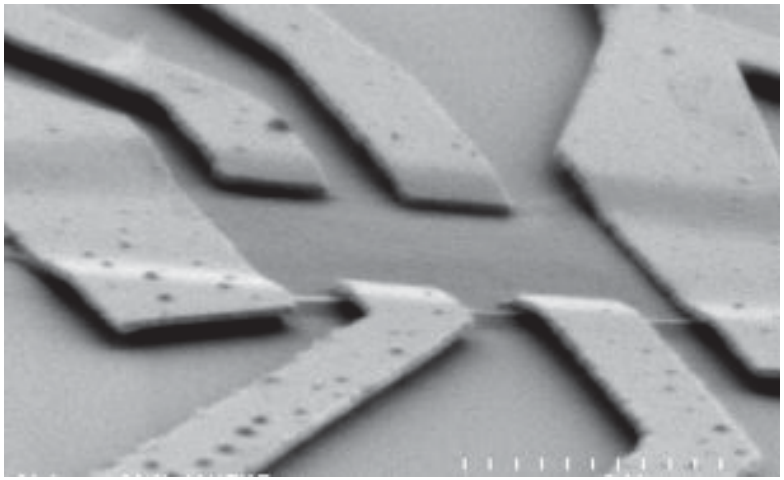


AFM image of suspended graphene

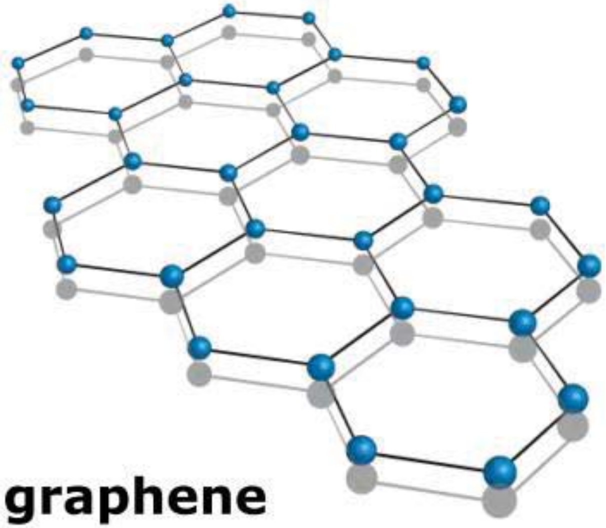
You should not apply to high gate voltage, otherwise…

Collapsed graphene devices…

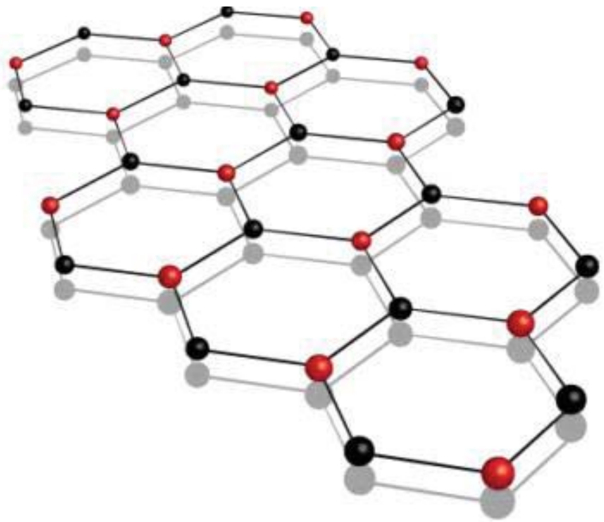




Hexagonal Boron Nitride



graphene

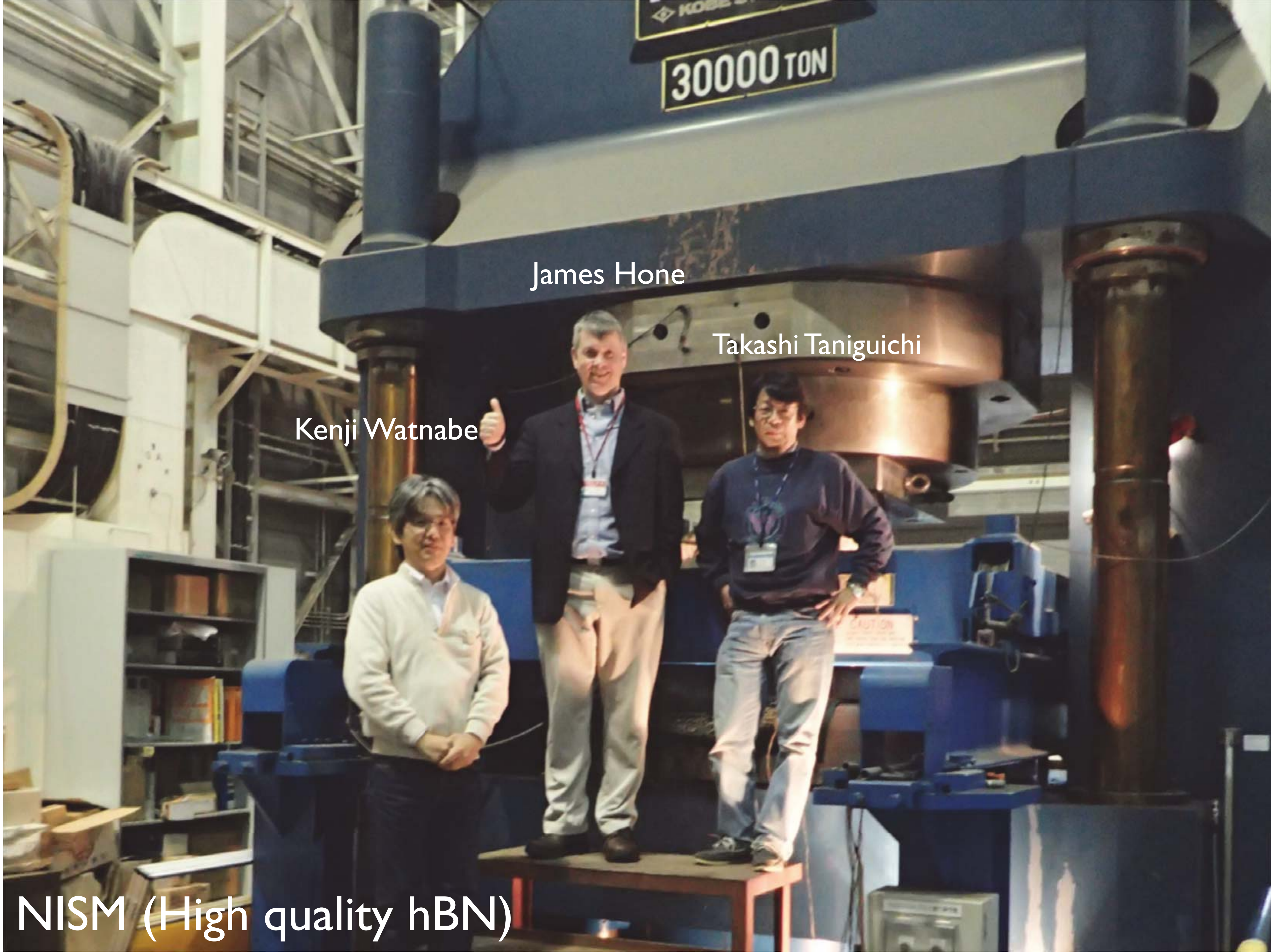


Boron Nitride

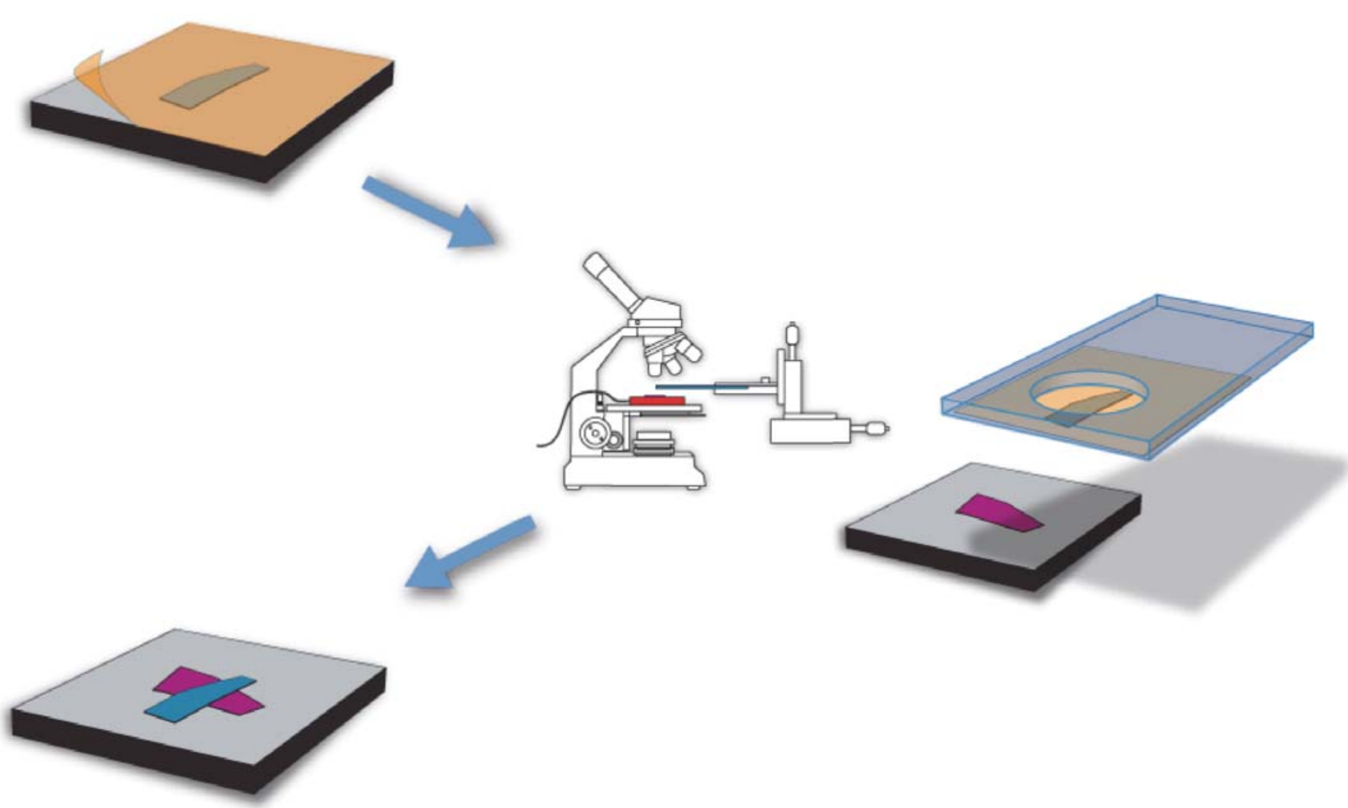
Comparison of h-BN and SiO_2

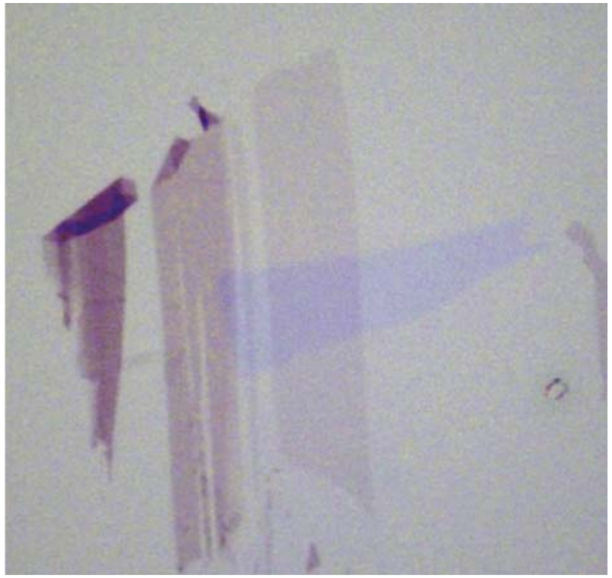
	Band Gap	Dielectric Constant	Optical Phonon Energy	Structure
BN	5.5 eV	~4	>150 meV	Layered crystal
SiO2	8.9 eV	3.9	59 meV	Amorphous

- < 2% lattice mismatch to graphene
- atomically flat
- chemically inert, stable to high temp.
- no dangling bonds- good dielectric properties


30000 TON
James Hone
Takashi Taniguichi
Kenji Watnabe
NISM (High quality hBN)

Polymer Transfer of Graphene onto hBN

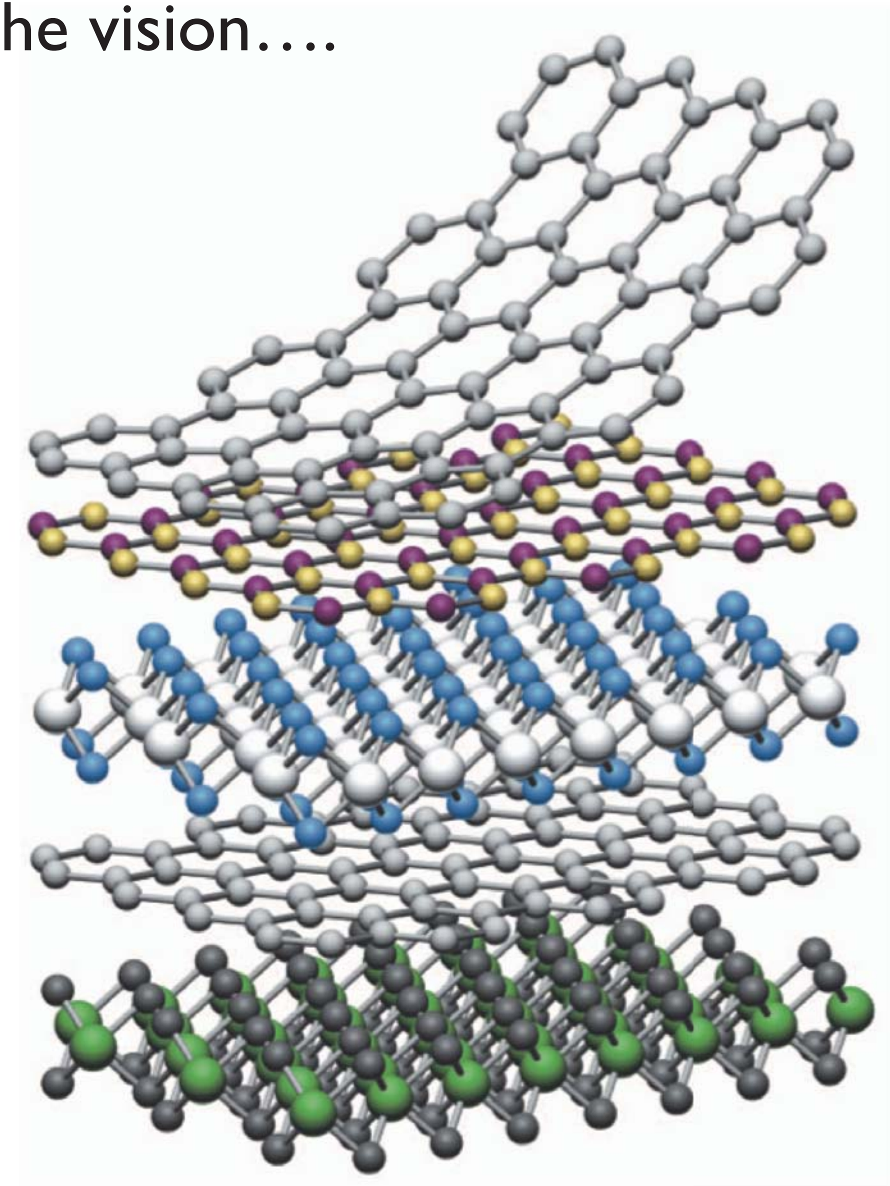




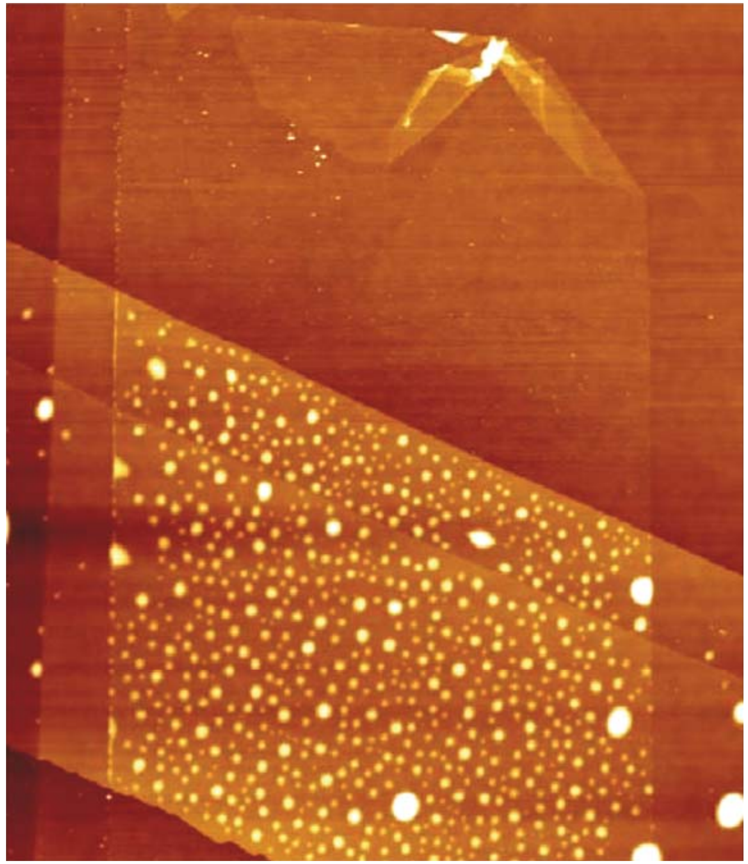
C.R. Dean

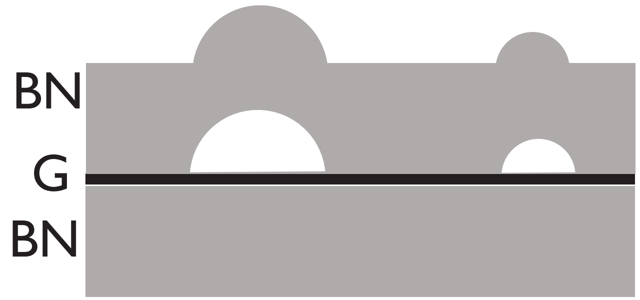
Making Layered Structures

The vision….

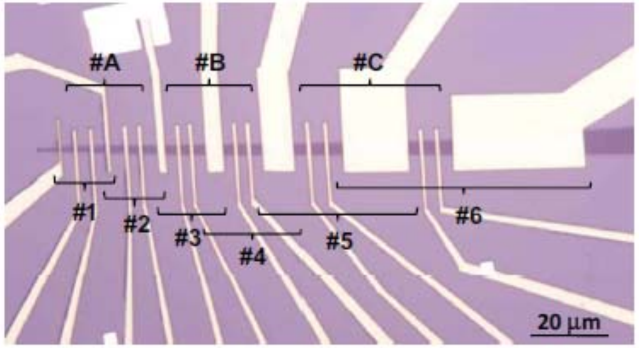


The reality…



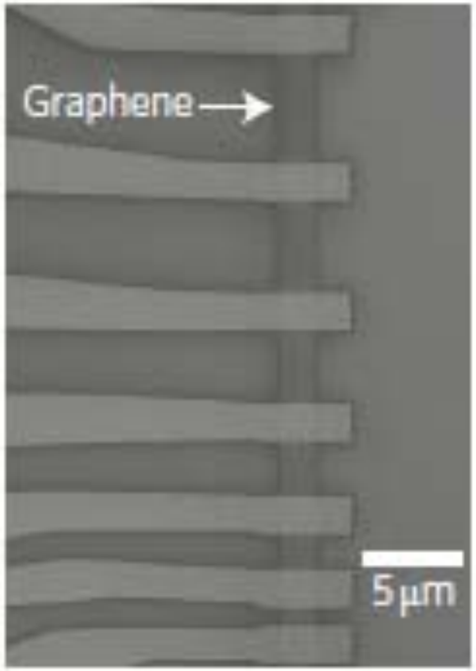


Motivation for Edge Contact

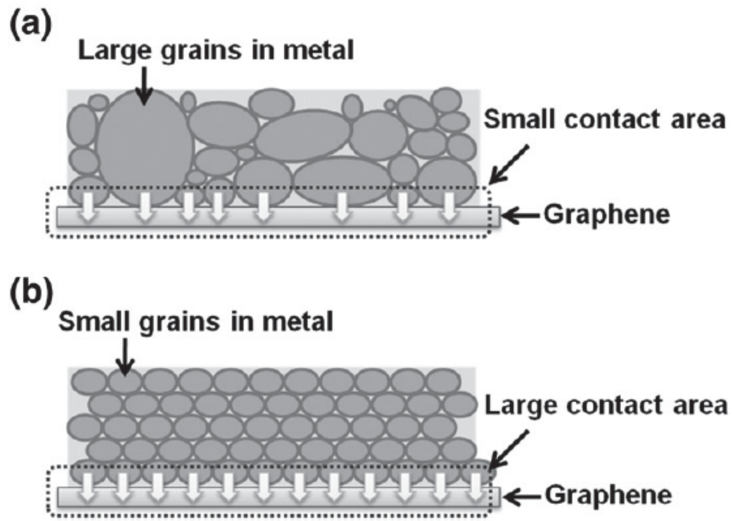


K. Nagashio, *et al* IEDM. 2009

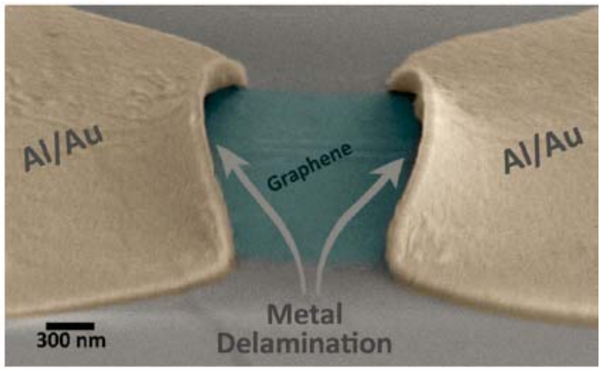
"Metal/Graphene Contact as a Performance Killer of Ultra-high Mobility Graphene"



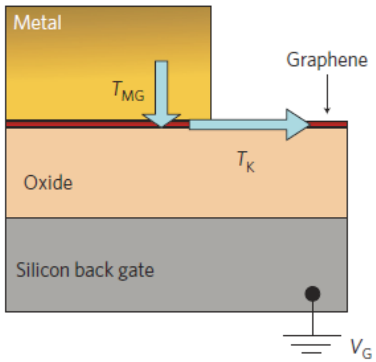
F. Xia *et al* Nature nano. 2011

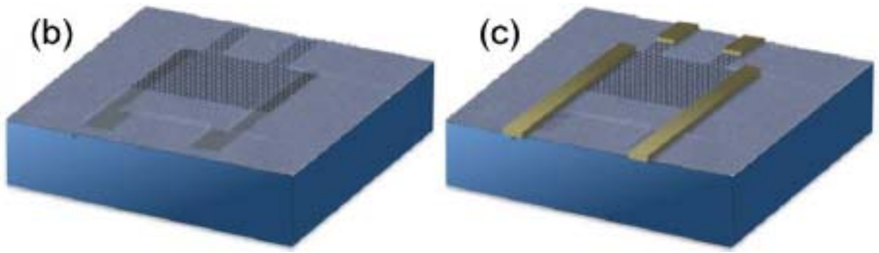


E. Watanabe *et al* D.R.M. 2012



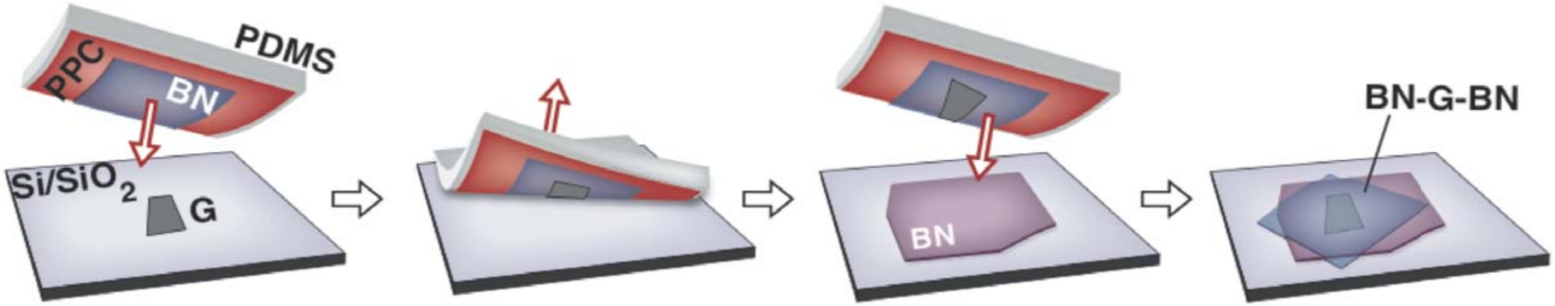
J.A. Robinson, *et al* APL. 2011

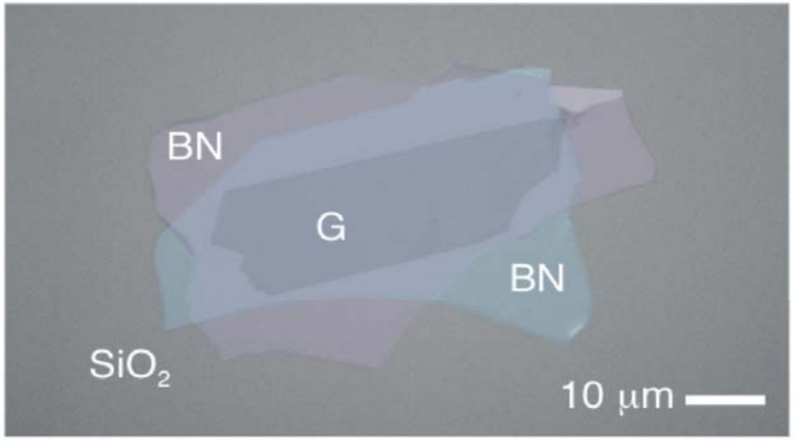


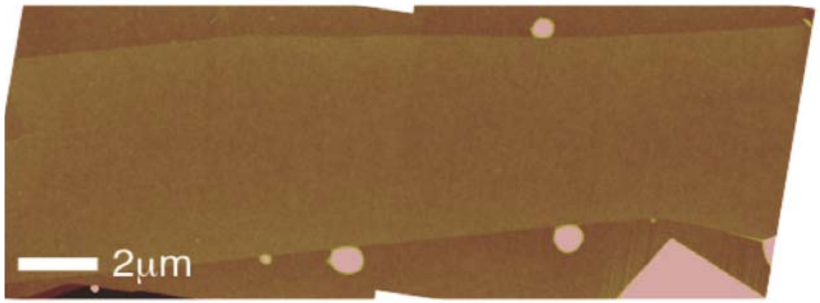


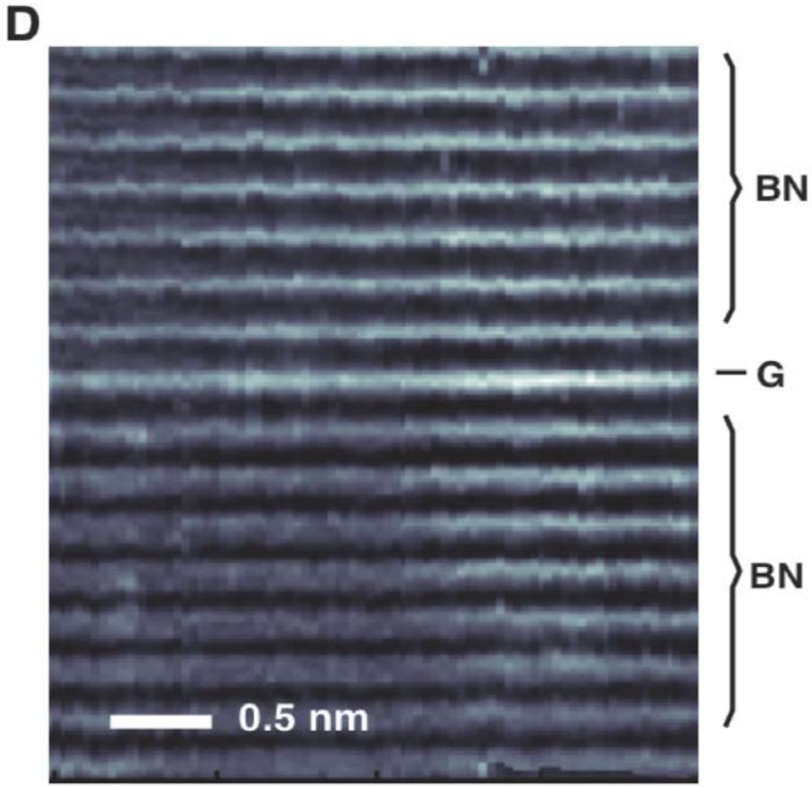
A. D. Franklin *et al* . IEEE EDL 2012

Van der Waals Assembly





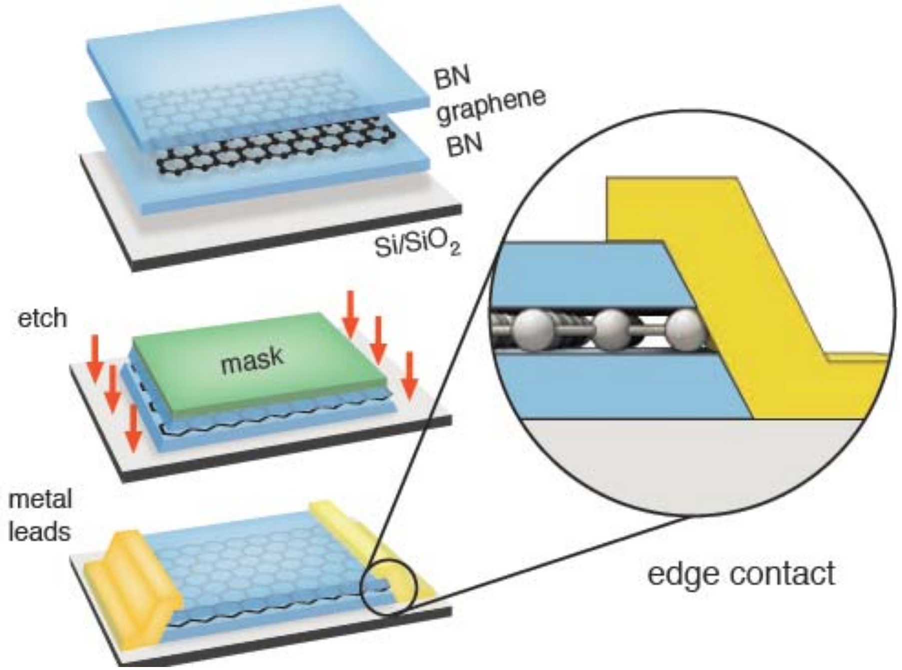


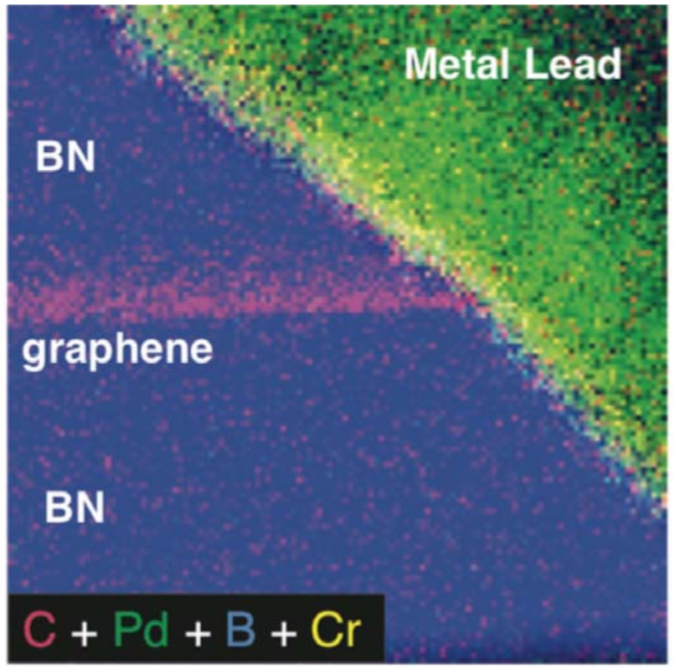


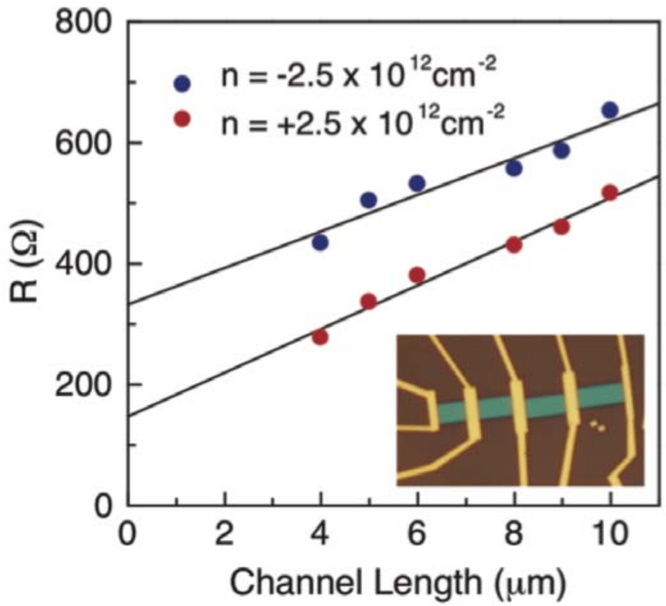
L. Wang et al, Science (2013)

