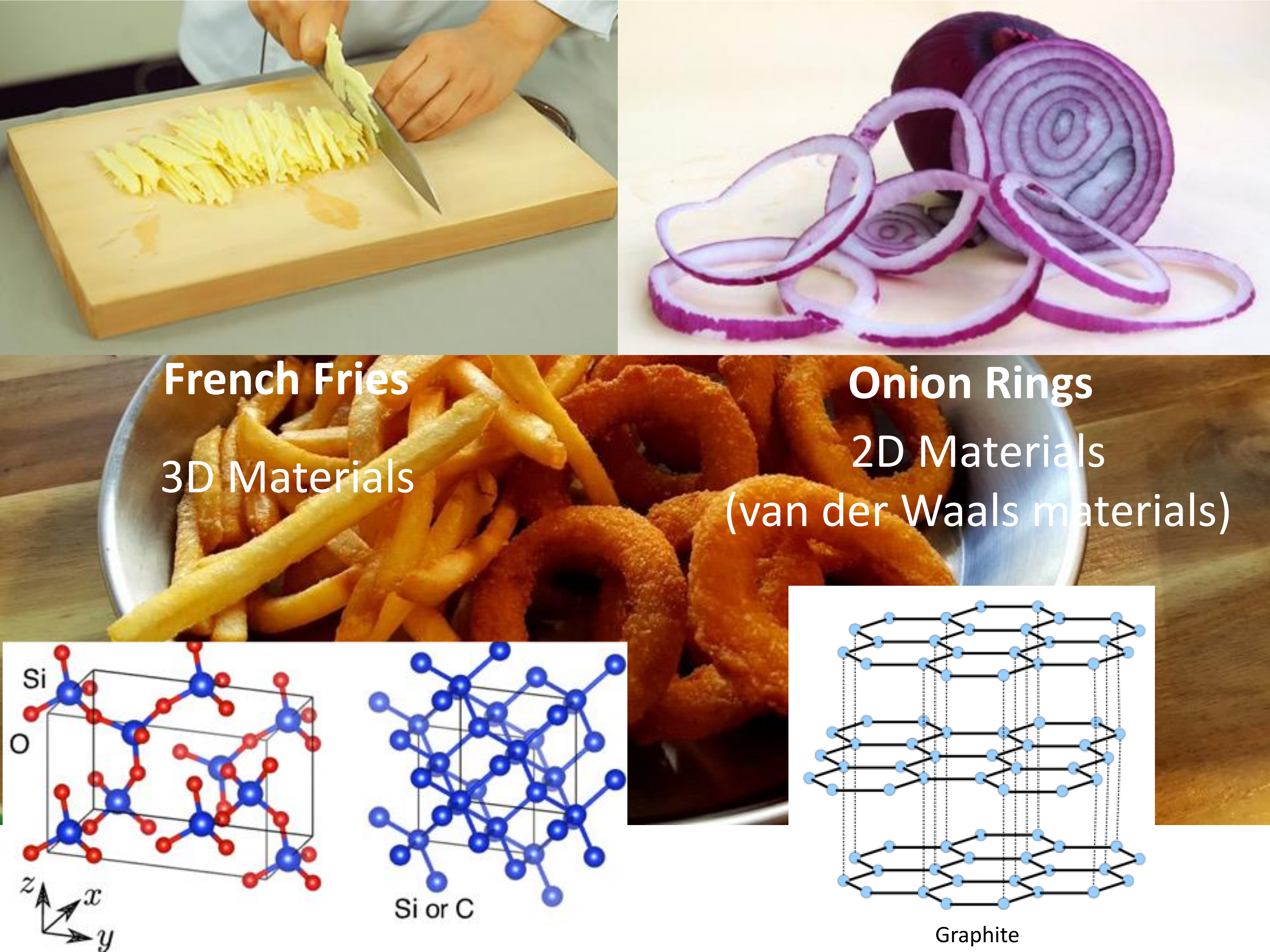
Two-dimensional van der Waals Heterostructures for Next-generation Light Source

Young Duck Kim

Department of Physics, Kyung Hee University

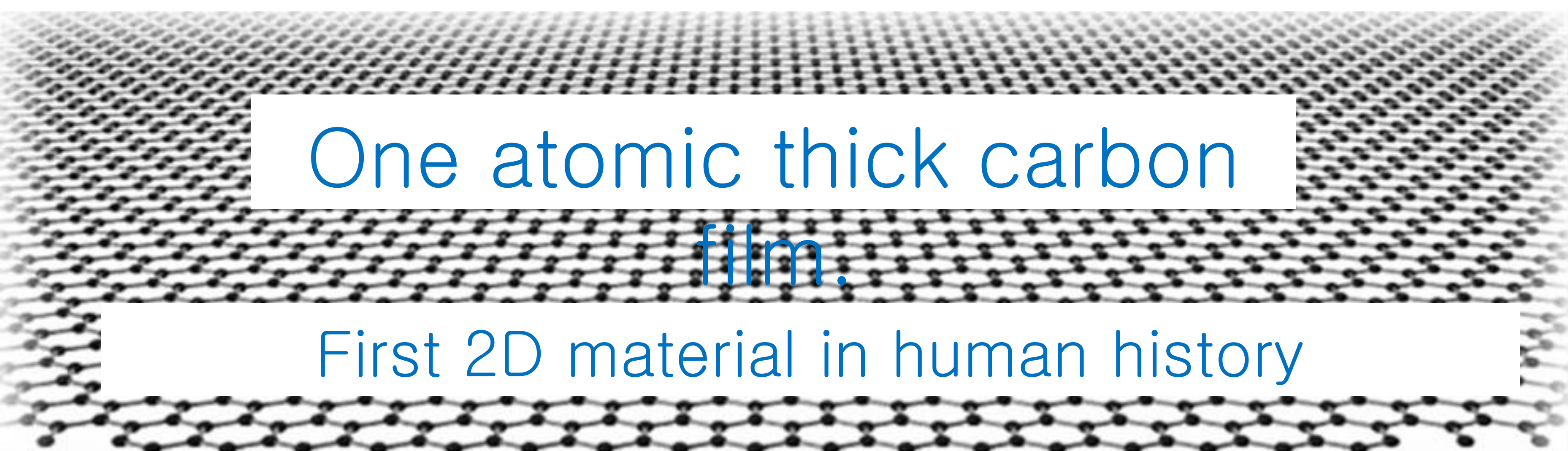
2019.11.27


French Fries
Onion Rings


French Fries
3D Materials
Onion Rings
2D Materials
(van der Waals materials)
Si
O
z
x
y
Si or C
Graphite

Van der Waals Materials

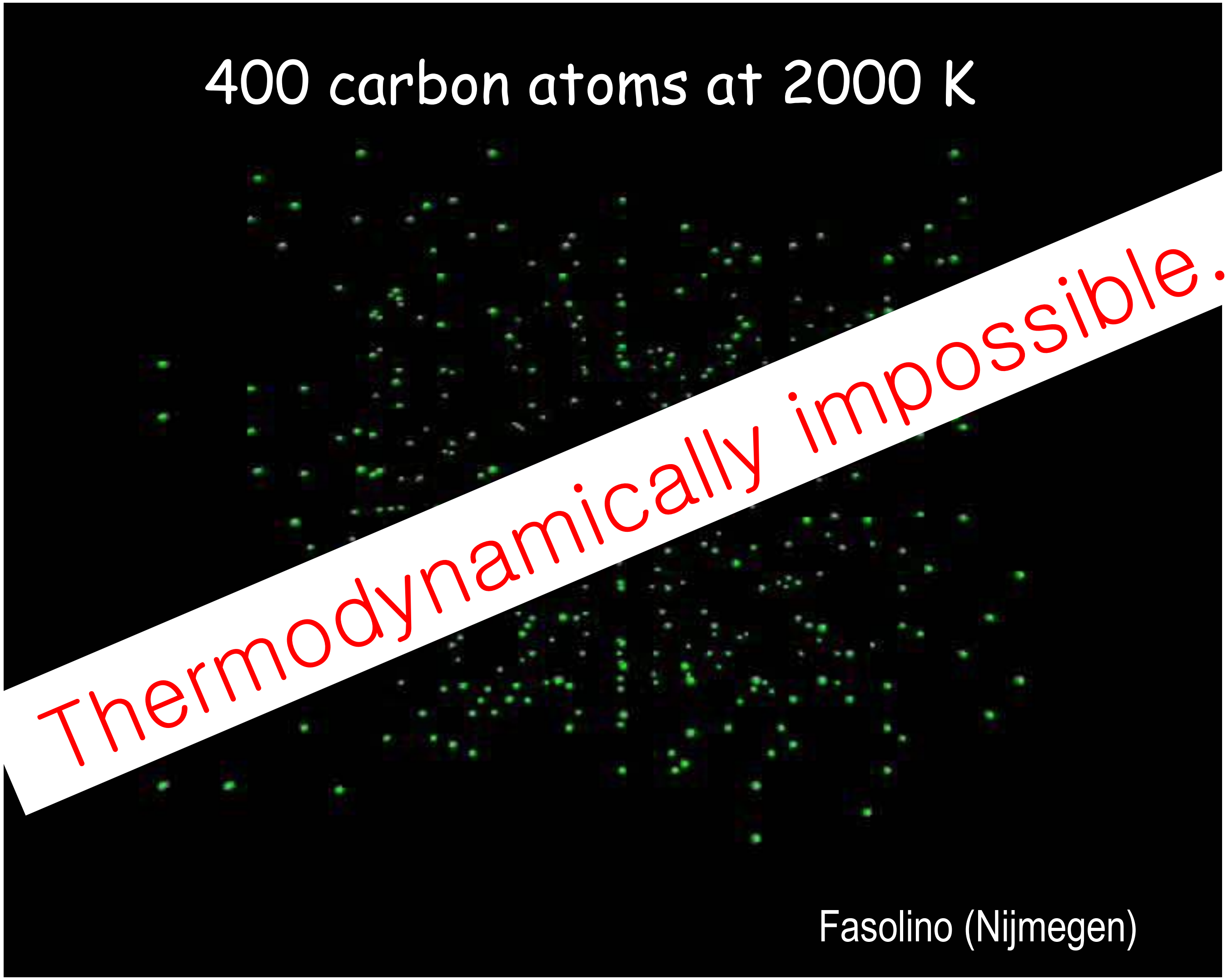
Graphene



One atomic thick carbon film.

First 2D material in human history

2D GROWTH IS FORBIDDEN



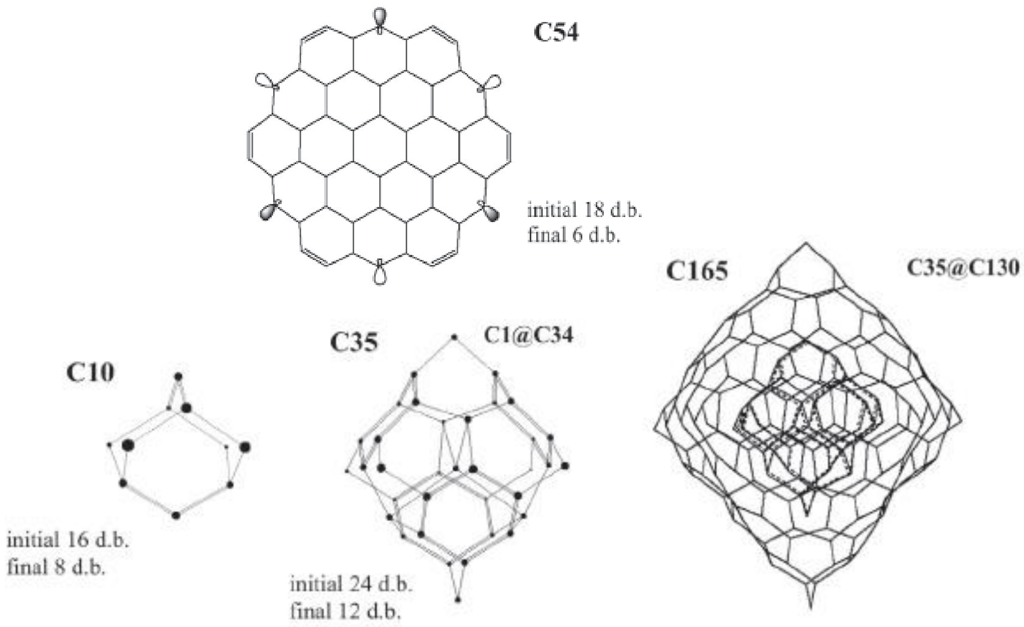
growth
means
temperature
close to melting
causes
violent
vibrations
destroys
order in 2D

A. Geim PPT slides

Peierls; Landau; Mermin-Wagner; …

(only nm-scale flat crystals are possible to grow *in isolation*)

THERMODYNAMIC STABILITY



graphene sheets
should scroll

Kaner Science 2003
Braga et al Nanolett 2004

graphene:
thermodynamically unstable
for <24,000 atoms or size < 20 nm

Shenderova, Zhirnov, Brenner Crit Rev Mat Sci 2002

THERMODYNAMICALLY UNSTABLE
does not mean IMPOSSIBLE
-JUST METASTABLE-

A. Geim PPT slides

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

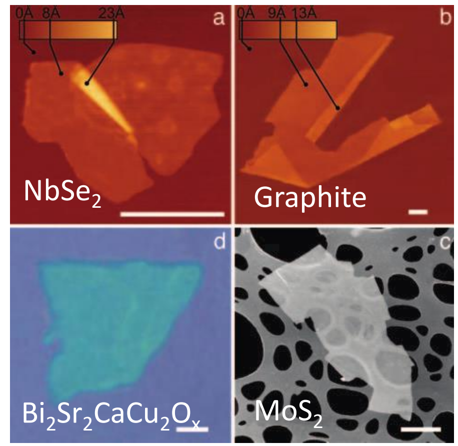
Edited by T. Maurice Rice, Swiss Federal Institute of Technology, Zurich, Switzerland, and approved June 7, 2005 (received for review April 6, 2005)

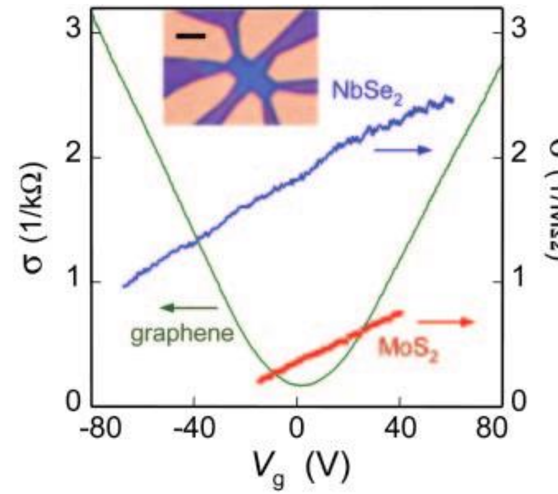
We report free-standing atomic crystals that are strictly 2D and can be viewed as individual atomic planes pulled out of bulk crystals or as unrolled single-wall nanotubes. By using micromechanical cleavage, we have prepared and studied a variety of 2D crystals including single layers of boron nitride, 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.

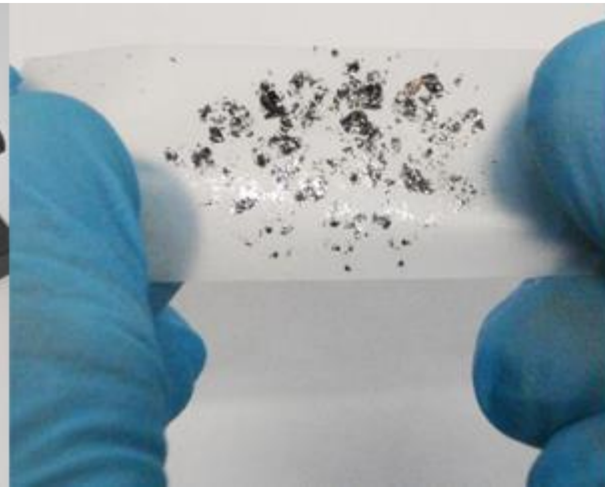
Despite its simplicity, the described cleavage technique has several nonobvious features that are instructive to analyze,

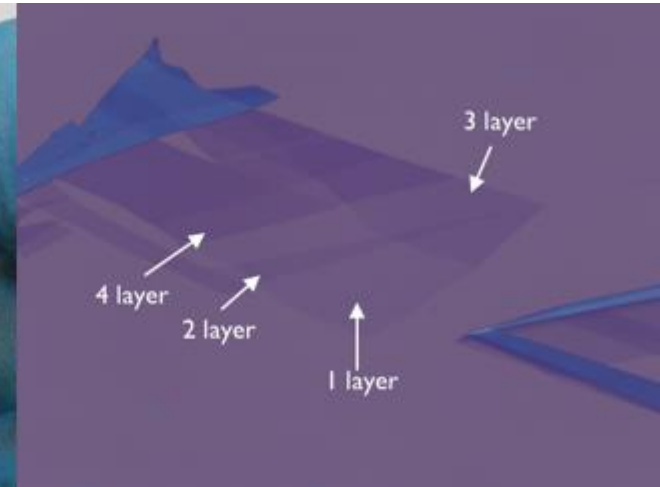




K. Novoselov et al, PNAS (2005)

Idea from "Friday Night Experiments (starting 1977)"

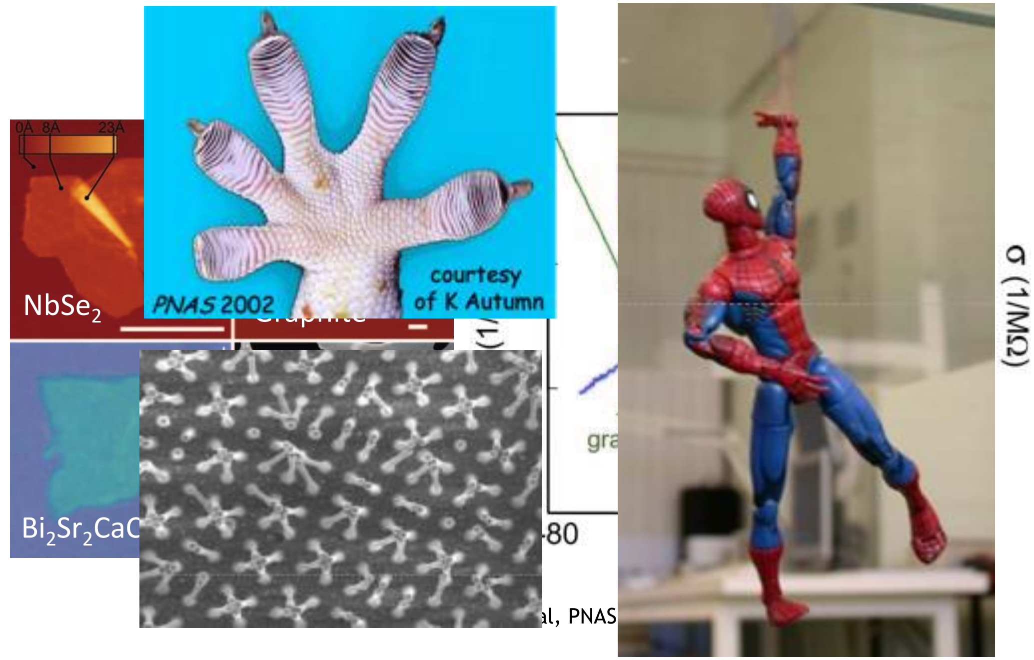




Discover of Graphene

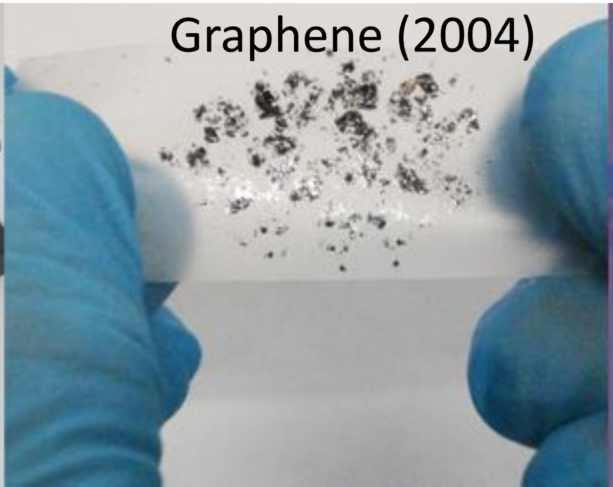
Flying Frog (1997)

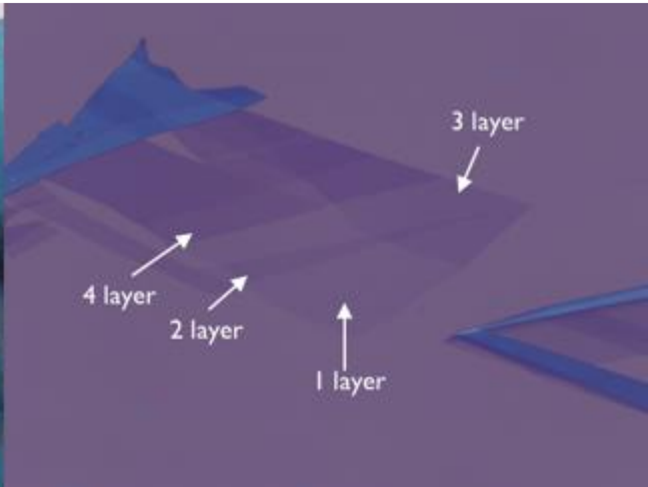
Gecko Tape (2003)

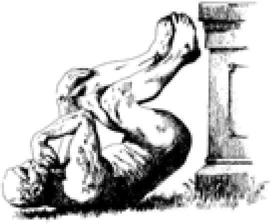


Idea from “Friday Night Experiments (starting 1977)”

Graphene (2004)







The 2000 Ig Nobel Prize Winners

The 2000 Ig Nobel Prizes were awarded on Thursday night, October 5th, 2000 at the 10th First Annual Ig Nobel Prize Ceremony, at Harvard's Sanders Theatre. The ceremony was webcast live. You can watch the video on our youTube Channel.

PHYSICS: Andre Geim of the University of Nijmegen (the Netherlands) and Sir Michael Berry of Bristol University (UK), for using magnets to levitate a frog. [REFERENCE: "Of Flying Frogs and Levitrons" by M.V. Berry and A.K. Geim, European Journal of Physics, v. 18, 1997, p. 307-13.] [REFERENCE: VIDEO]
NOTE: Ten years later, in 2010, Andre Geim won a Nobel Prize in physics (for research on another subject).

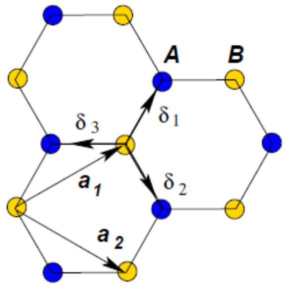
The Nobel Prize in Physics 2010

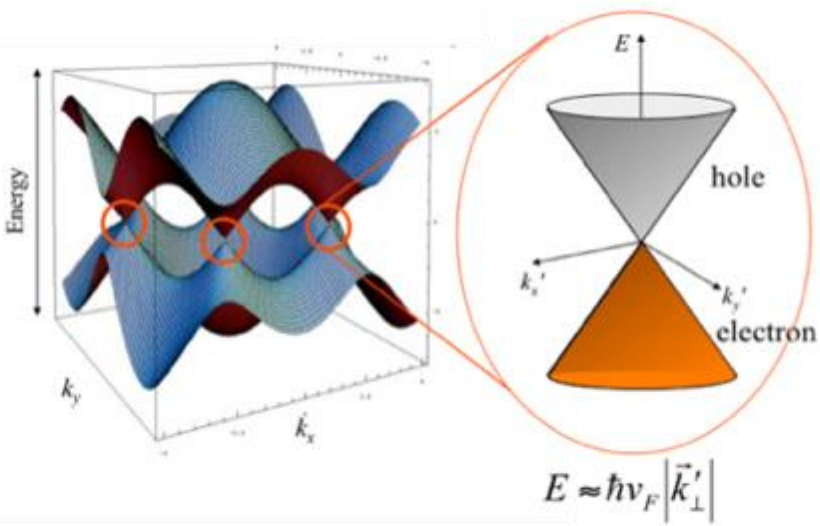
© The Nobel Foundation. Photo: U. Montan
Andre Geim
Prize share: 1/2

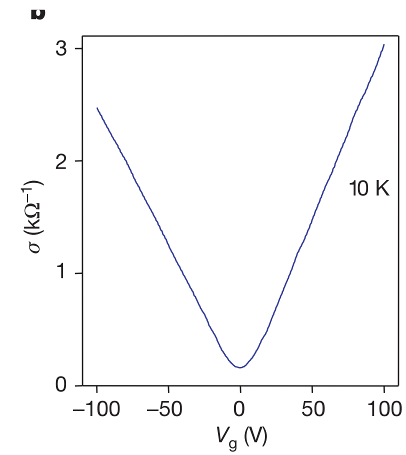
© The Nobel Foundation. Photo: U. Montan
Konstantin Novoselov
Prize share: 1/2

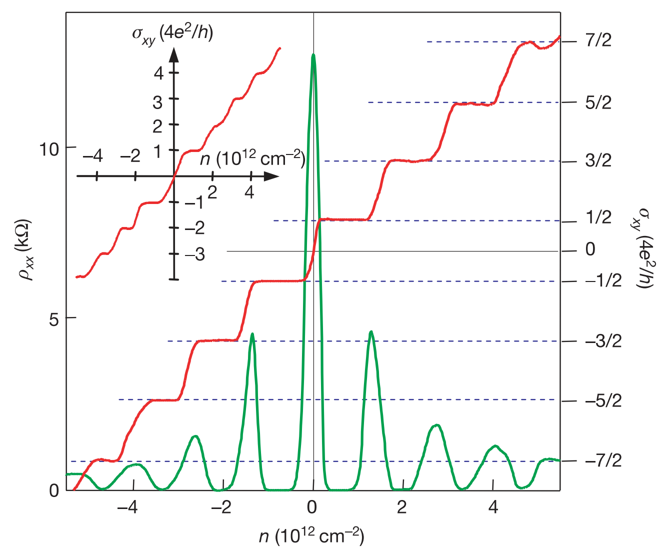
The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov "for groundbreaking experiments regarding the two-dimensional material graphene."

Graphene: Dirac Particles in 2D





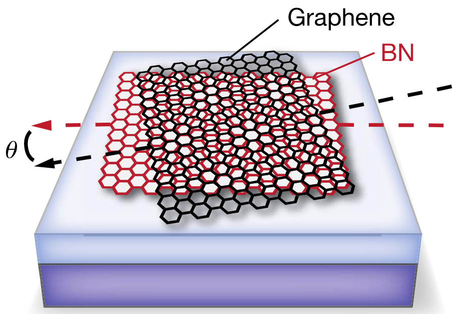


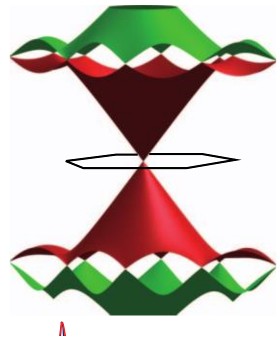


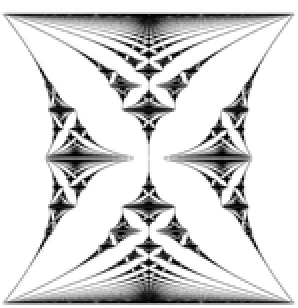
Linear dispersion relation
Zero band gap
Dirac fermion
Integer quantum Hall effect

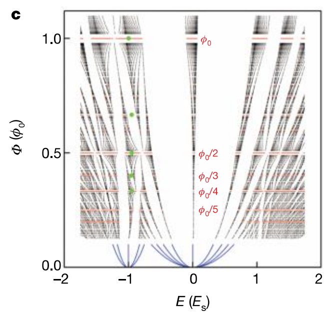
Graphene Quantum Transport

Superlattice and Hofstadter butterfly



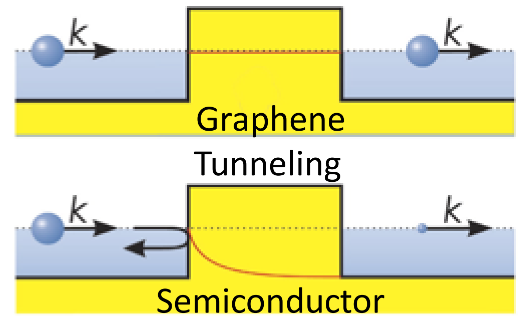


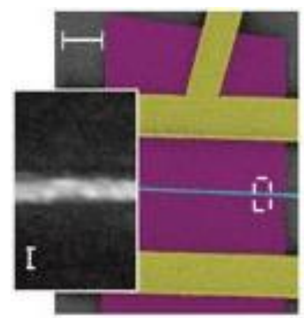


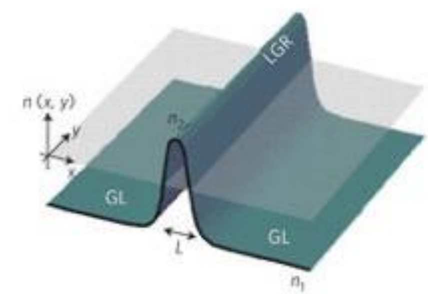


Columbia, Manchester, MIT

Klein tunneling in graphene

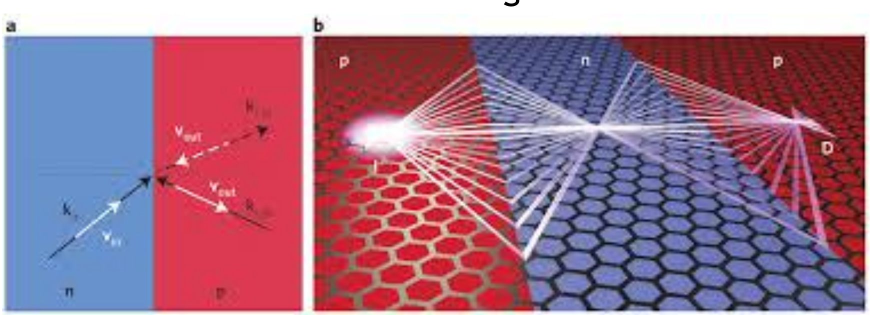




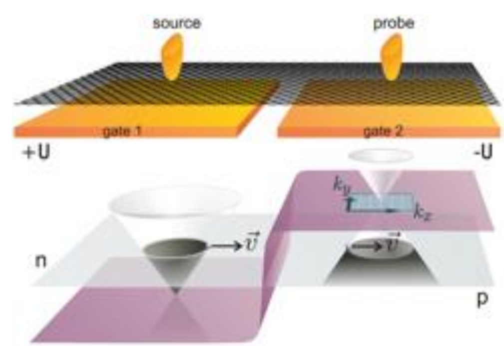


Columbia, Manchester, MIT

Negative refraction and Veselago lens (Electro-Optics)

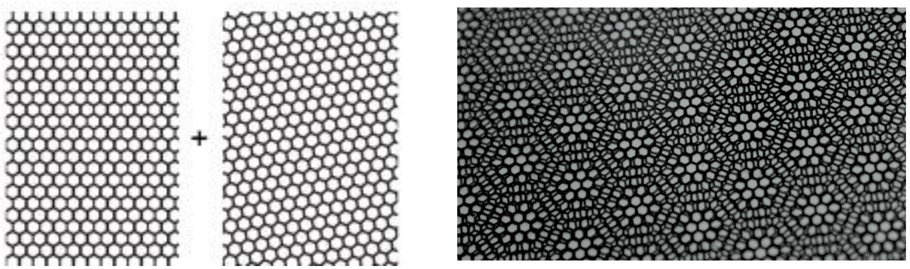


Columbia, Stanford, Postech

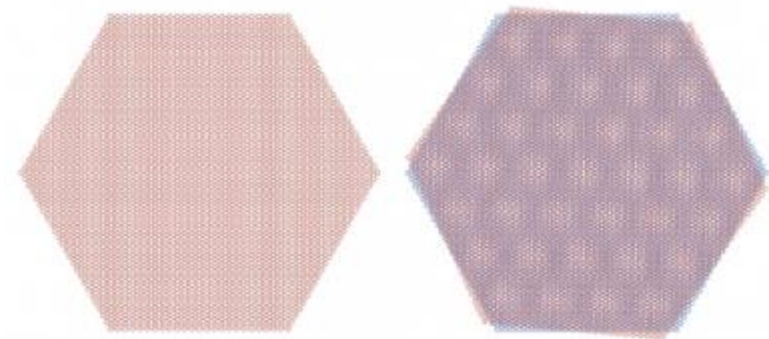


Twistronics in van der Waals Heterostructure

Twisted bi-layer graphene
One + One is Two?

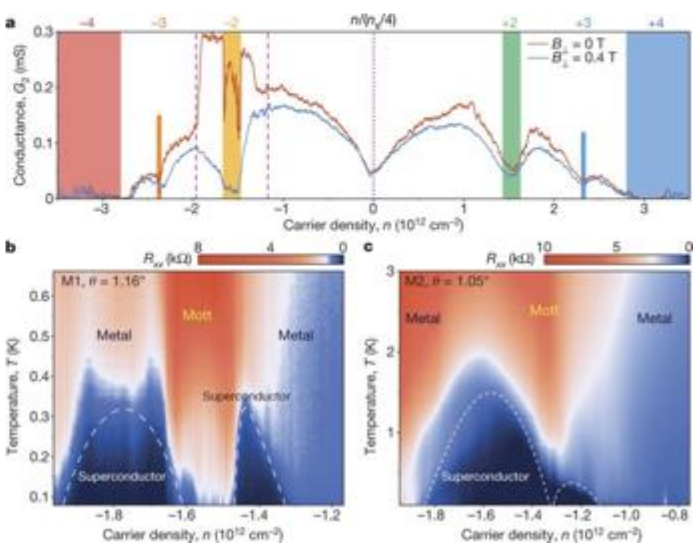


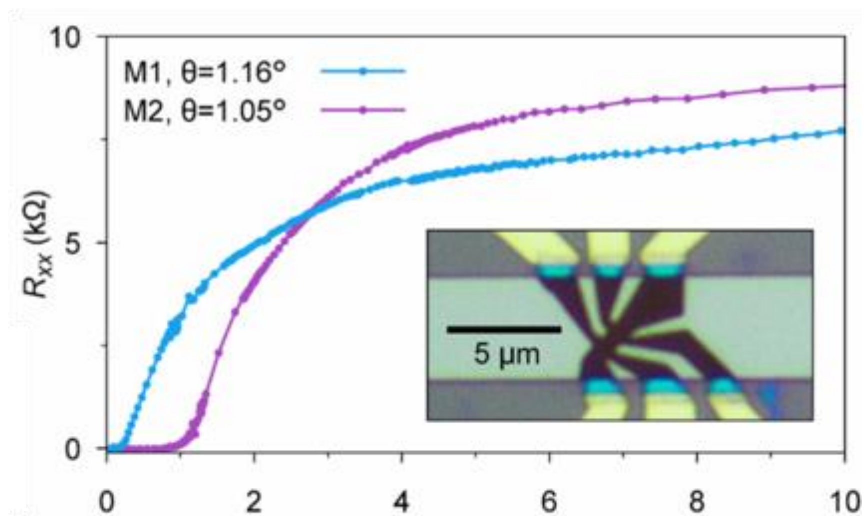
Superlattice in 2D electrons (~10 nm scale)



Magic angle ~ 1.1 degree

Analogy to high Tc superconductor?

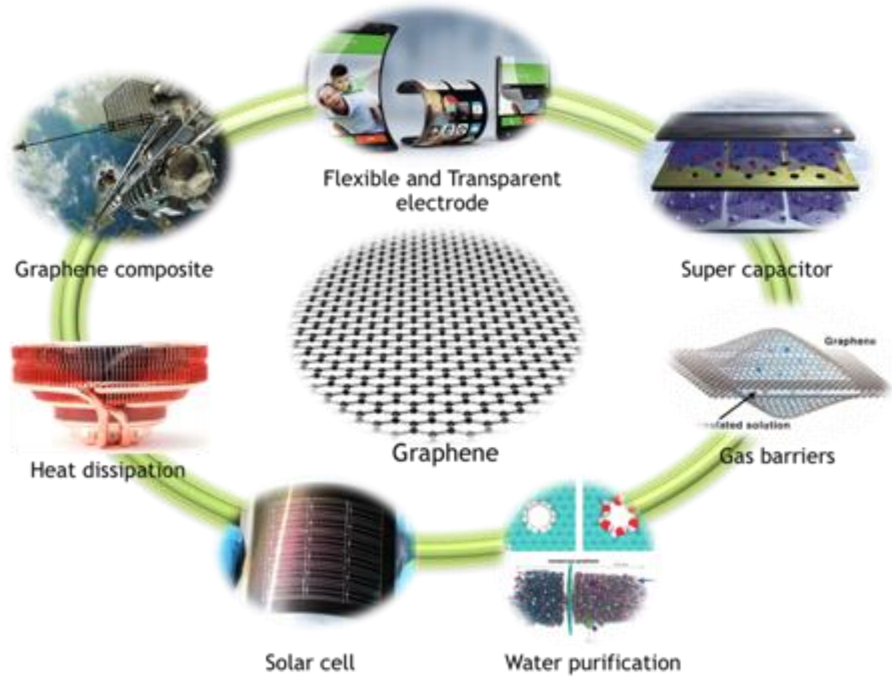




Y. Cao et al, Nature (2018)

Not possible bulk crystal structure

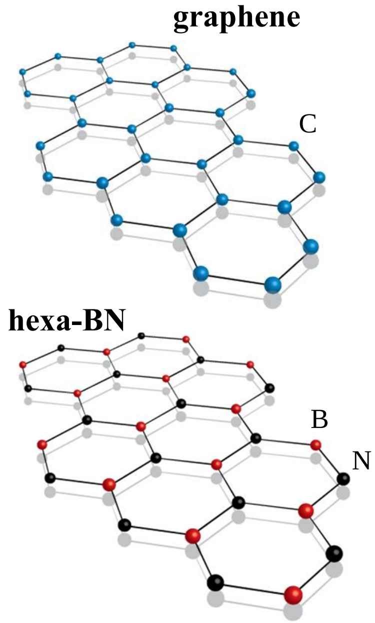
Graphene Applications

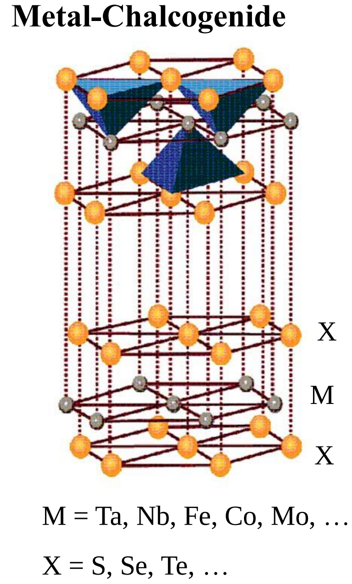


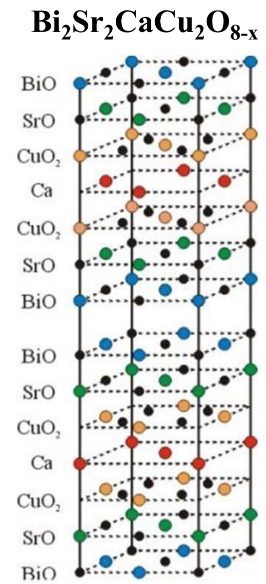
Graphene have great potential for future technology

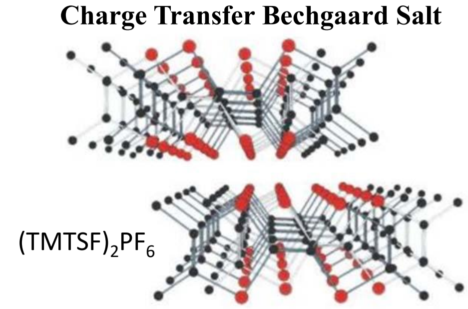
Graphene alone is not enough to change the world ! (due to zero-band gap)

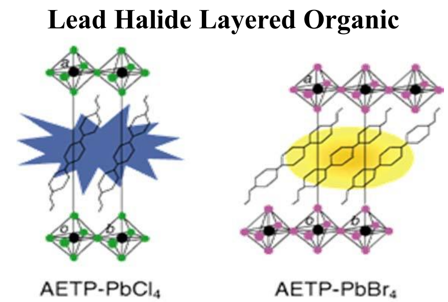
Van der Waals Materials



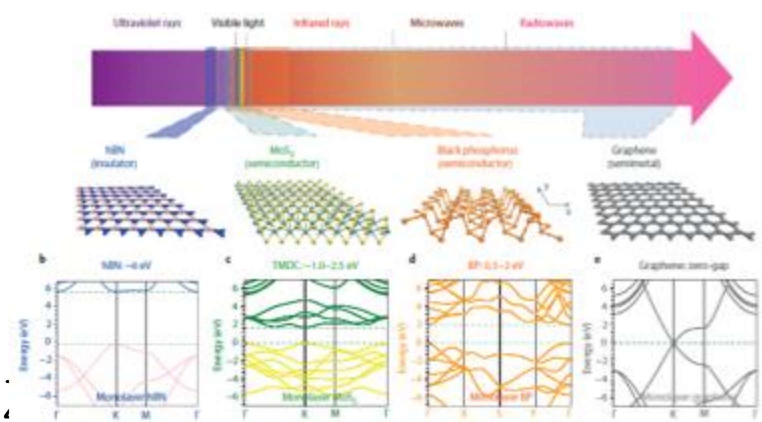








from P. Kim group



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

Semi metal: Graphene, …

Insulator: hBN, …

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

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

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

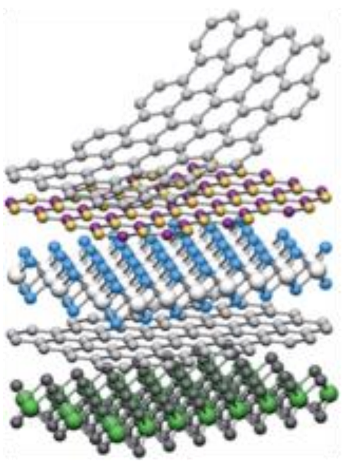
2D van der Waals Heterostructure

2D building block

Lego.com

Multifunctional Quantum Material

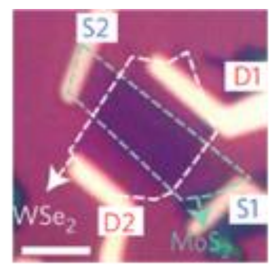
Van der Waals Heterostructure



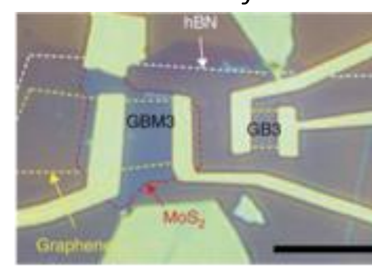
No lattice match
Control angle orientation