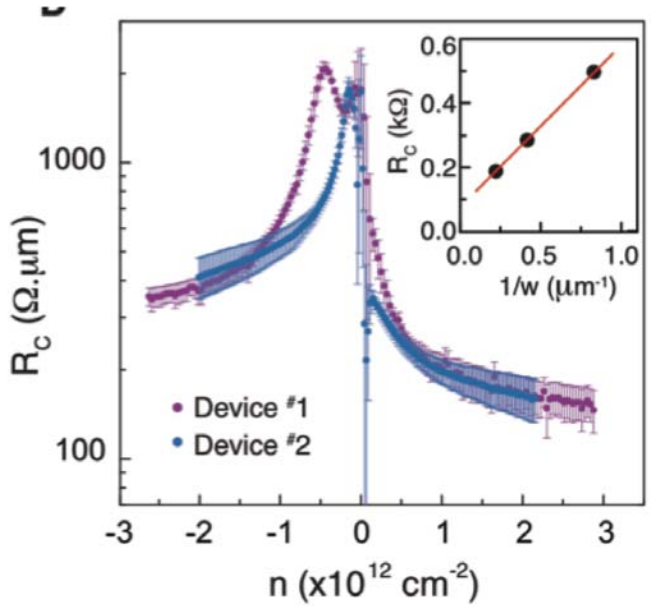
Ultraclean technique – graphene never exposed to polymer

Edge Contacts



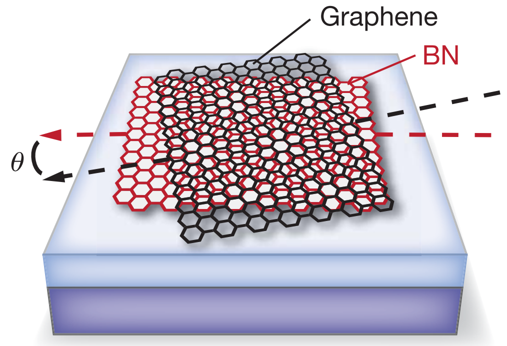


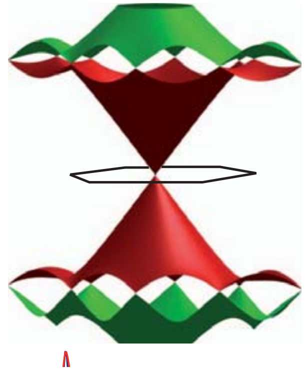


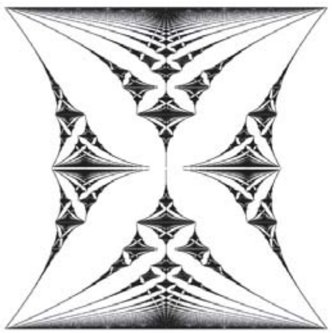


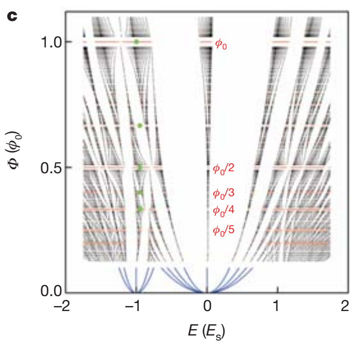
Graphene Quantum Transport

Superlattice and Hofstadter butterfly

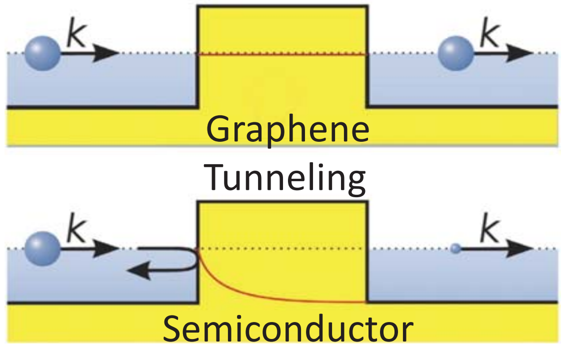


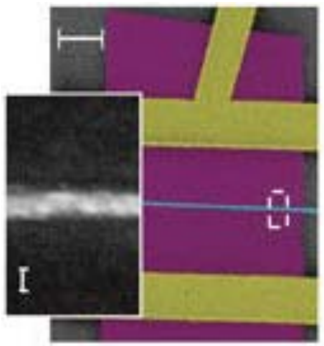


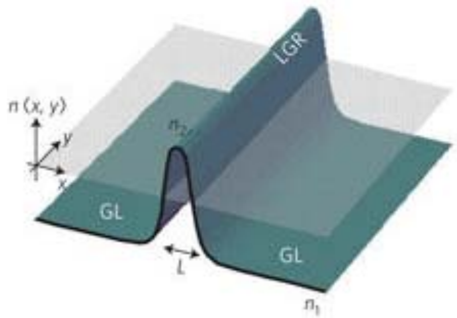




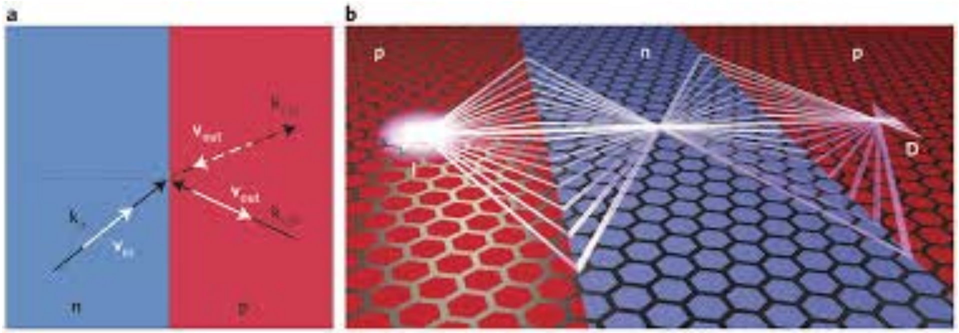
Klein tunneling in graphene

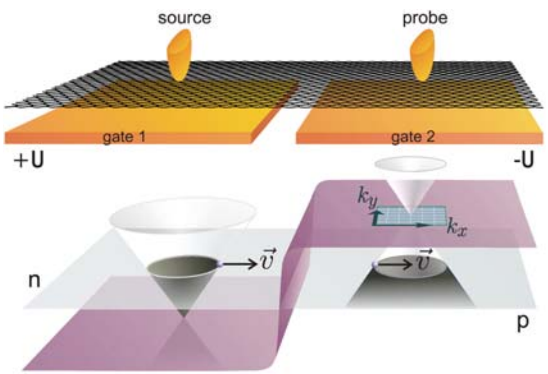




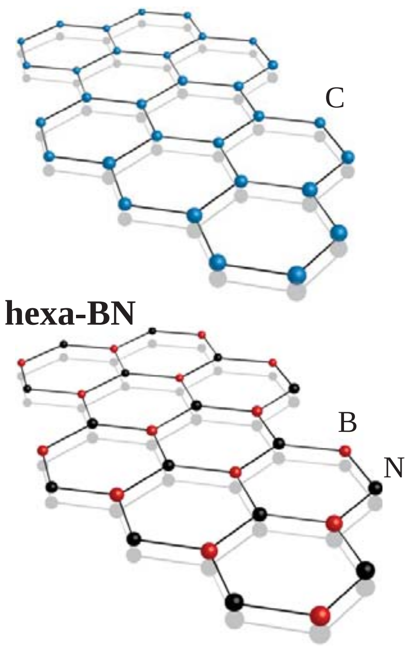


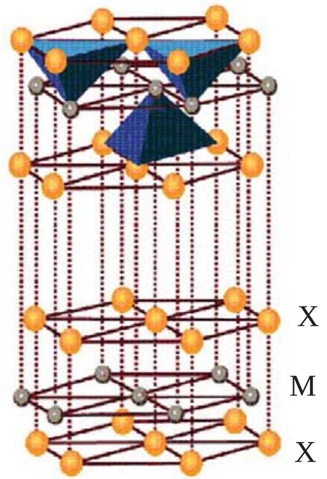
Negative refraction and Veselago lens (Electro-Optics)

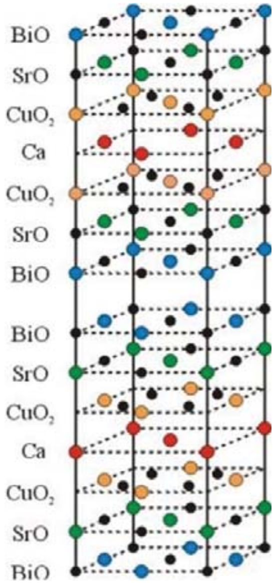


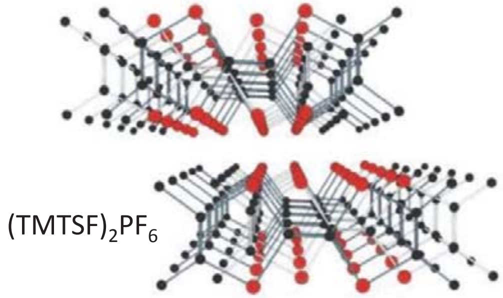


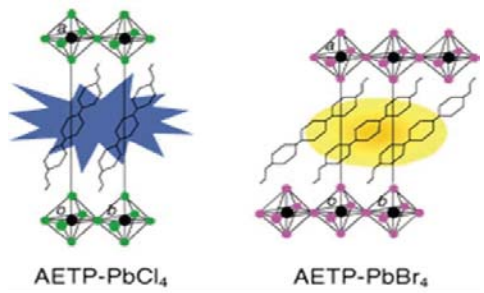
Beyond Graphene











from P. Kim group

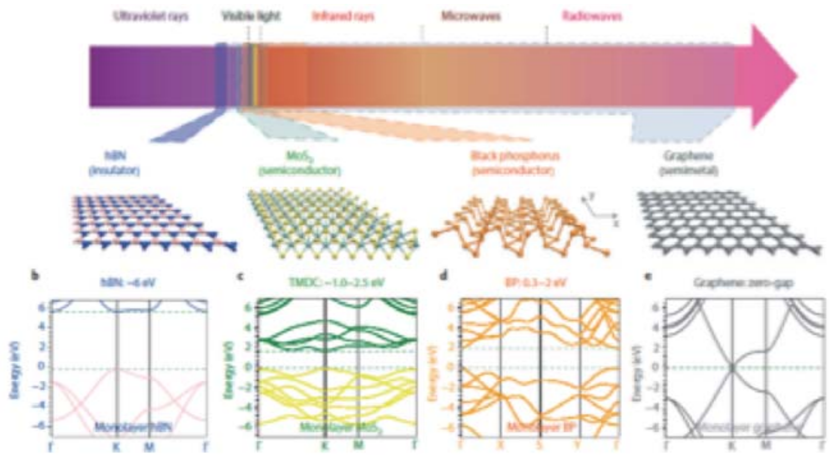
Semi metal: Graphene, …

Insulator: hBN, …

Semiconductor: MoS_2, $MoSe_2$, WSe_2, WS_2, …

Superconductor: $NbSe_2$, $Bi_2Sr_2CaCu_2O_{8-x}$, ZrNCl …

Complex-metallic compound: TaS_2, $TaSe_2$, …



F. Xia et al., Nature Photonics 8, 899 (2014)

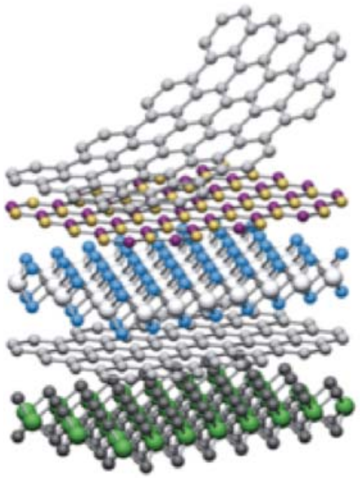
van der Waals Heterostructure

2D building block

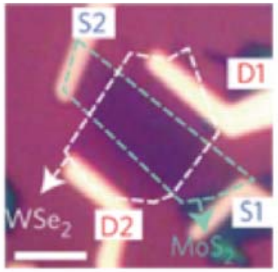
Lego.com

Advanced technology

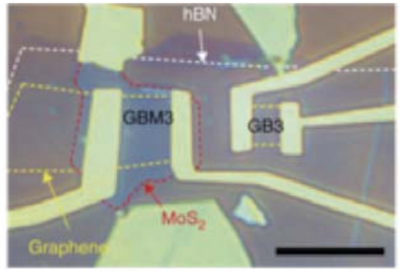
Van der Waals Heterostructure



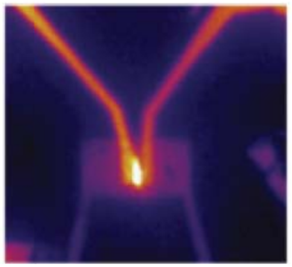
P-N Junction



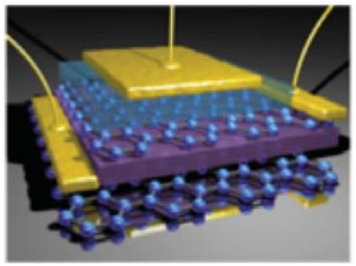
Memory



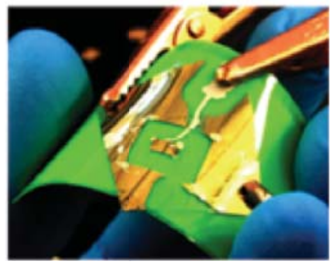
LED



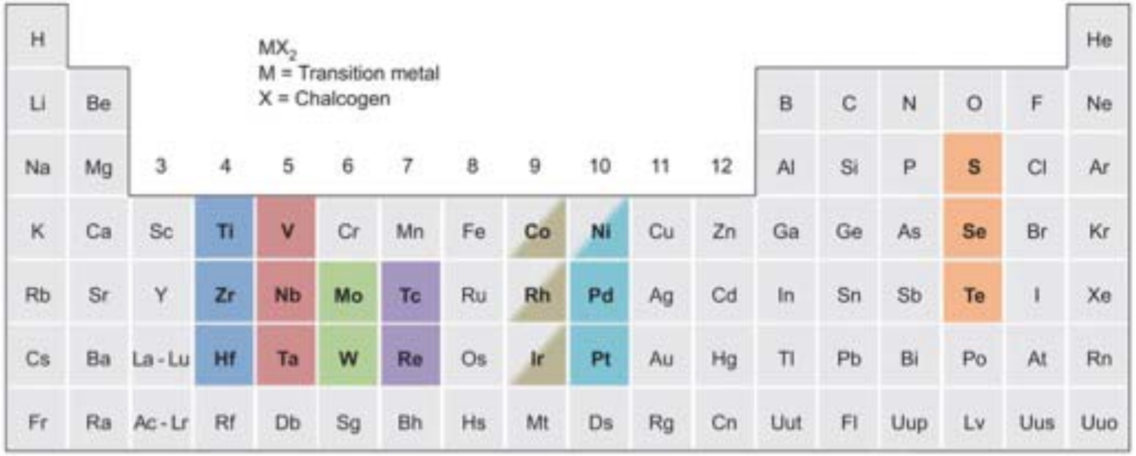
Tunneling Diode



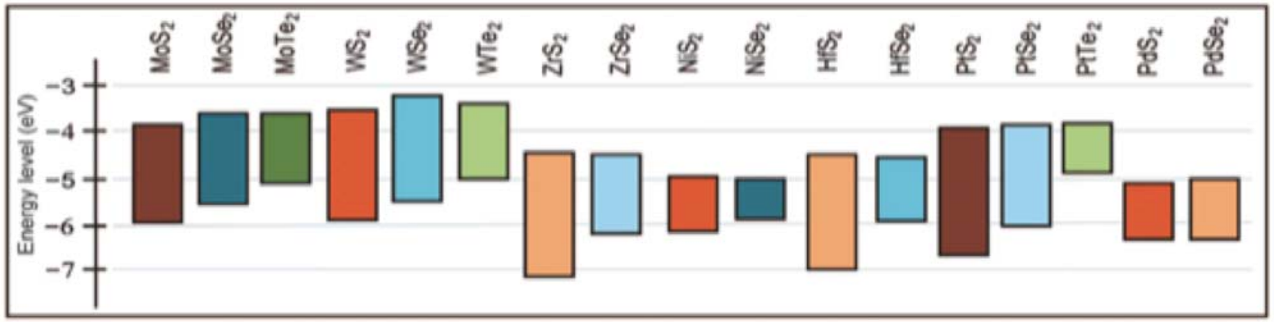
Solar cell



Transition Metal Dichalcogenides (TMDCs)



M. Chhowalla et al, Nature Chemistry (2013)



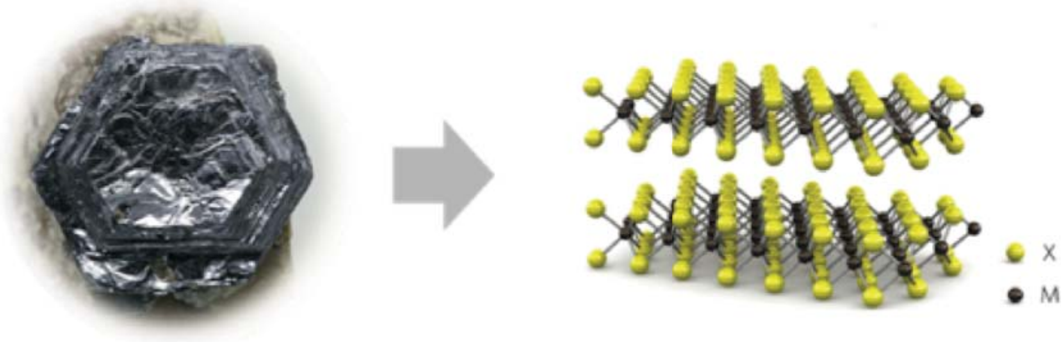
K. Kalantar-zade et al, Advanced Funct. Mat. (2015)

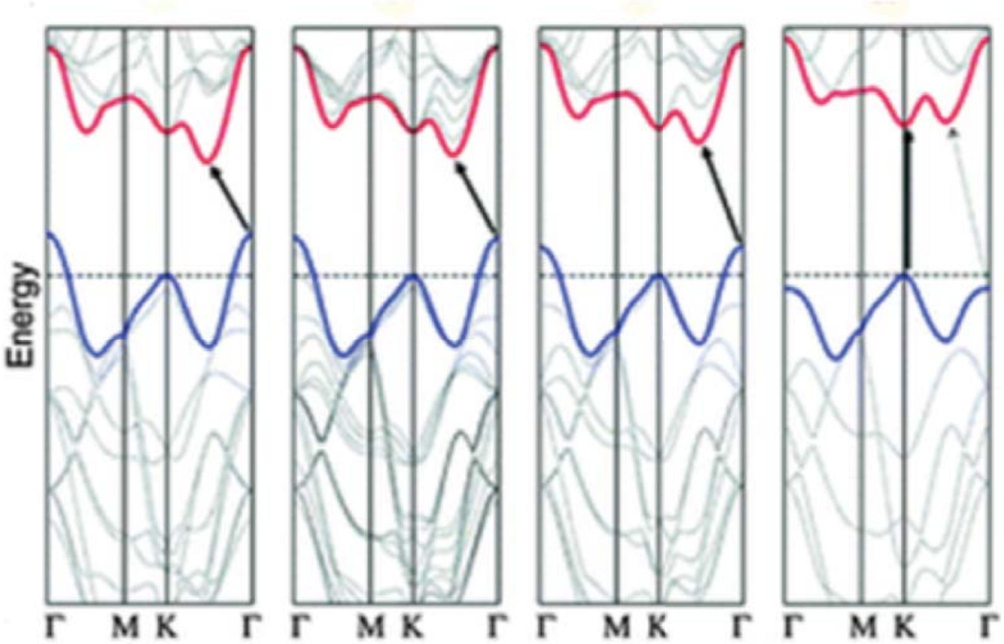
- Semiconductor MoS_2, $MoSe_2$, WS_2, WSe_2, etc (Bandgap 1 ~ 2.5 eV, N/P-type)
- Superconductor: $NbSe_2$, NbS_2
- Charge density wave: TaS_2
- Topological materials: $MoTe_2$, WTe_2

New physics at 2D limit

2D Semiconductor

MoS_2

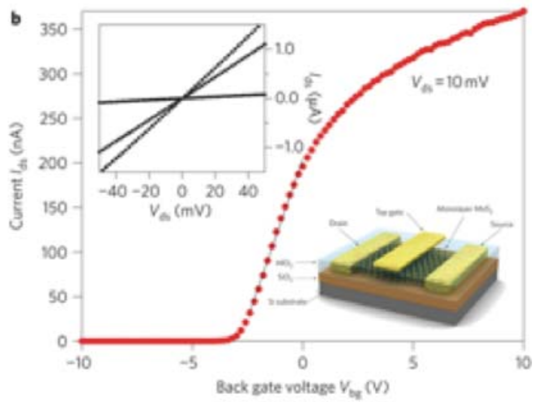




Thickness decreases. →

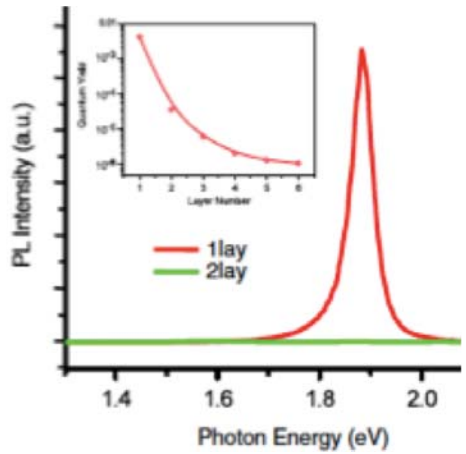
Strong quantum confinement effect

Intrinsic Band gap - High on/off ratio



B. Radisavljevic et al, Nature Nanotech. (2011)

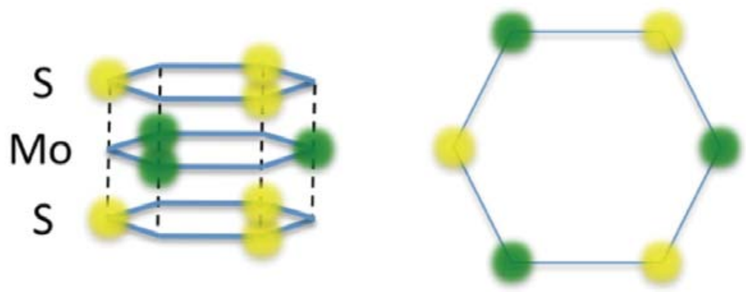
Direct band gap - Photoluminescence



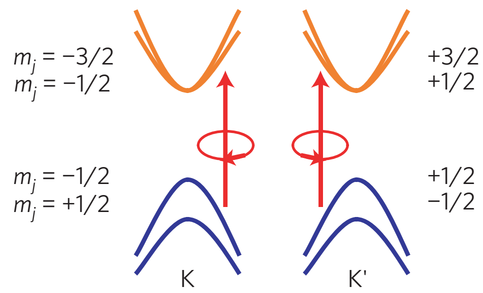
KF. Mak et al, Phys. Rev. Lett. (2010)

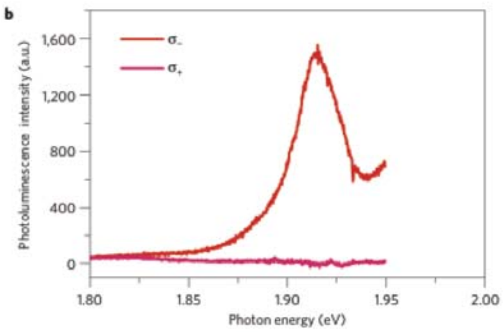
Monolayer TMDC: MoS_2

Broken inversion symmetry



Valley dependent optical selection rule

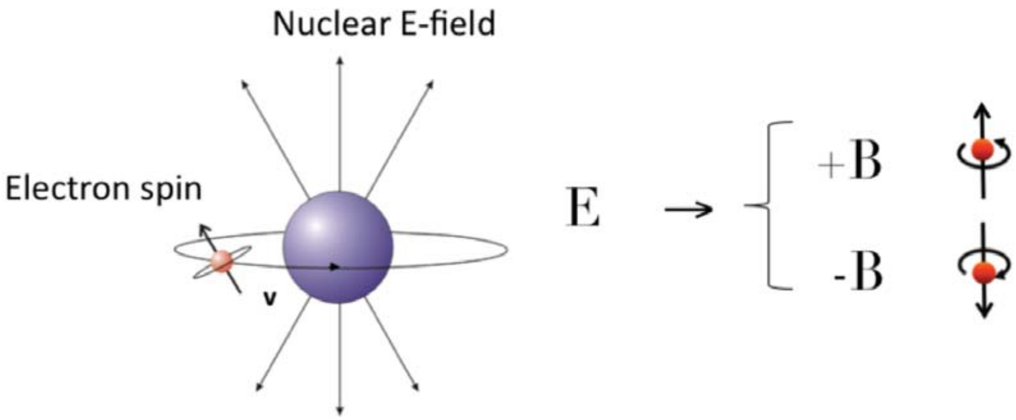




K. F. Mak et al, Nature Nanotechnology (2013)

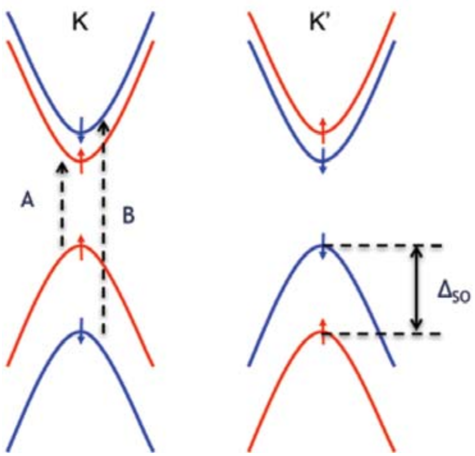
Valley degree of freedom and Berry curvature

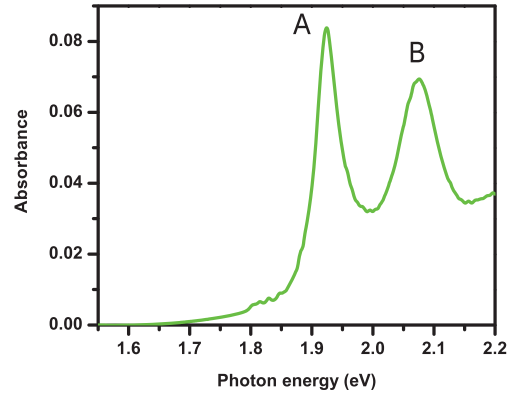
Strong spin-orbit coupling



Spin splitting at zero magnetic field

Optical absorption spectra

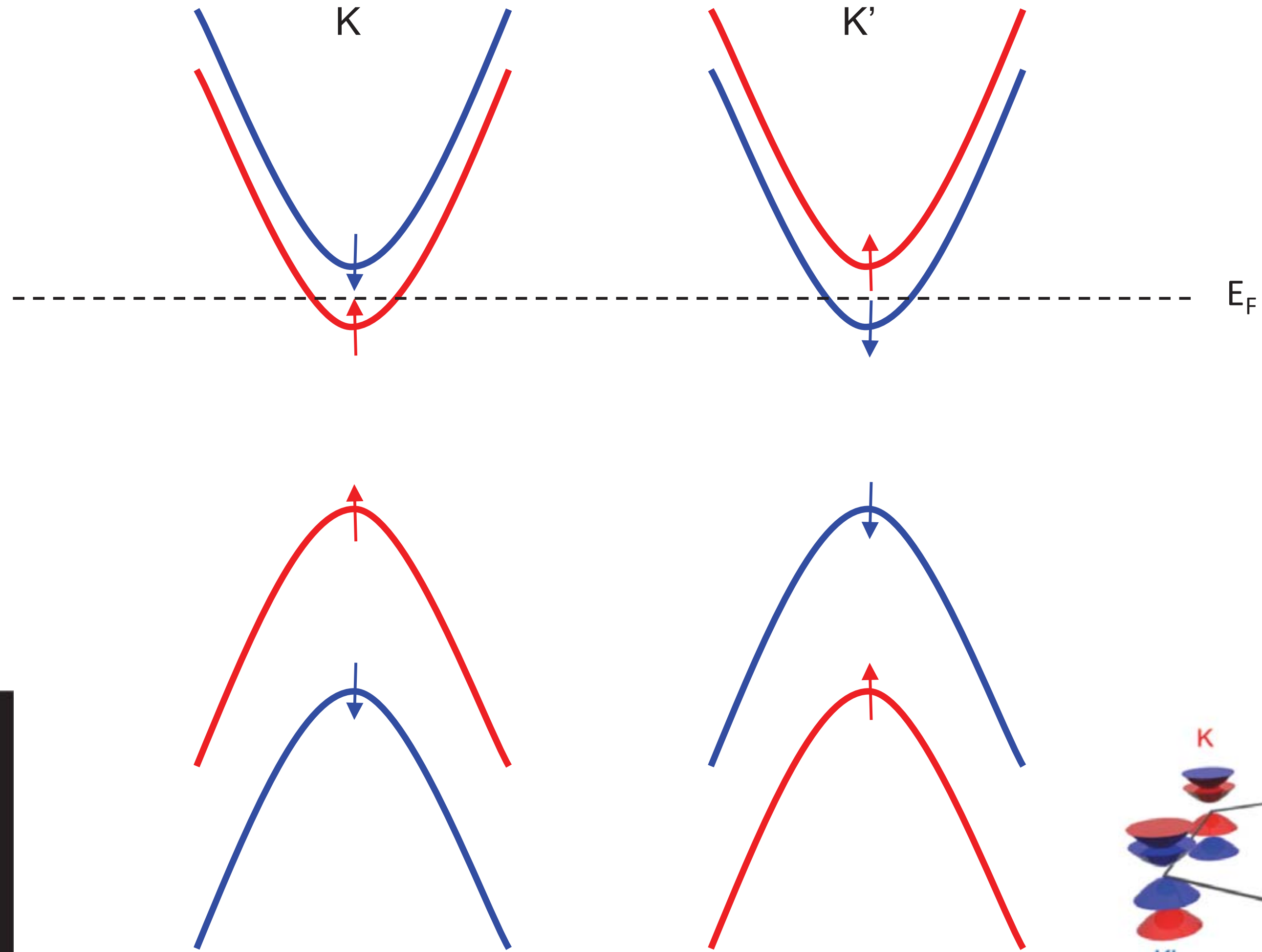




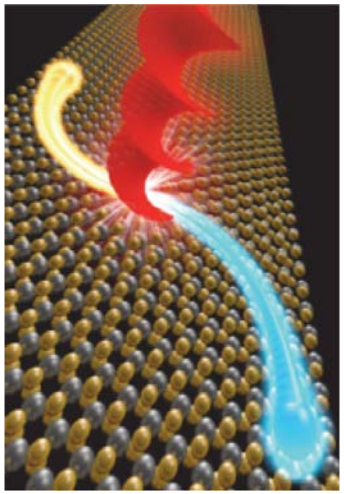
Δ_{SO} ~ 150 meV (MoS_2)

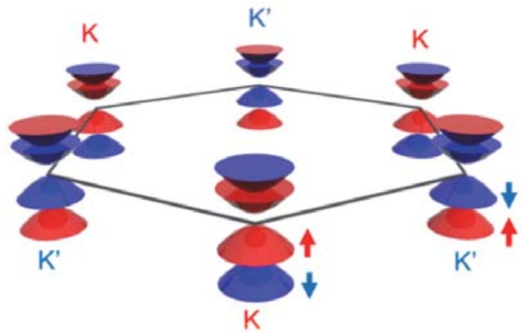
~ 400 meV (WSe_2)

Monolayer TMDC: MoS_2



Valleytronics



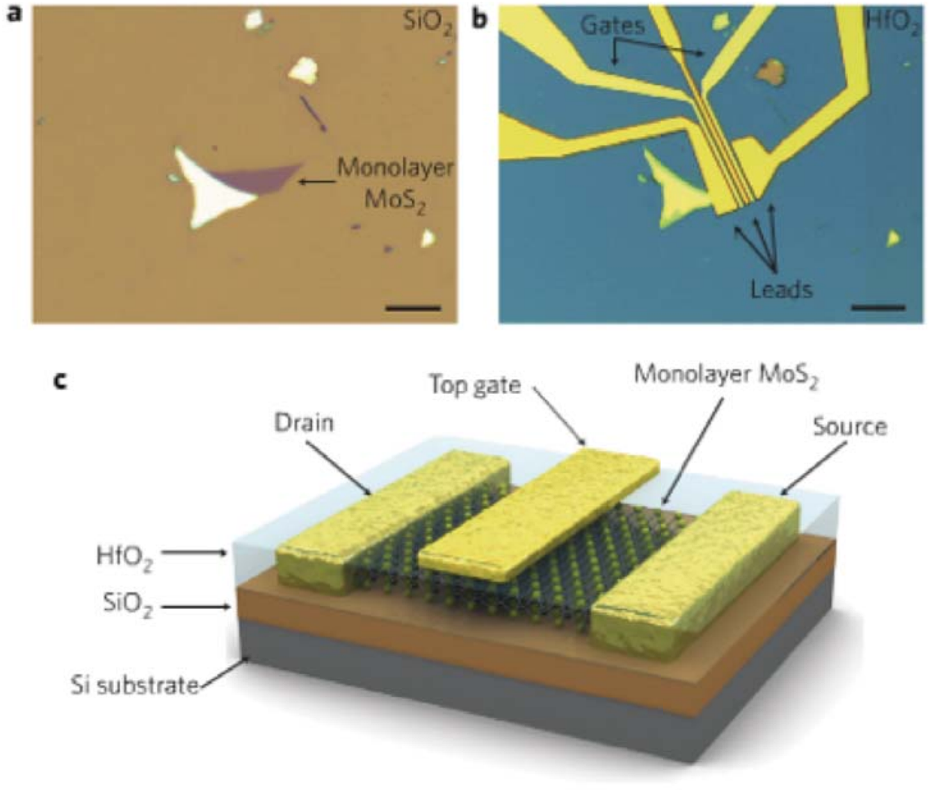


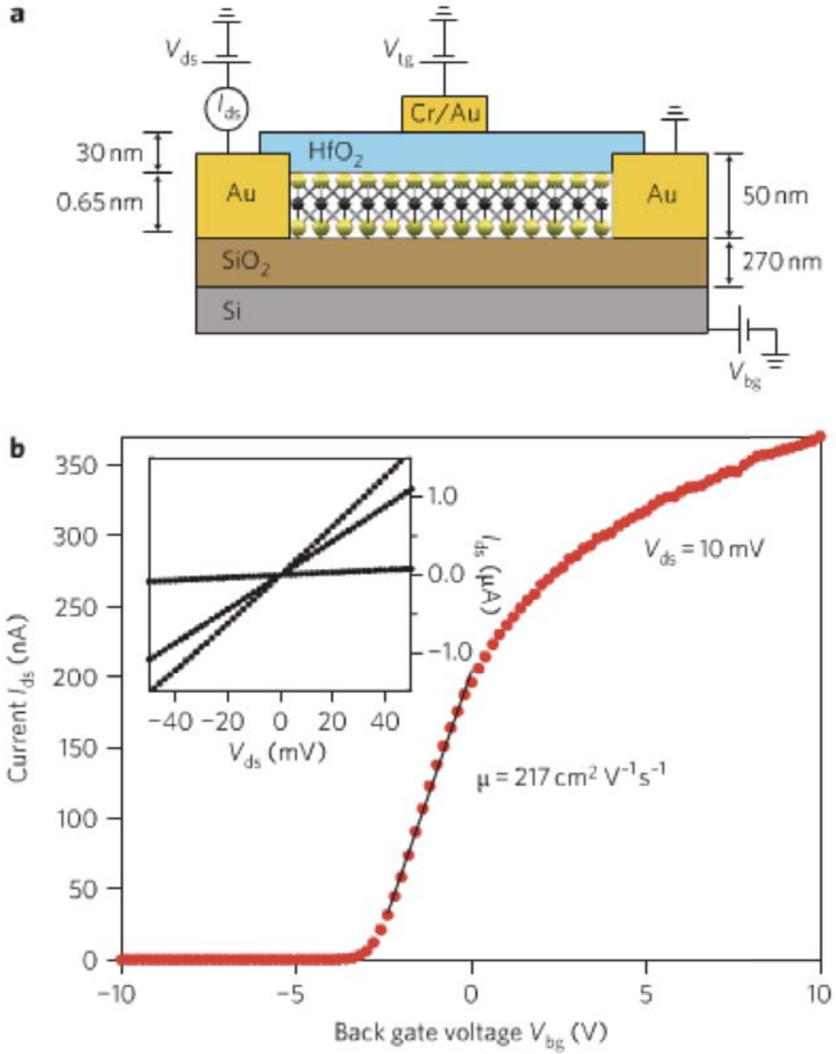
Coupled valley-spin physics

For exotic quantum transport from monolayer MoS_2

1. High mobility?
2. Low contact resistance?

TMDC Electrical Properties

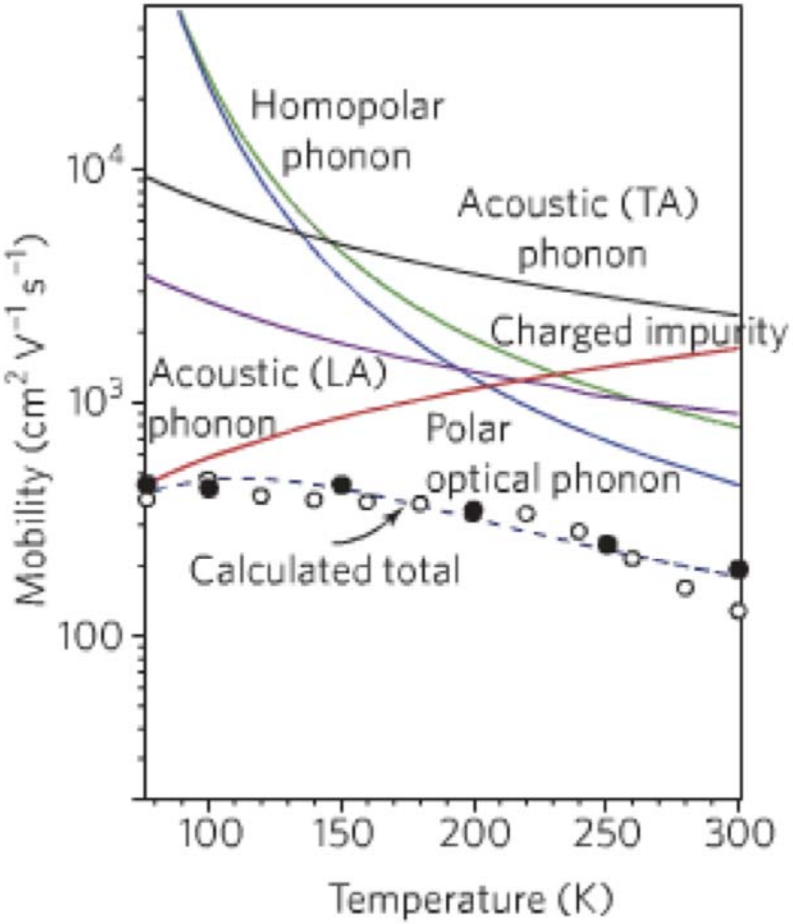




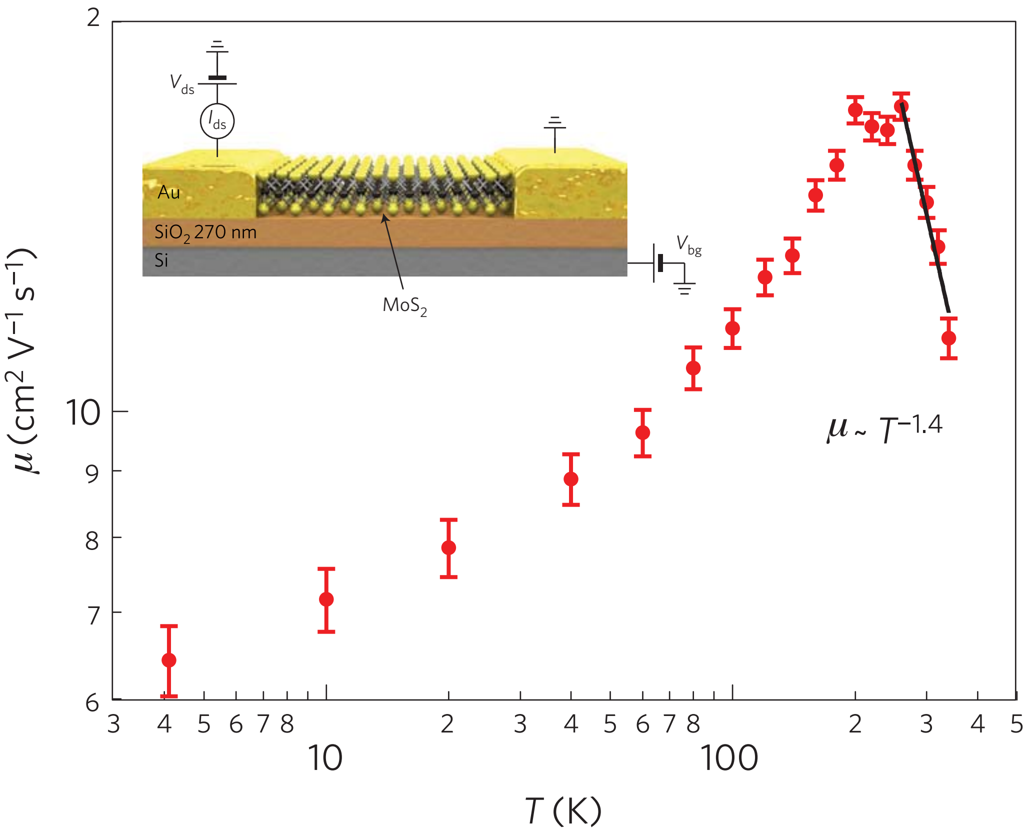
- Direct bandgap at monolayer (1.8 ~ 2.0 eV)
- High on/off ratio (~ 10^8)
- High mobility (1 ~ 100 cm^2/Vs at RT)
- Piezoelectricity

B. Radisavljevic et al., Nature Nanotech. 6, 147 (2011)

TMDC Electrical Properties (mobility)



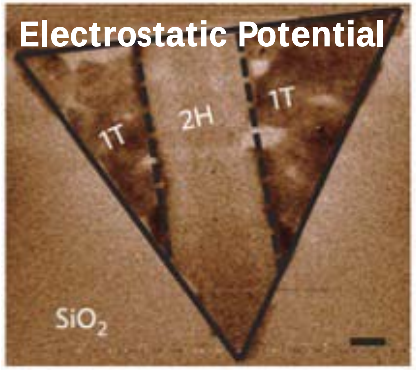
Q.H. Wang et al., Nature Nanotech. 7,699 (2012)



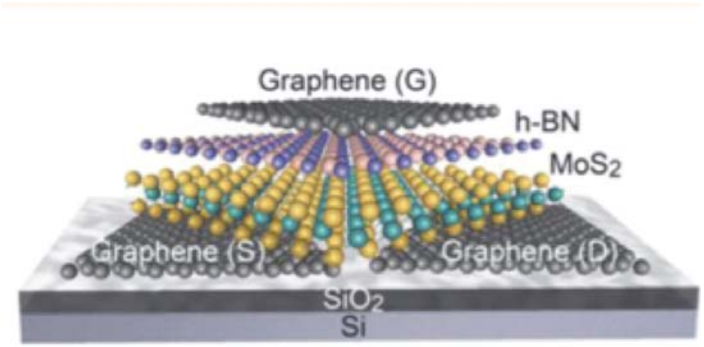
B. Radisavljevic et al., Nature Nanotech. 6, 147 (2011)

- 2D materials are extremely sensitive extrinsic effect.
- Intrinsic limit – acoustic and optical phonon
- Charged impurity scattering dominant at LT.
- Surface roughness of substrate
- Contact resistance dominant.

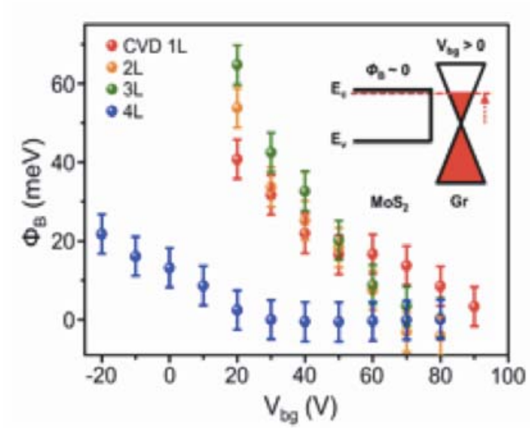
Contact Issue



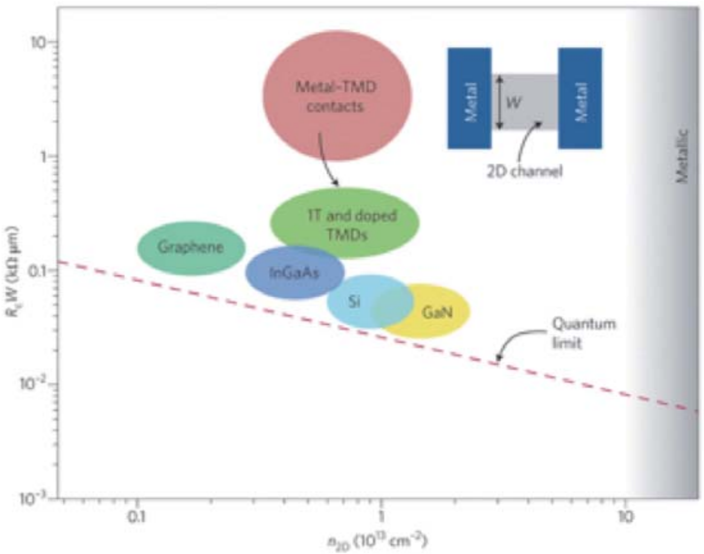
R. Kappera et al., Nature Mater. 13, 1128 (2014)



T. Roy et al. ACS Nano 8, 6259 (2014)

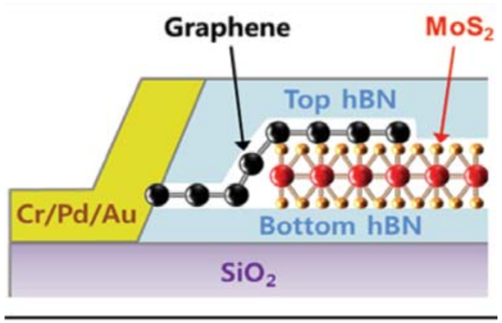


X. Cui et al., Nature Nanotech. 10, 534 (2015)



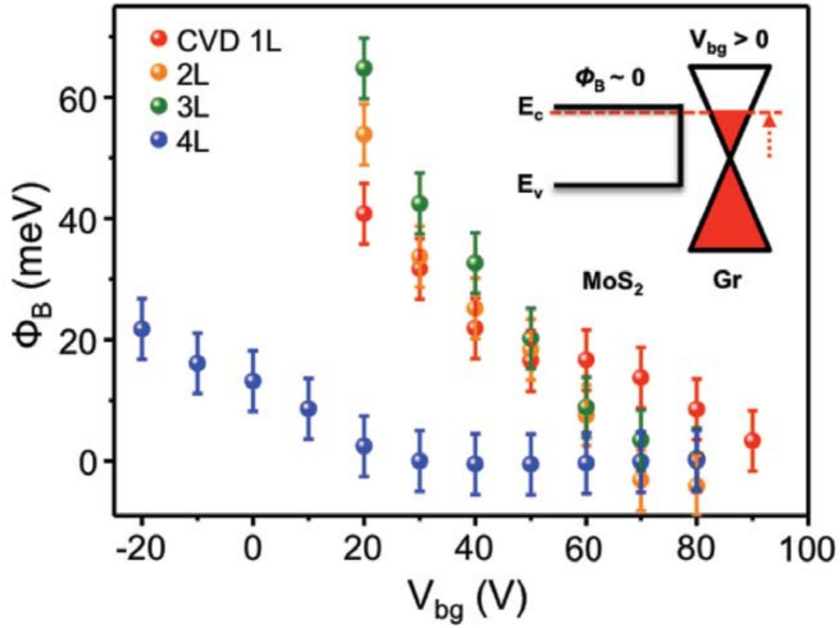
- TMDC performance limited by contact
- Finite Schottky barrier (TMDC/Metal interface)
- 1T-phase engineering (Decrease of contact resistance)
- Graphene electrode (Ohmic contact at LT)

Graphene/MoS_2 Contact

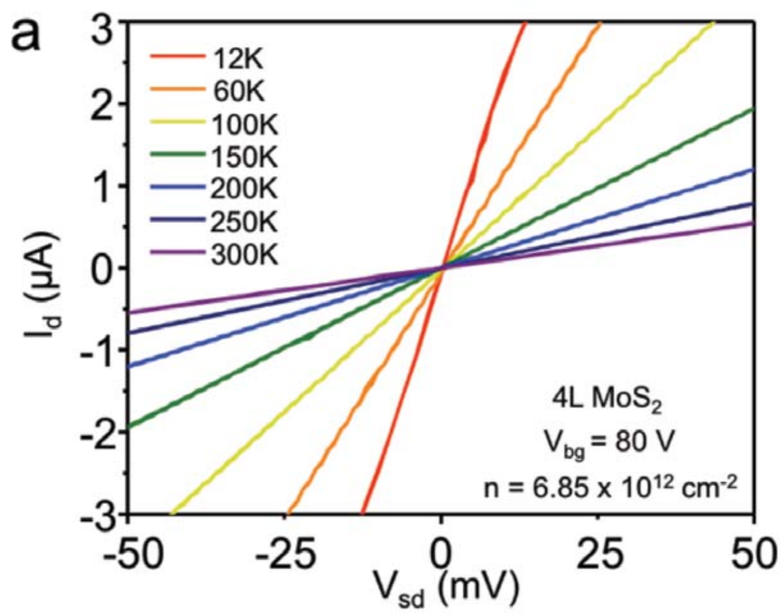


Barrier free contact at MoS2/Graphene interface

Tunable Scottky barrier height

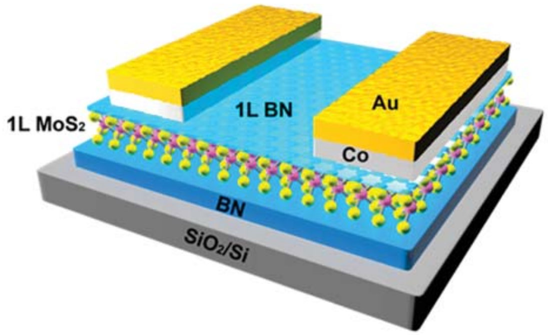


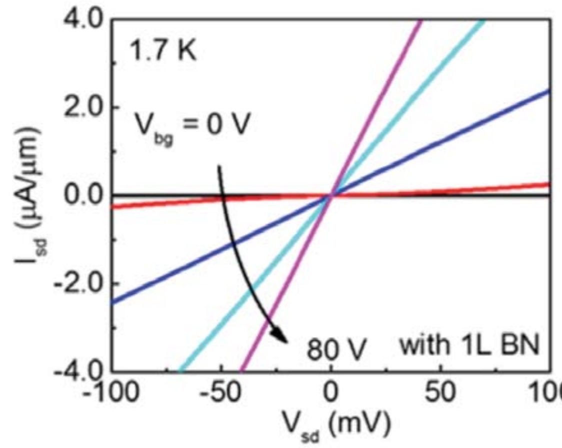
Ohmic contact at low temperature

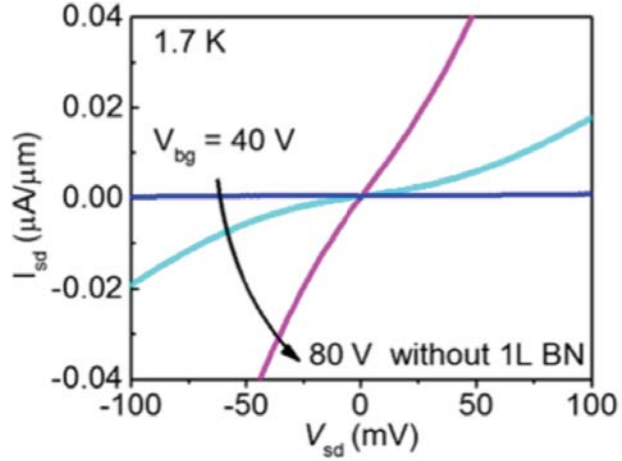


Large tunable of Fermi every of graphene

Co Contact with Monolayer hBN



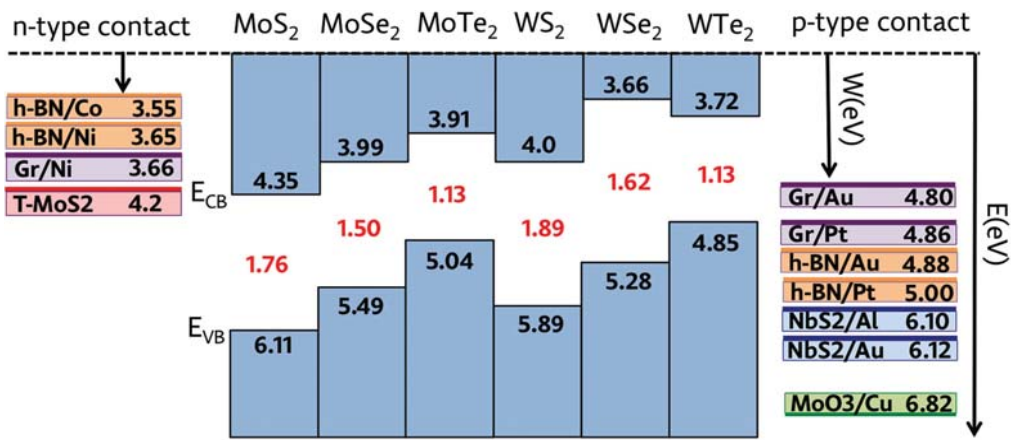




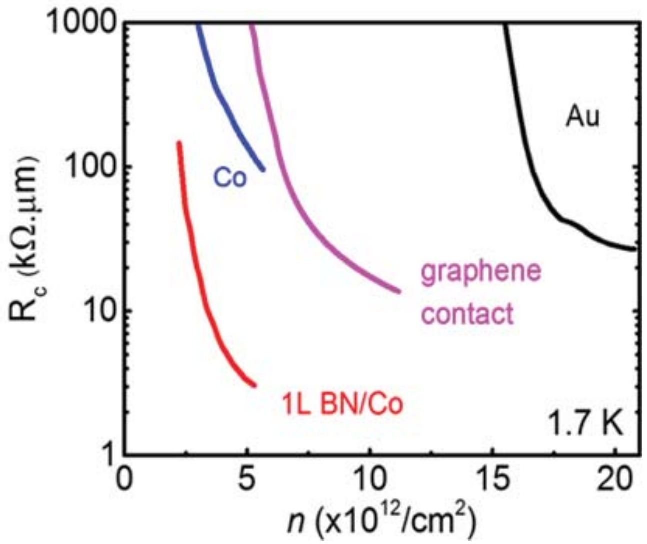
X. Cui *et al*, Nano Letters (2017)

Ohmic contact with monolayer hBN layers.

Large change of work function by monolayer hBN

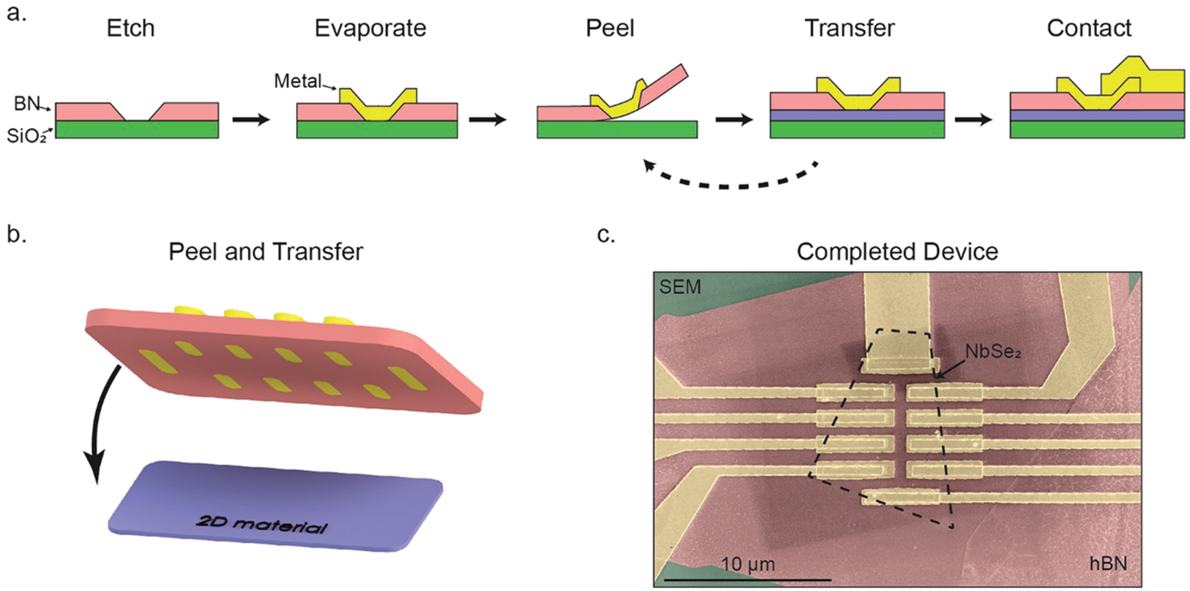


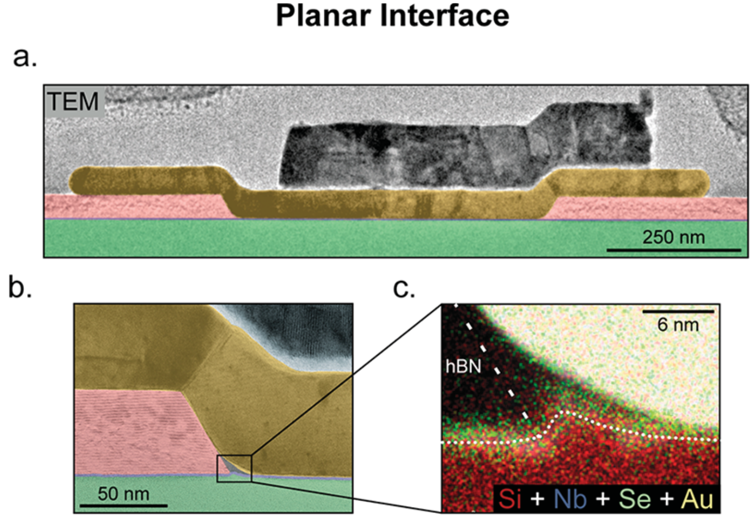
M. Famanbar *et al*, Adv. Electronic Materials (2016)

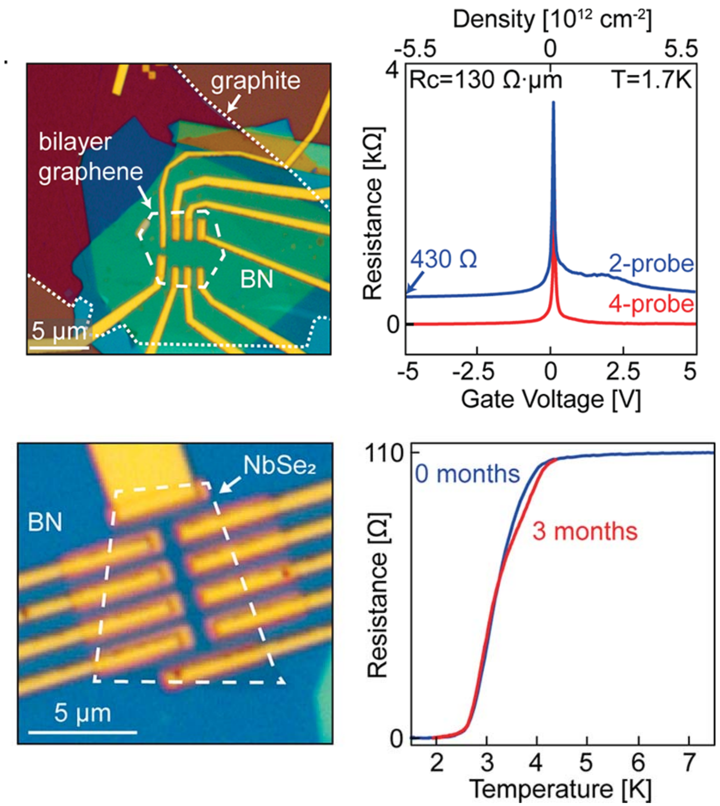


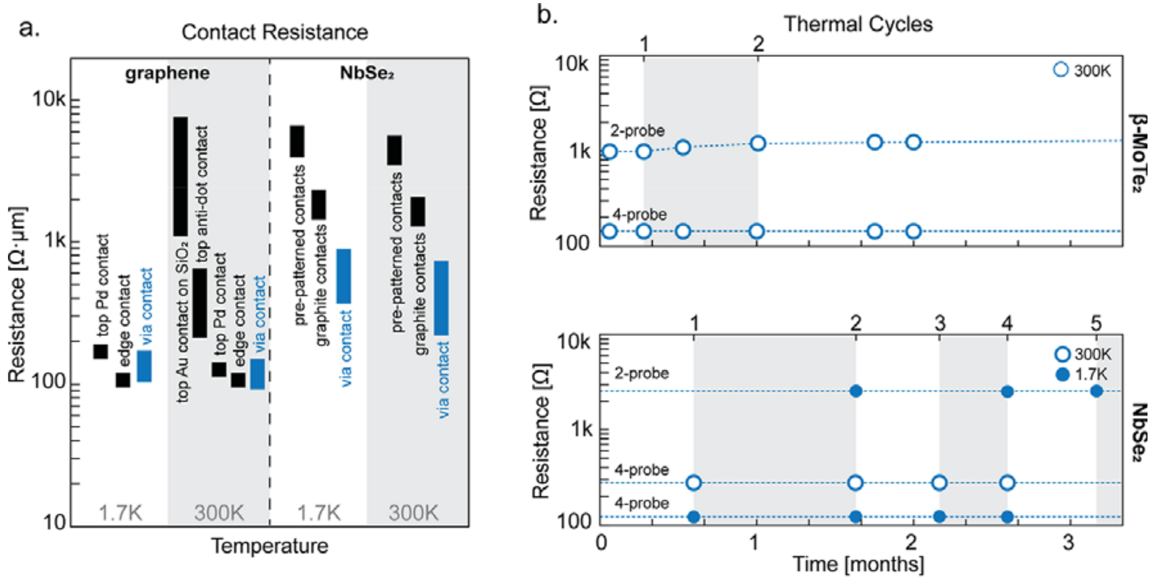
Approaching to low carrier density regime.