Next-generation technolgoy

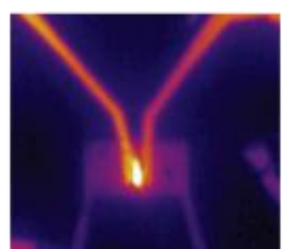
P-N Junction



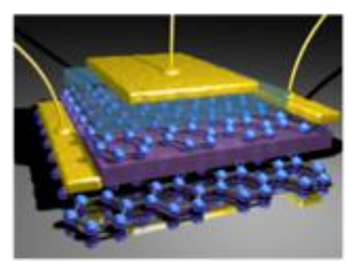
Memory



Light emitting device



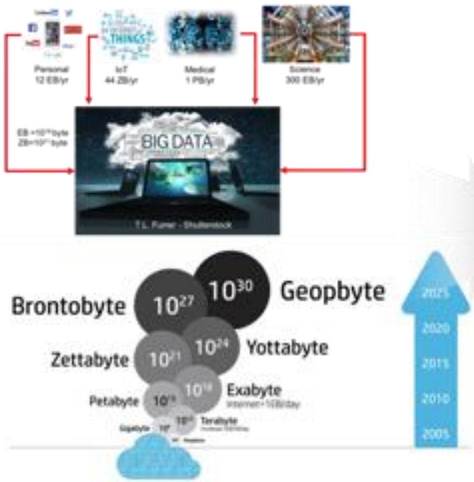
Tunneling Diode

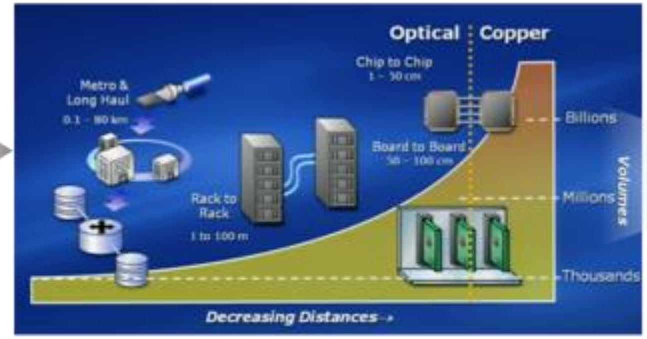


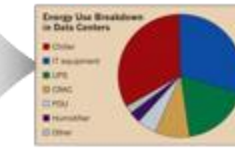
Solar cell

Ultrafast Optoelectronics

Information processing challenges



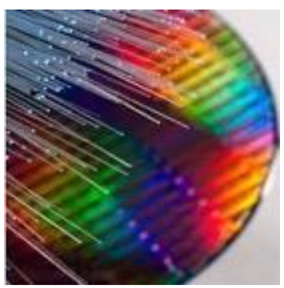


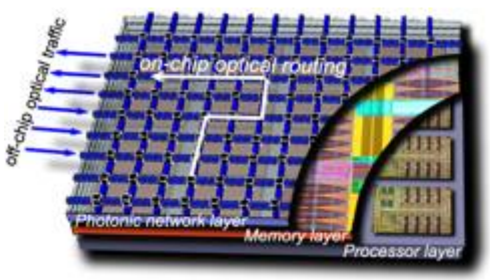


Electrical interconnect- Energy problem and internet traffic

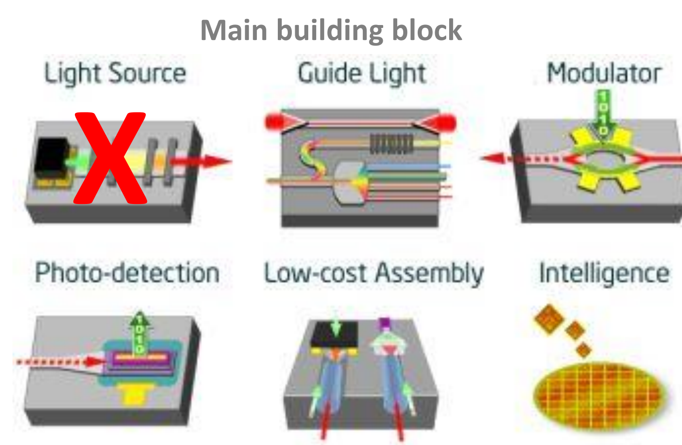
Optical interconnect

Silicon photonics integrated circuit: Optical communications+ CMOS technology





- High bandwidth
- Energy efficiency
- No Cross-talk
- Next generation network system

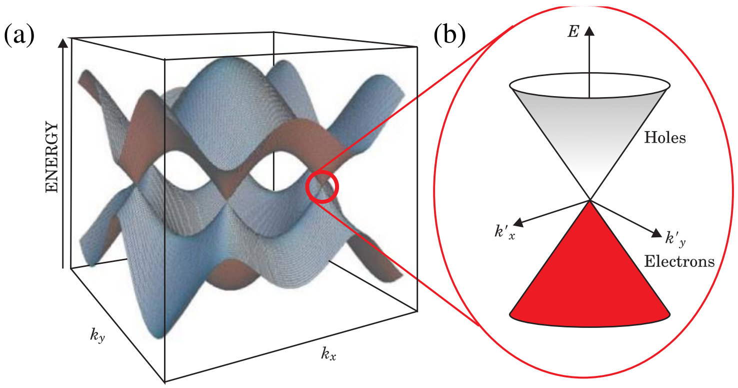


No Monolithic light source

Graphene Based Optoelectronics

Graphene properties

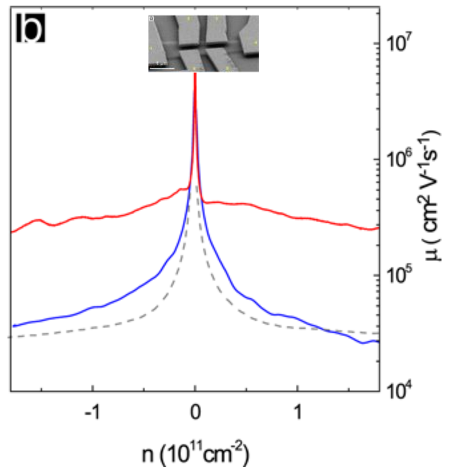
Linear dispersion relation



Sarma, Das el al. Rev. Mod. Phys. (2011).

$$E_F = \pm \hbar v_F k_F ,$$
$$\text{where}, v_F \sim 10^6 \text{ m/s}, k_F = \sqrt{\pi n}$$

Ultrahigh mobility

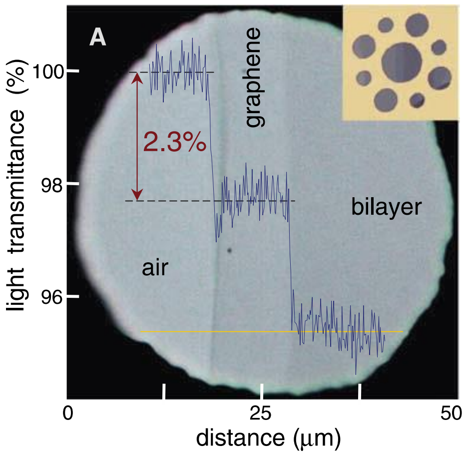


Bolotin, K. I. et al. Solid State Communications (2008).

Drude model $\mu = \sigma / en$

$\mu > 200{,}000 \text{ cm}^2/\text{Vs}$

Transparency



Nair, R.R. et al. Science (2008).

Graphene absorption
$\pi e^2 / \hbar c = \pi\alpha = 2.3\%$

Graphene optoelectronic device

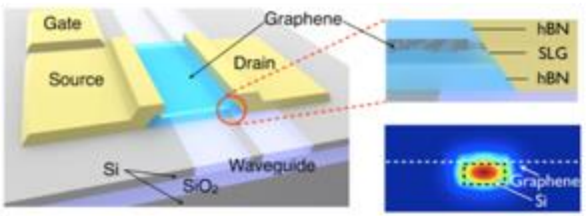
Broadband response

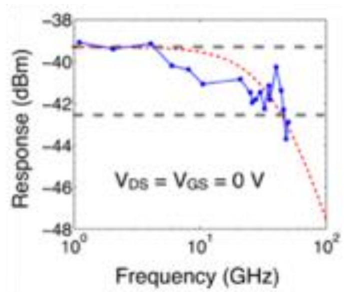
Ultrafast dynamics

Strong light-matter interaction

Graphene Based Nanophotonics

42 GHz Chip integrated hBN/Gr/hBN photodetector (Columbia University, MIT)

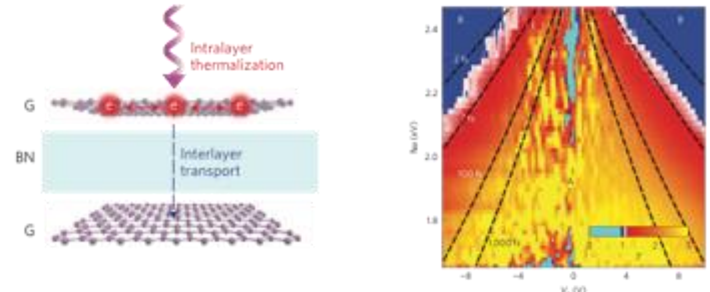




Nano Lett. (2015)

fc =42 GHz, Responsivity: 360 mA/W, 1 pJ/bit
(down to 5 fJ/bit by reducing area)

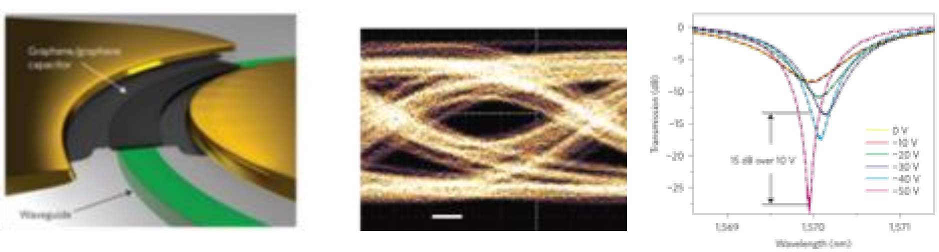
Tuning thermalization pathway in Gr/hBN/Gr (MIT)



Nature Phys. (2016)

Interlayer photocurrent response time (< 100 fs) by adjusting interlayer bias voltage.

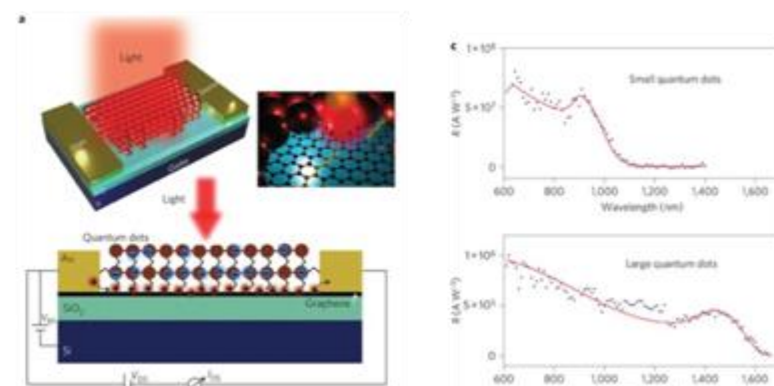
30 GHz Graphene electro-optic modulator (Columbia)



Nature Photons. (2015)

30 Gbps, 15 dB per 10 V, 800 fJ/bit

Hybrid graphene-quantum dot photodetector (ICFO, Spain)

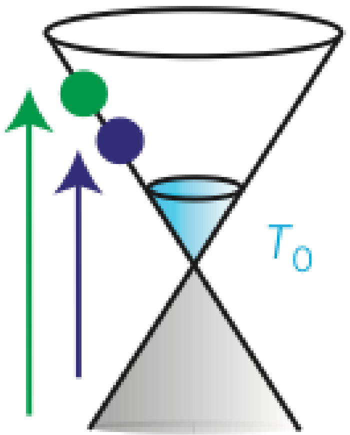


Nature Nanotech. (2012)

Responsivity: 10^7A/W

Hot Electrons in Graphene

Excitation



Strong e-e interaction
- Carrier multiplication
- Hot electrons

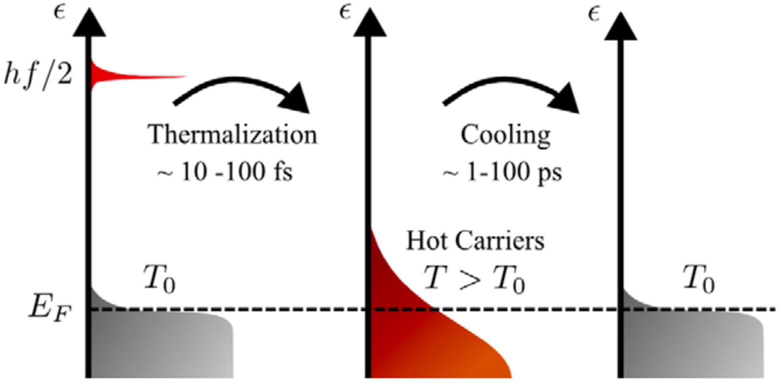
Electron cooling in intrinsic graphene ?

Bucket

Bottleneck

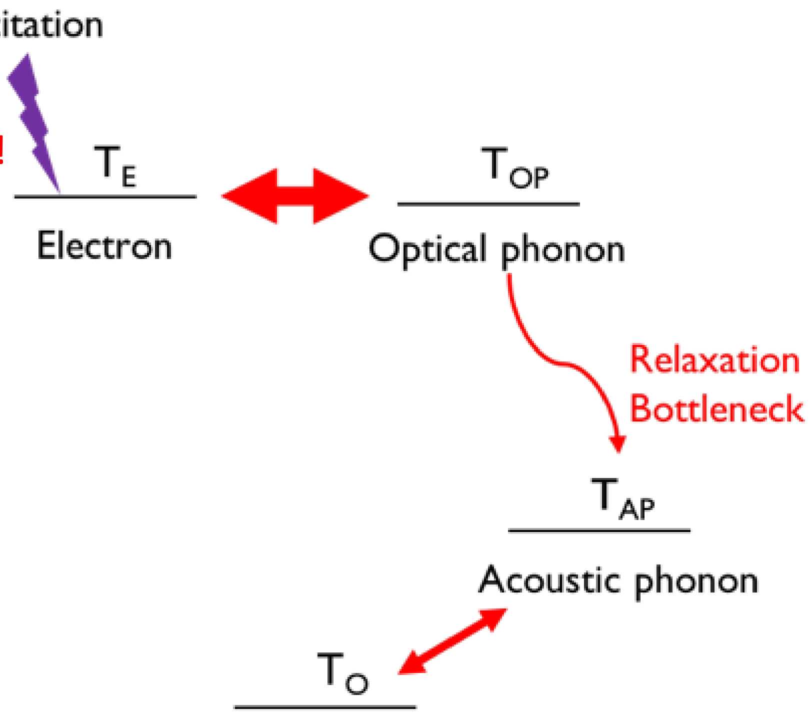
Long lived hot electrons in Graphene

Excitation



Energy Relaxation in Graphene

Heating is very fast process!
(<100 fs)



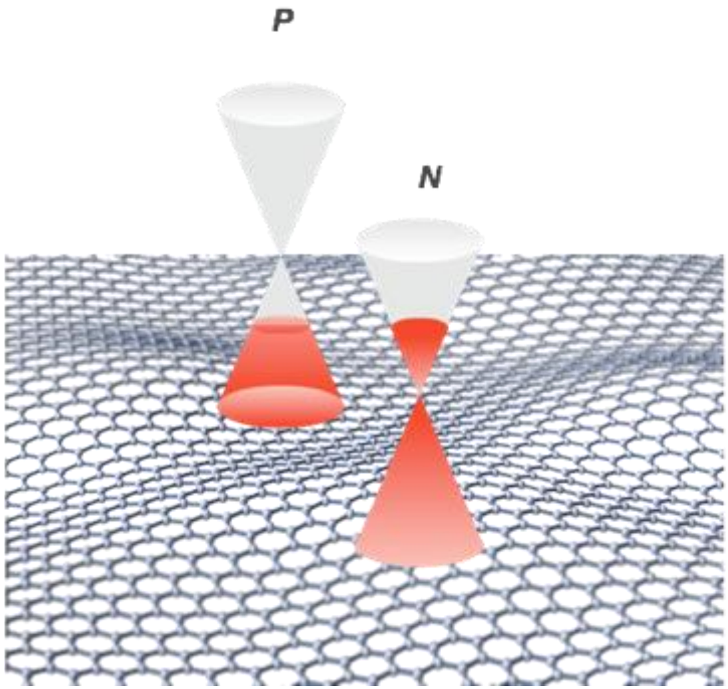
Cooling is very slow process!
(10~100 ps)

- Hot electrons cooling pathway bottleneck
- Very weak electron-acoustic phonon coupling.
- Non-equilibrium phonon mode.

- **Non-equilibrium temperature of graphene**

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

Light Emission from Graphene ?



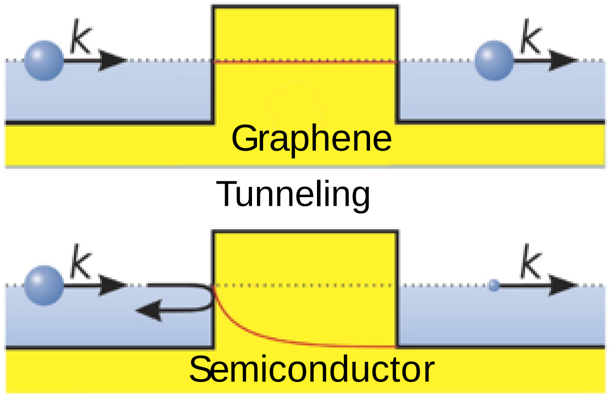
Graphene

•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

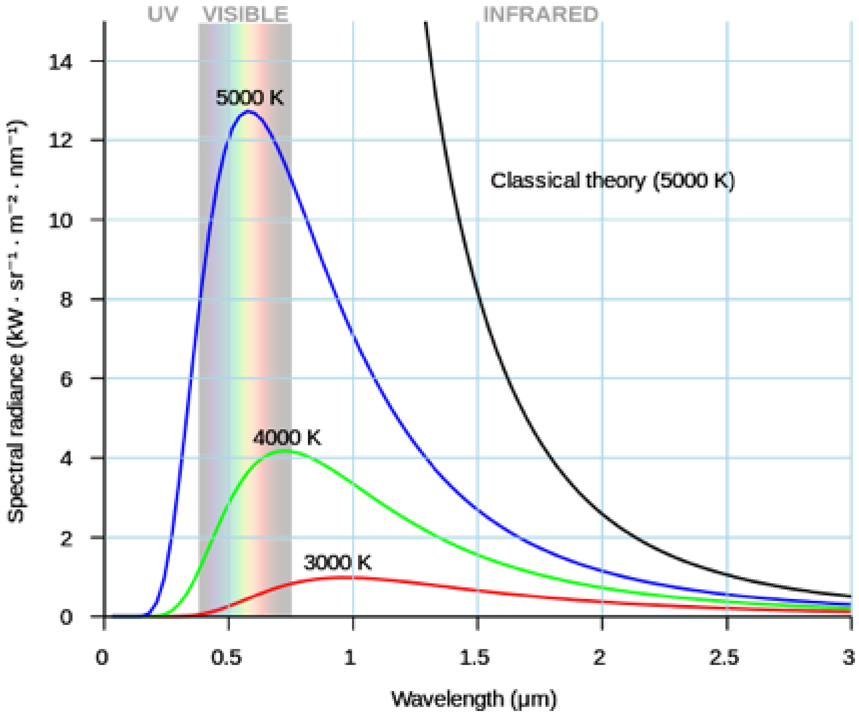


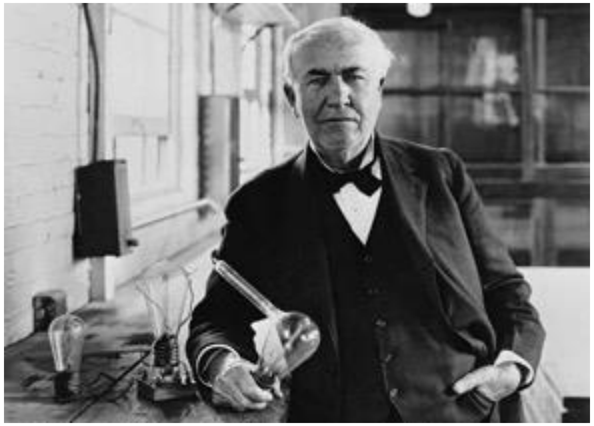
Non-efficient radiative electron-hole recombination

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

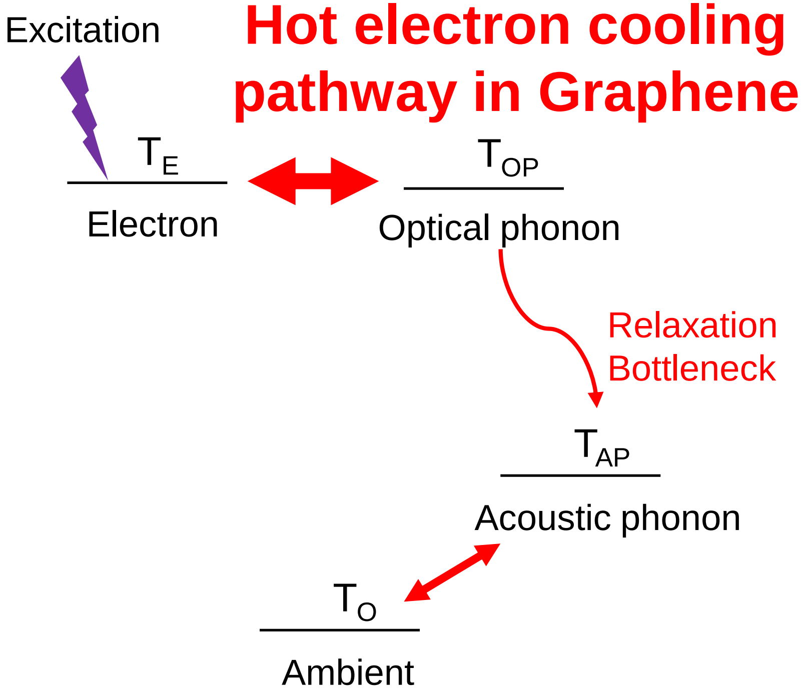
Electron temperature is important, not phonon temperature.

Hot Electrons Luminescence in Graphene

Superior properties of graphene

- High **current density** — $J \sim 10^9$ A/cm^2
- **World's Strongest Material** — $E \sim 1$ TPa
- High **Melting Point** — $T \sim 5{,}000$ K

Hot electron cooling pathway in Graphene



Ideal material for thermal radiation

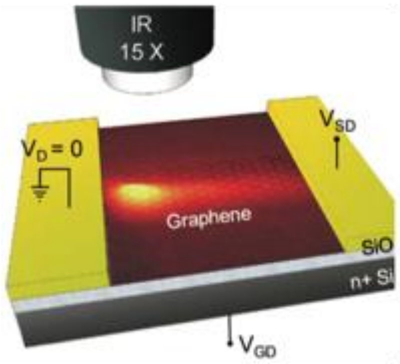
Planck's law $I(\omega) \sim 1/(\exp(\hbar\omega/k_B T_e) - 1)$

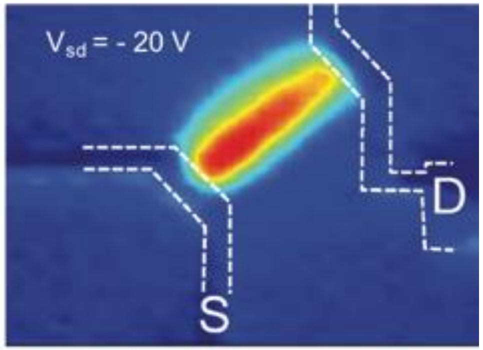
- Very weak electron-acoustic phonon coupling.
- Non-equilibrium phonon mode.
- **Non-equilibrium temperature of graphene**

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

Efficient thermal radiation source

Graphene on Substrate



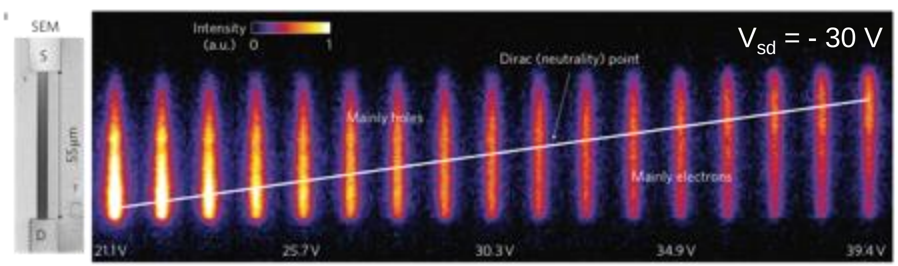


M.-H Bae *et al*, Nano Lett. (2010)

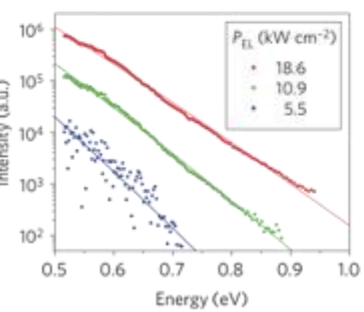
- •Graphene under high bias.
- •Thermal radiation at near IR emission.
- •Follow Planck's law (T < 600 K).