Via contact to 2D Material





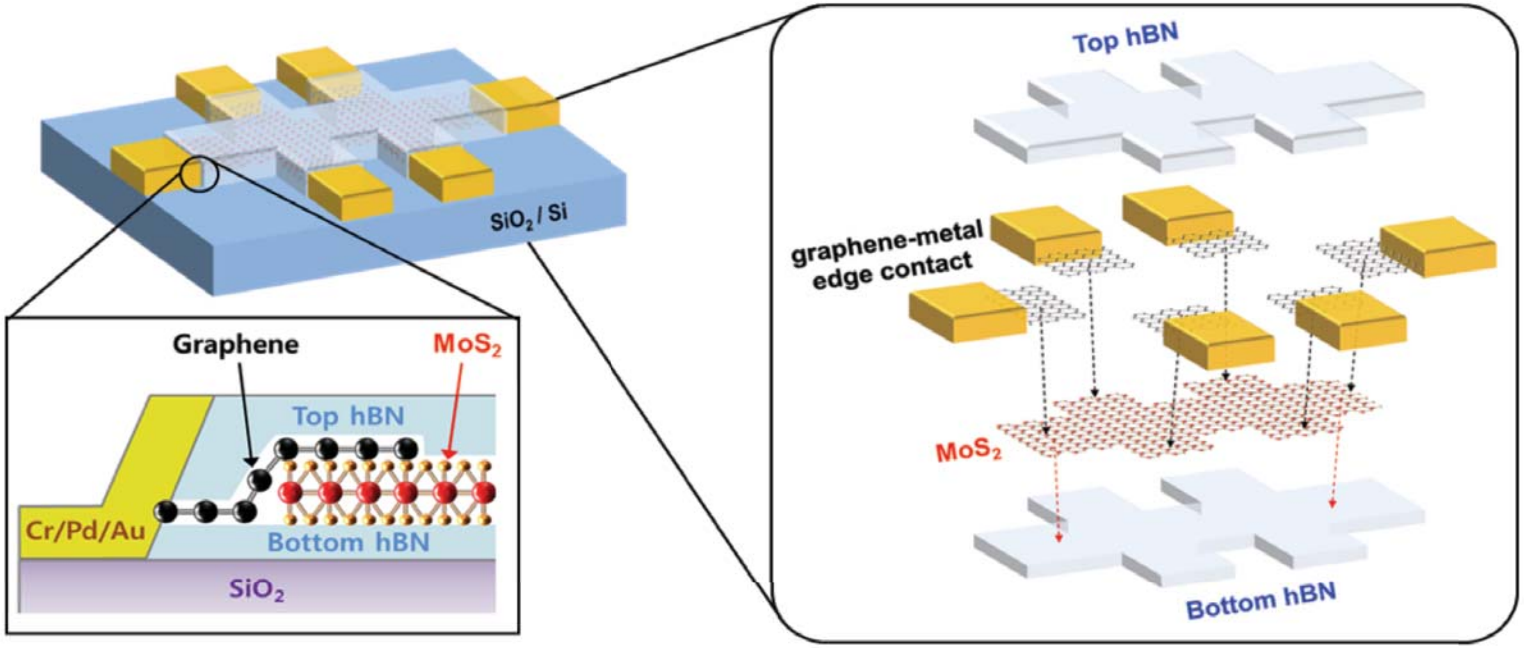


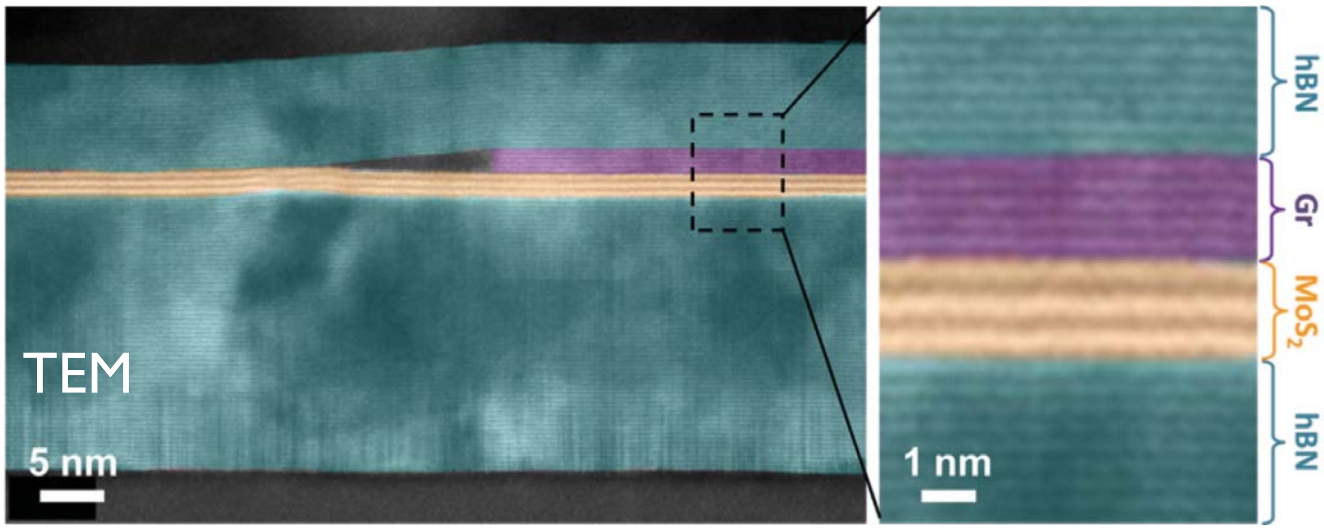


E. Telford *et al*, Nano Letters (2018)

- Robust electrical contact.
- Avoid direct pattering on 2D materials.
- Atomic printed circuit board.

MoS_2 Heterostructure





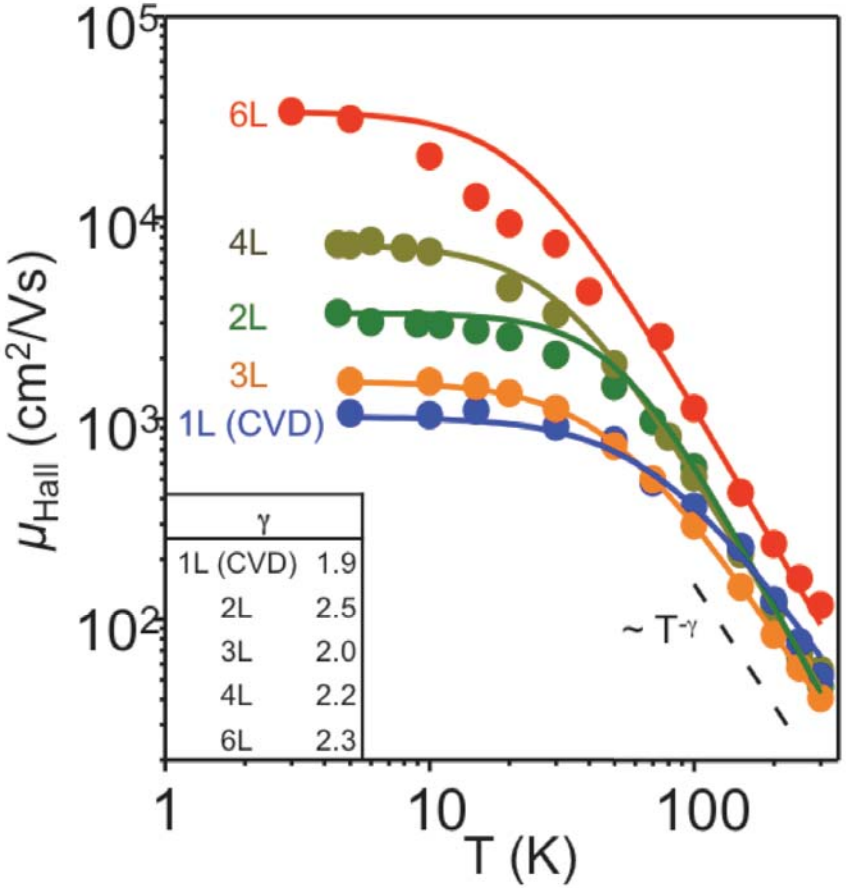
X. Cui, G.H. Lee, **Y.D. Kim** *et al*, Nature Nanotech. (2015)

Ultraclean van der Waals interface

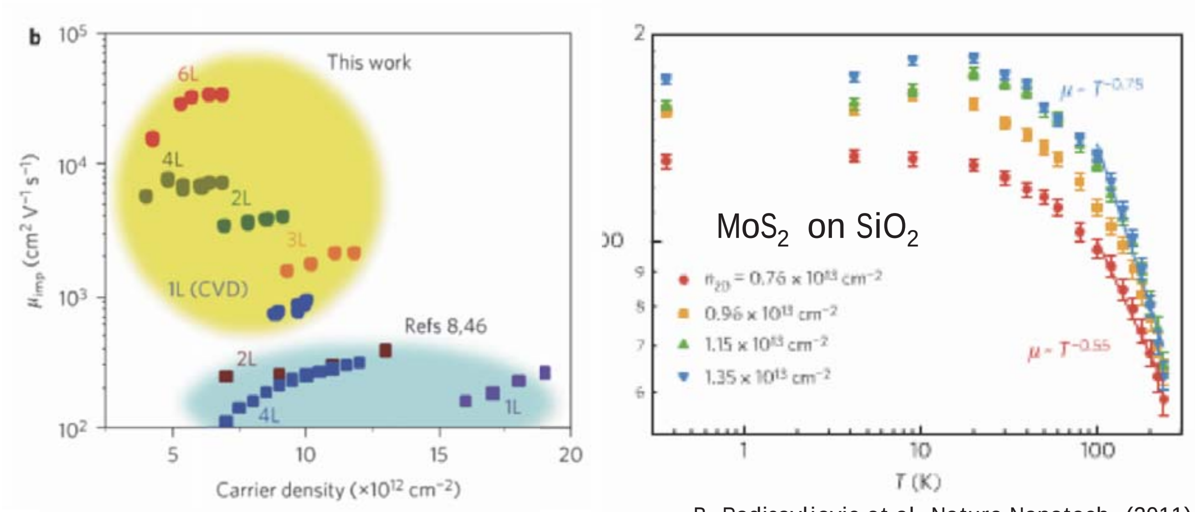
Universal platform for 2D material

MoS_2 Heterostructure

Record high mobility in MoS_2



Comparison of mobility of MoS_2



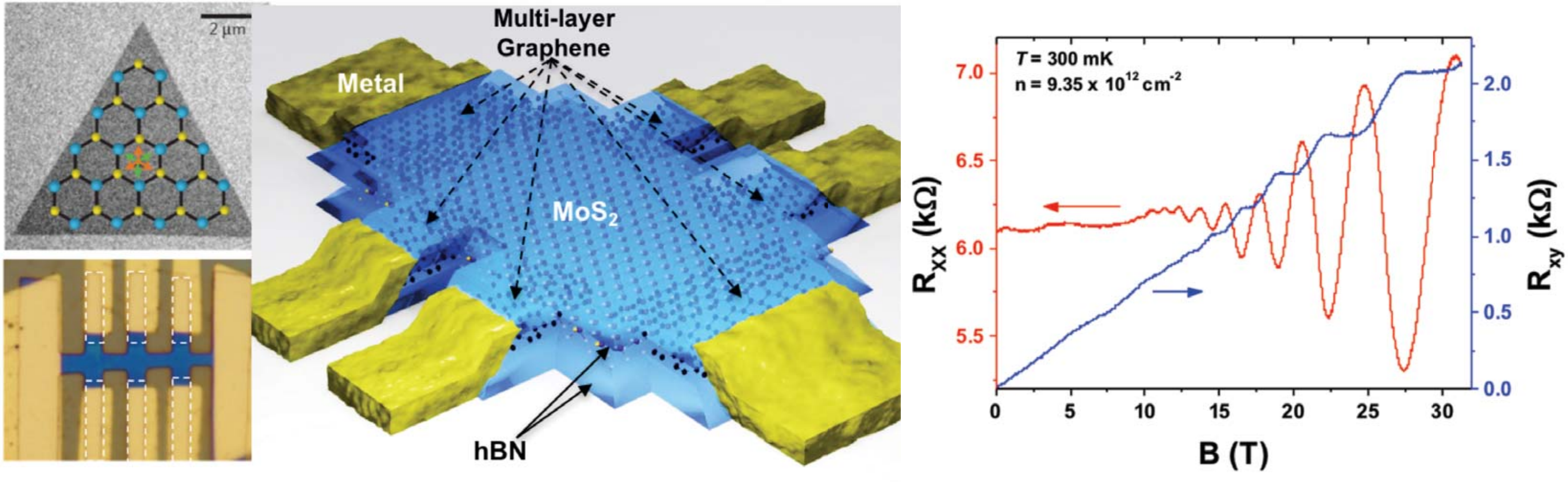
B. Radisavljevic et al, Nature Nanotech. (2011)

$\sigma = ne\mu_{Hall}$, where n is carrier density

Hall mobility of MoS_2 = 1,000 ~ 30,000 cm²/Vs
Reduce the charged impurity densities by clean interface

Quantum Transport in Monolayer MoS_2

First observation of quantum oscillation from monolayer MoS_2

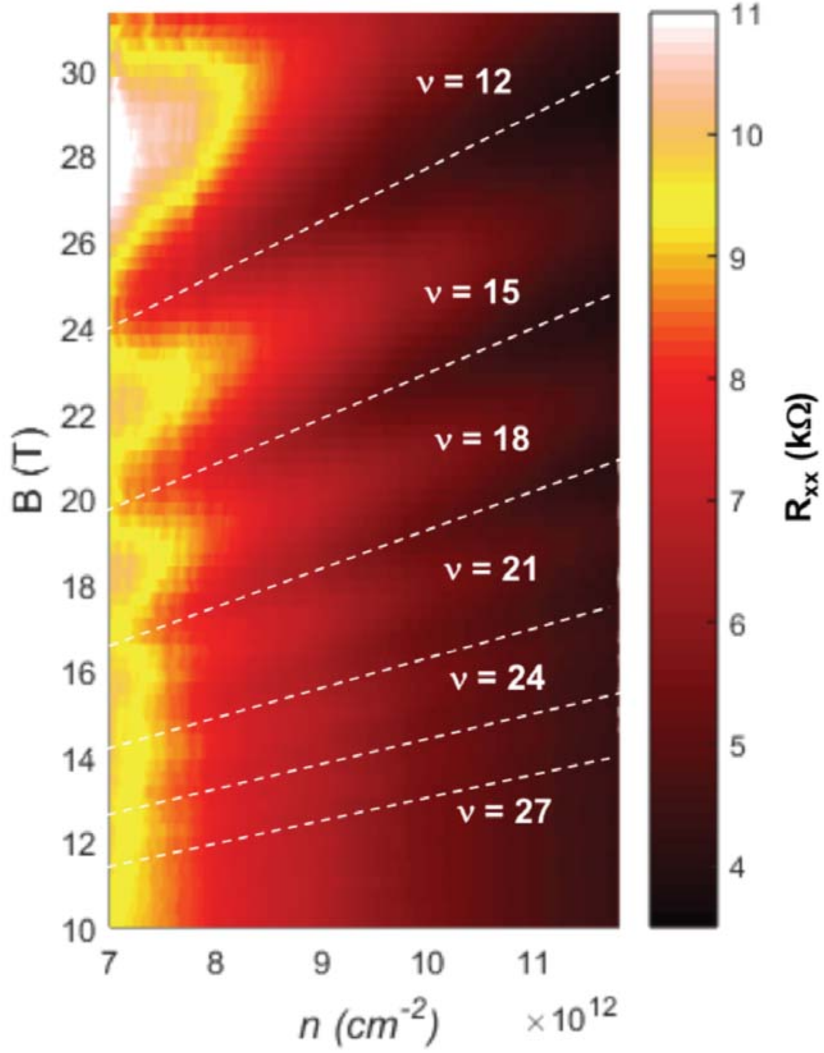


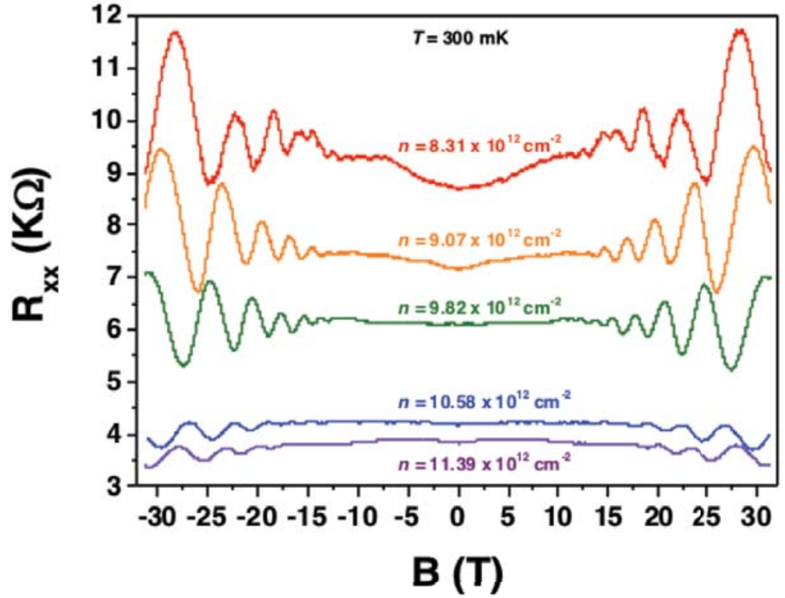
Quantum mobility μ_Q ~ 1,400 cm²/Vs (one set oscillation 6.7 T)

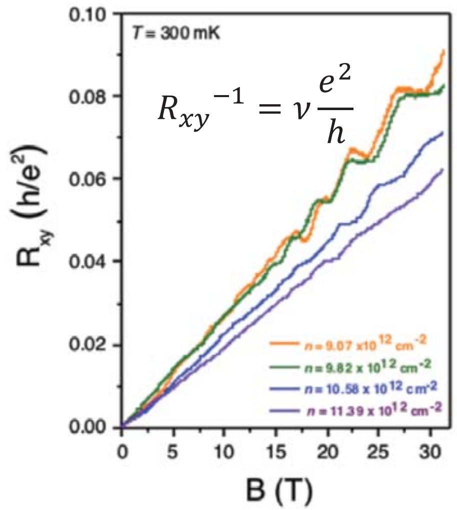
$$\mu_Q = 1 / B_q$$

Quantum Transport in Monolayer MoS_2

Landau fan diagram and periodicity changed by gate voltage





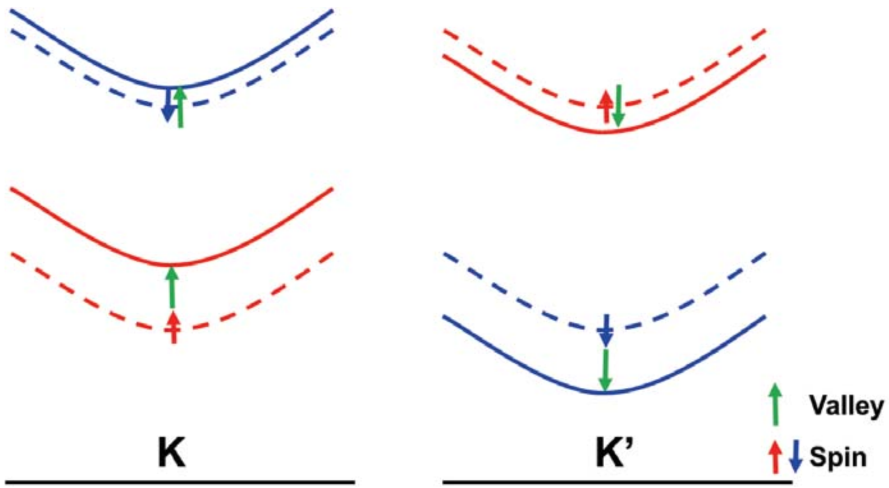


Y.D. Kim *et al*, in preparation

Anomalous quantum plateau:
Valley and spin Zeeman effect?

Quantum Transport in Monolayer MoS_2

Valley and spin Zeeman effect



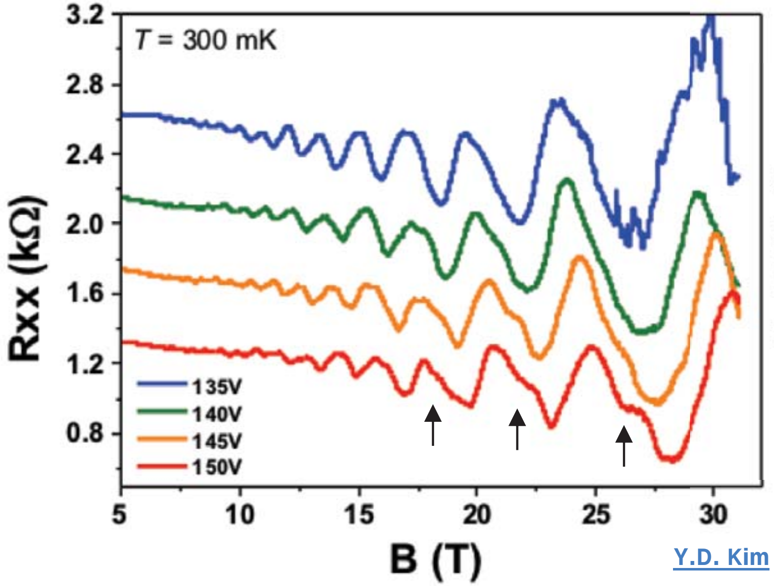
Valley and spin polarization under magnetic field

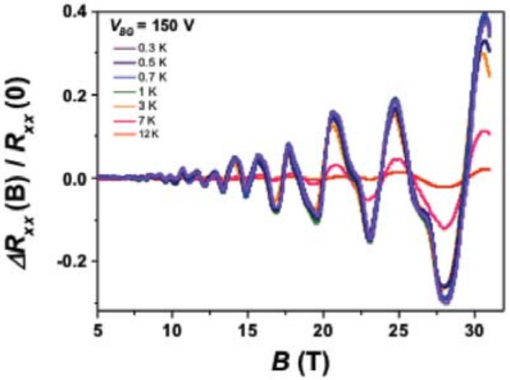
Spin Zeeman effect: $2S_z\mu_B B$

Valley Zeeman effect: $\alpha\tau_z\mu_B B$

where $\mu_B = \frac{e\hbar}{2m_e} = 0.05$ meV/T is Bohr magneton, $\alpha = m_0/m^*$, and m^* is the effective mass.

Observation of coupled valley-spin Zeeman effect





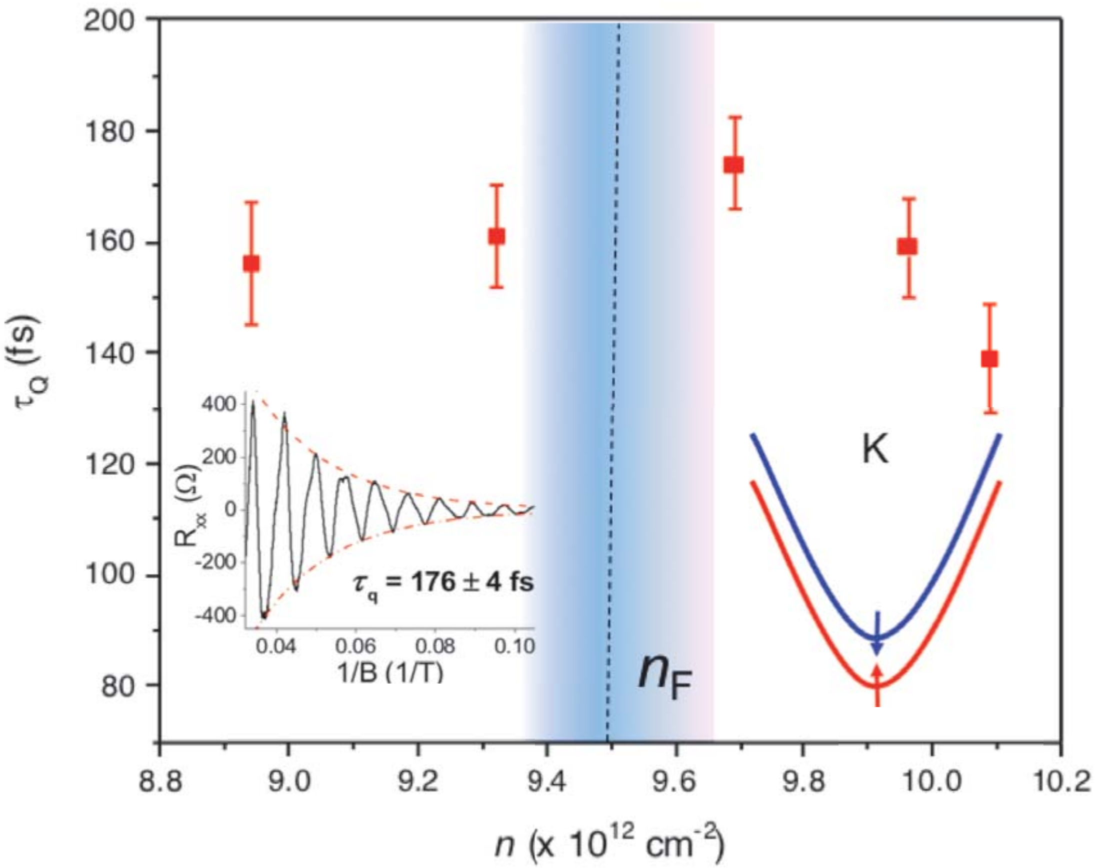
Y.D. Kim *et al*, in preparation

Peak splitting at high carrier density
Smearing of peak splitting at high Temp.

Effective mass ~ 0.49 m_o

Quantum Transport in Monolayer MoS_2

Spin sub-band crossover



Quantum scattering time:
From Ando formula and Dingle term

$$\tau_Q \rightarrow \frac{\Delta\rho_{xx}}{\rho_0} = 4\gamma_{th}\exp(-\frac{\pi}{\omega_c\tau_Q}),$$

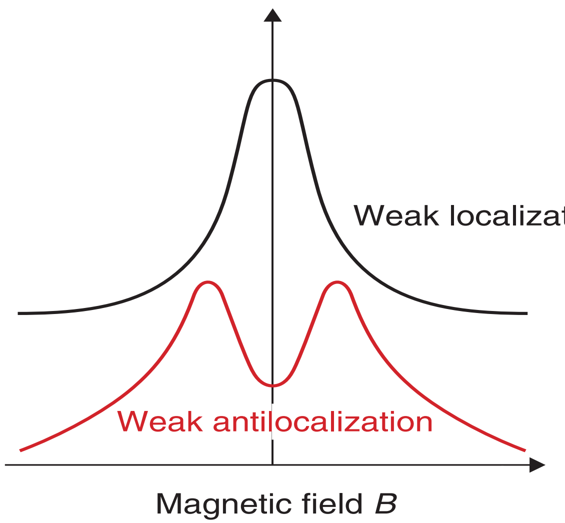
where $\gamma_{th} = \alpha/\sinh(\alpha)$, $\alpha = 2\pi^2 k_B T/\hbar\omega_c$

Open extra scattering pathway:

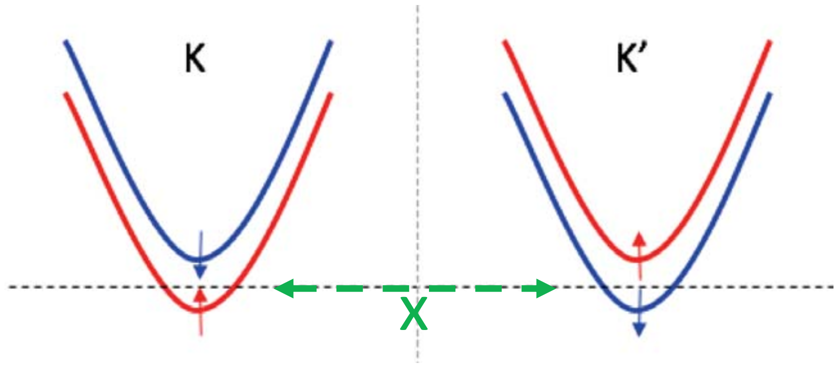
Band cross point: $n_F \sim 9.5 \times 10^{12}\ cm^{-2}$

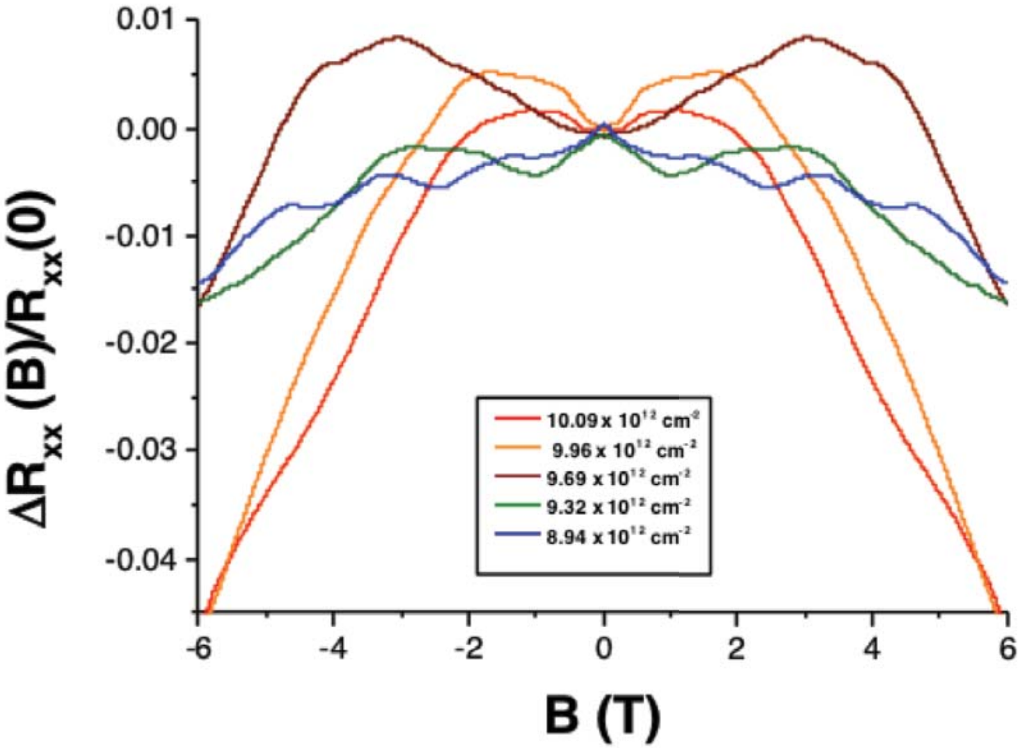
Conduction band spin splitting Δ_{SO} = ~ 10 meV

Quantum Transport in Monolayer MoS_2



Weak Localization





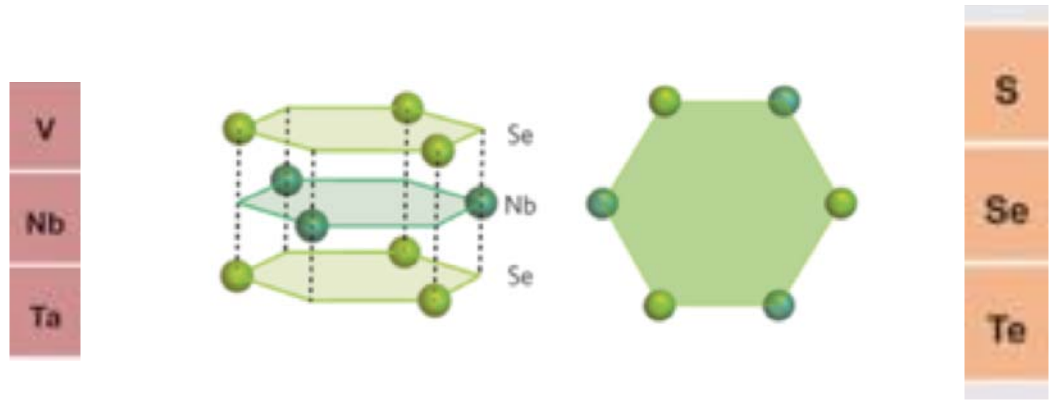
Inter/Intra-valley scattering in MoS_2

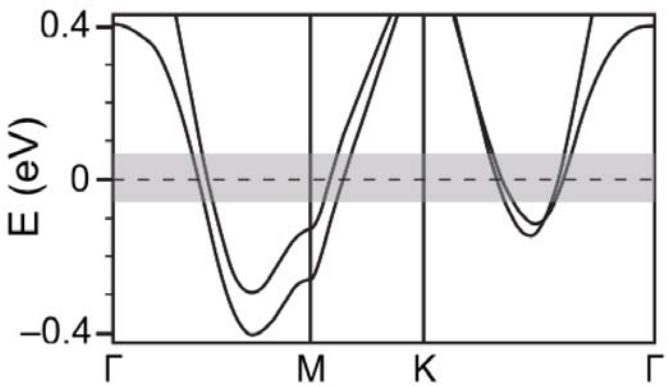
WL: Spin conserved scattering
WAL: Spin-flip scattering

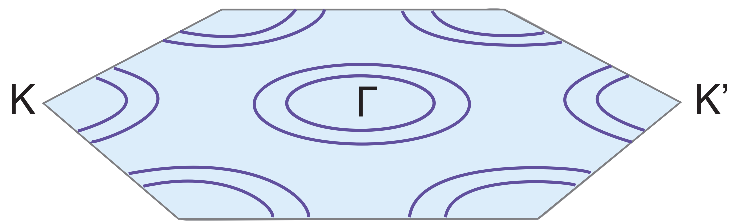
Suppression of spin-flip inter-valley scattering

Transition to WAL:
- Spin sub-band cross over
- Open intra-valley spin flip scattering

TMDC Metal





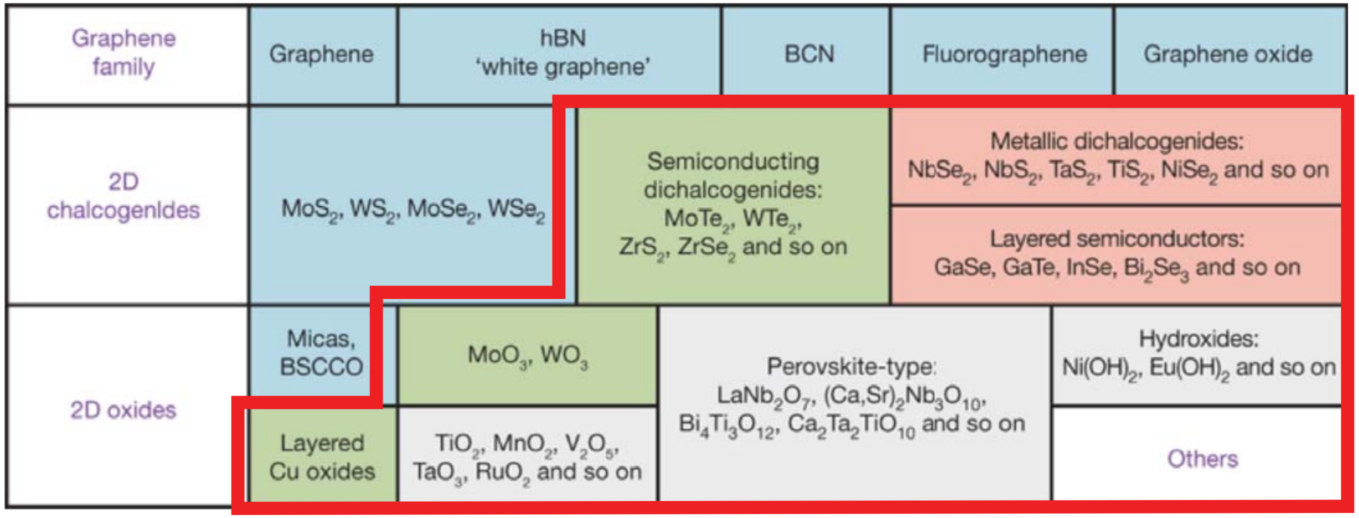


•$NbSe_2$, NbS_2, TaS_2, $TaSe_2$

•High electronic density

•Electronic instability (Charge density wave, Superconductivity, Magnetism)

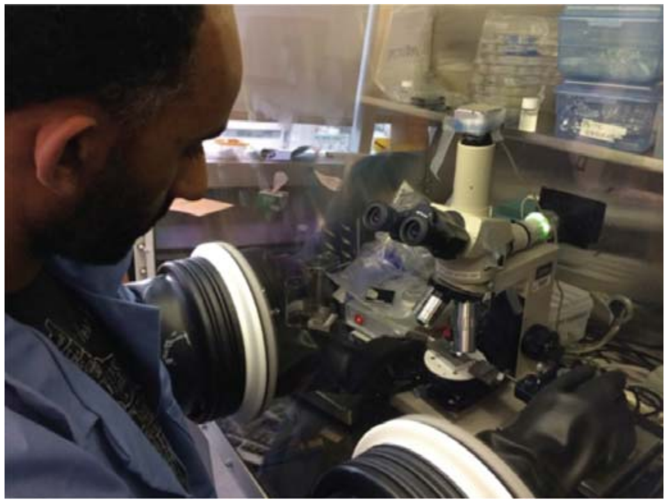
Air sensitive van der Waals Materials



Semiconductor: Black phosphorous
Superconductor: $NbSe_2$, NbS_2, FeSe
High Tc superconductor: BSCCO
Charge density wave: TaS_2, $NbSe_2$
Topological material: $MoTe_2$, WTe_2
Ferromagnetic: $CrSiT_3$
Magnetic insulator: EuS_2

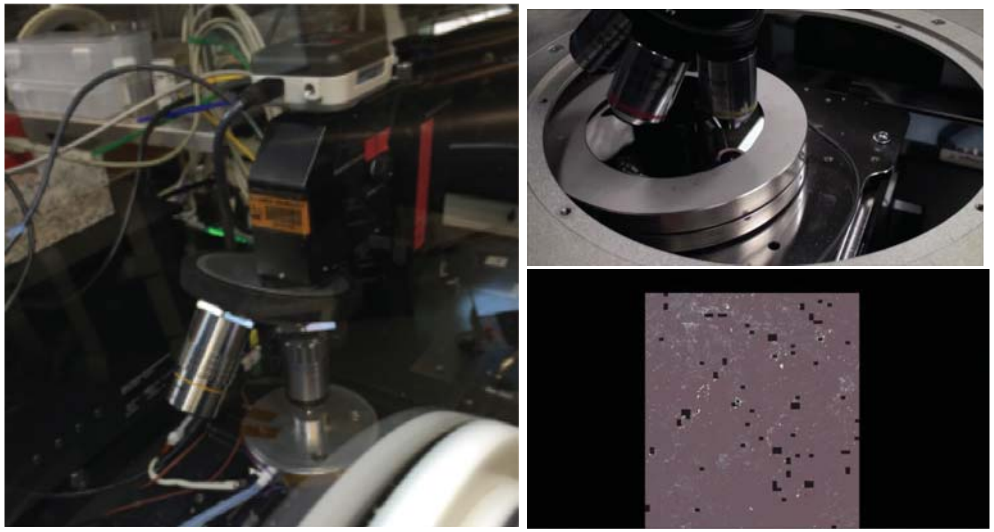
Surface oxidation alter intrinsic properties at 2D limit!

Hard work



Manually search and stack

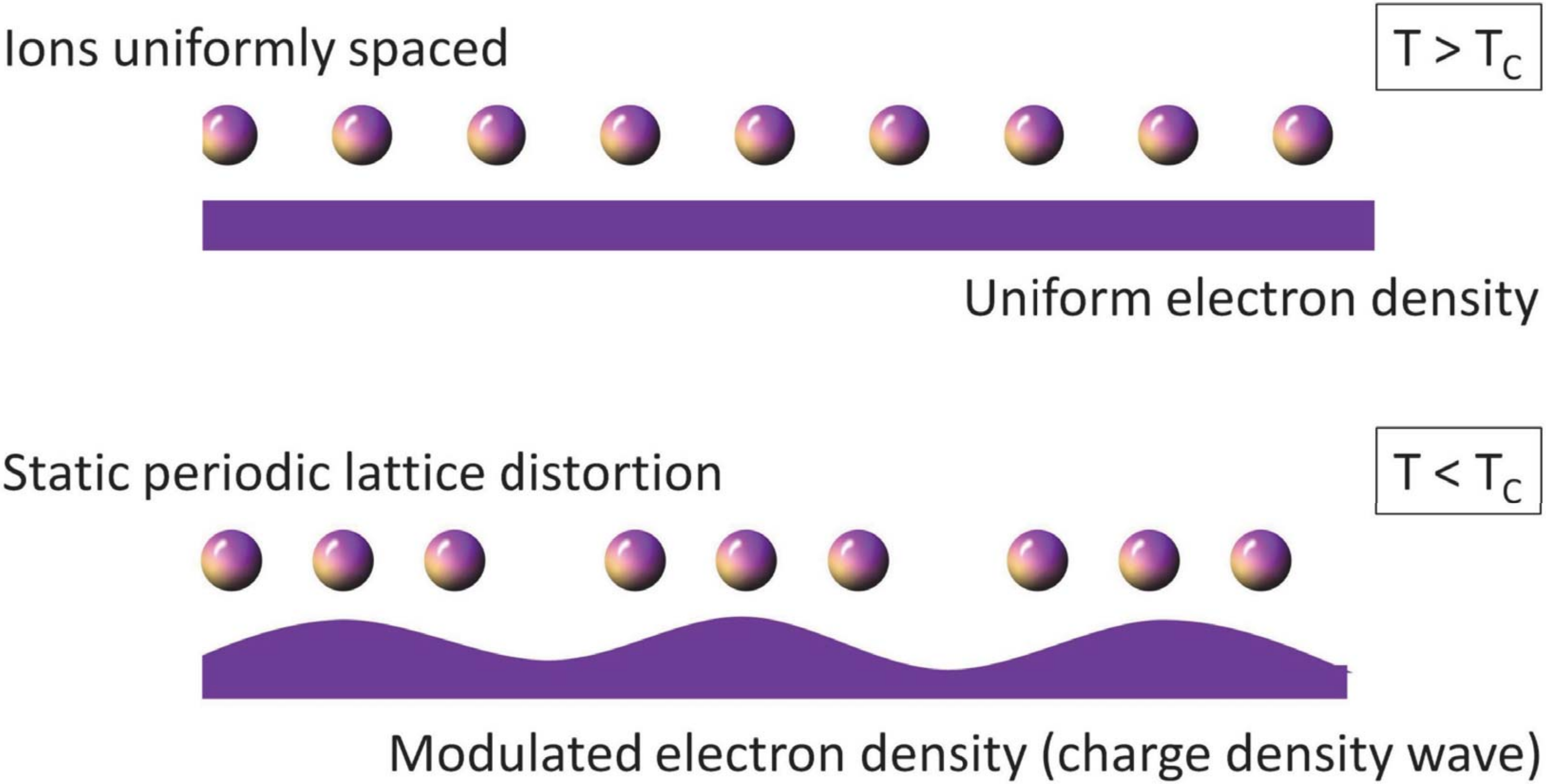
Automatic system



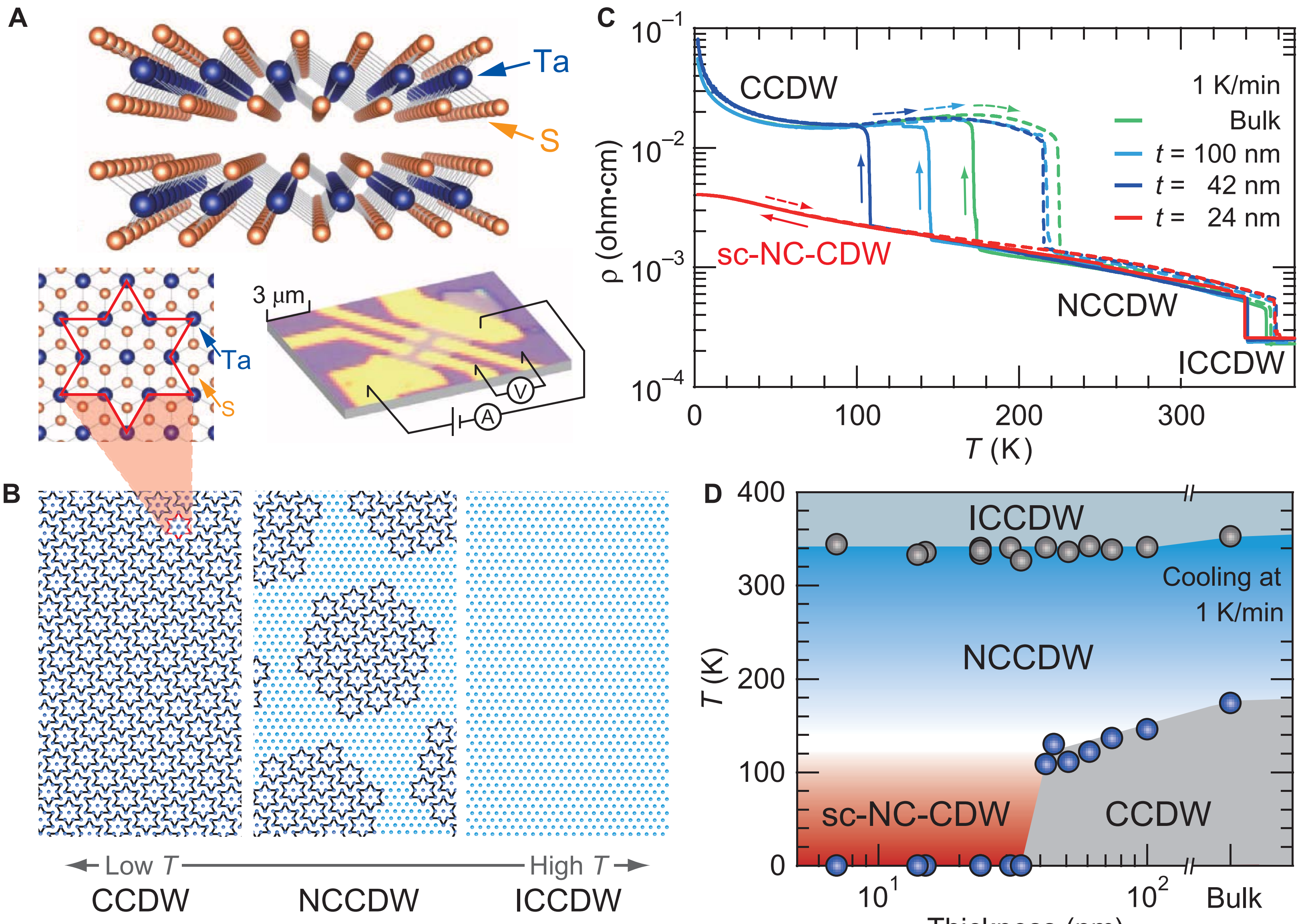
Home-built automatic, exfoliation, searching and stacking

Allow efficient and systematic study at intrinsic limit!

Charge Density Wave



Charge Density Wave in 1T-TaS$_2$



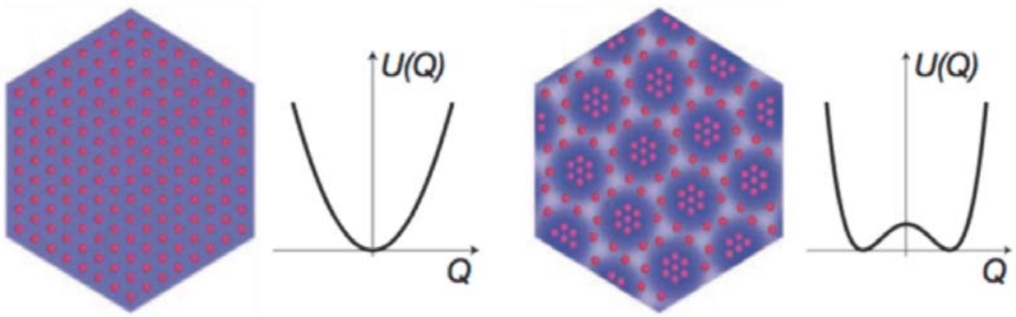
Yoshida et al. Sci. Adv. (2015)

No CDW wave at 2D limit!

Charge Density Wave in 1T-TaS_2

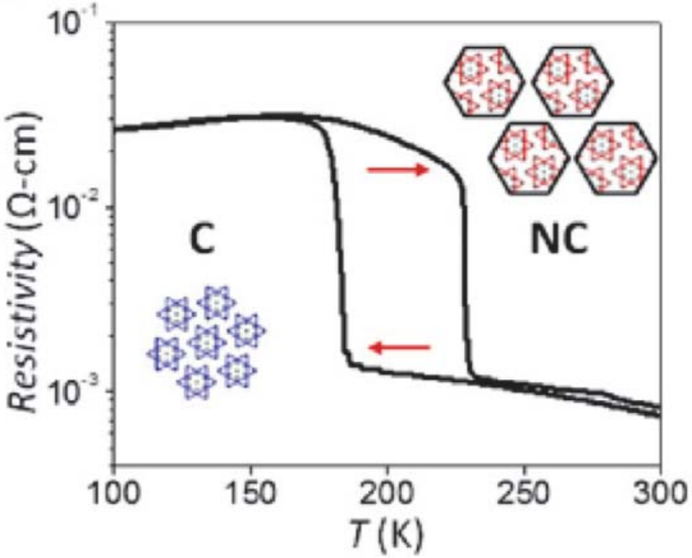
Metallic

CDW



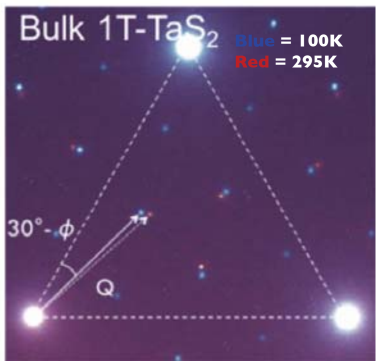
Modulation of electron density by distortion of ion lattice.

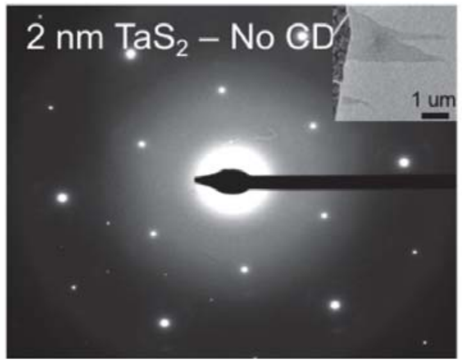
Transport

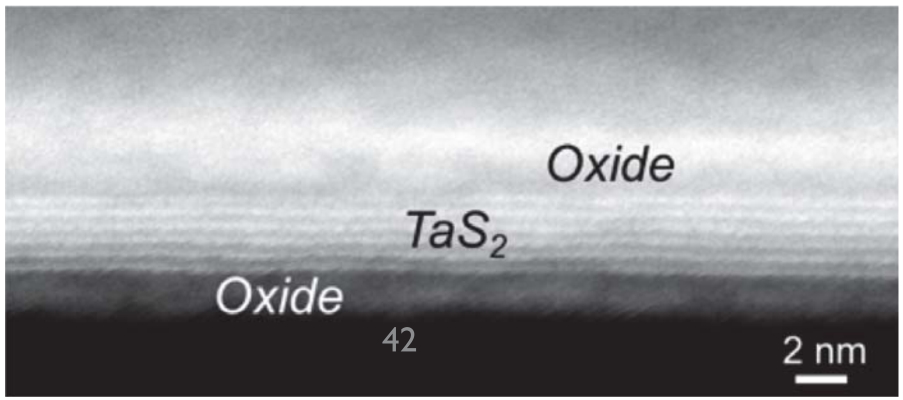


Oxide on TaS2 (Stack in air)
Phase transition suppressed by disorder

Electron diffraction from TEM

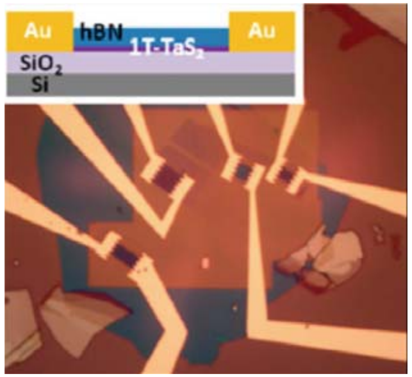


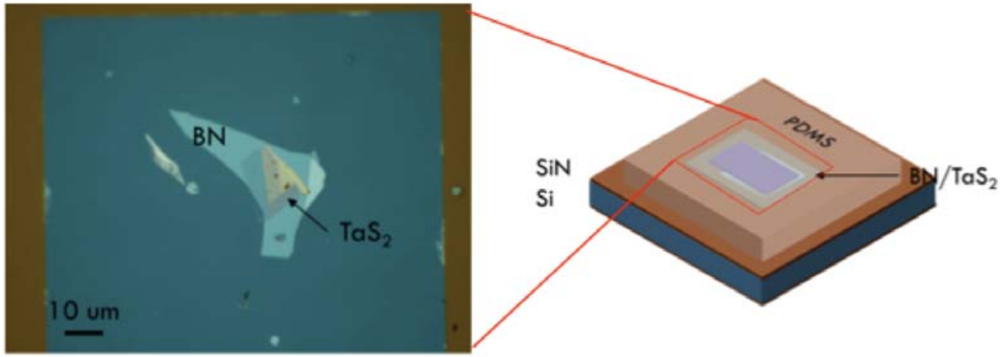


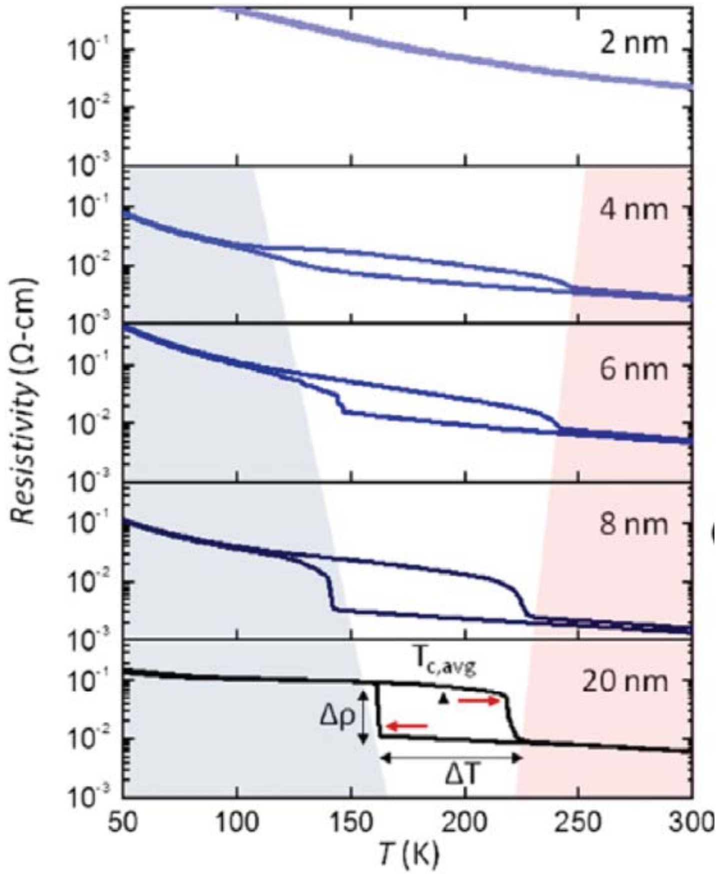


Charge Density Wave in TaS_2

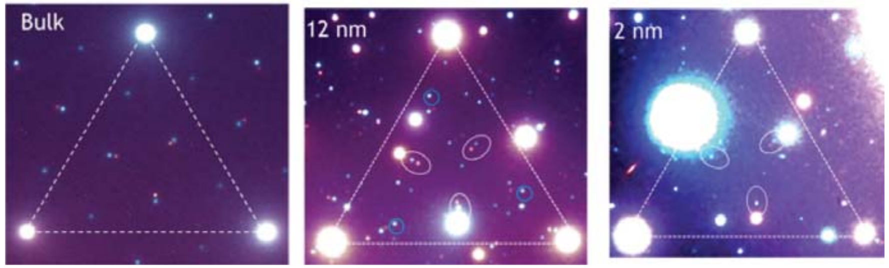
TaS2 Heterostructure
Atomically thin CDW at clean limit

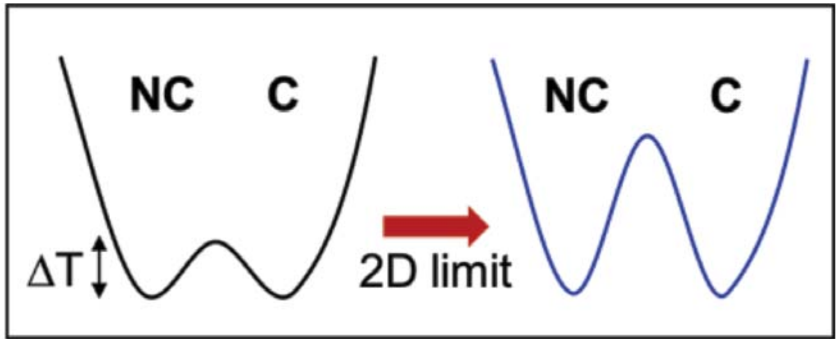






Clear CDW at 2 nm





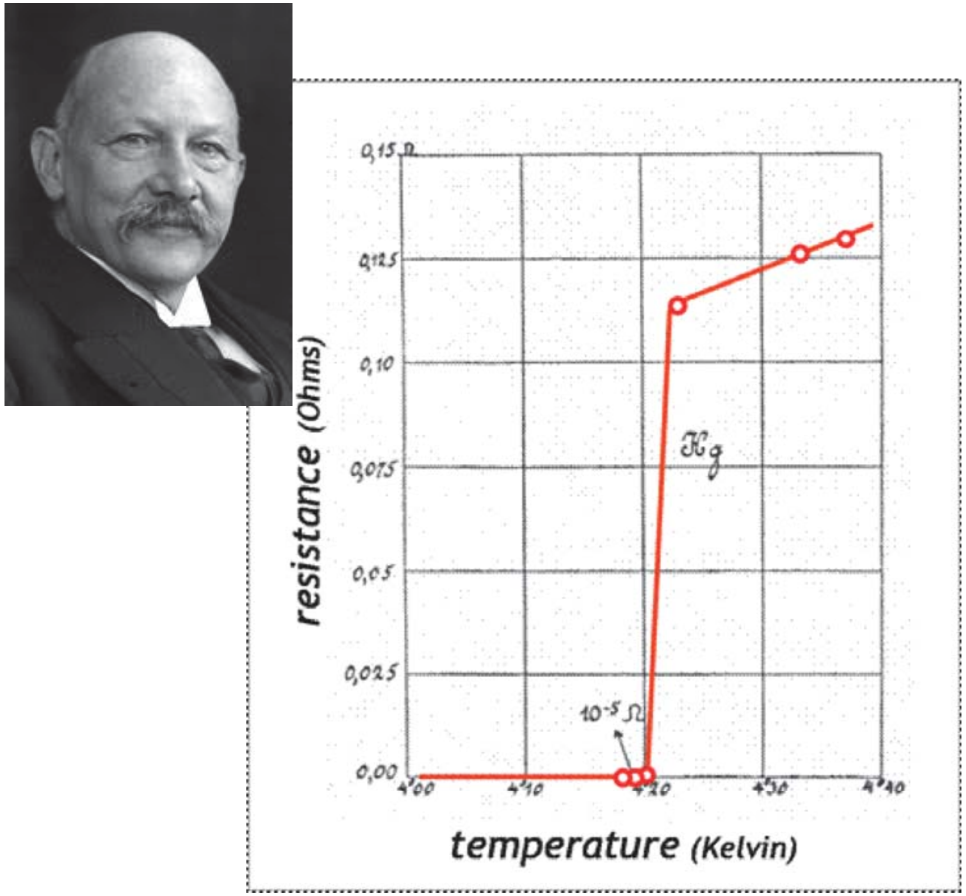
CDW in 2D limit: increase barrier height

A. W. Tsen and **Y.D. Kim** *et al*, PNAS (2015)

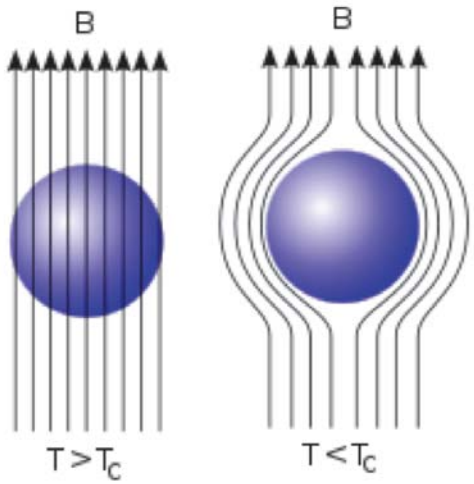
Superconductivity

Zero resistance

Meissner effect

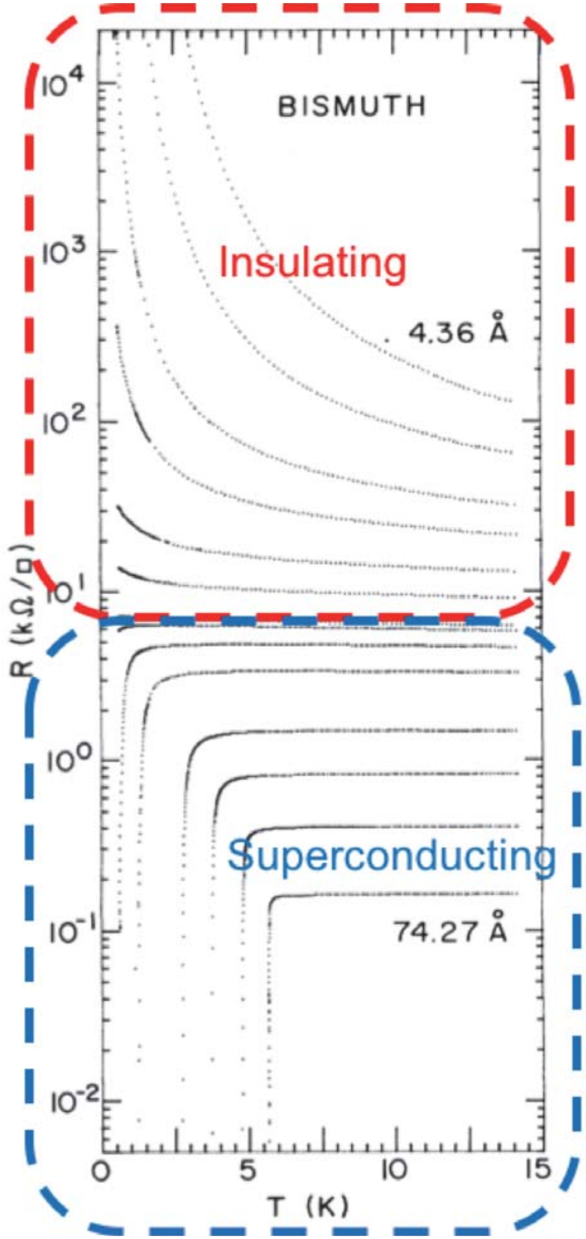


1911: K. Onnes discover superconductor



2D Superconductor

Amorphous thin Bi film

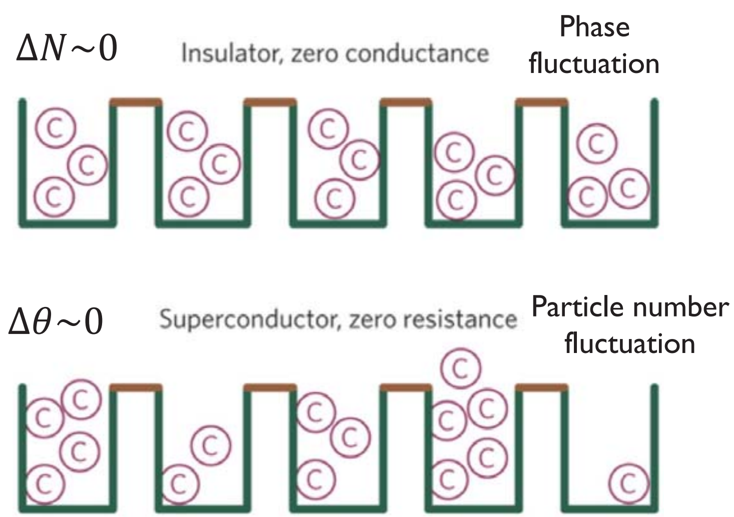


D. B. Haviland *el al*, Phys. Rev. Lett. (1989)

Superconductivity

$$\psi(r) = |\psi(r)|e^{i\theta}$$

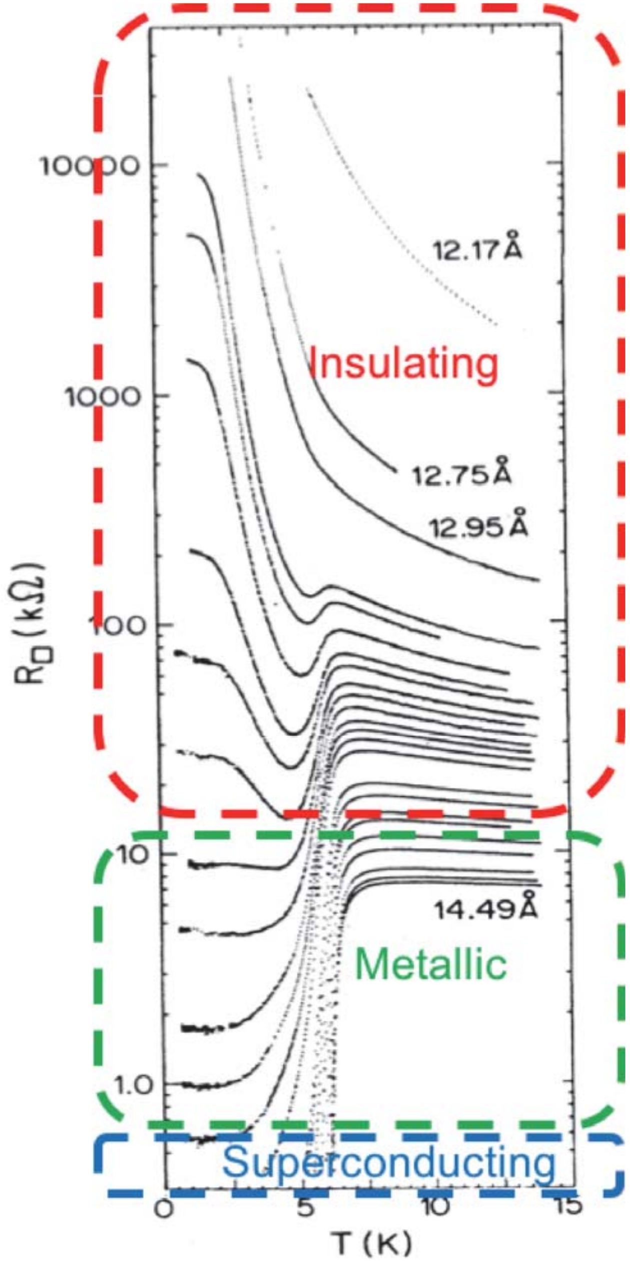
Cooper pairs (Bosonic) ground states at 2D limit



Phase and particle number are conjugate varia
Uncertainty relation $\Delta N \Delta\theta \gtrsim 1$

Fluctuation by disorder or magnetic field

Amorphous thin Ga film



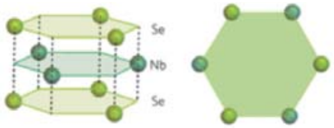
H. M. Jaeger *el al*, Phys. Rev. B (1986)

What is nature of intermediate metallic phase?
New quantum metallic phase (Bose metal)?