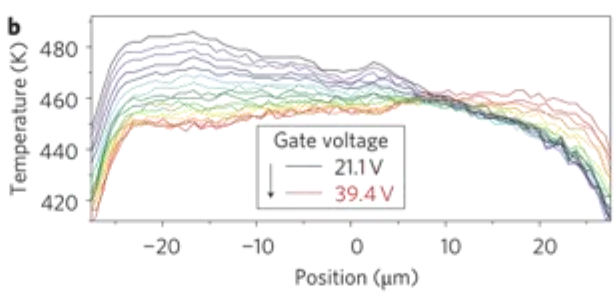
$$I(\omega) \sim \omega^3 / (\exp(\hbar\omega / k_B T) - 1)$$

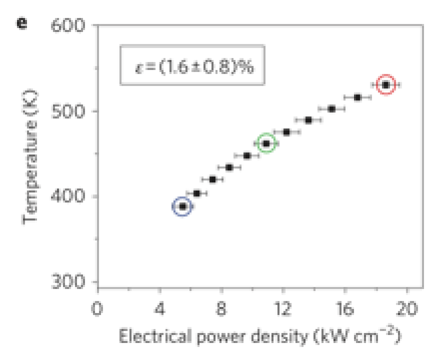
- •Low radiation efficiency (~10^{-6})
- - Dominant heat dissipation by substrate
- - Strong electron scattering (charged impurity, defects of substrate)



Performance of graphene light emitters are limited by substrate.

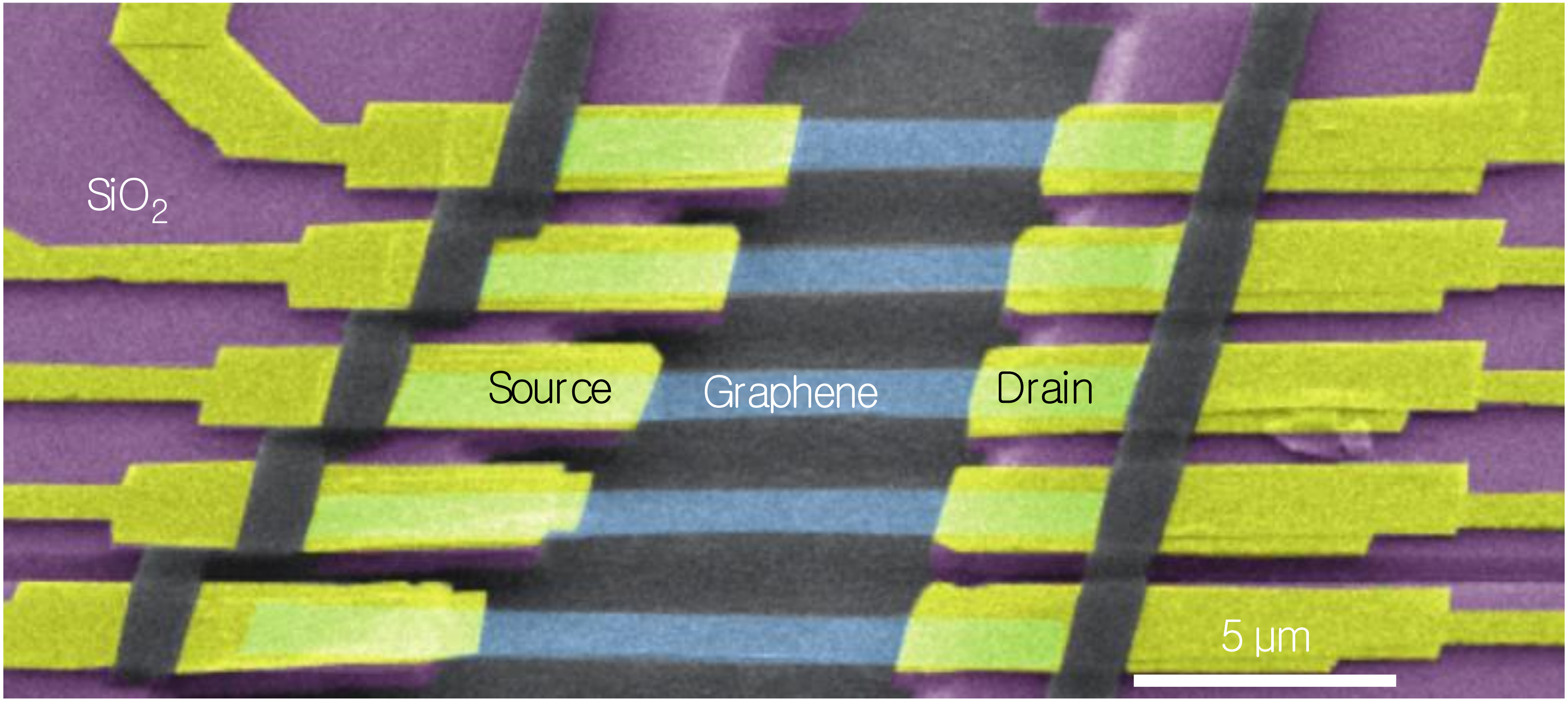






M. Freitag *et al*, Nature Nanotech. (2010)

Suspended Graphene



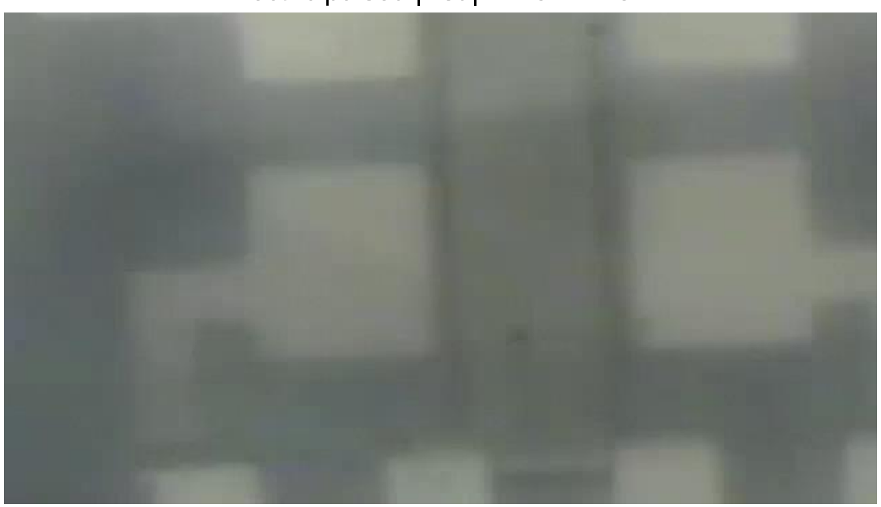
Y. D. Kim *et al*, Nature Nanotech. (2015)

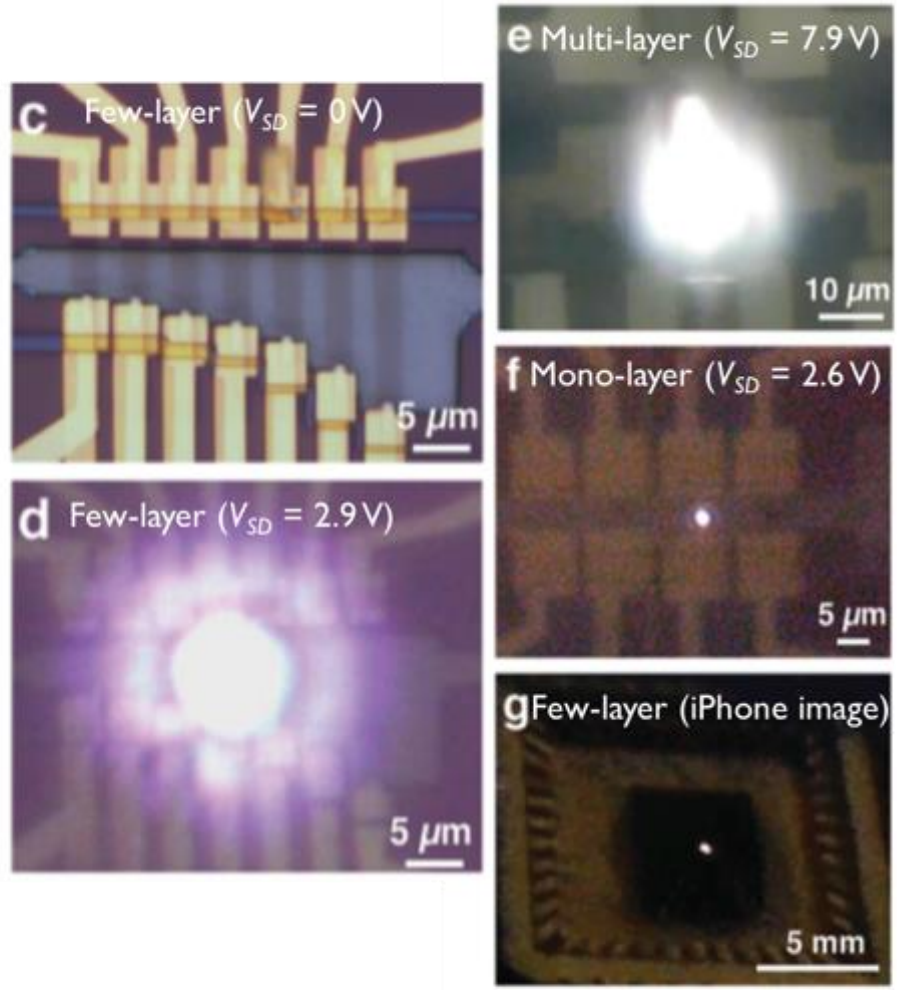
- Minimize the substrate effect
- Reduce vertical heat dissipation to substrate
- Approaching to the intrinsic characteristic

Bright Visible Light Emission from Graphene

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

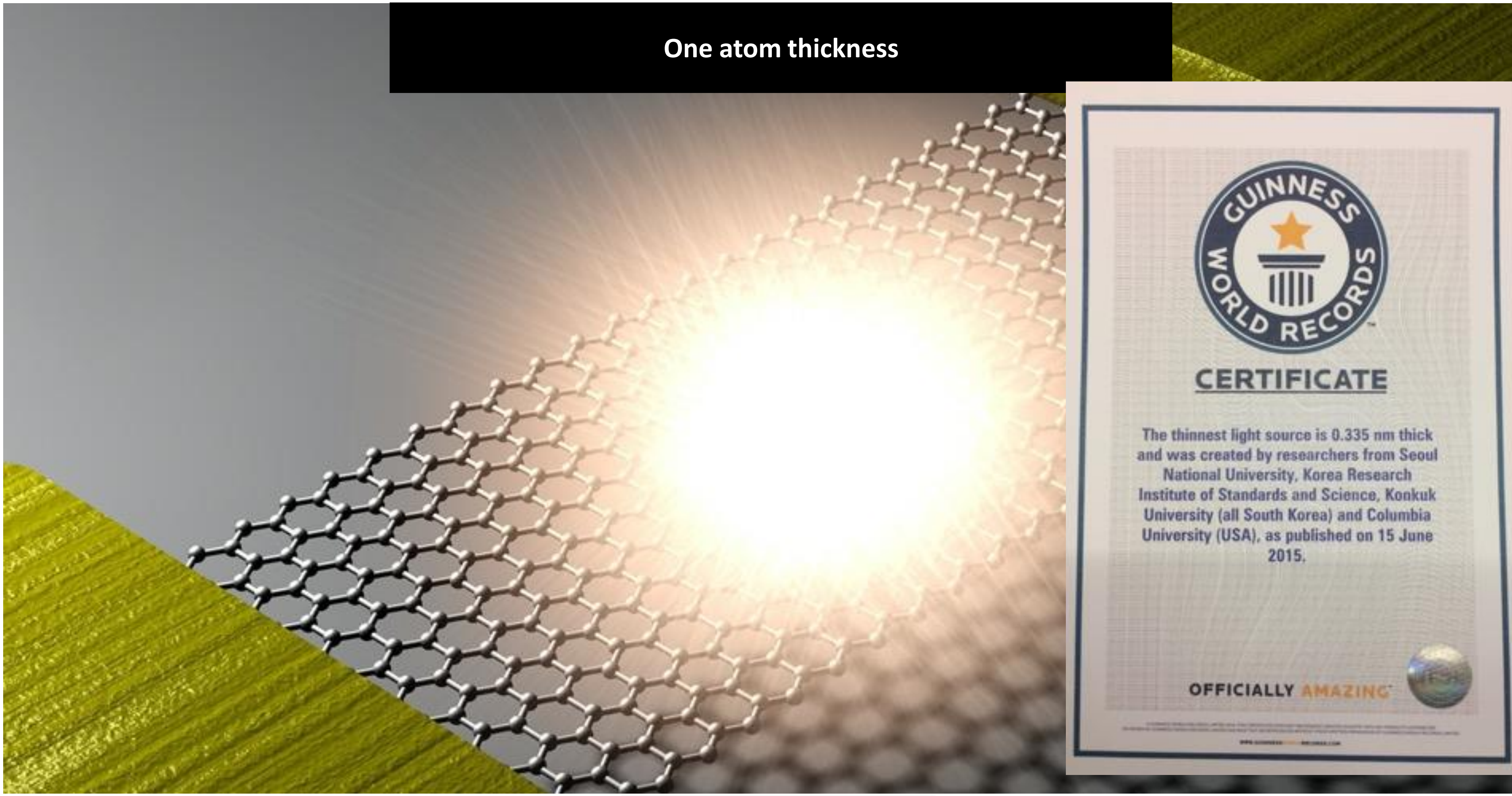
Electric pulsed |Vsd| = 7.5 V -> 8 V





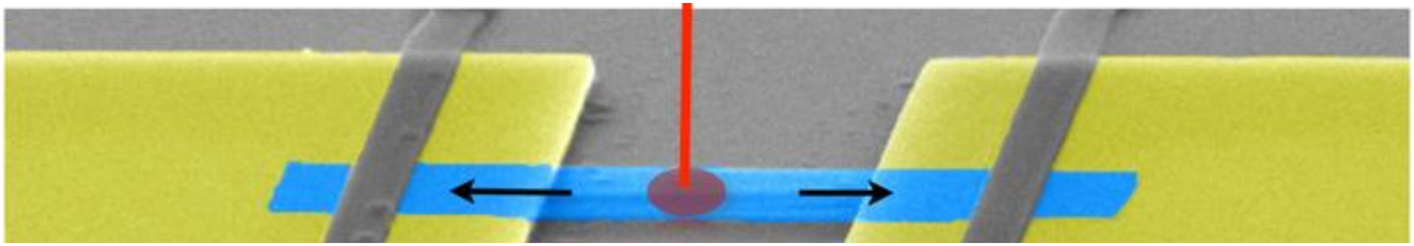
Y. D. Kim *et al*, Nature Nanotech. (2015)

World’s Thinnest Light Source



POPULAR SCIENCE
THE WALL STREET JOURNAL. FOX NEWS INDEPENDENT
nature NATIONAL GEOGRAPHIC WIRED.CO.UK Daily Mail materialstoday

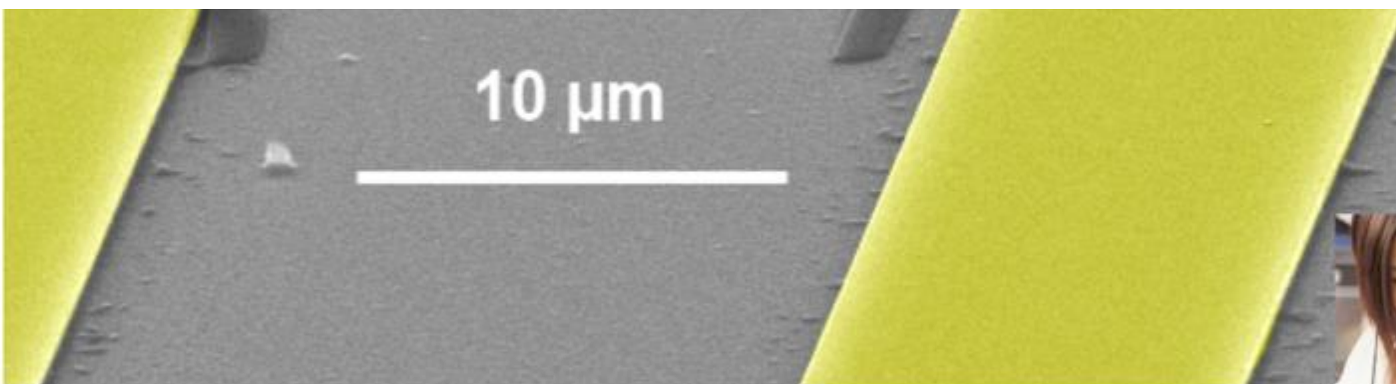
Plan: Electrical measurements of mechanical oscillation of graphene



Problem: Dirty graphene

Solution: Current annealing

Try, but fail!



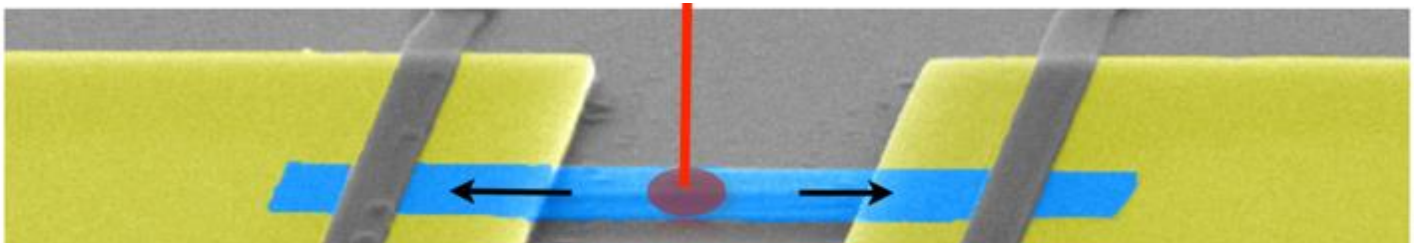
Thermal induced stress $T = -\alpha \Delta t E \omega t$

Negative thermal expansion coefficient : Tensile stress

Positive thermal expansion coefficient : Compressive stress

From 2012 Ph.D. Defense ppt Slides

Plan: Electrical measurements of mechanical oscillation of graphene



Problem: Dirty graphene

Solution: Current annealing

Try, but fail!

Discovery something new by wrong Labview programming.