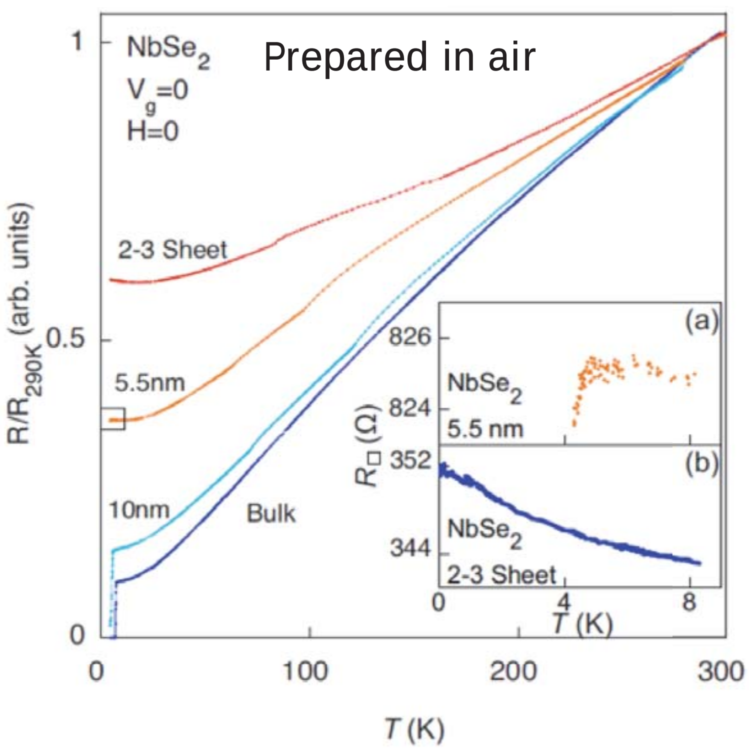
2D Superconductor

$NbSe_2$: Single crystalline type II superconductor

Atomically thin $NbSe_2$



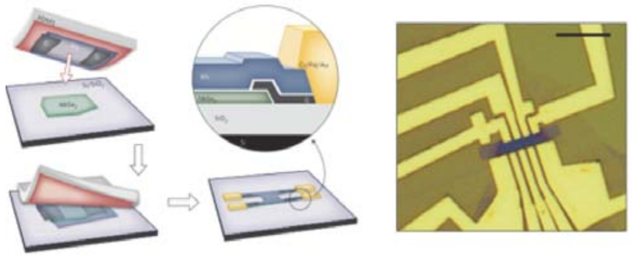
Tc: 7.2 K (bulk)

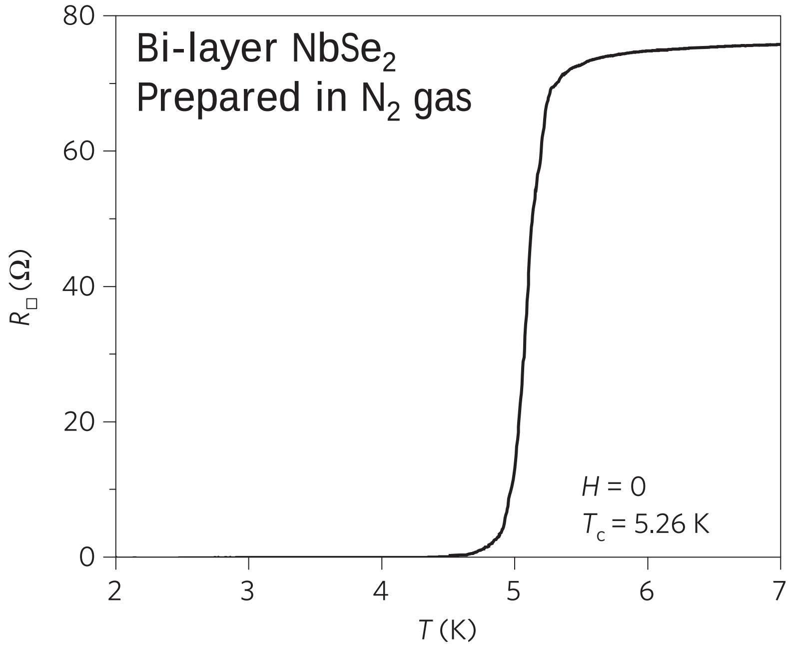


N. E. Staley *et al*, Phys. Rev. B (2009)

Superconducting or insulating transition only?
Surface oxidation layer alter electronics properties?

$NbSe_2$ heterostructure



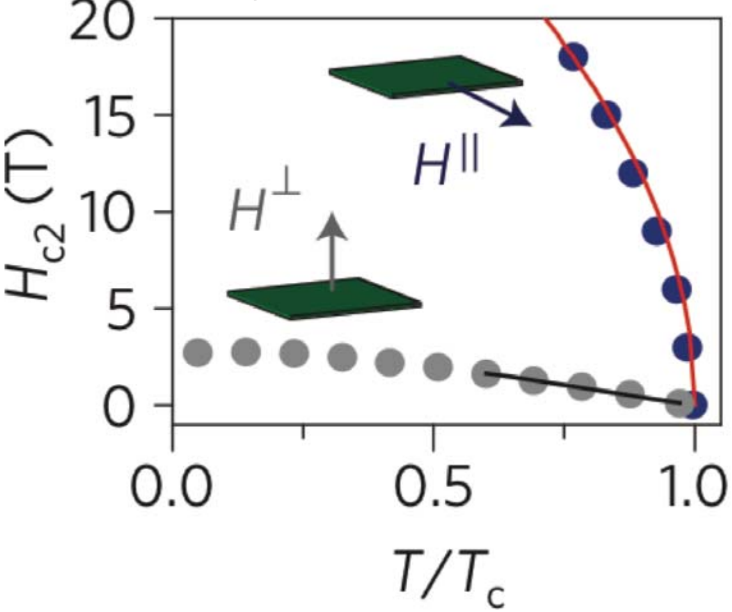


A. W. Tsen, B. Hunt, **Y.D. Kim** *et al*, Nature Physics (2016)

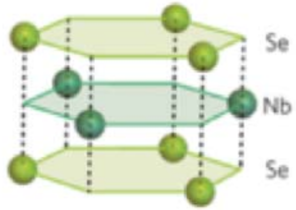
Zero-resistance superconducting transition
Real 2D superconductor!

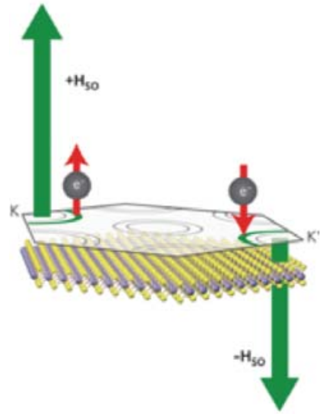
2D Superconductor

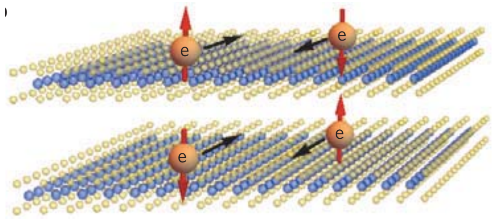
Large in-plane critical field



Out of plane spin-orbit field







$$H_{SO} \propto k \times E_{crystal}$$

In-plane critical field

Pauli paramagnetism limit

$$\mu_B H_P \sim |\Delta|$$

$$H_P = \frac{4T_c}{\pi\mu_B} = 1.84 T_c \sim 9.5 \text{ T}$$

Van Vleck paramagnetism

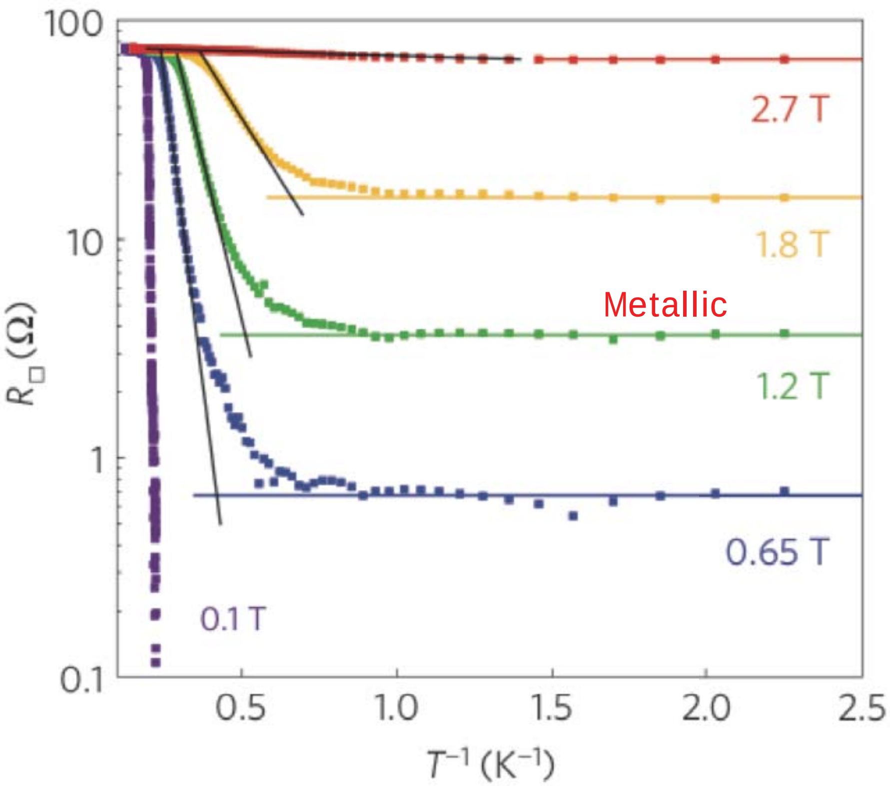
$$\mu_{\|} \sim \frac{H}{H_0}\mu_B$$

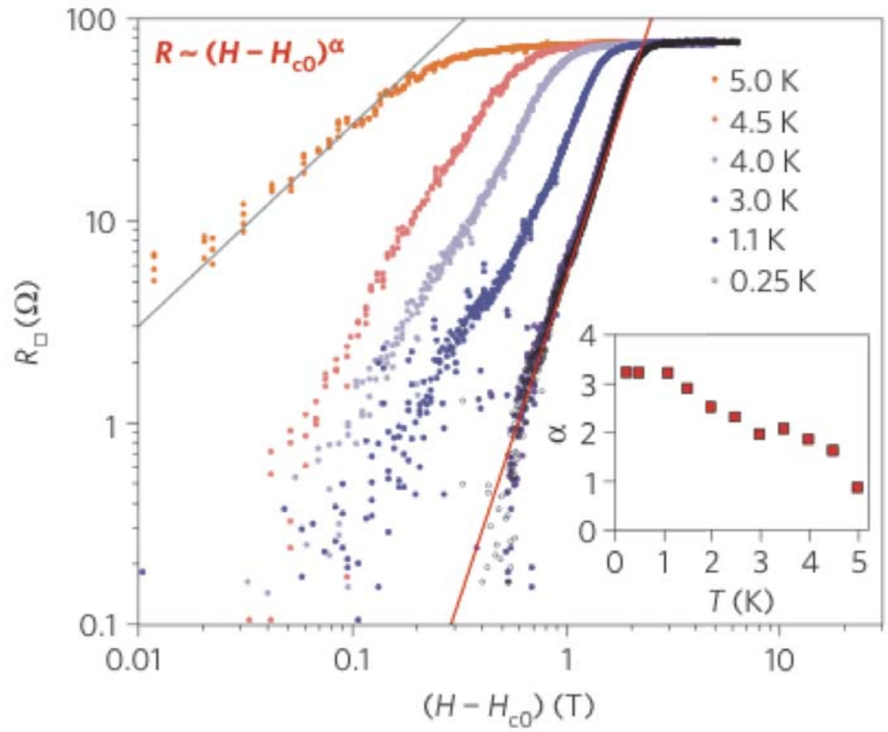
$$\mu_B \frac{H^2}{H_0} \sim |\Delta|$$

$$H_{c2} \sim \sqrt{H_{so}H_p} \sim 50\ T \gg H_p$$

- In-plane critical field: > 20 T
- Larger than Pauli paramagnetic limit of 9.58 T
- $2\Delta_{so} = 80\ meV, H_{so} = 700\ T$

2D Superconductor





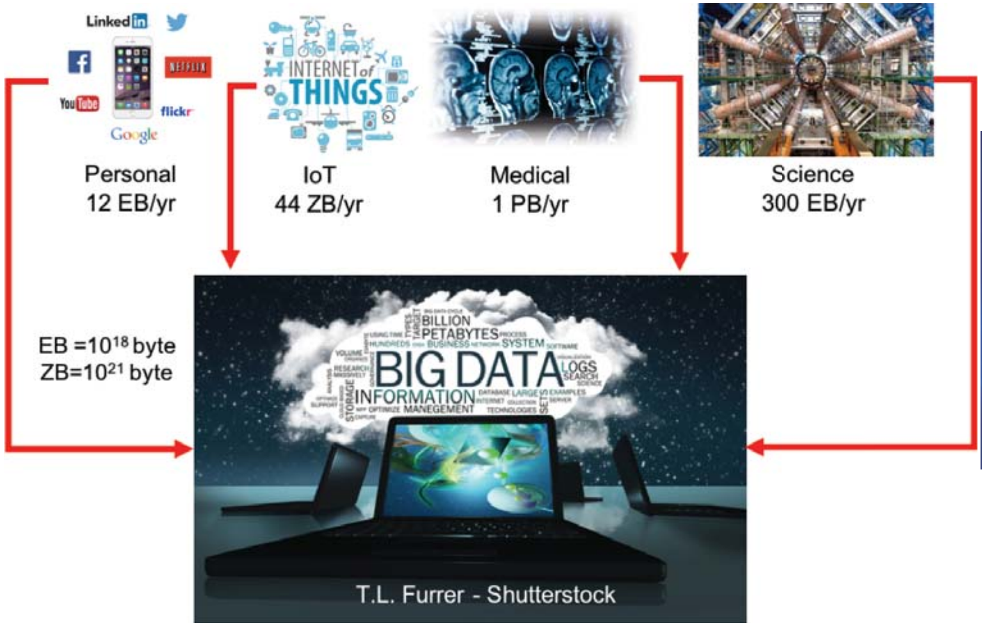
- Clear metallic transition
- No insulating transition
- Large phase fluctuation not kill

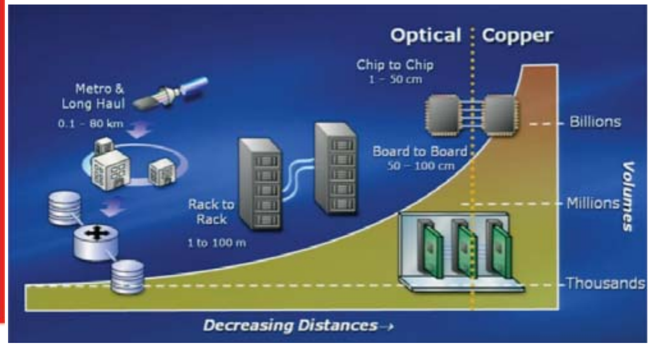
Cooper pair number fluctuation

Nature of quantum metallic phase (Bose metal) ?

Ultrafast Optoelectronics

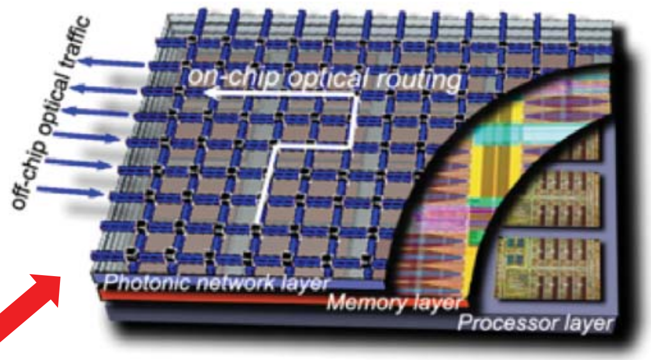
Internet of Things and Big Data
What is problem?





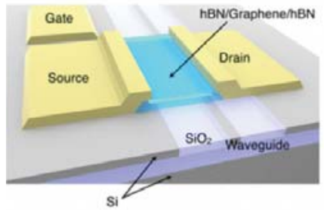
electrical interconnect => optical interconnect

Optical interconnect



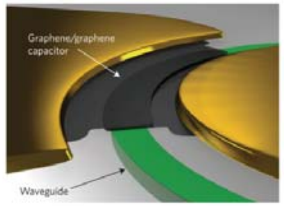
2D material based light source ?

Photodetector (~ 42 GHz)



R.-J. Shiue *et al*, Nano Lett. (2015)

Optical modulator (~ 30 GHz)



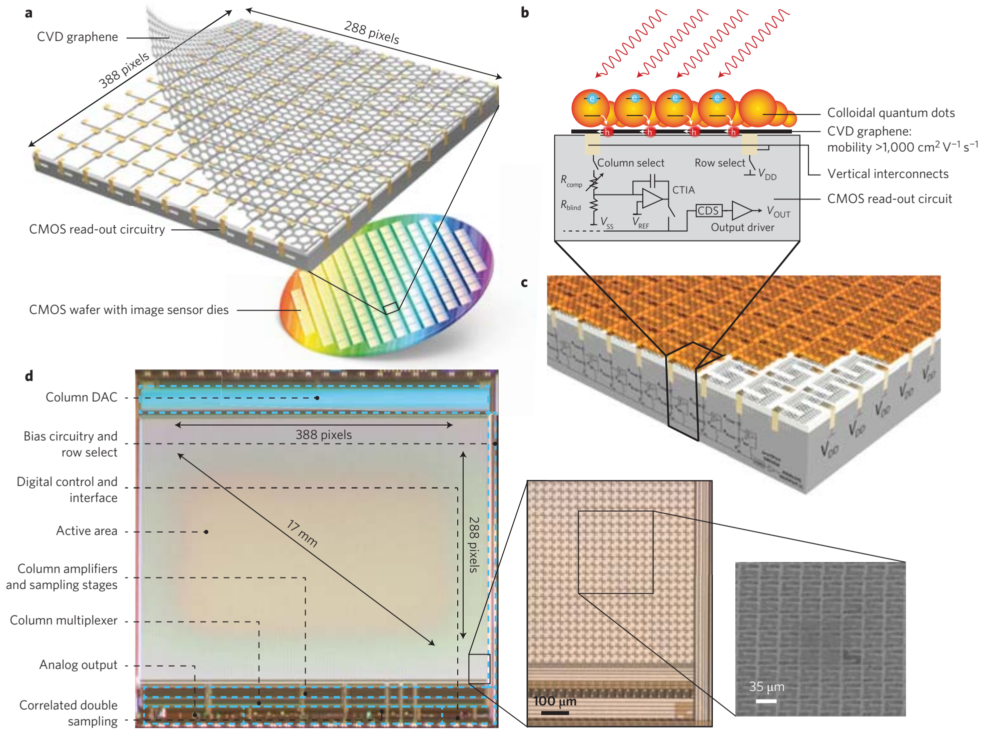
C. T. Phare *et al*, Nature Photonics (2015)

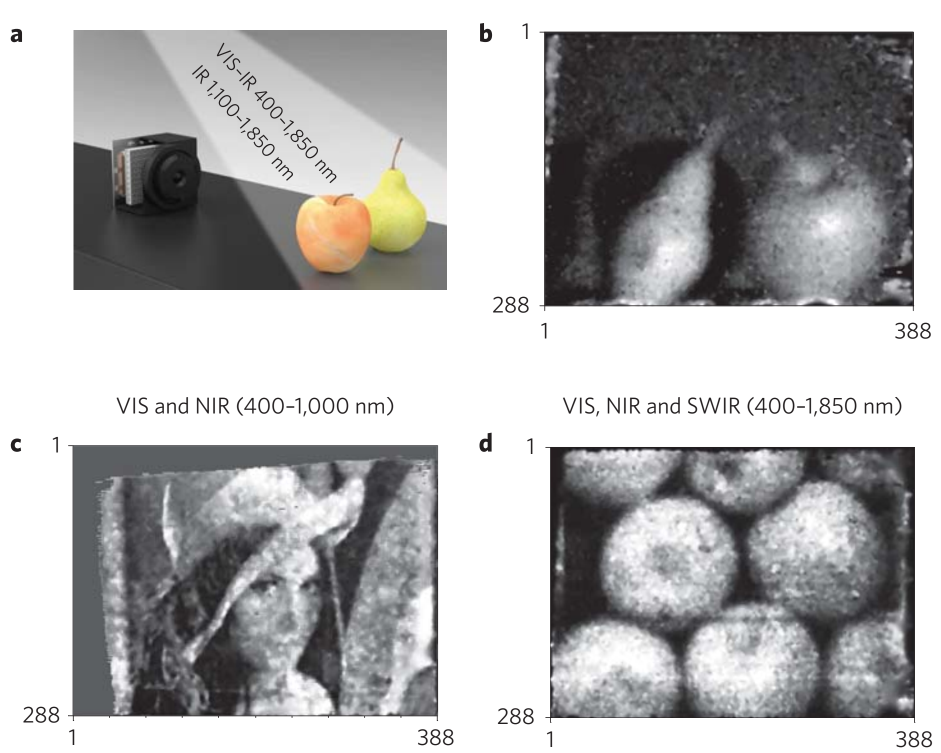
Large Scale Graphene Image Sensor

ARTICLES
PUBLISHED ONLINE: 29 MAY 2017 | DOI: 10.1038/NPHOTON.2017.75
nature photonics

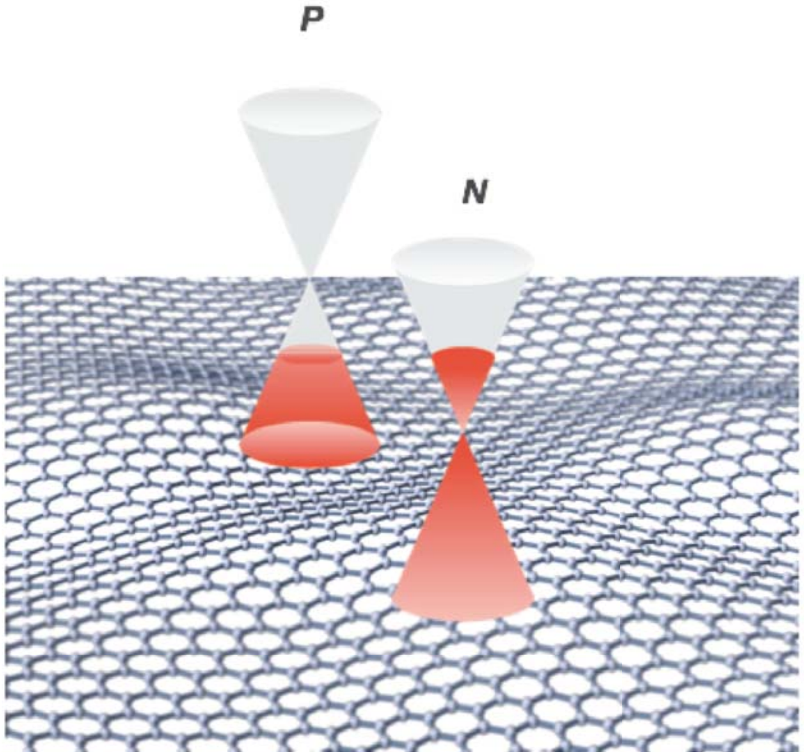
Broadband image sensor array based on graphene-CMOS integration

Stijn Goossens[1†], Gabriele Navickaite[1†], Carles Monasterio[1†], Shuchi Gupta[1†], Juan José Piqueras[1], Raúl Pérez[1], Gregory Burwell[1], Ivan Nikitskiy[1], Tania Lasanta[1], Teresa Galán[1], Eric Puma[1], Alba Centeno[2], Amaia Pesquera[2], Amaia Zurutuza[2], Gerasimos Konstantatos[1,3]* and Frank Koppens[1,3]*





Light Emission from Graphene ?



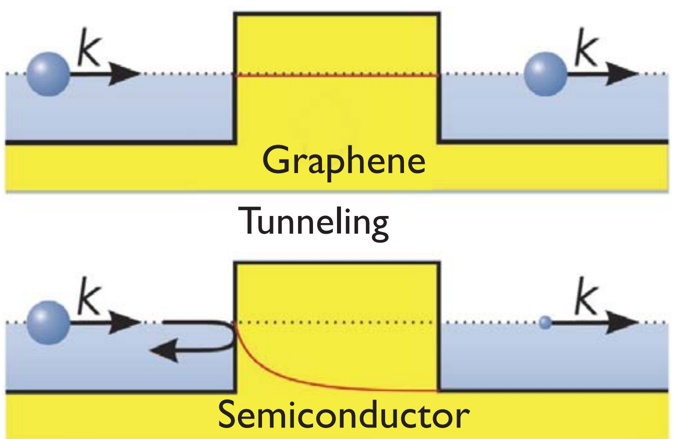
Graphene

•Zero-bandgap

•Klein tunneling (No rectification in p-n junction)

•Ultrafast energy relaxation
-Electron-electron: ~ 10 fs
-Electron - optical phonon: 10 ~ 100 fs
-Optical phonon decay to acoustic phonon: ~ 1 ps

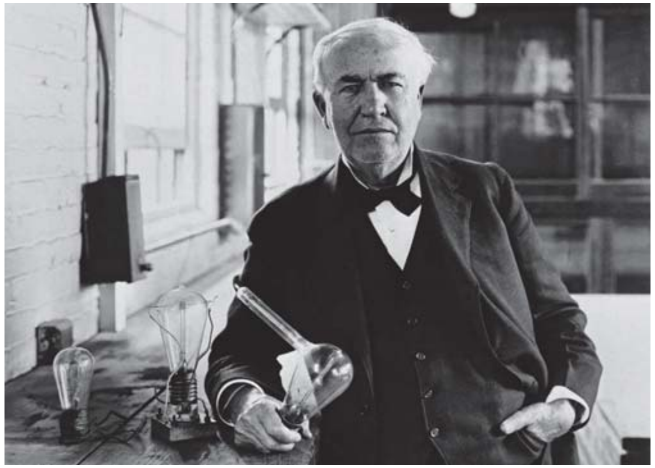
Klein Tunneling



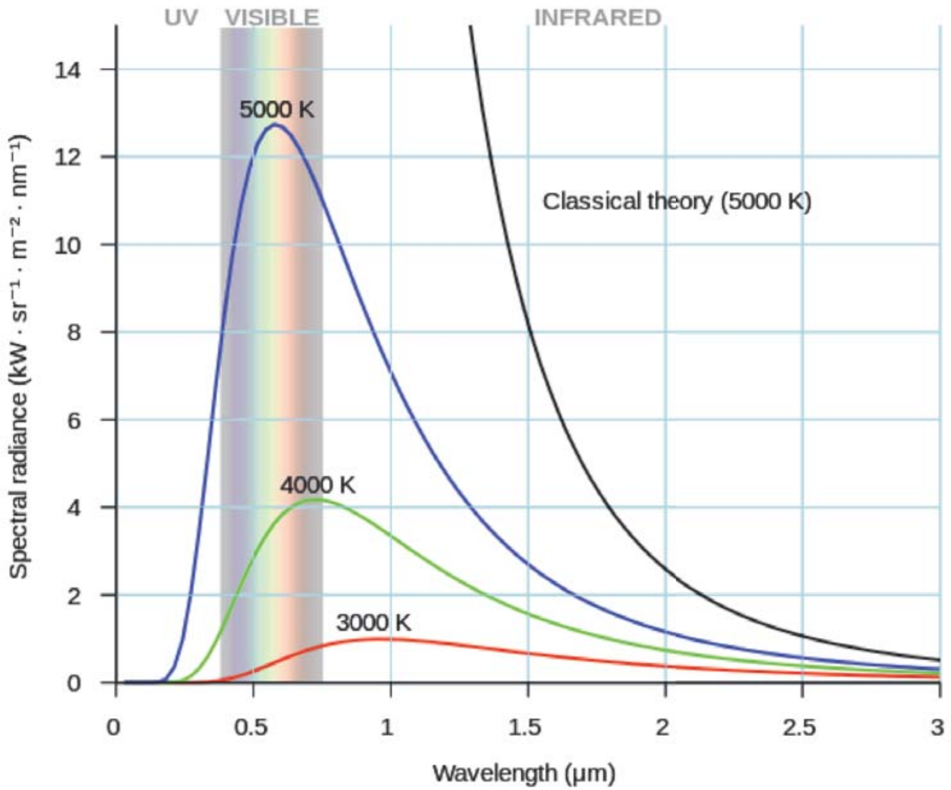
Non-efficient radiative electron-hole recombination

Incandescence

Light bulb



Blackbody radiation



Planck's law

$$I = \frac{2hc^2}{\lambda^5}\left(\exp\frac{hc}{\lambda k_B T} - 1\right)$$

T : electron temperature

Hot Electrons Luminescence in Graphene

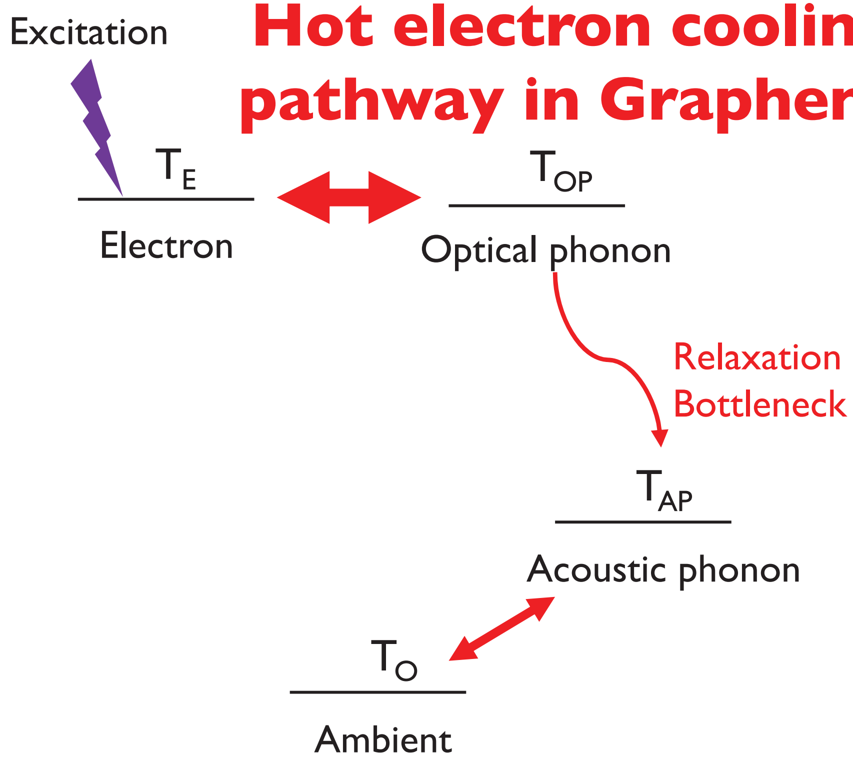
Superior properties of graphene

High current density	World's Strongest Material	High Melting Point
J ~ 10^9 A/cm^2	*E* ~ 1 TPa	*T* ~ 5,000 K