Discovery:

The

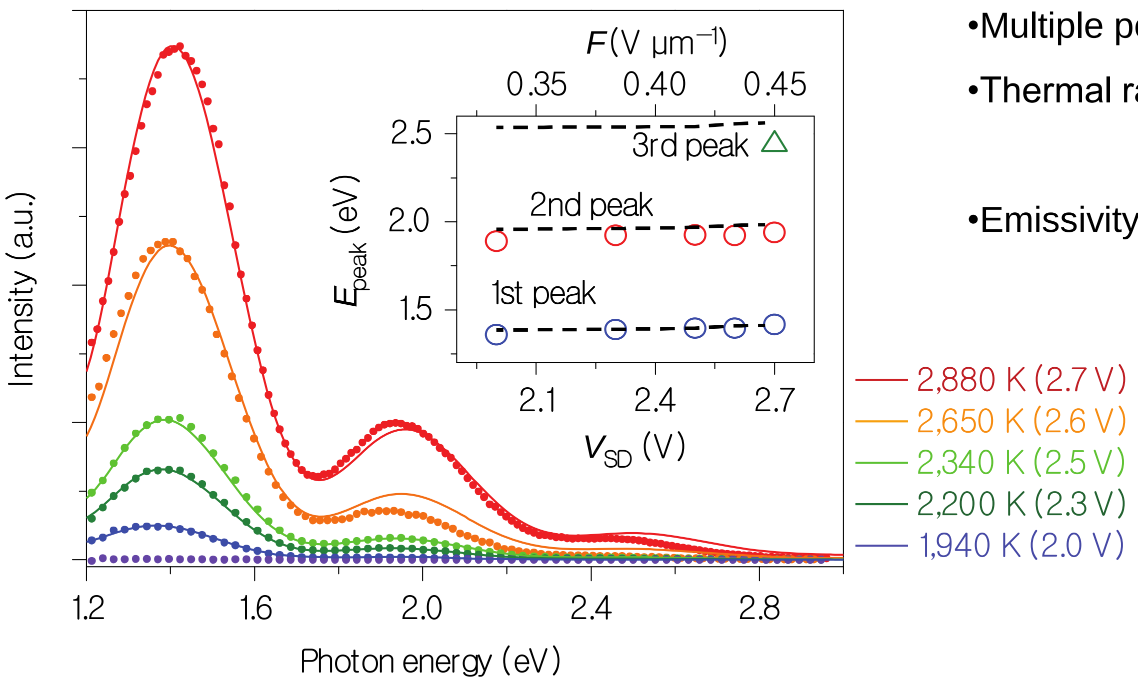
Negati

Positive

From 2012 Ph.D. Defense ppt Slides

Radiation Spectrum of Graphene Light Emitter

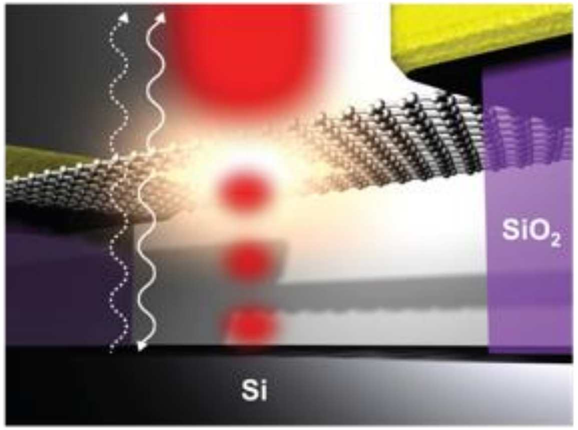
Monolayer graphene (L = 6 µm, W = 3 µm, D ~ 1 µm)

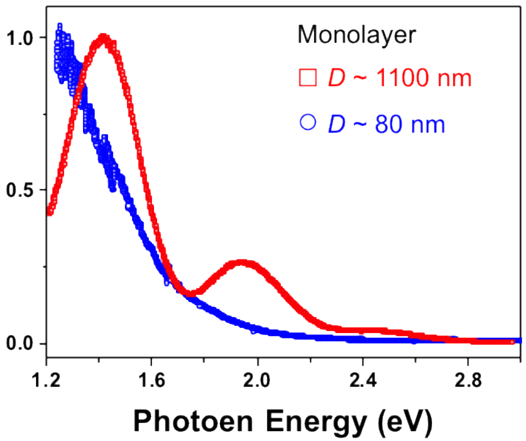


- Multiple peak at visible range
- Thermal radiation by Planck's law
- Emissivity modulation by interference effect

$$I(\omega) \sim \epsilon(\omega)\, \omega^3 / (\exp(\hbar\omega / k_B T_e) - 1)$$

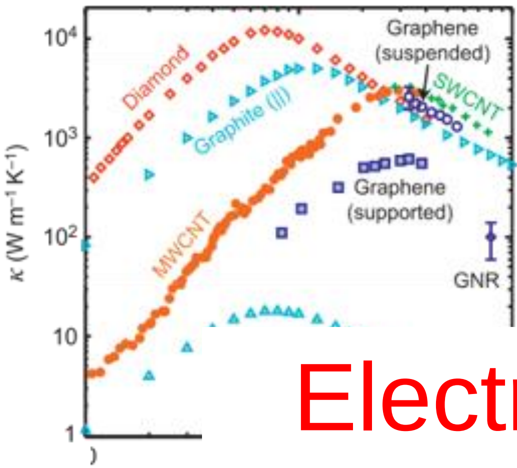
$$I(\omega;D) = I_0(\omega)\left(\frac{1+|r(\omega)|^2}{2} + \mathrm{Re}\left[r(\omega)\exp(i2\omega D/c)\right]\right)$$



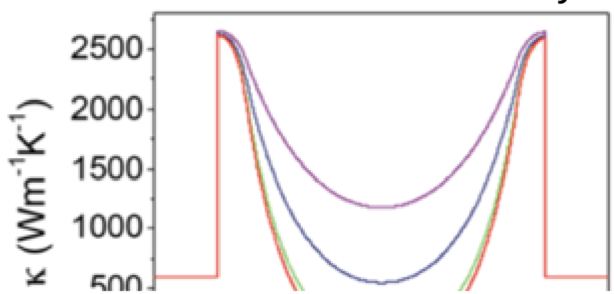


- Electron temperature ~ 3,000 K
- Thermal radiation efficiency ~ 0.45 % (1000 more efficient than graphene on substrate)
- Color tuning by strong light-matter interaction

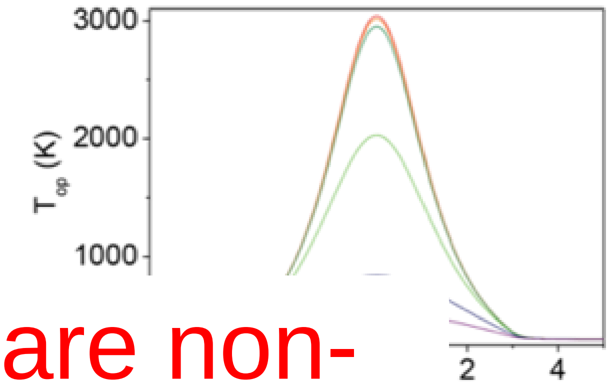
Hot Electron Localization



Thermal conductivity



Temperature distribution



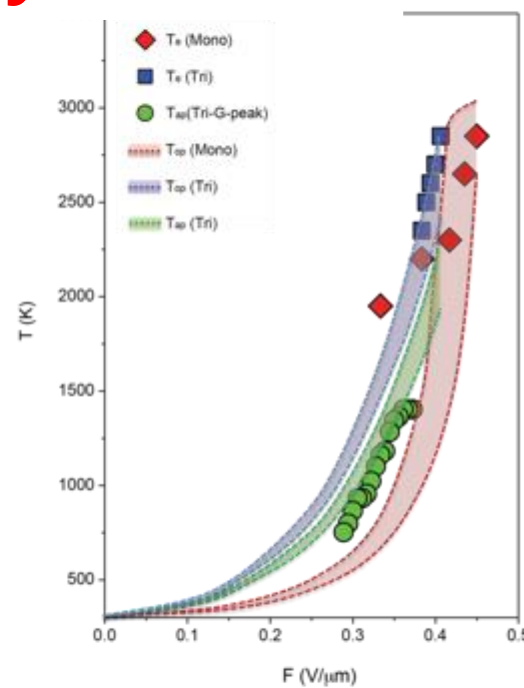
Electron and Phonons are non-equilibrium under steady sate.

E. Pop

mperature

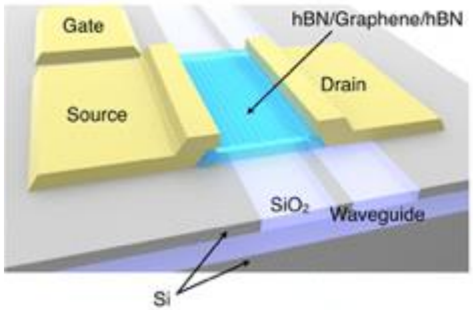
- Abrupt decrease of thermal conductivity $k = k_0(T_0/T_{ap})^{1.92}$
- Significant reduced lateral heat dissipation under high bias (2700 -> 65 $Wm^{-1}K^{-1}$)
- Heat localization at center of graphene ~ 3000 K
- No melting of electrode ~ 300 K
- Non-equilibrium temperature

$$T_e = T_{ap} + \alpha(T_{ap} - T_0)\text{, } \alpha \sim 0.2\text{-}0.3$$



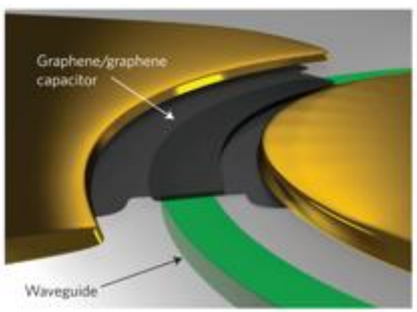
Graphene-Si Hybrid Photonic Circuit

Photodetector (~ 42 GHz)

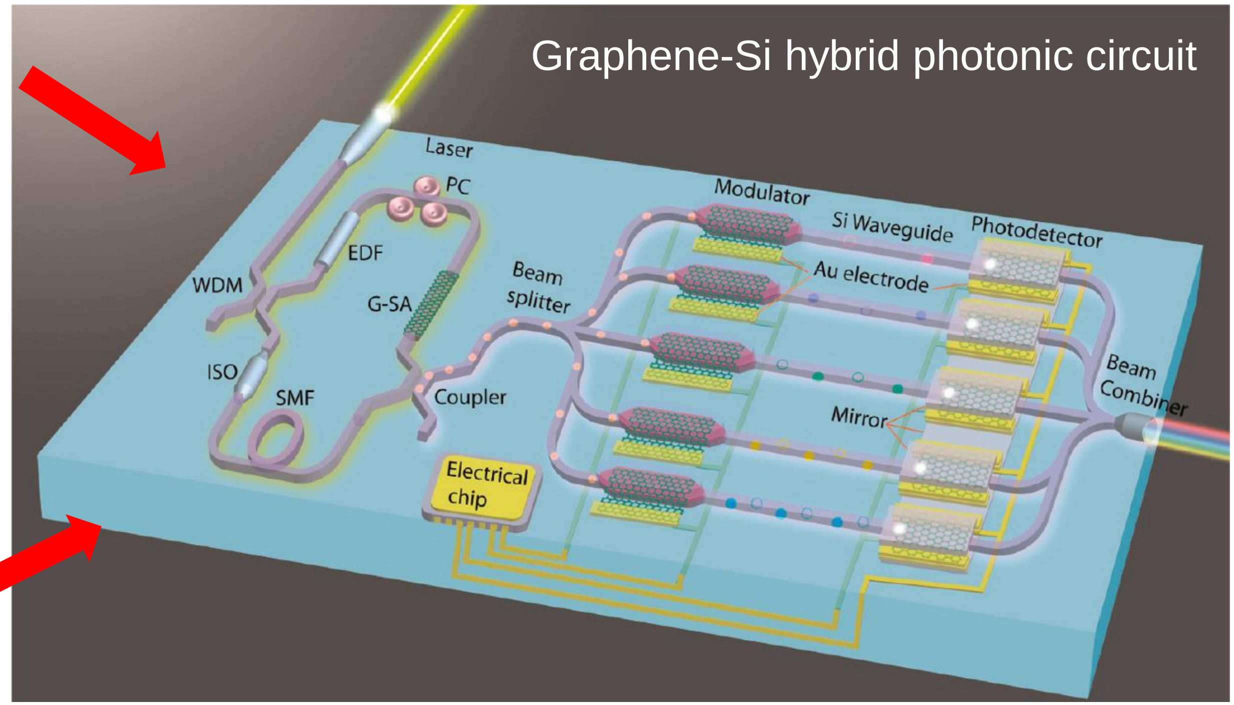


R.-J. Shiue et al. Nano Lett. (2015)

Optical modulator (~ 30 GHz)



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

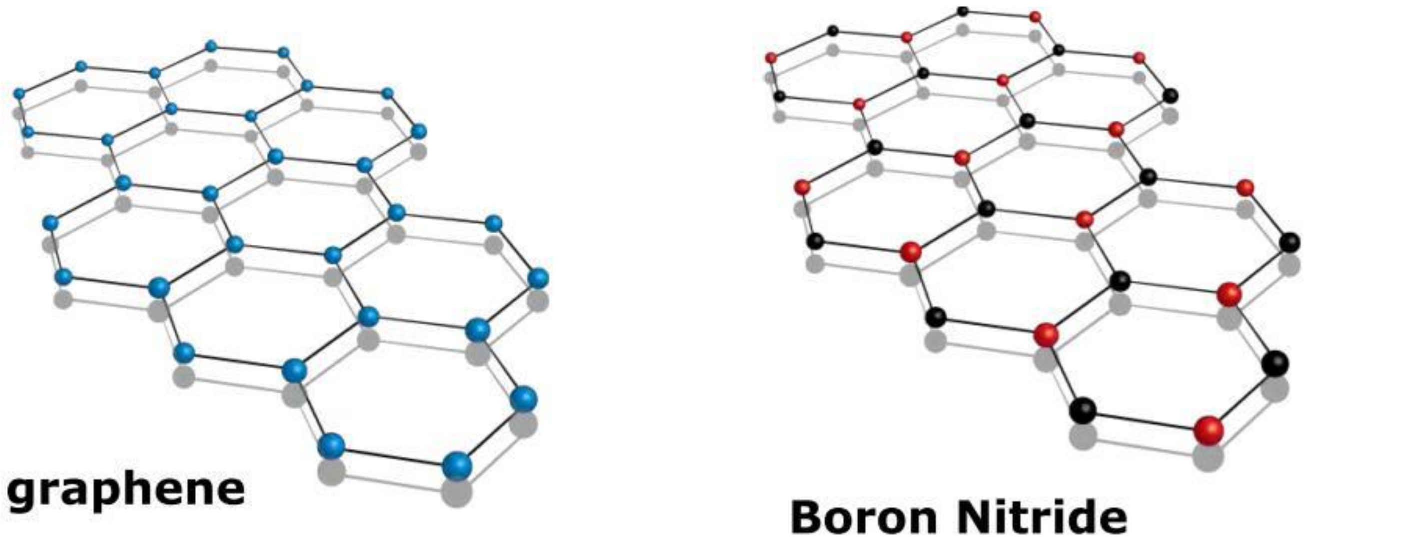


Q. Bao and K.P. Loh, ACS Nano (2012)

Graphene light emitter?

How fast light modulation?

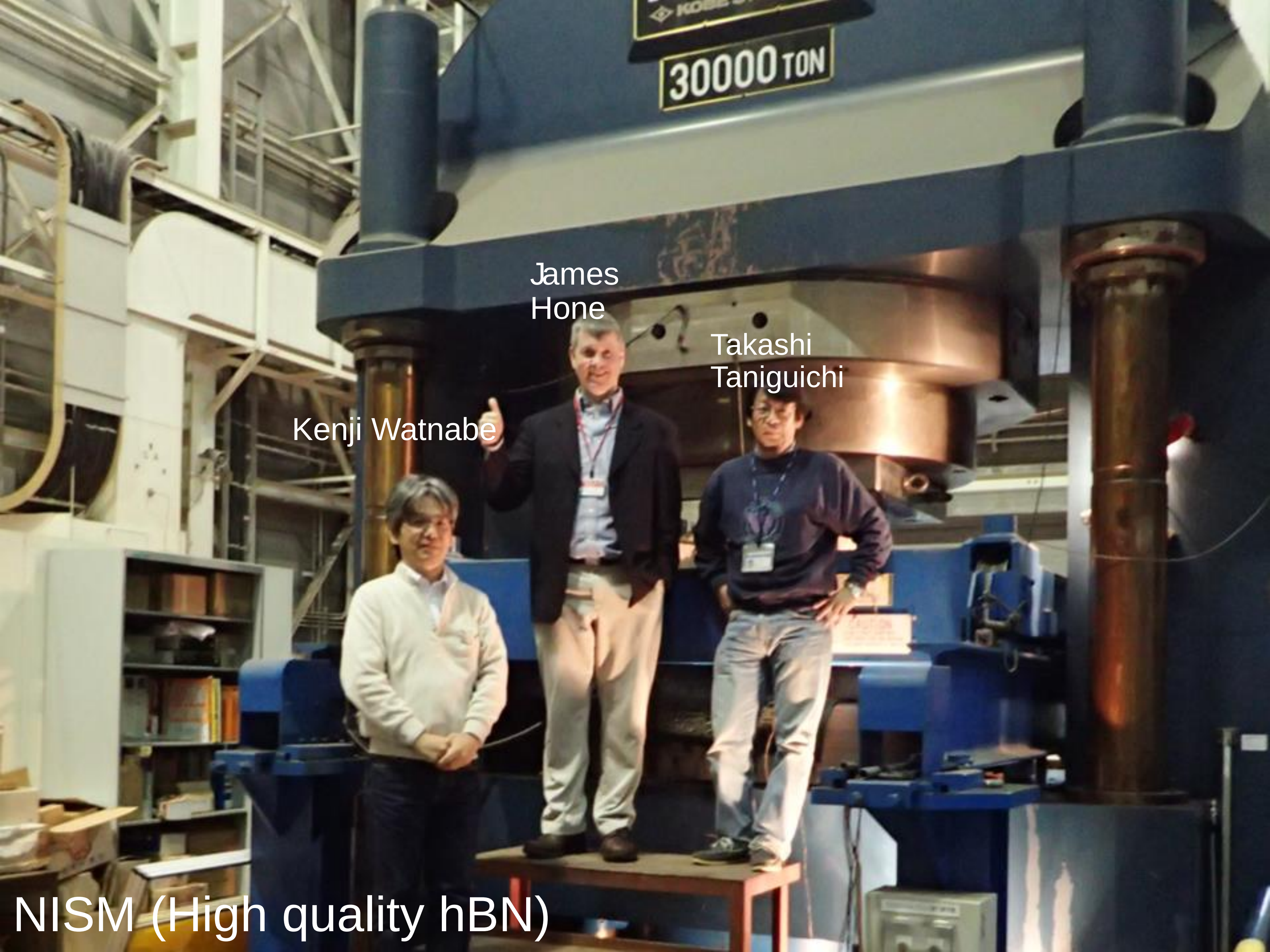
Rising of Hexagonal Boron Nitride



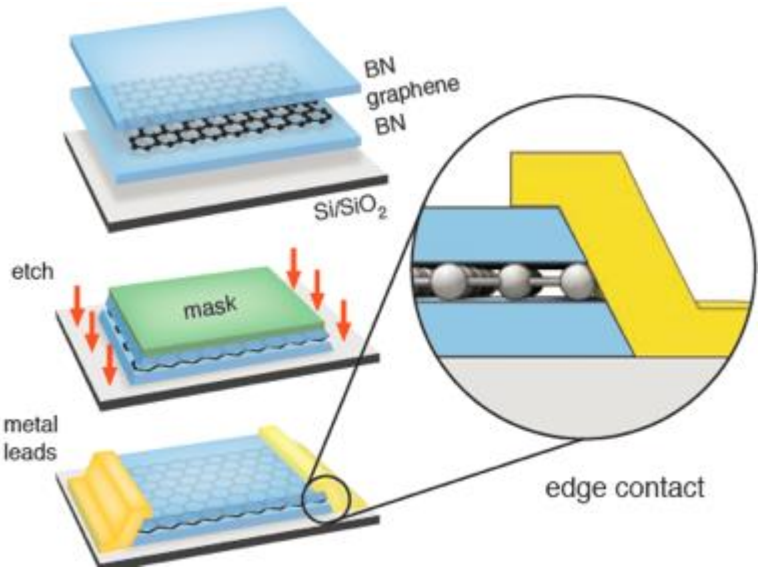
Comparison of h-BN and SiO_2

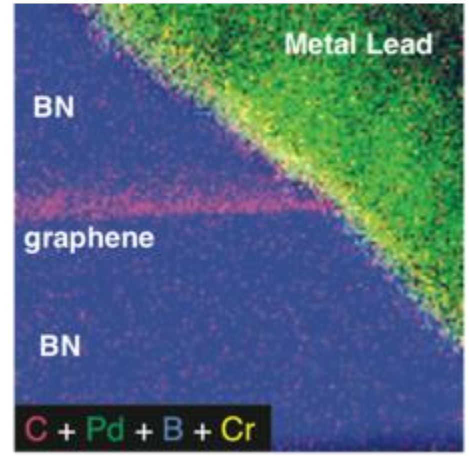
	Band Gap	Dielectric Constant	Optical Phonon Energy	Structure
BN	6.4 eV	~4	>150 meV	Layered crystal
SiO2	8.9 eV	3.9	59 meV	Amorphous

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

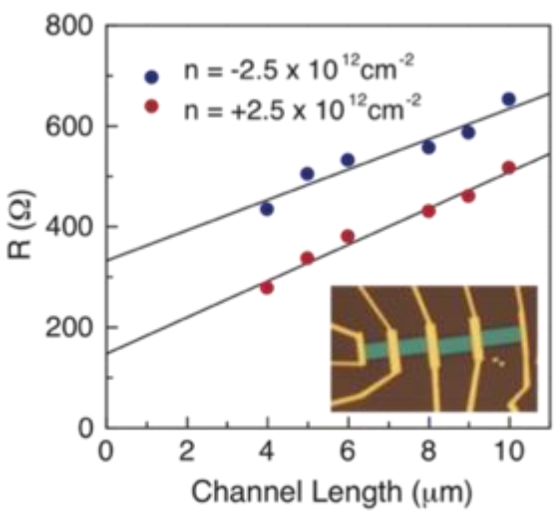

30000 TON
James
Hone
Takashi
Taniguichi
Kenji Watnabe
NISM (High quality hBN)

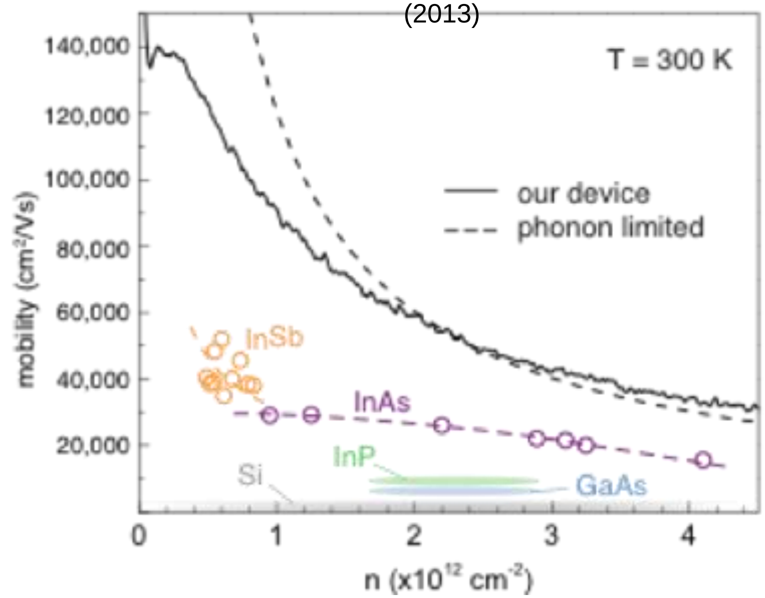
hBN Encapsulated Graphene





L. Wang et al, Science (2013)





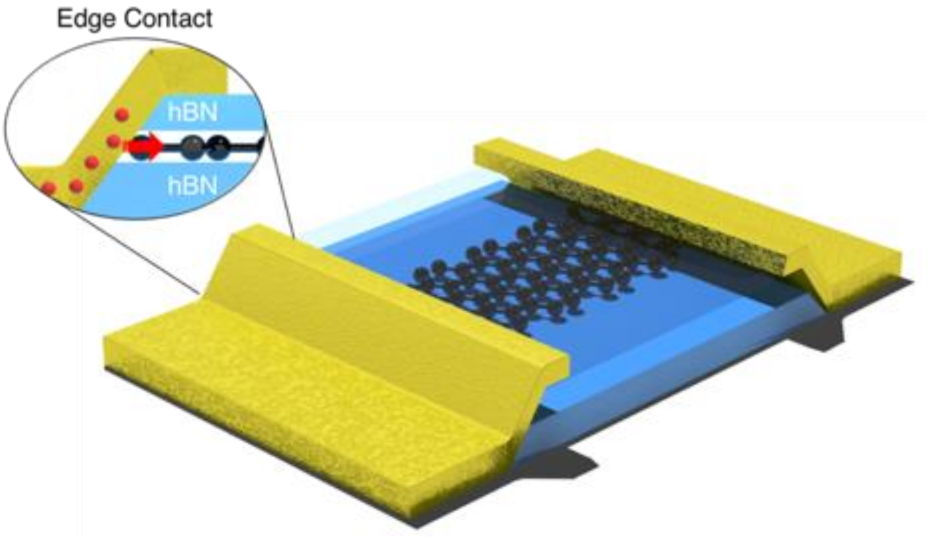
Low contact resistance

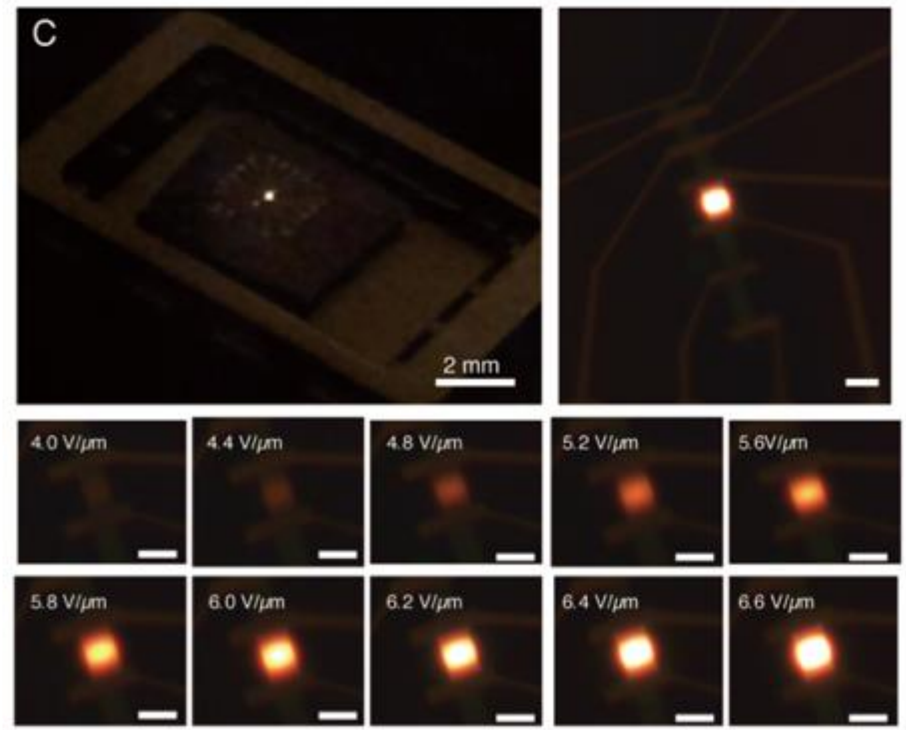
At limit of acoustic phonon scattering.