Ideal material for thermal radiation

Planck's law $I(\omega) \sim 1/(\exp(\hbar\omega/k_B T_e) - 1)$

Hot electron cooling pathway in Graphene

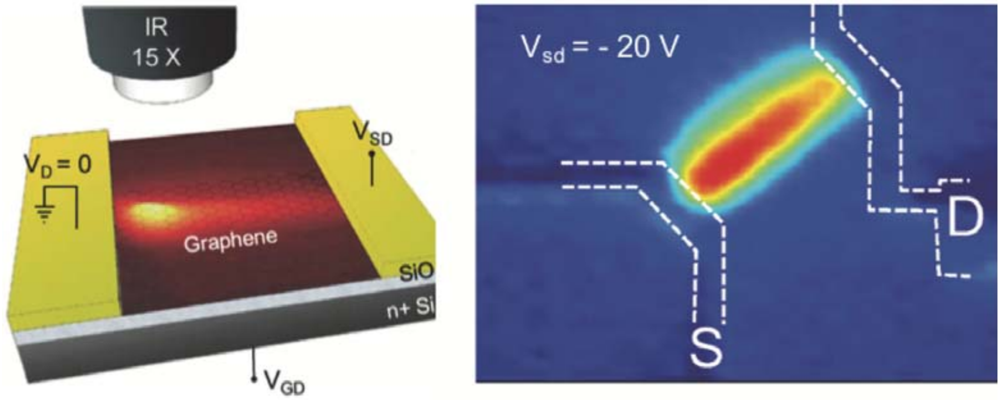


- Very weak electron-acoustic phonon coupling.
- Non-equilibrium phonon mode.
- **Non-equilibrium temperature of graphene**

$T_E \sim T_{OP} > T_{AP}$

Efficient thermal radiation source

Graphene on Substrate

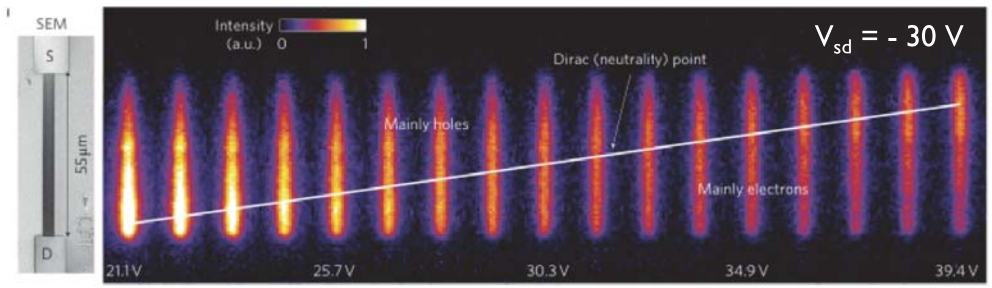


M.-H Bae *et al*, Nano Lett. (2010)

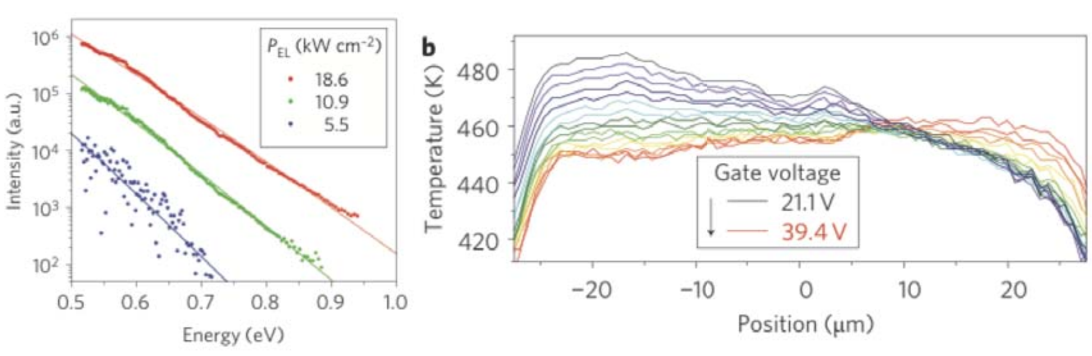
- •Graphene under high bias.
- •Thermal radiation at near IR emission.
- •Follow Planck's law (T < 600 K).

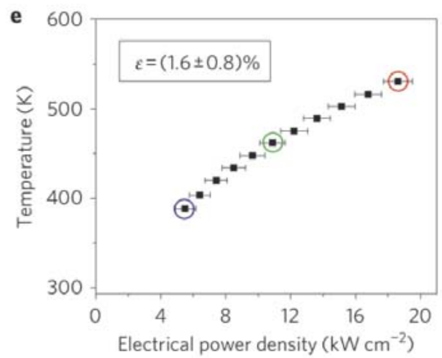
$$I(\omega) \sim \omega^3/(\exp(\hbar\omega/k_B T) - 1)$$

- •Low radiation efficiency (~10^{-6})
  - Dominant heat dissipation by substrate
  - Strong electron scattering (charged impurity, defects of substrate)



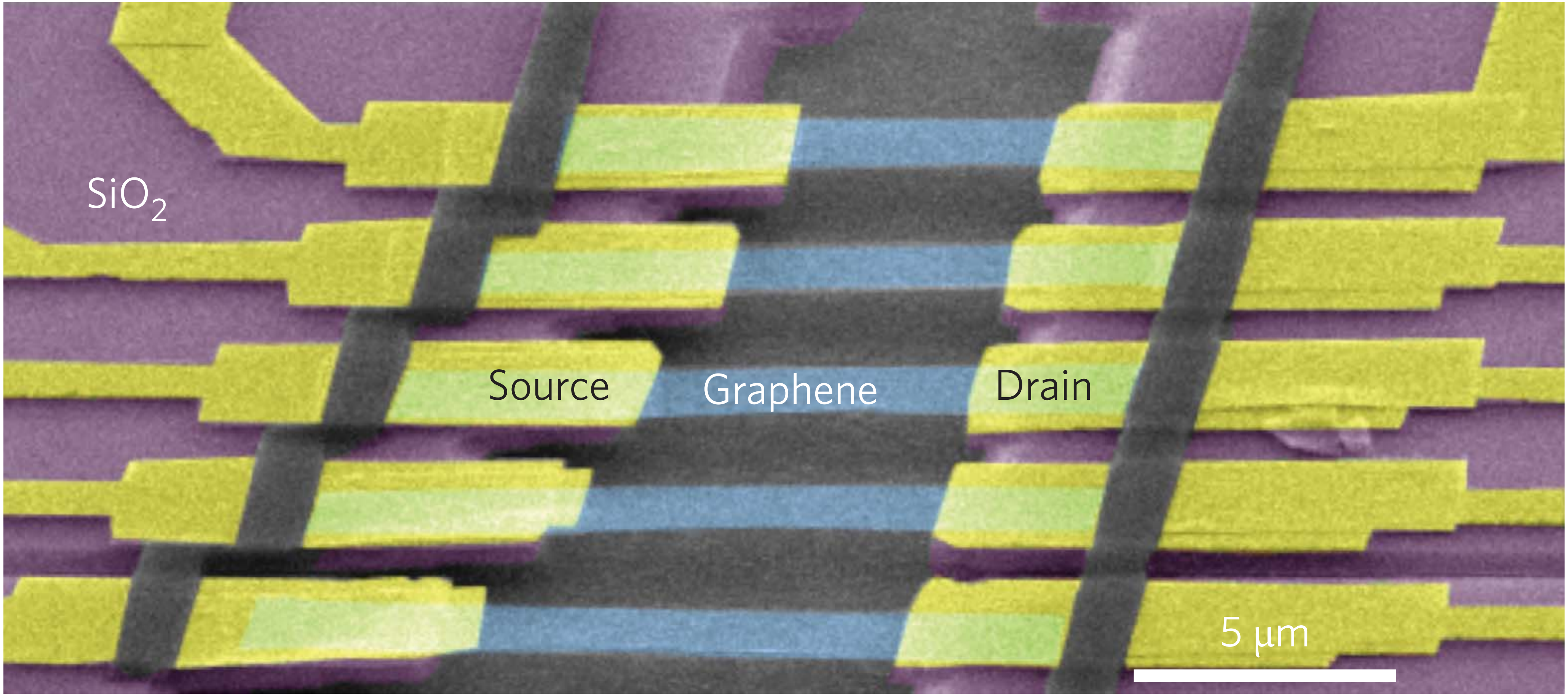
Performance of graphene light emitters are limited by substrate.





M. Freitag *et al*, Nature Nanotech. (2010)

Suspended Graphene



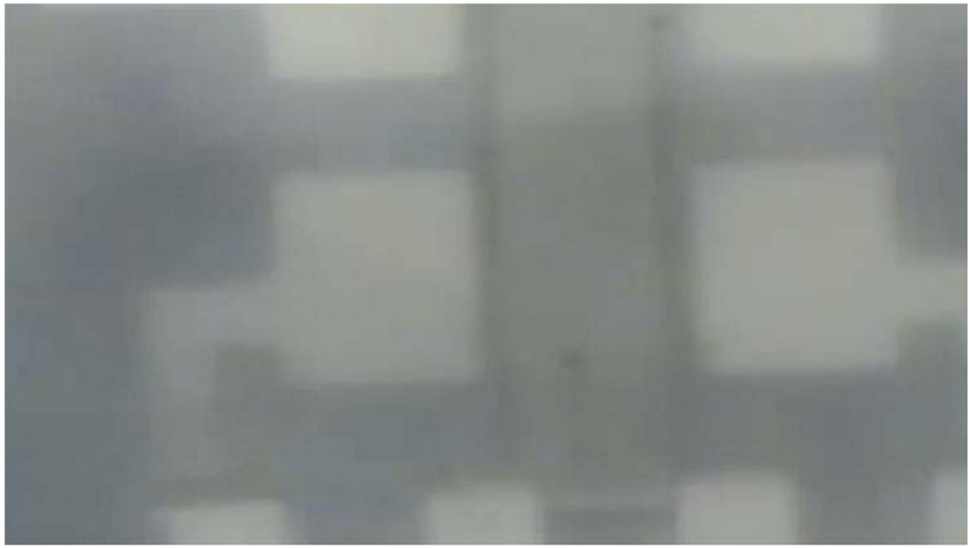
Y. D. Kim *et al*, Nature Nanotech. (2015)

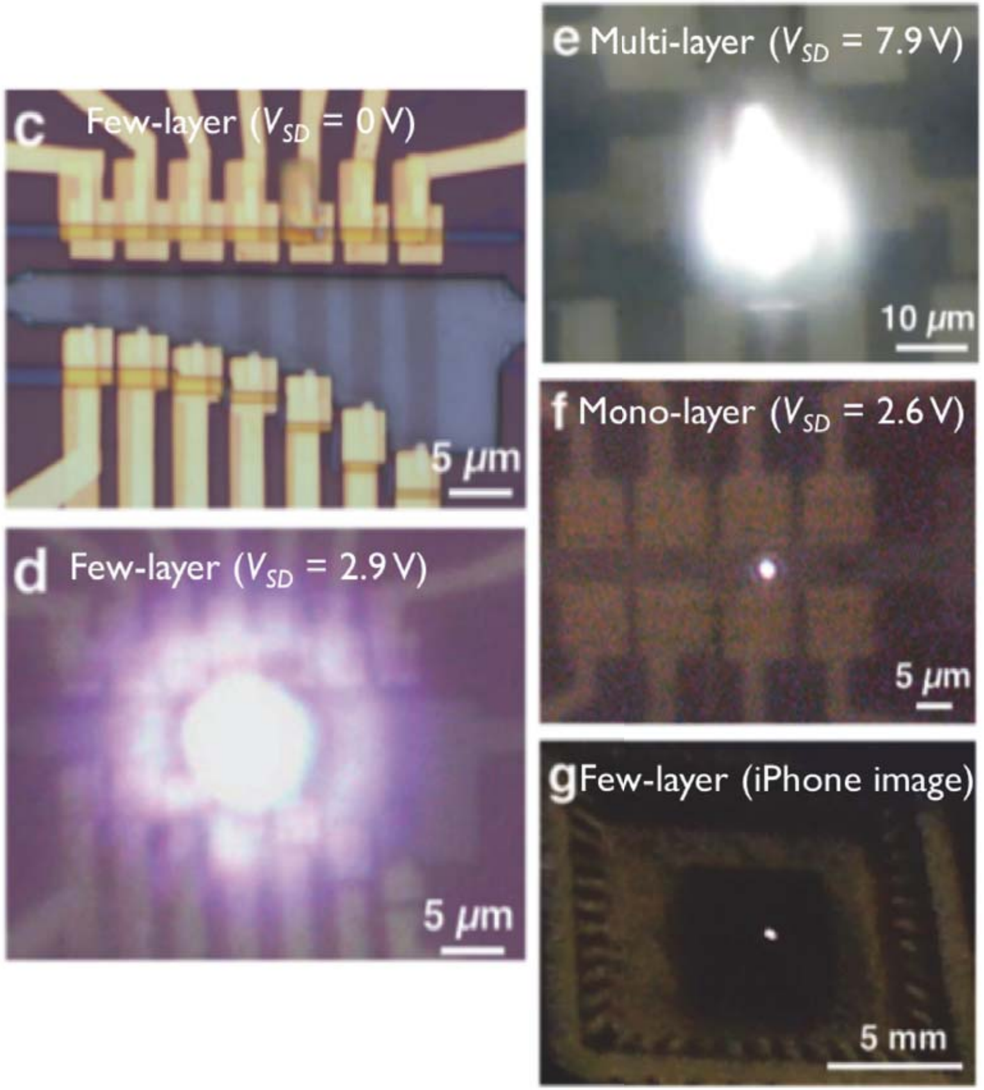
- Minimize the substrate effect
- Reduce vertical heat dissipation to substrate
- Approaching to the intrinsic characteristic

Bright Visible Light Emission from Graphene

Vsd = 2.4V -> 2.9V -> 2.4V

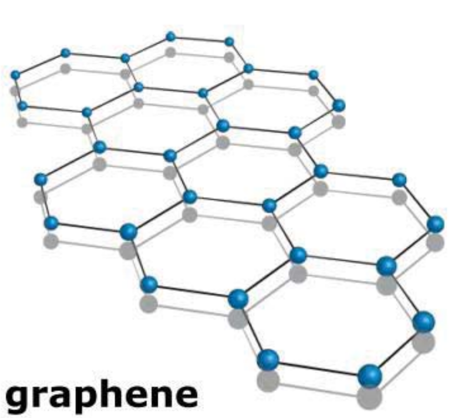
Electric pulsed |Vsd| = 7.5 V -> 8 V

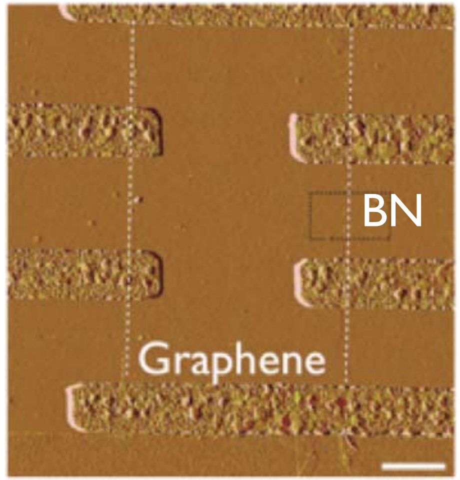


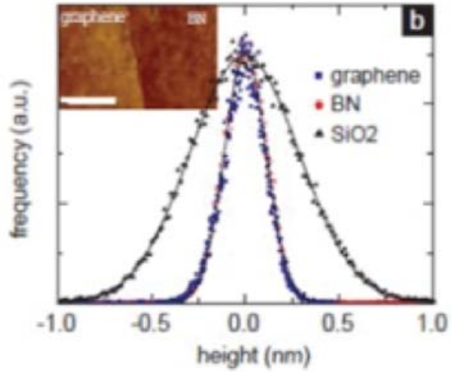


Y. D. Kim *et al*, Nature Nanotech. (2015)

Hexagonal Boron Nitride (hBN)



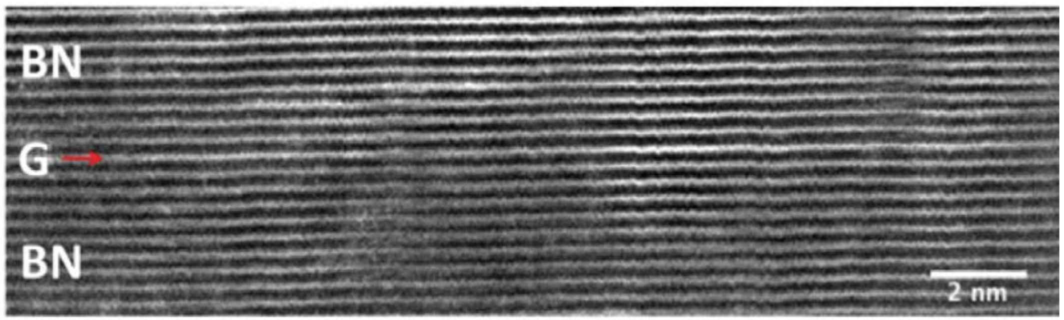




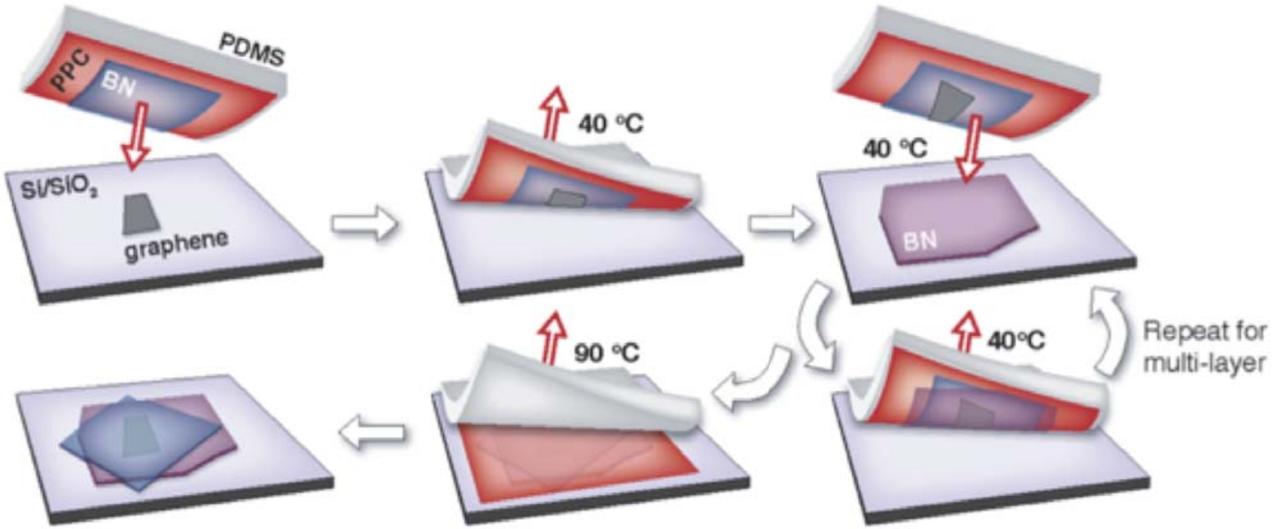
Comparison of h-BN and SiO_2

	Band Gap	Dielectric Constant	Optical Phonon Energy	Structure
BN	5.5 eV	~4	>150 meV	Layered crystal
SiO2	8.9 eV	3.9	59 meV	Amorphous

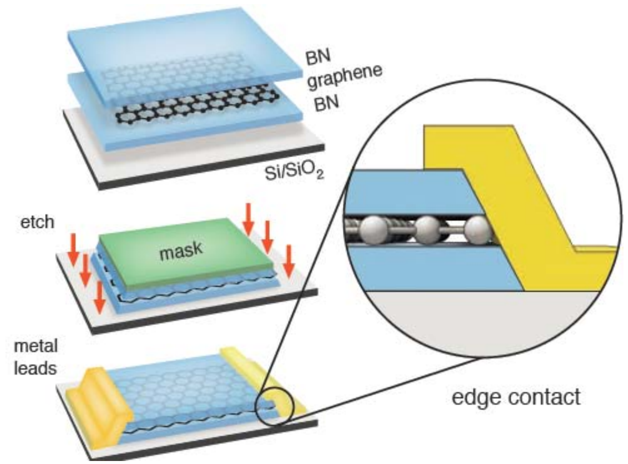
- Single-crystal, atomically flat, no defect.
- High optical phonon energy.
- Ideal dielectric material for 2D material.

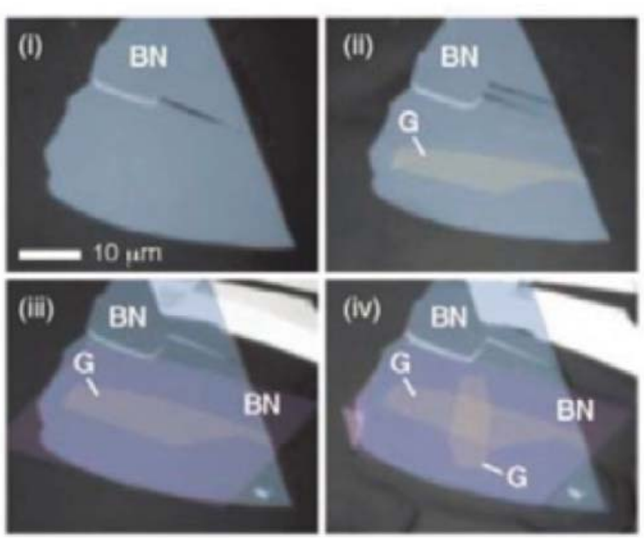


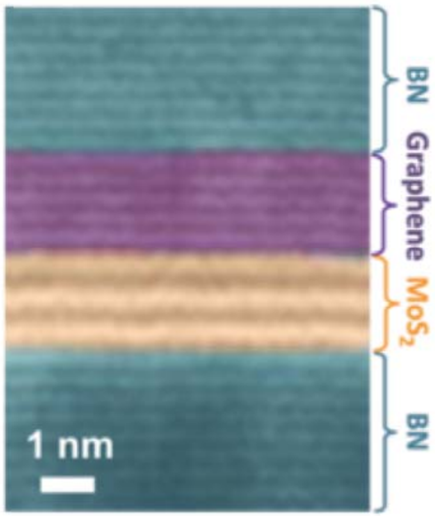
van der Waals Heterostructure

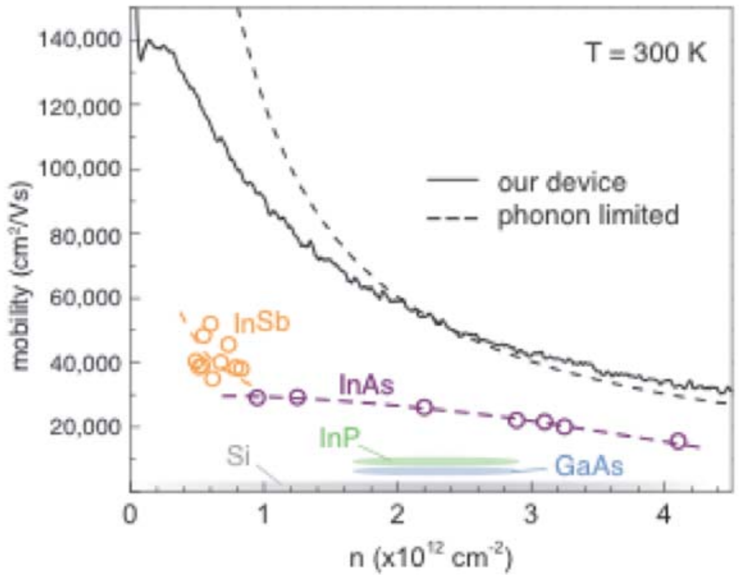


L. Wang et al., Science (2015)







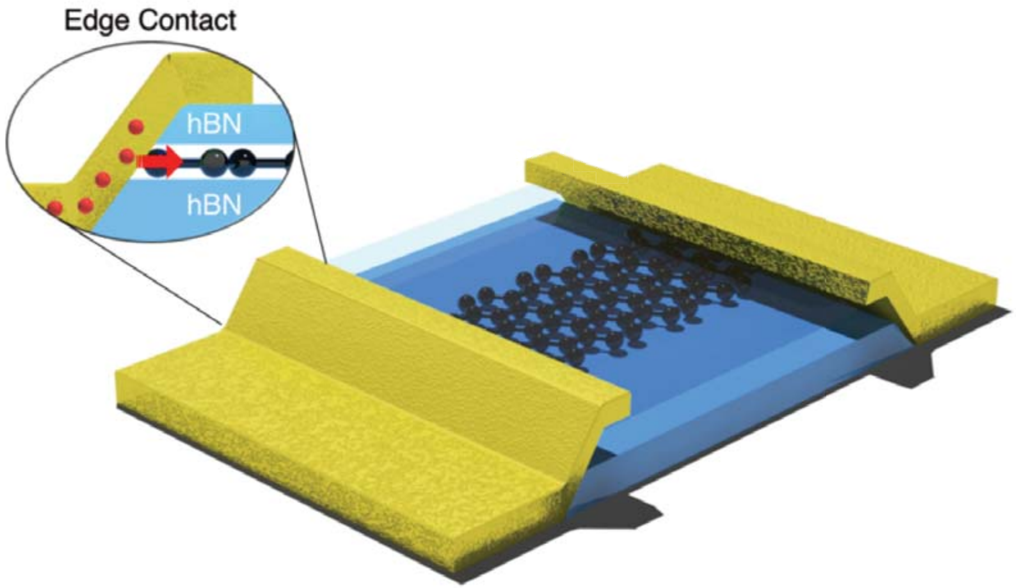


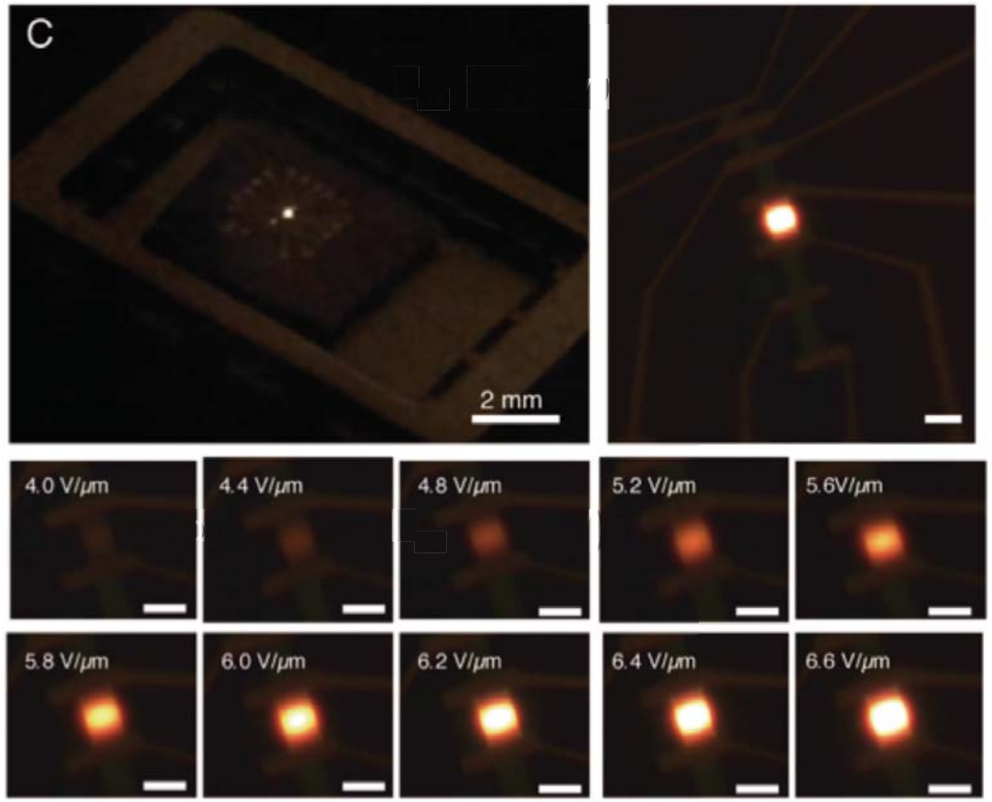
At limit of acoustic phonon scattering.

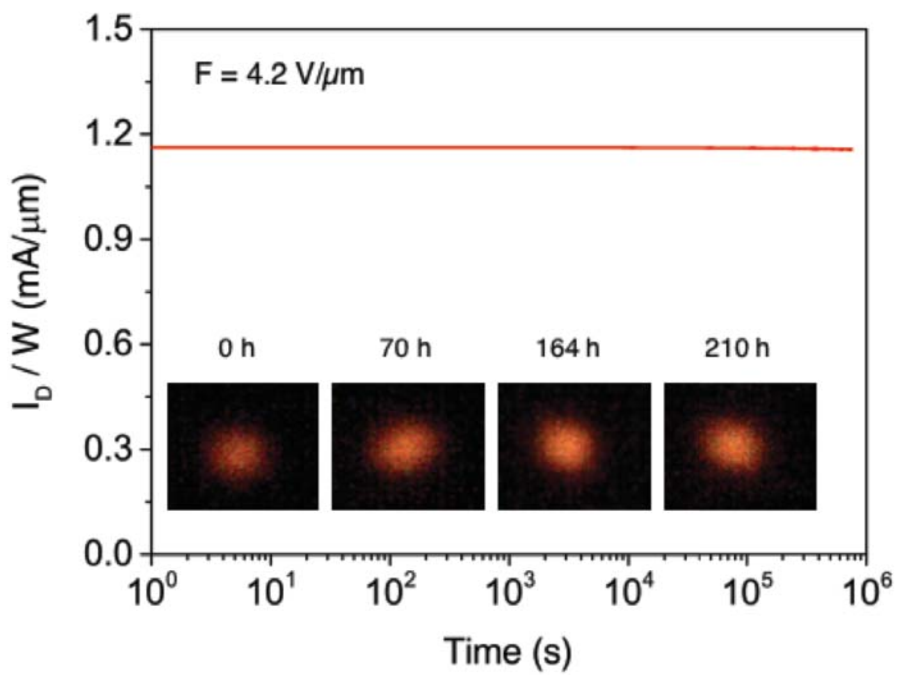
Intrinsic transport-suppress electron scattering

Ultrafast Graphene Light Emitter

hBN/Gr/hBN heterostructure

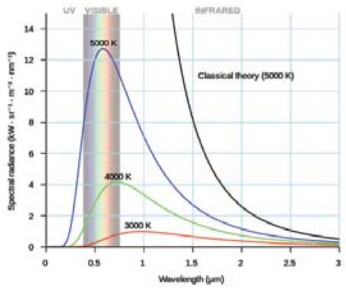






- Bright visible light emission
- Electron scattering suppress is more dominant
- hBN encapsulation for practical light source even in ambient condition
- Life-time above 4 year

Tailoring Thermal Radiation of Graphene



Black body thermal radiation

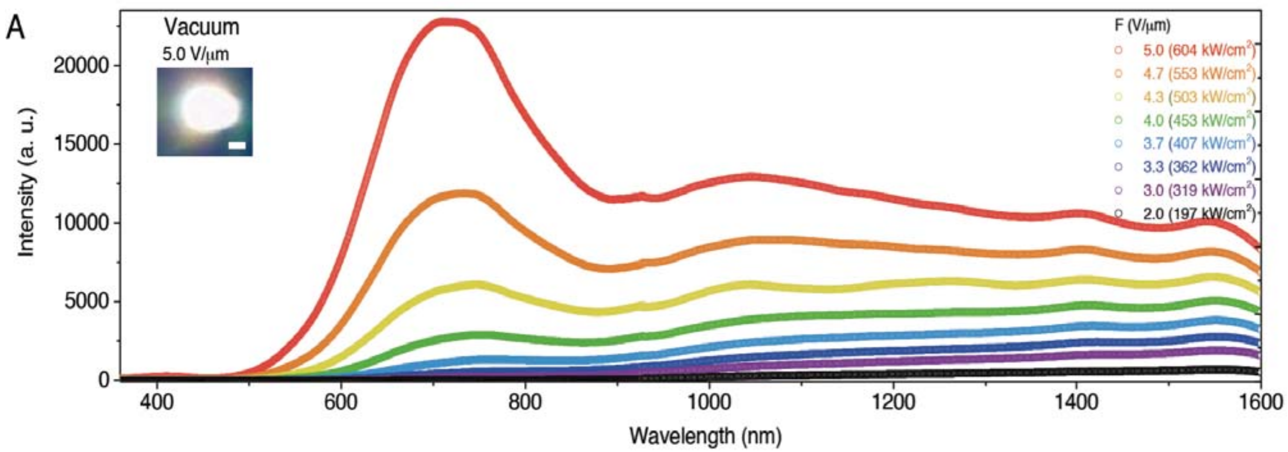
$$I(\omega, T) = E(\omega)n(\omega, T)D(\omega)$$

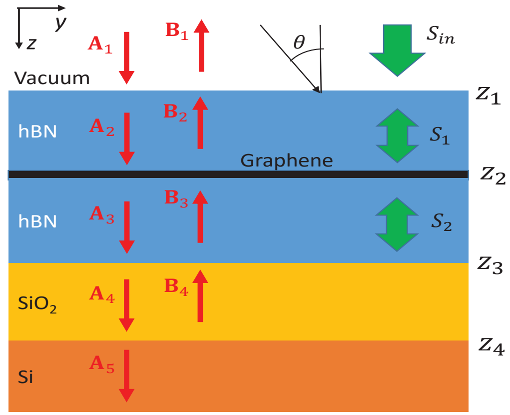
$E(\omega)$: Mode energy, $n(\omega, T)$: photon occupation

$D(\omega)$: Local optical density

- Strong light-matter interaction of graphene
- Engineering local optical density in sub-wavelength
- Easy to integration to arbitrary structures

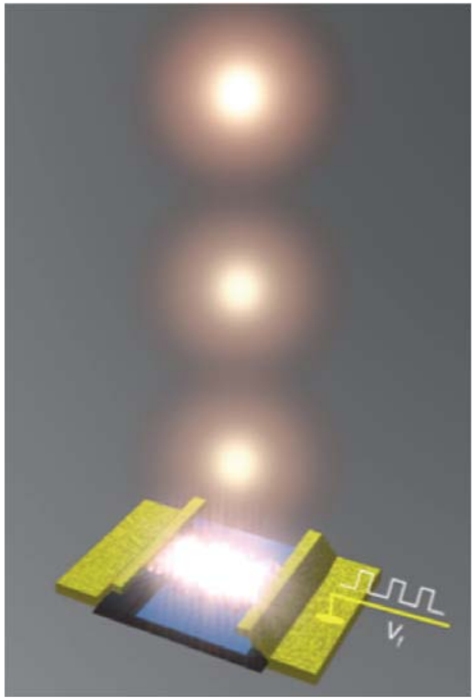
Optical cavity mode





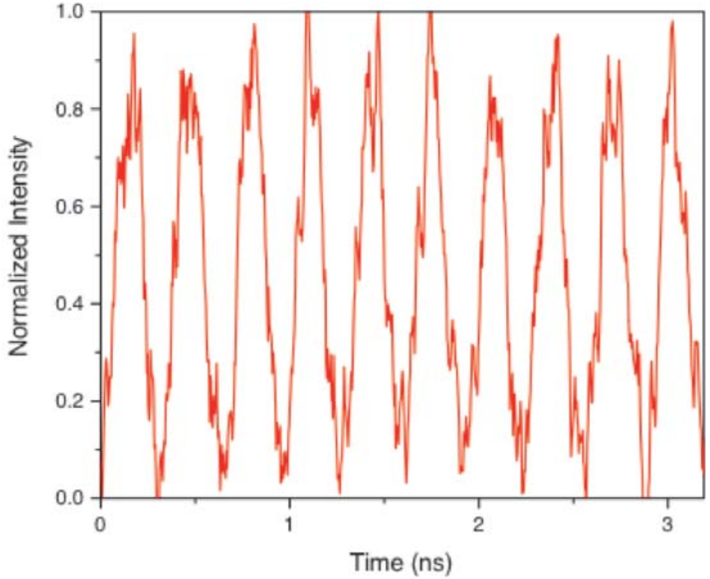
Y.D. Kim *et al, Nano Letters (2018).*

Ultrafast Graphene Light Emitter

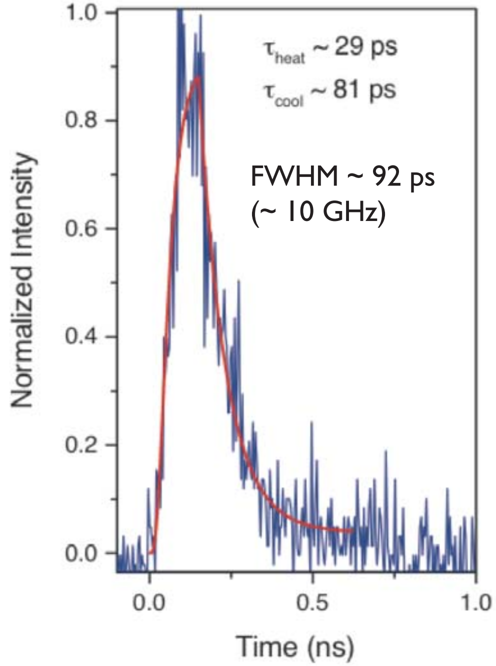


GHz bandwidth graphene light emitter

3 GHz light modulation

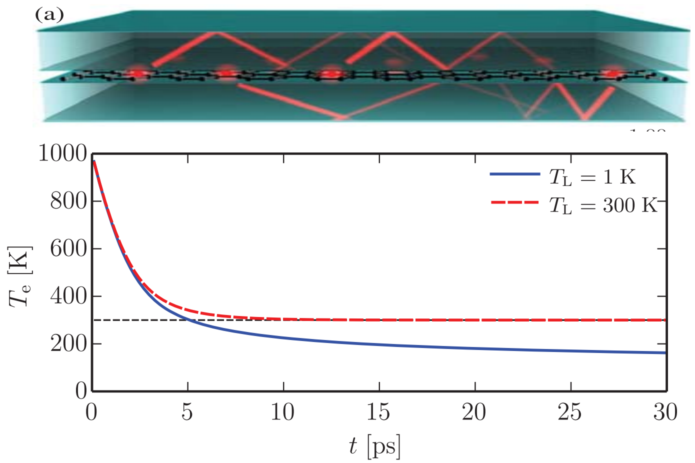


10 GHz bandwidth



Y.D. Kim *et al*, *Nano Letters (2018).*

Hyperbolic plasmon-phonon polariton

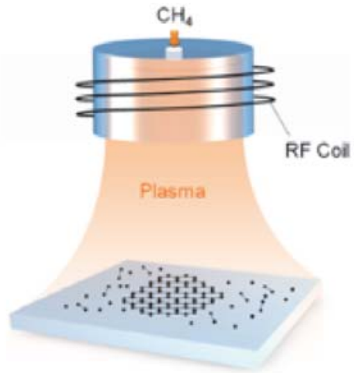


A. Principi et al, PRL (2017)

- •Electrically driven GHz range thermal radiation source
- •10 GHz bandwidth (FWHM ~ 92 ps)
- •Thermal relaxation time $\tau = C_e/\Gamma$ (heat capacity of graphene and hot electron cooling rate) – Significant heating of 3 nm hBN layers at interface
- •Direct and efficient electron cooling pathway by graphene/hBN interface - Intrinsic thermal radiation modulation speed above 100 GHz

Large Scale Graphene Light Emitter

PECVD Graphene on arbitrary substrate

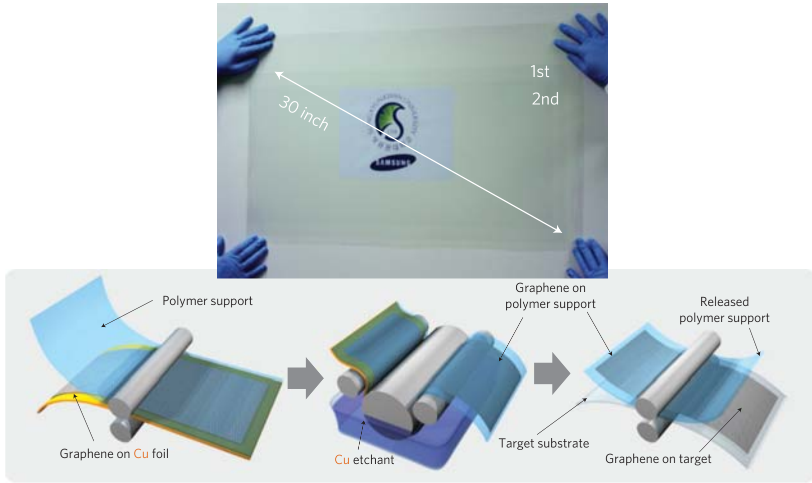


4 inch
Graphene wafer

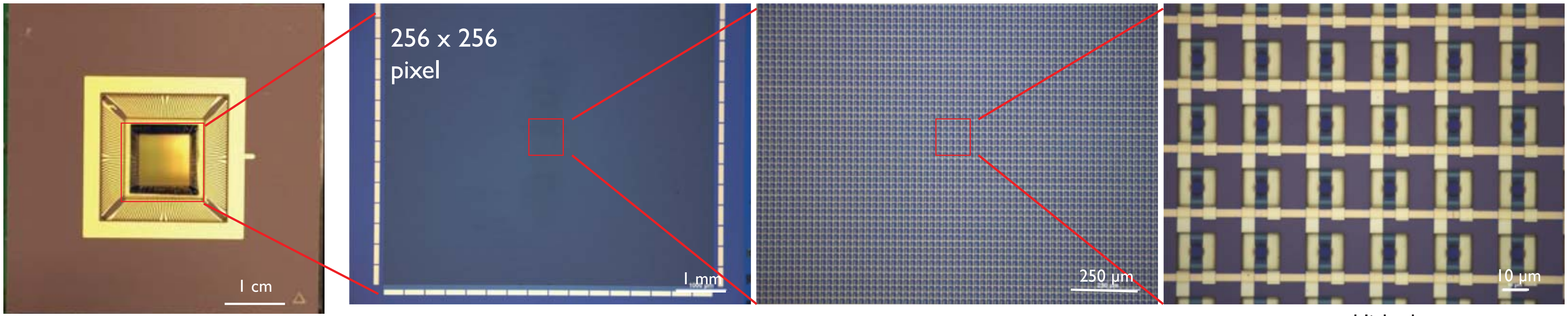
4 inch
SiO_2/Si

Kim, Y. S. et al., Nanoscale (2014)

CVD Graphene on Cu foil



S. Bae et al., Nature Nanotechnology (2010)



unpublished

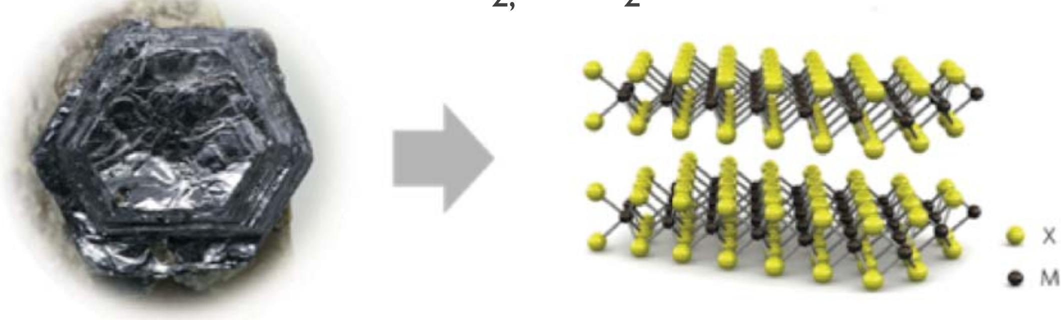
Hyung-sik Kim
Ken Shepard group/
Samsung Display

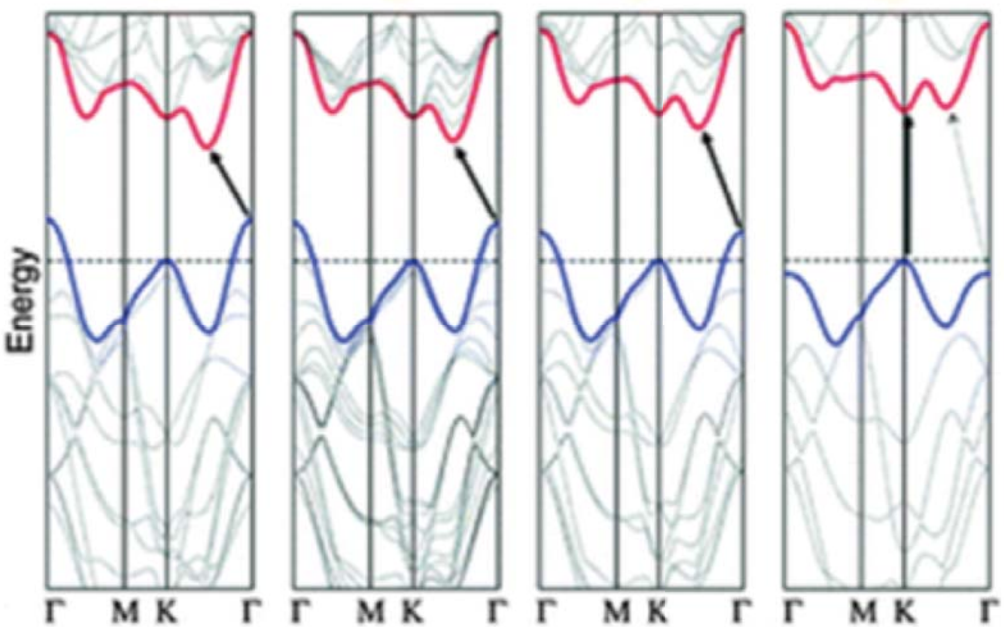
- Scale up using large scale CVD graphene
- Over 60,000 graphene light emitter array on chip
- PECVD graphene – No need transfer process
- CMOS technology compatibility

2D Semiconductor

Transition Metal Dichalcogenides

MoS_2, WSe_2

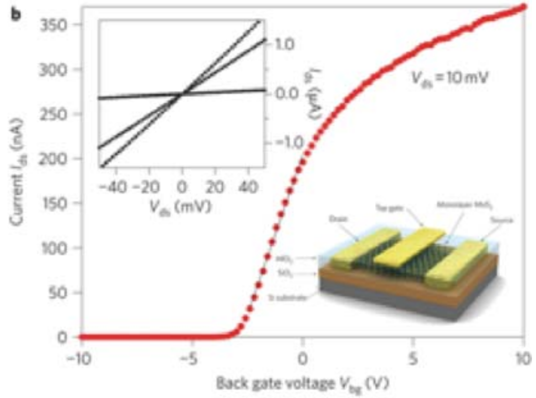




Thickness decreases. →

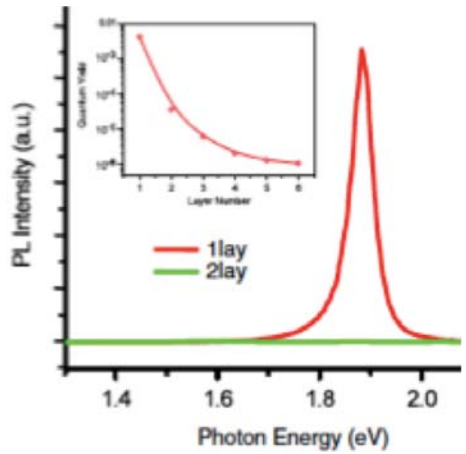
Strong quantum confinement effect

Intrinsic Band gap - High on/off ratio



B. Radisavljevic et al, Nature Nanotech. (2011)

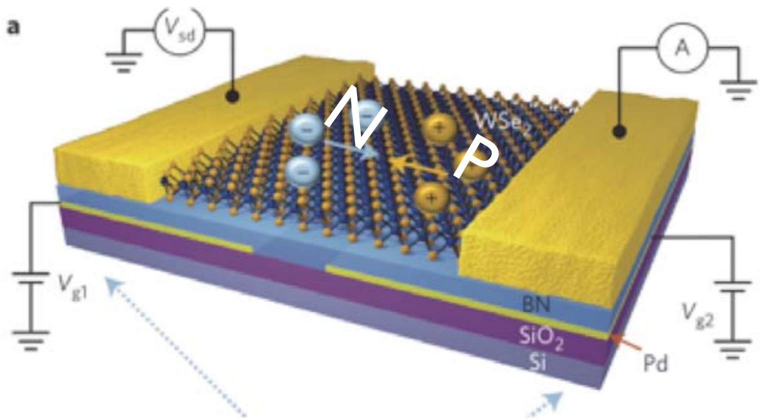
Direct band gap - Photoluminescence



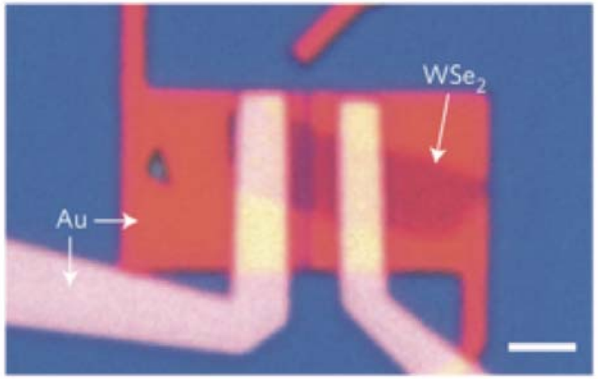
KF. Mak et al, Phys. Rev. Lett. (2010)

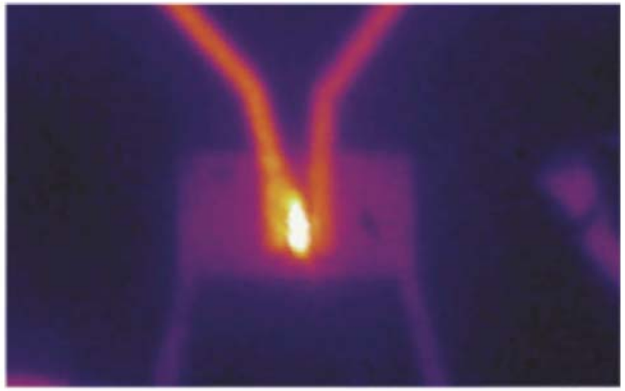
2D Semiconductor Lateral LED

Lateral P-N junction



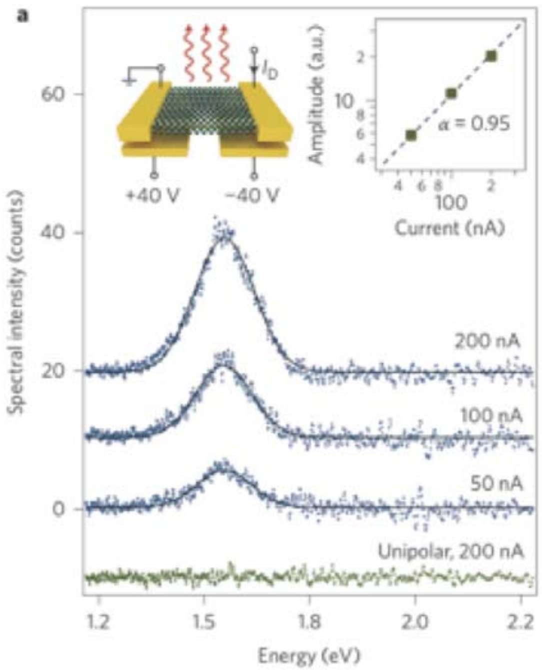
J. S. Ross et al., Nature Nanotech. (2015)





B. W. H. Baugher et al., Nature Nanotech. (2015)

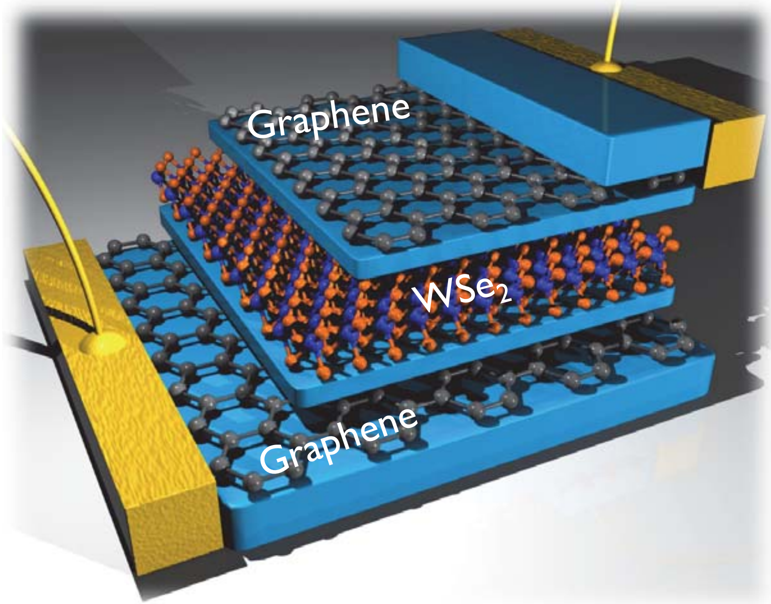
- Atomically thin LED from WSe_2, MoS_2, WS_2. etc
- Formation lateral P-N junction by split gate
- Light emission from P-N junction interface
- EQE: ~ 0.2 % limited by contact resistance

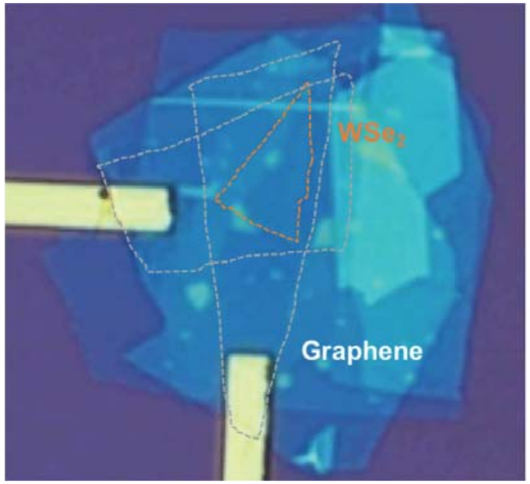


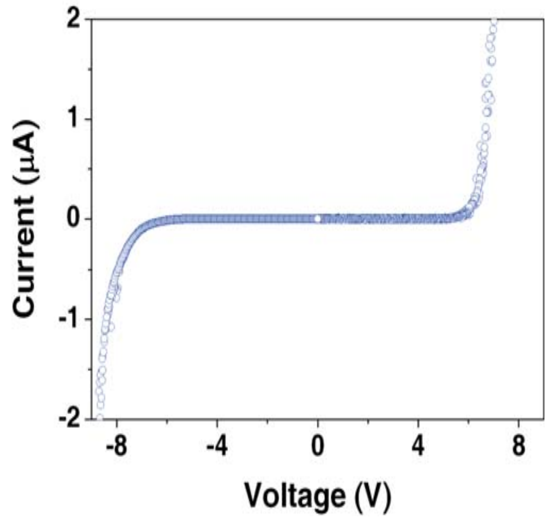
A. Pospischil et al., Nature Nanotech. (2015)

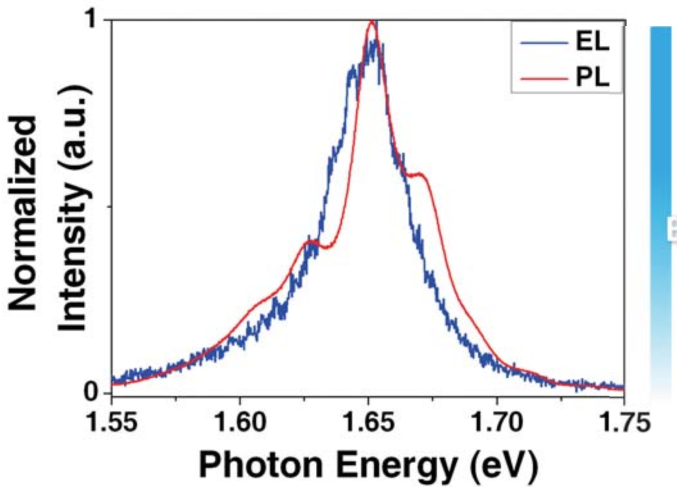
2D Semiconductor Vertical LED

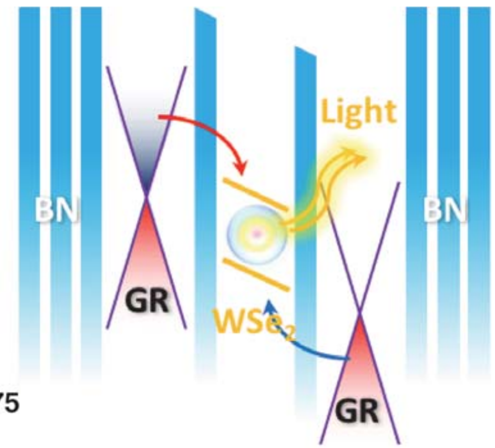
Vertical tunneling structure









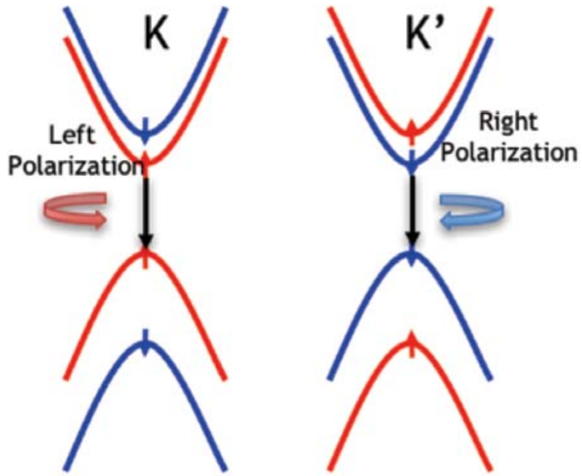


- •Gr/hBN/WSe_2/hBN/Gr vertical heterostructure
- •Coincide the EL and PL at 1.65 eV
- •Direct electron and hole injection via tunneling
- •EQE: 1~8 %
- •Helicity light emission is possible

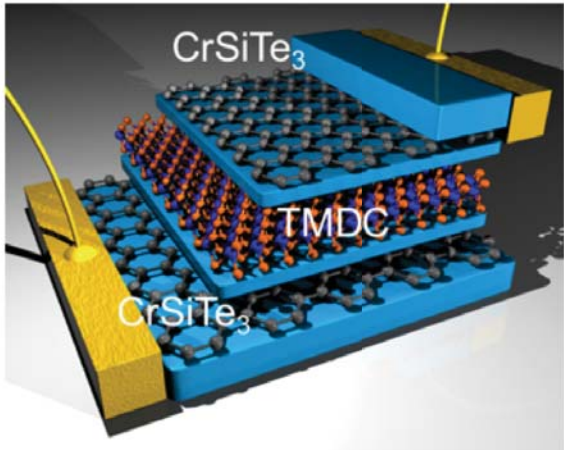
Y.D. Kim *et al*, in preparation and demonstrated by Manchester group

Beyond LED

Valleytronics LED



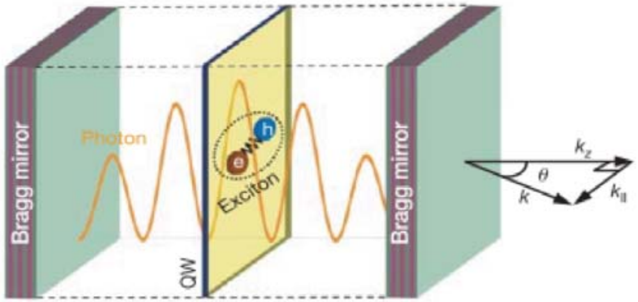
Valley polarized LED



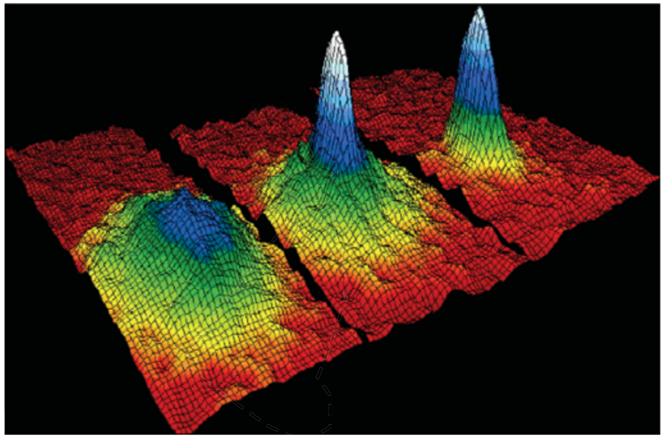
2D ferromagnetic/TMDC heterostructure

Exciton-Polariton BEC

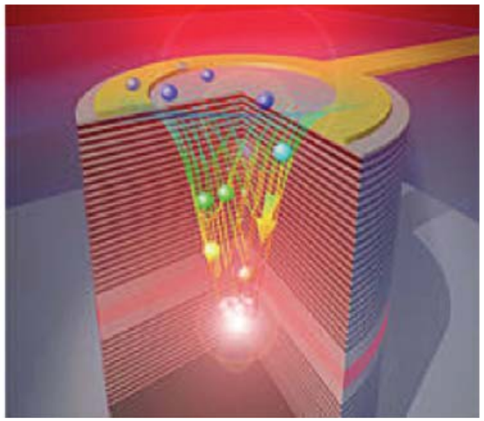
Polariton



Strong light matter interaction
Exciton-Photon (Bosonic)



Polariton Laser



Ultra-low threshold lasing

Quantum Emitter at Room Temperature

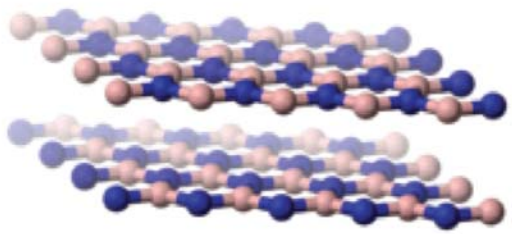
3D

NV center diamond

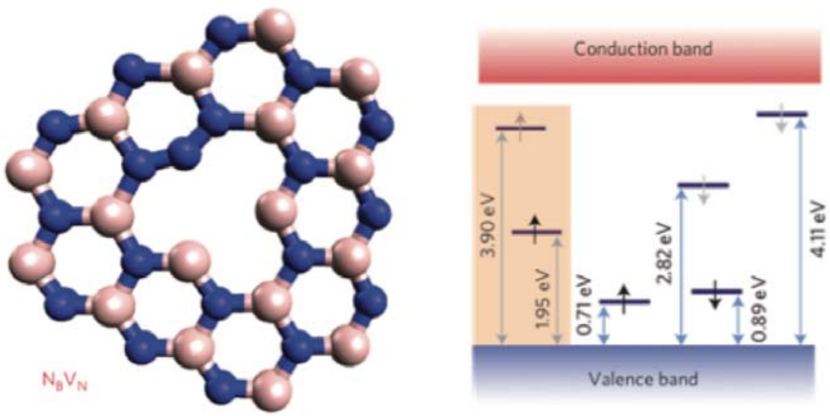
vs

2D

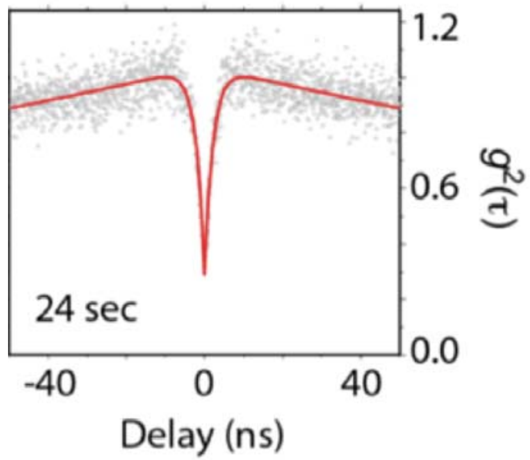
NV center hBN



2D single photon source



T. T. Tran *et al*, Nature Nanotech. (2016)



Single photon source at room temperature

Developing electrically driven single photon source

Potential for optical quantum information process

Thank you very much!

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