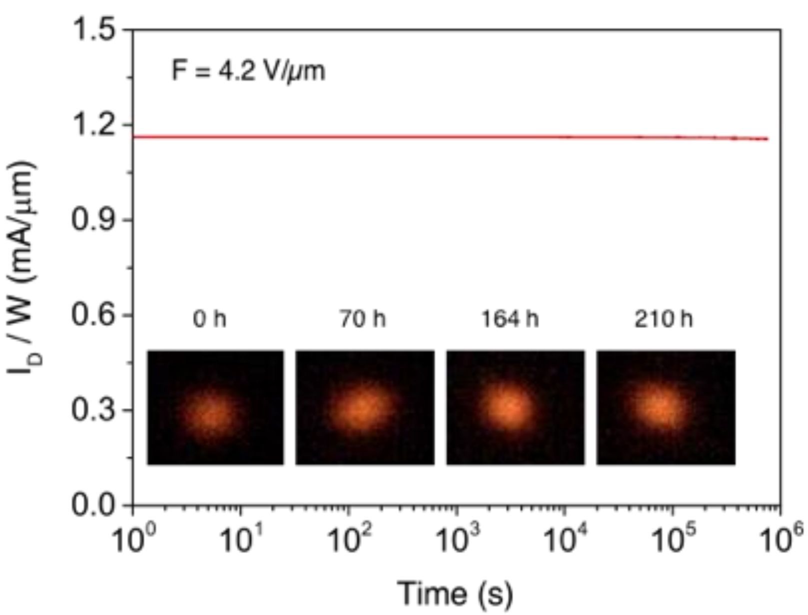
World best graphene device

Ultrafast Graphene Light Emitter

hBN/Gr/hBN heterostructure

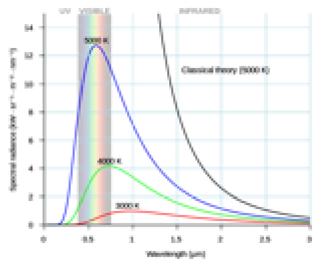






- •Bright visible light emission
- •Electron scattering suppress is more dominant
- •hBN encapsulation for practical light source even in ambient condition
- •Life-time above 4 year

Tailoring Thermal Radiation of Graphene



Black body thermal radiation

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

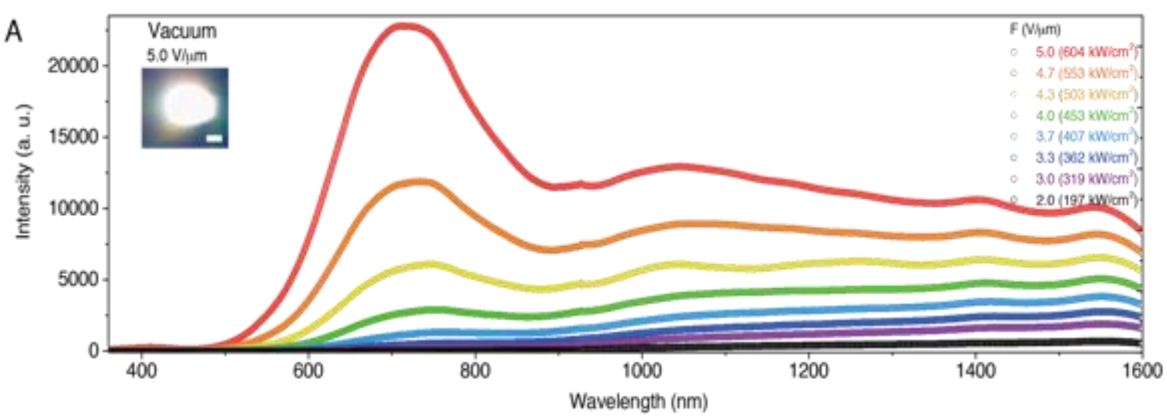
$E(\omega)$: Mode energy, $n(\omega,T)$: photon occupation

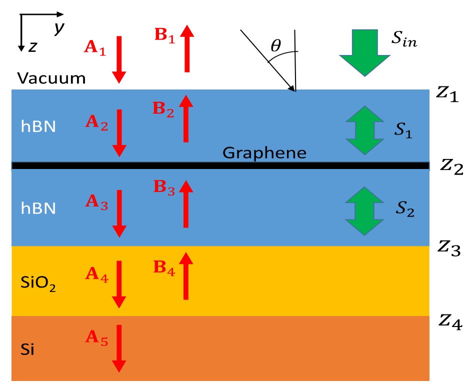
$D(\omega)$: Local optical density

- Strong light-matter interaction of graphene
- Engineering local optical density in sub-wavelength

Optical cavity mode

- Easy to integration to arbitrary structures

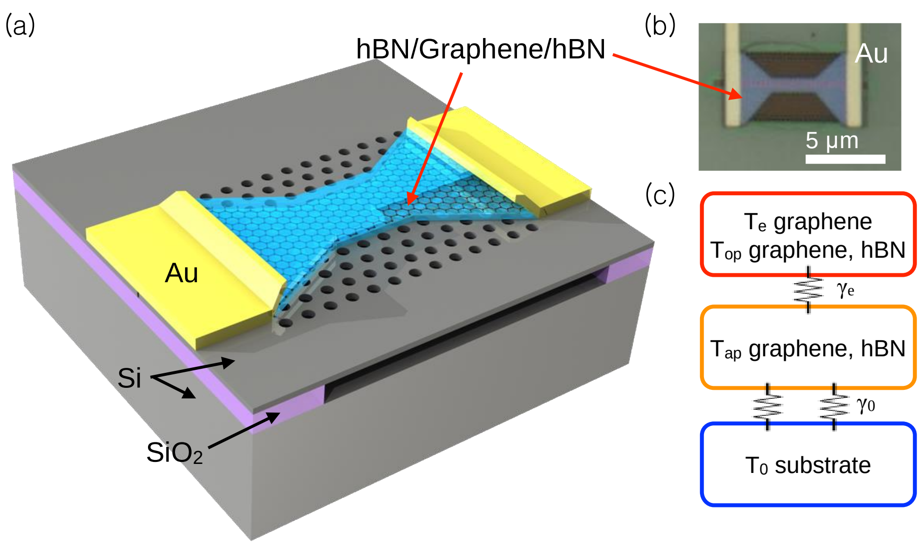


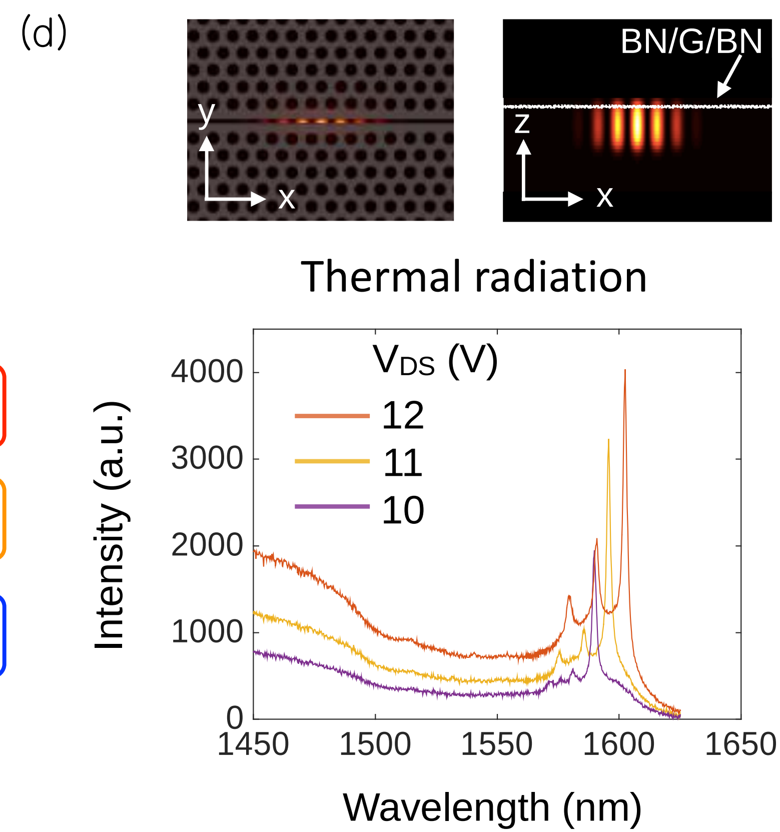


Y.D. Kim *et al*, *Nano Letters (2018).*

Tailoring Thermal Radiation of Graphene

Photonic crystal

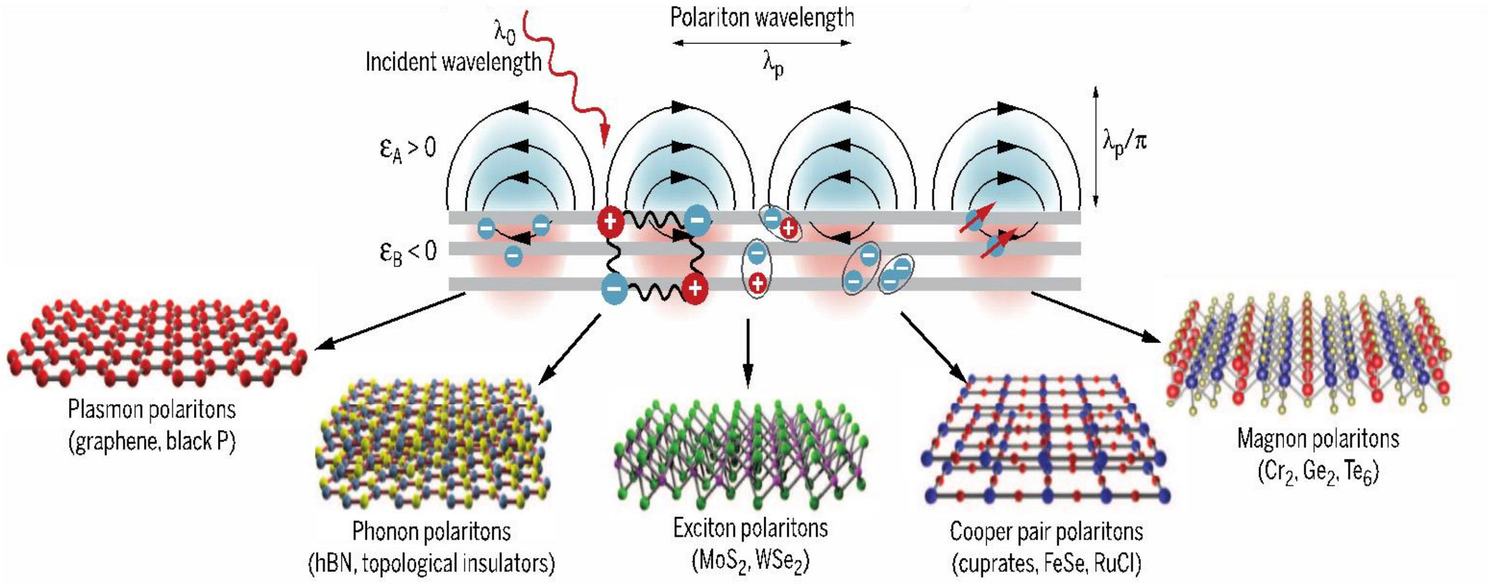




Under review

- Graphene light emitter hybrid to Si photonic crystal
- Resonance at telecommunication wavelength (1550~1600 nm)
- Strong light-matter interaction- enhance radiation efficiency

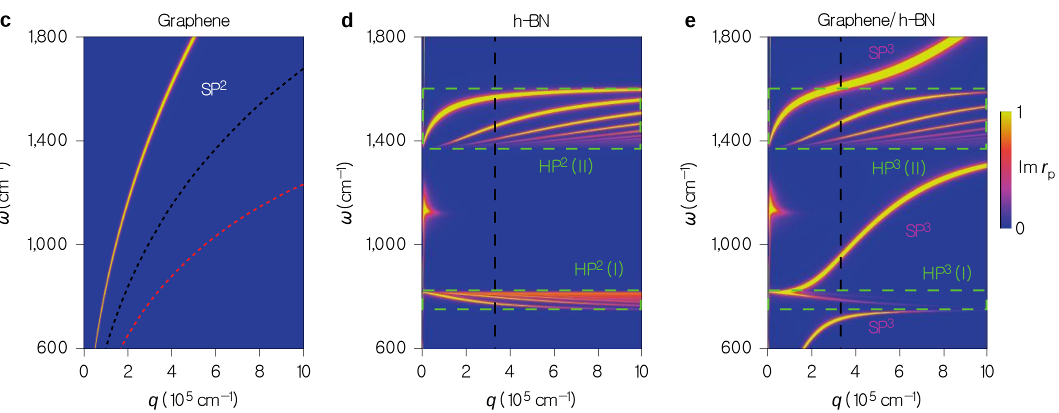
Polaritons in van der Waals interface



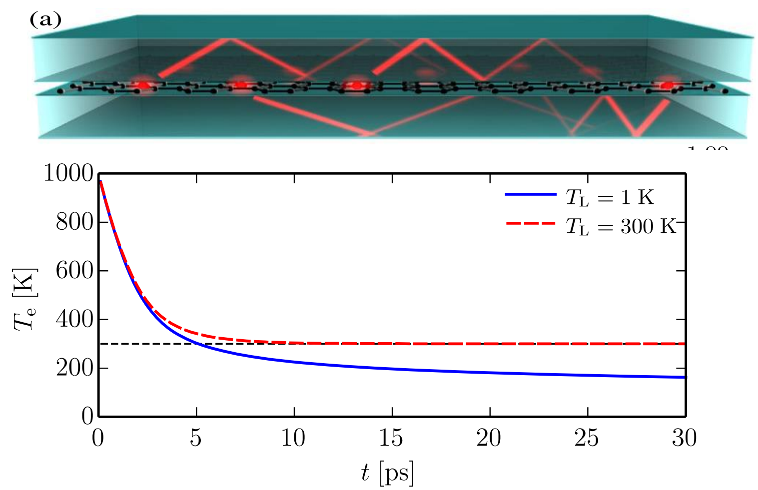
D. N. Basov et al., Science (2016)

Hybrid of
Graphene plasmon- hBN phonon polariton

Direct efficient electronic cooling pathway
(Graphene-hBN interface)

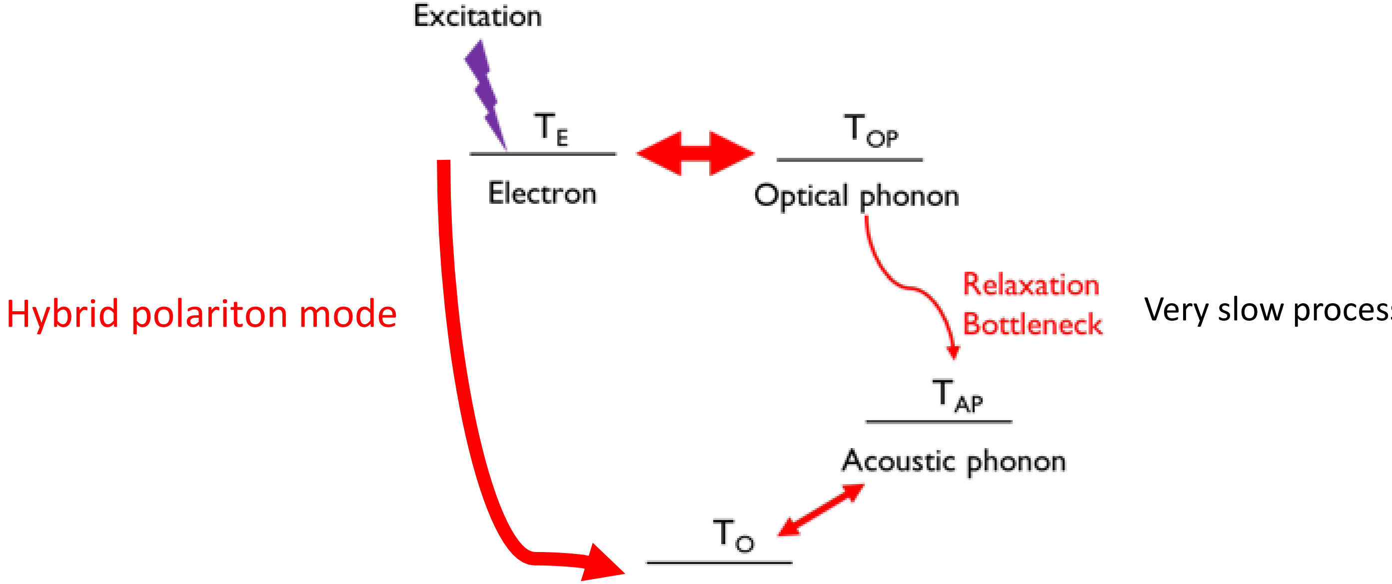


S.Daii et al., Nature Nano. (2015)

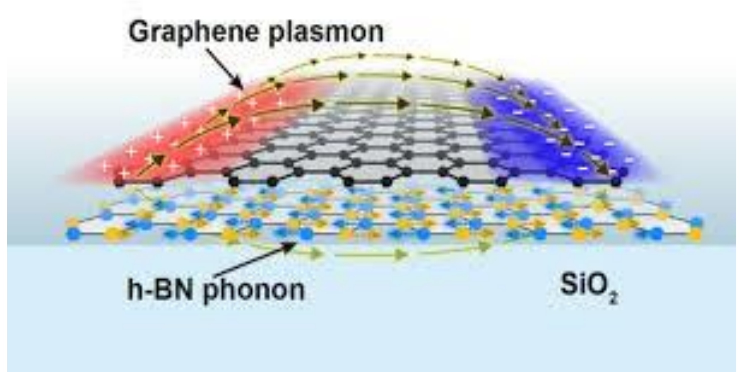


A. Principi et al., PRL (2017)

Polaritons in van der Waals interface

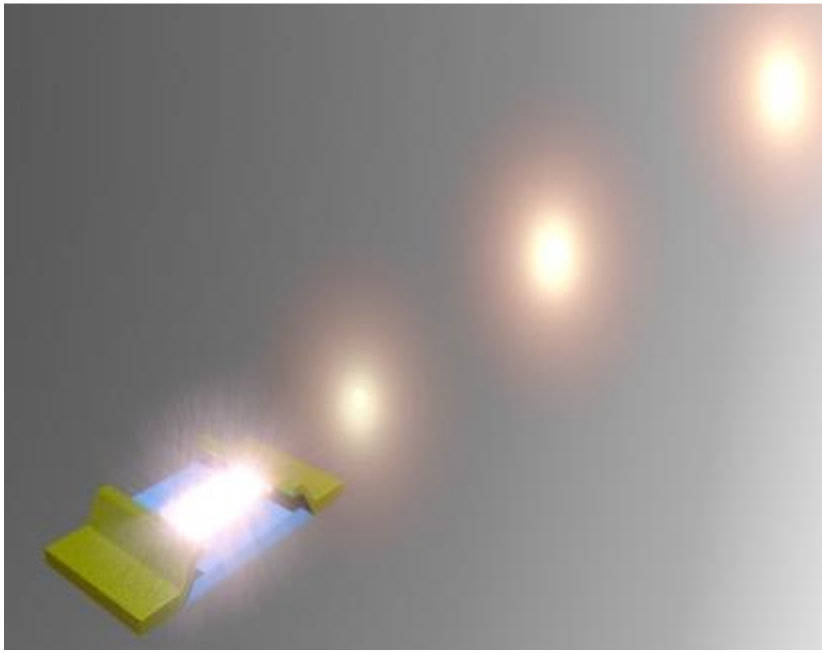


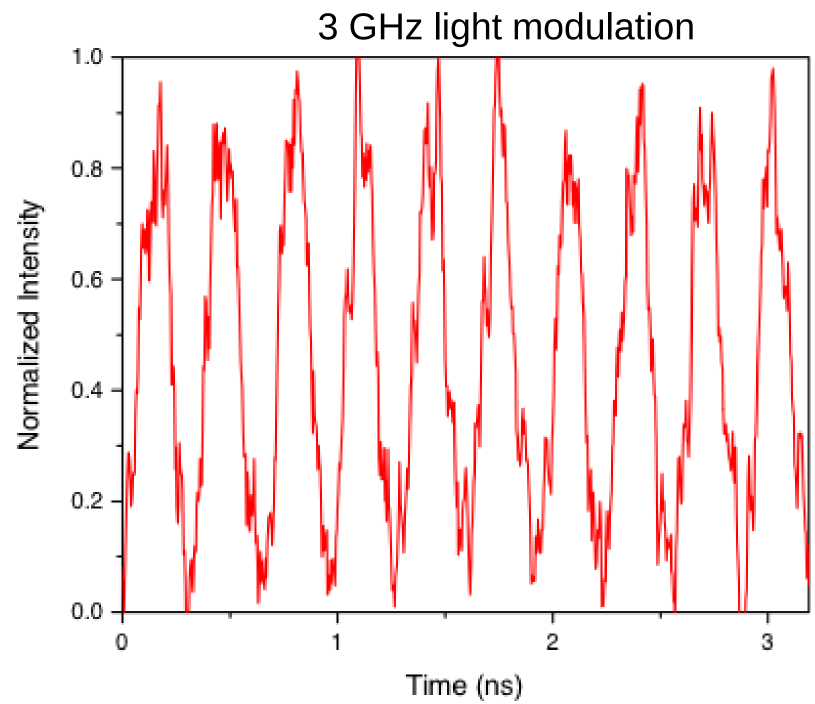
Hybrid graphene plasmonic- hBN phonon polariton mode
Extra hot electron cooling pathway



D. N. Basov et al., Science (2016)

Ultrafast Graphene Light Emitters





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

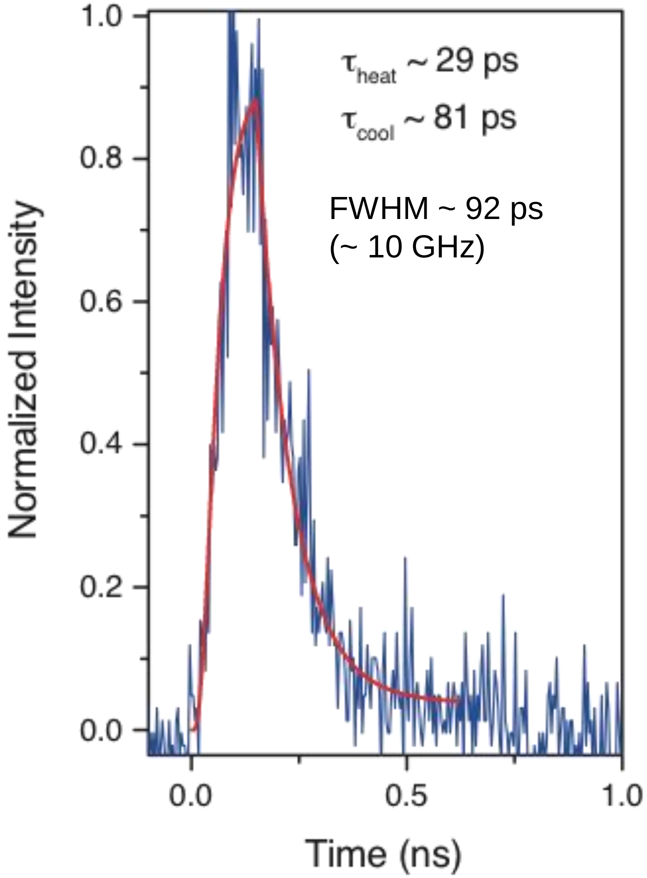
•Electrically driven GHz range thermal radiation source

•Thermal relaxation time $\tau = C_e/\Gamma$ (heat capacity of graphene and hot electron cooling rate)

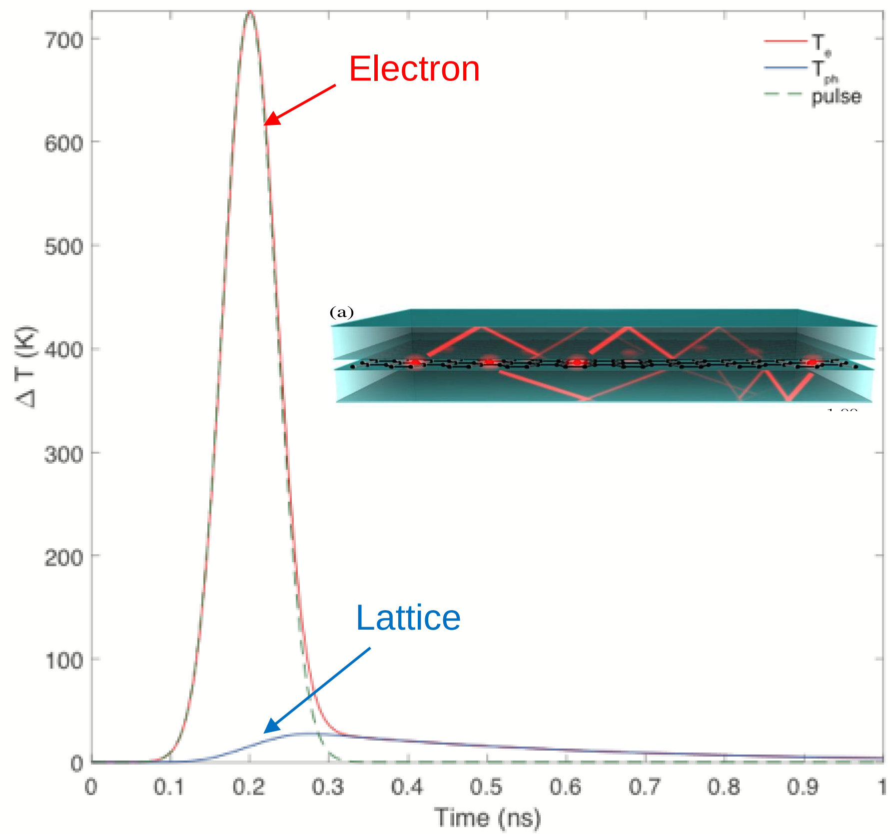
Ultrafast Graphene Light Emitters

80 ps electrical excitation

Experiment

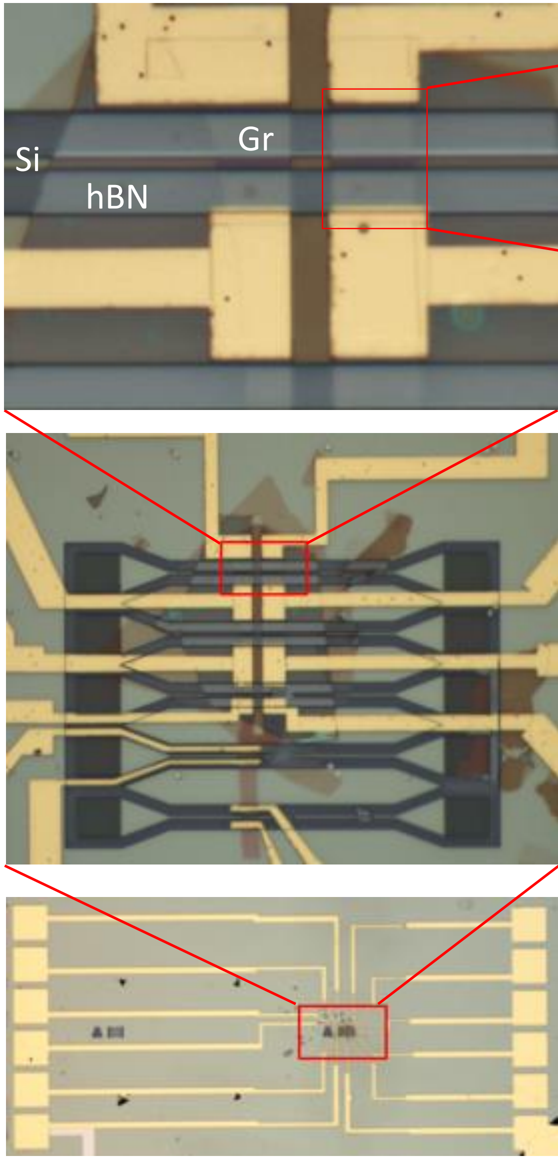


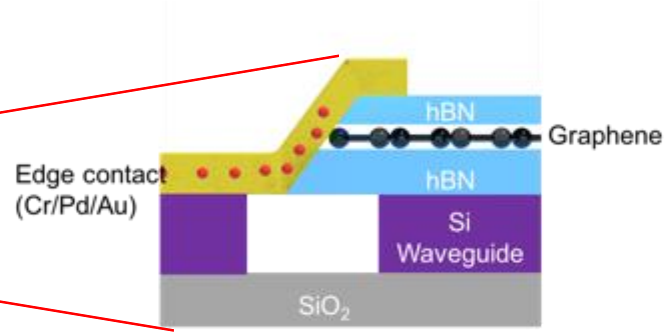
Simulation



- 10 GHz bandwidth (FWHM ~ 92 ps)
- Hybrid graphene plasmon-hBN phonon polariton (2~3 nm hBN contribution)
- Direct and efficient electron cooling pathway by graphene/hBN interface

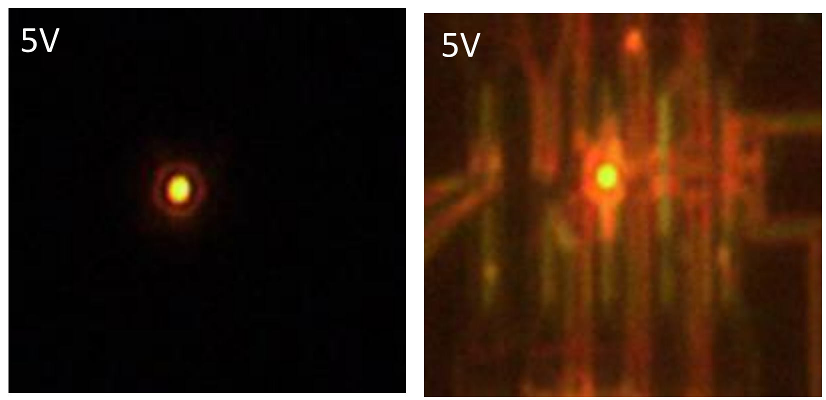
Chip-Integrated Graphene Light Emitter

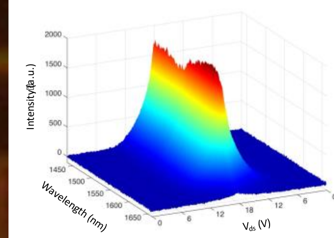




Raman mapping

Light emission



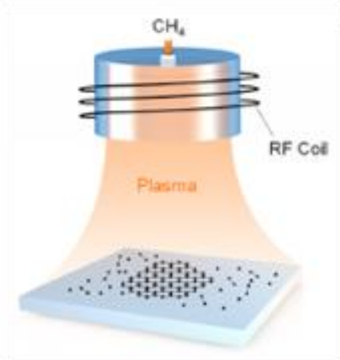


unpublished

- Hybrid photonic circuit and ultrafast graphene light source
- Strong coupling of thermal radiation to Si waveguide
- Combination of graphene photodetector, optical modulator
- Promising for on-chip ultrafast optical communication

Large Scale Graphene Light Emitter

PECVD Graphene on arbitrary substrate

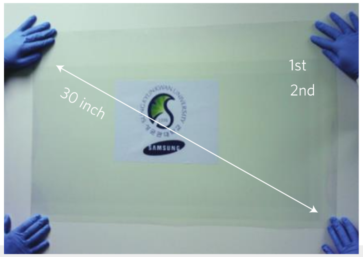


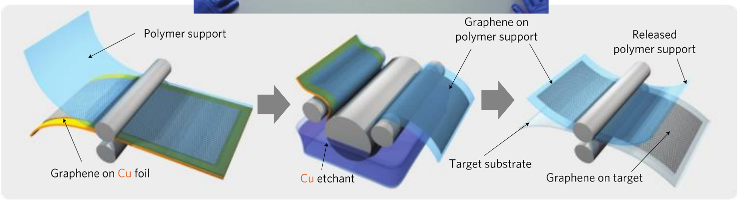
4 inch
Graphene wafer

4 inch
SiO_2/Si

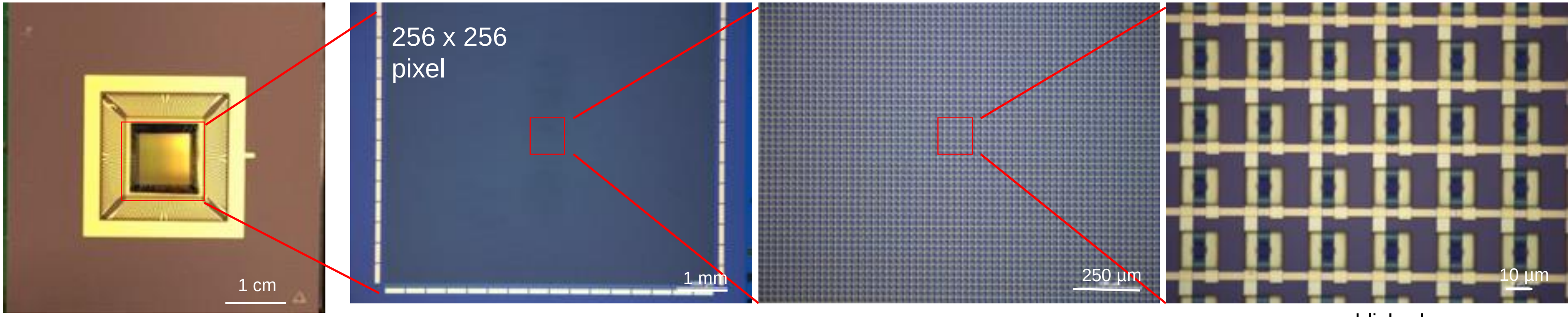
Kim, Y. S. et al., Nanoscale (2014)

CVD Graphene on Cu foil





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

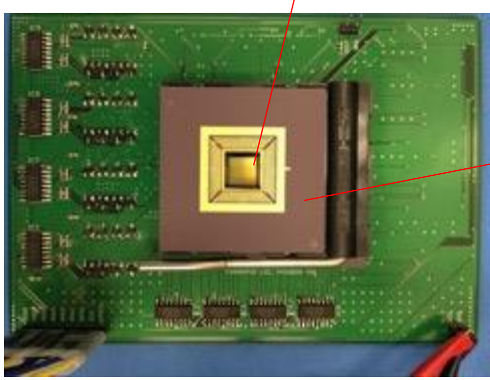


unpublished

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

Large Scale Graphene Light Emitter



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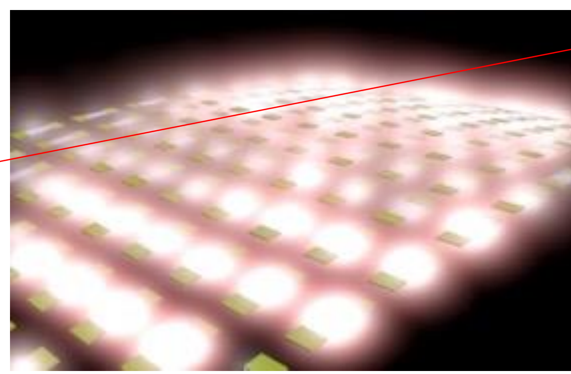
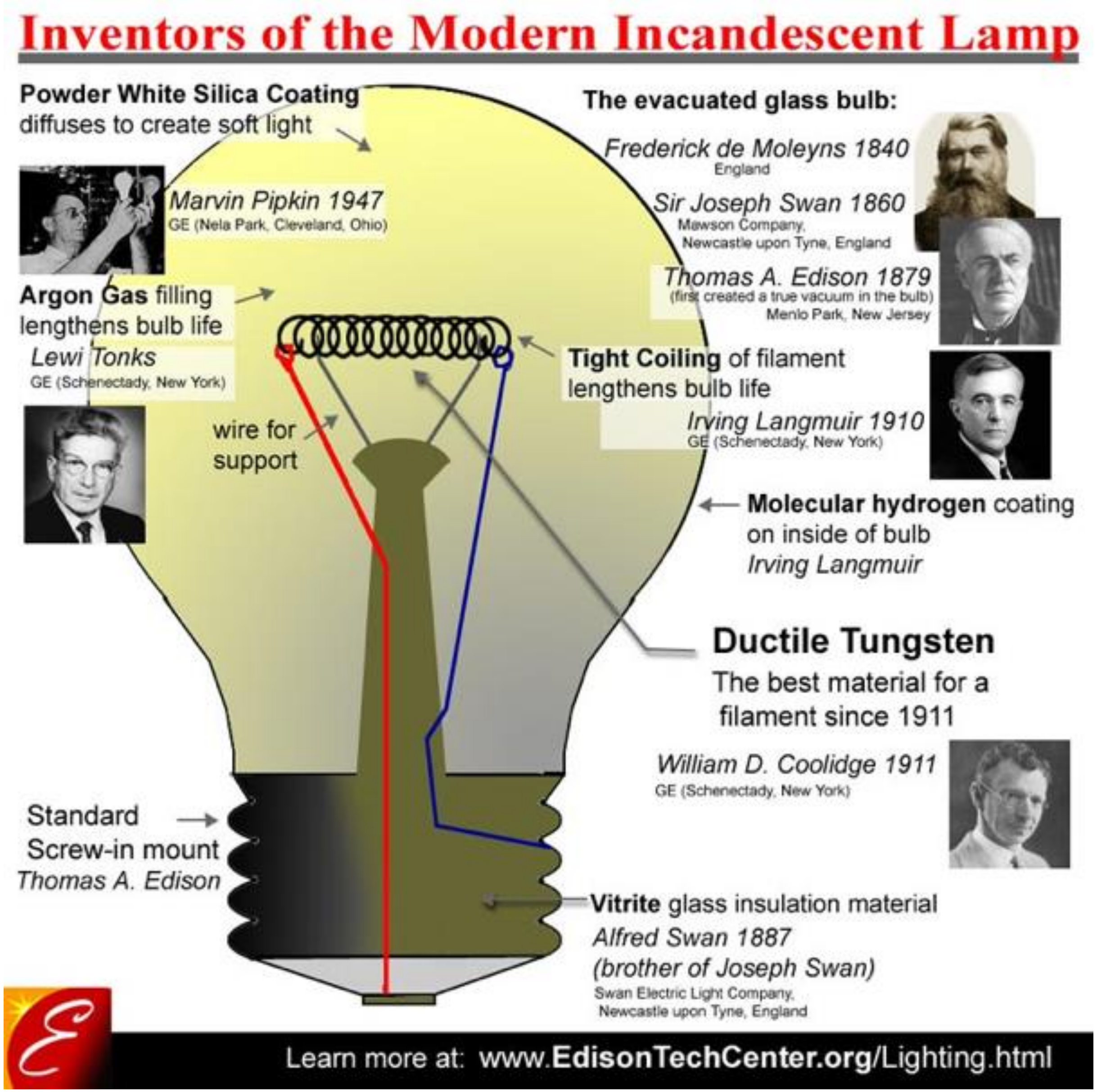


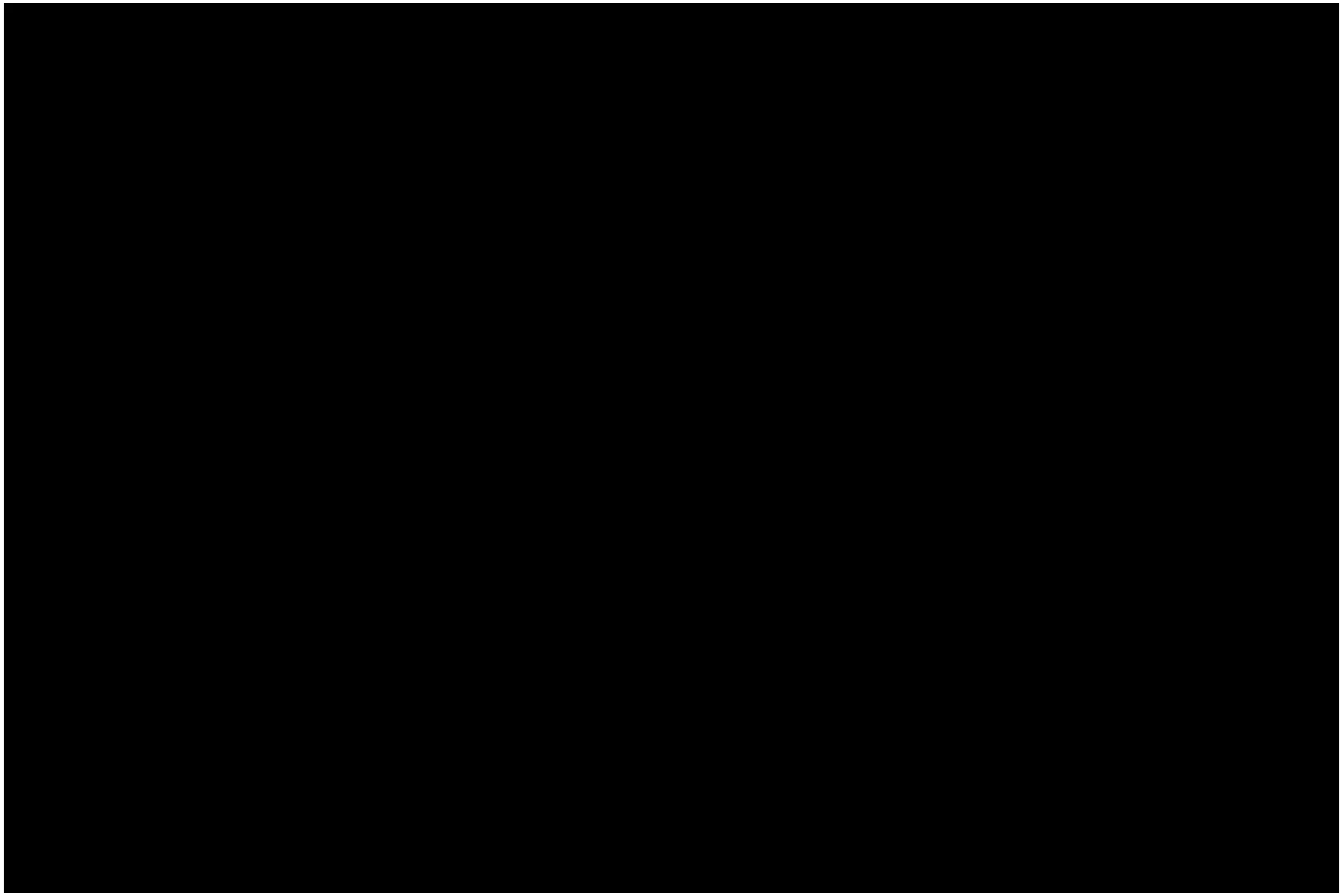
- Large-scale graphene light emission
- Potential transparent display module and augmented reality display

Incandescent Lamp



Large bulb is essential for vacuum and inert gas!

Nernst Lamp



Walther Nernst (1864-1941)

The Nobel Prize in … …ded to
Walther Her… …n of his work
in ther…

Walther Nern… …n 1921. During the selection process in 1920, the
Nobel Commi… …e of the year's nominations met the criteria as outlined in
the will of Alfr… …obel Foundation's statutes, the Nobel Prize can in such a case be
reserved until th… …this statute was then applied. Walther Nernst therefore received his
Nobel Prize for 19… …ater, in 1921.

No need bulb for vacuum!

3rd law of thermodynamics

"The entropy of a system approaches a constant value a… its temperature approaches absolute zero"

Parts of the Nernst Lamp

The elements of the Nernst Lamp are the glower, heater (made up of two or four *heater tubes*), ballast and cut-out. These are assembled in the lamp body and the holder.

FIG. 3. NAMES OF PARTS OF THE NERNST LAMP HOLDER

Glower The glower, or light giving element, is a white porcelain-like rod about 1/25 inch in diameter by 1 inch long. It is fastened to the holder mechanically and electrically by means of terminal wires and small aluminum plugs.

Invented in 1897

…xide (ZrO_2)
…um Oxide (Y_2O_3)

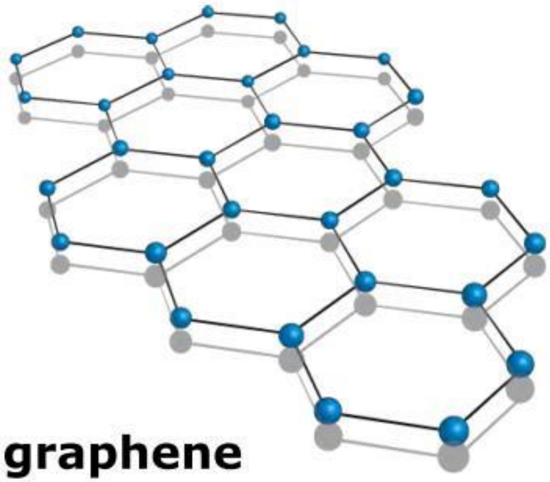
No oxidation under high temperature and air.

No need vacuum and noble gas

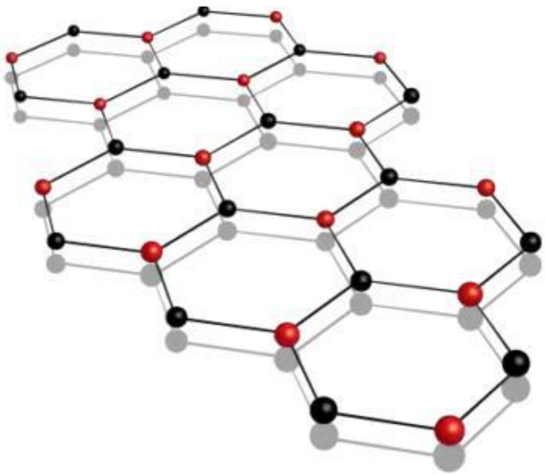
No current flow at room temperature.

Heater

Hexagonal Boron Nitride



graphene



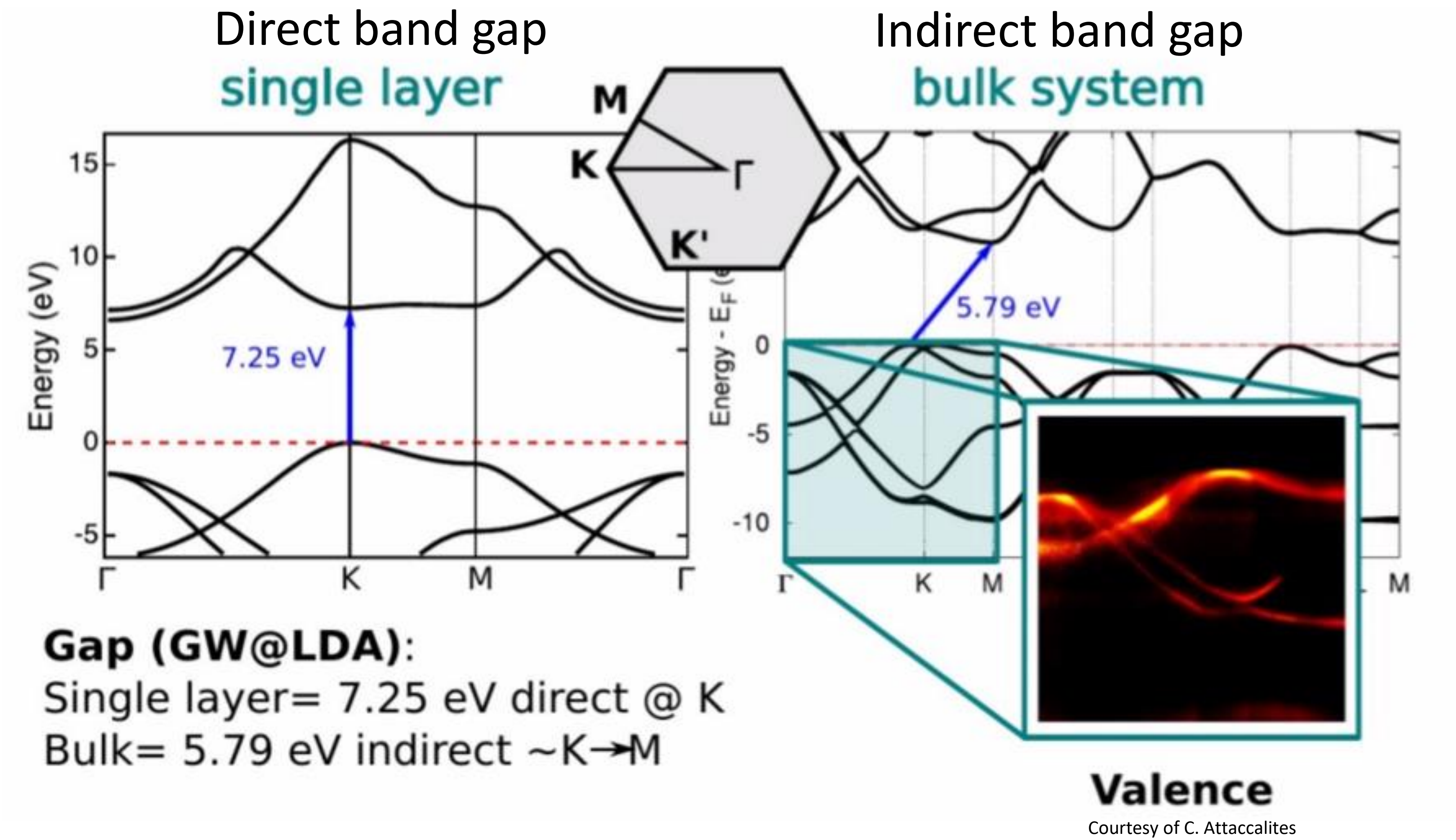
Boron Nitride

Comparison of h-BN and SiO_2

	Band Gap	Dielectric Constant	Optical Phonon Energy	Structure
BN	6.4 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

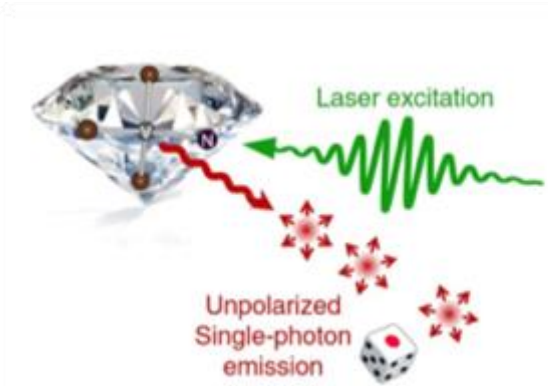
hBN Band Structure

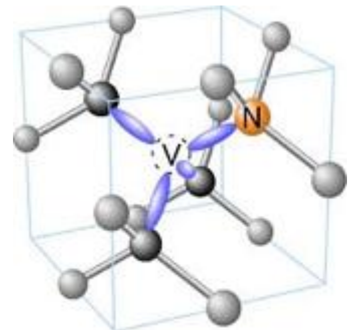


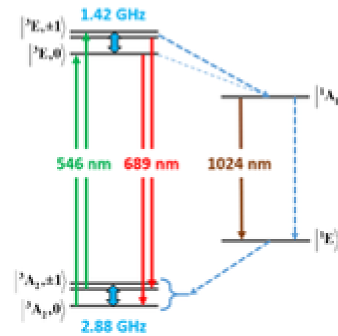
Wide bandgap (>7.25 eV) and Indirect bandgap material.
Very large exciton binding energy (0.2 eV).

Quantum Emitter in Wide Bandgap Material

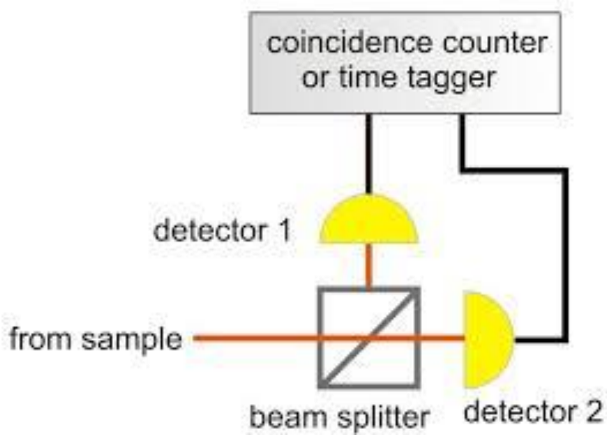
NV center Diamond (3D)

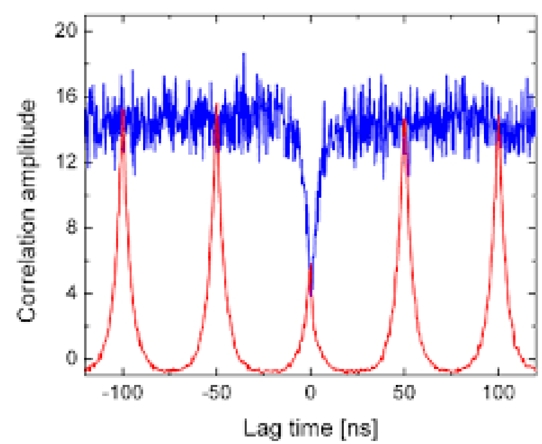






Single photon source at Room Temperature.

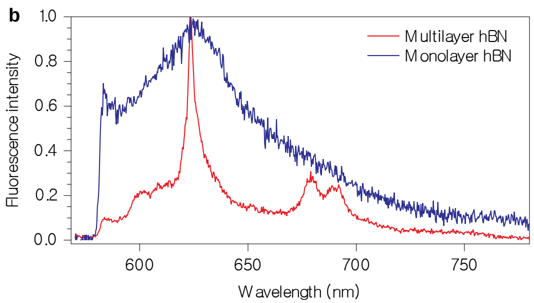


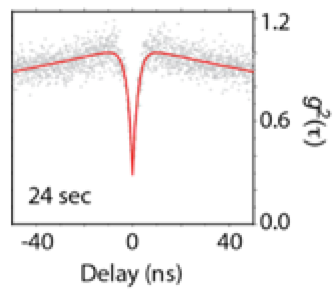


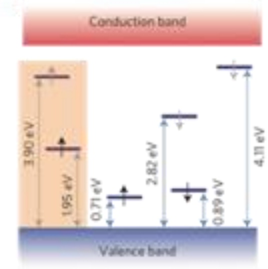
Key material for quantum information system.

hBN based Quantum Emitter

Singe color center (Defect) in hBN (2D)
Single photon source at Rom Temperature

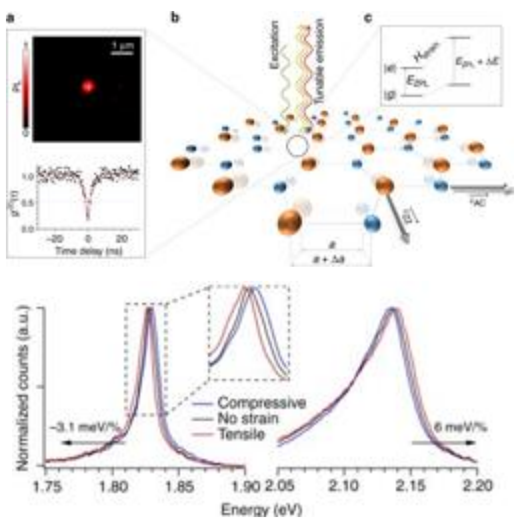






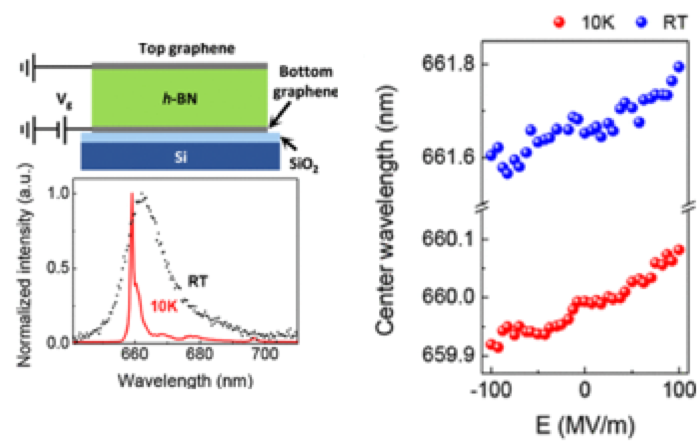
T. T. Tran *et al*, Nature Nanotech. (2016)

Tunable quantum emitter by strain



G. Grosso *et al*, Nature Comms. (2017)

Electric field Stark tuning

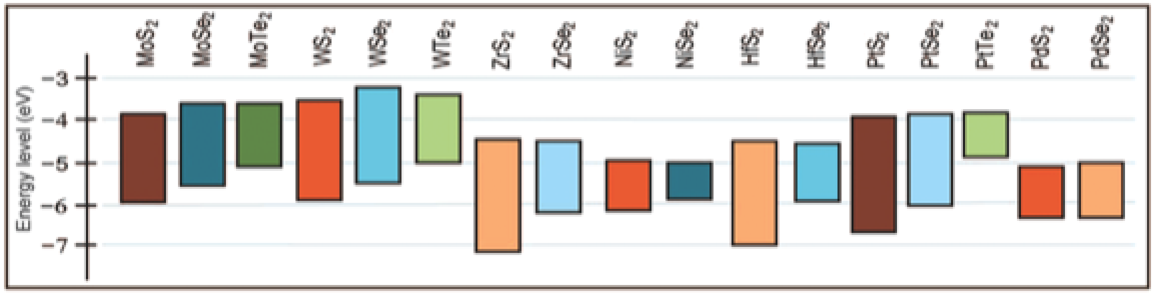


G. Noh *et al*, Nano Lett. (2018)

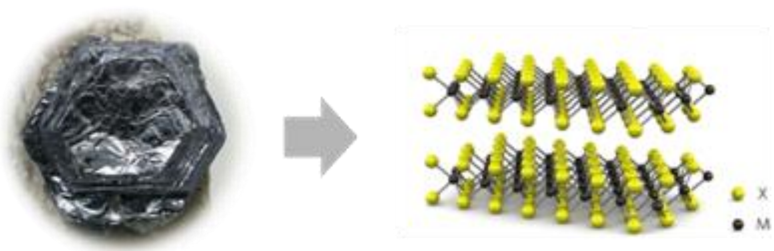
2D Quantum emitter with various tunability!

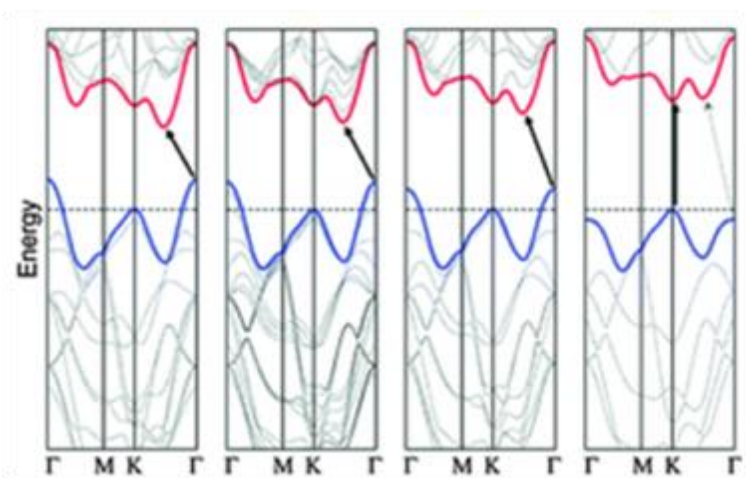
2D Semiconductors

Transition metal dichalcogenide (TMDC)



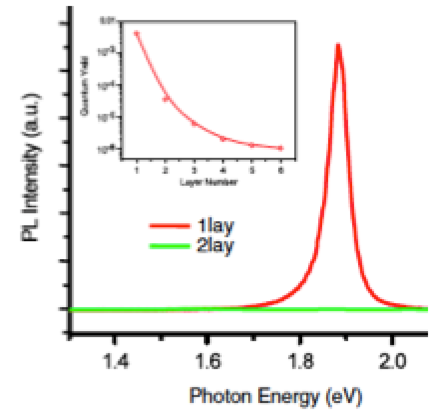
K. Kalantar-zade *et al*, Advanced Funct. Mat. (2015)





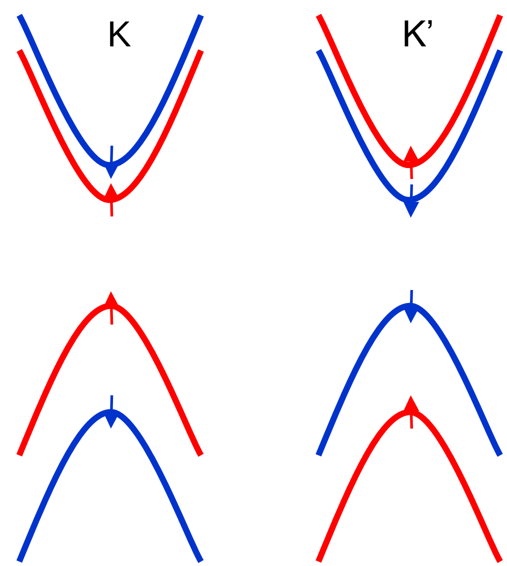
Thickness decreases. ⟶

Direct band gap - PL

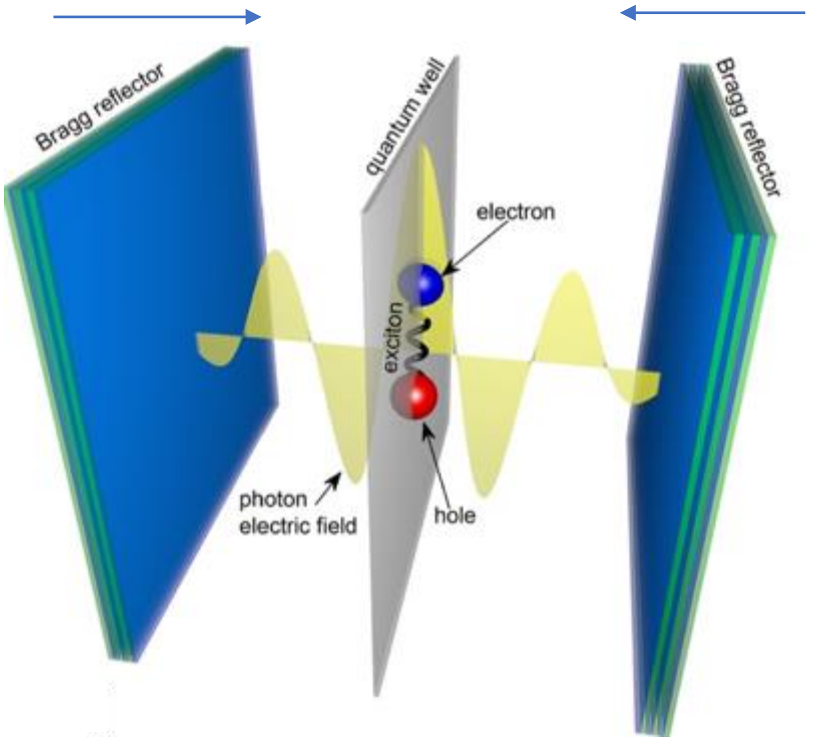


KF. Mak *et al*, Phys. Rev. Lett (2010)

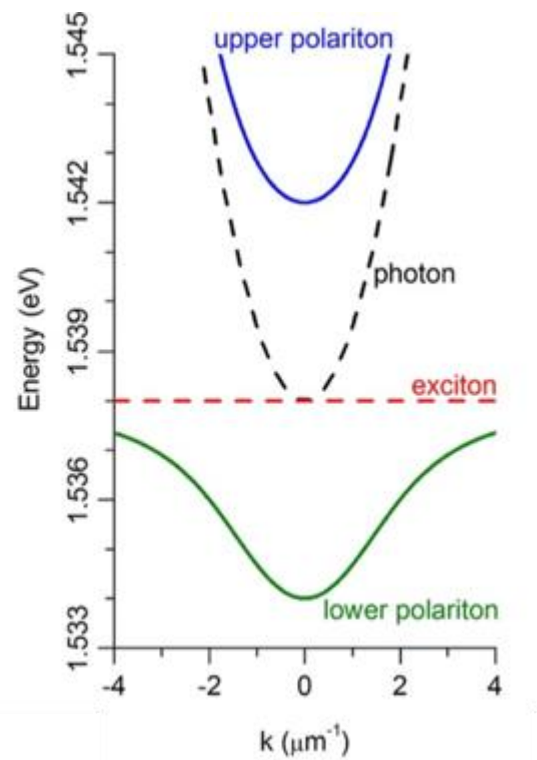
Spin-valley physics



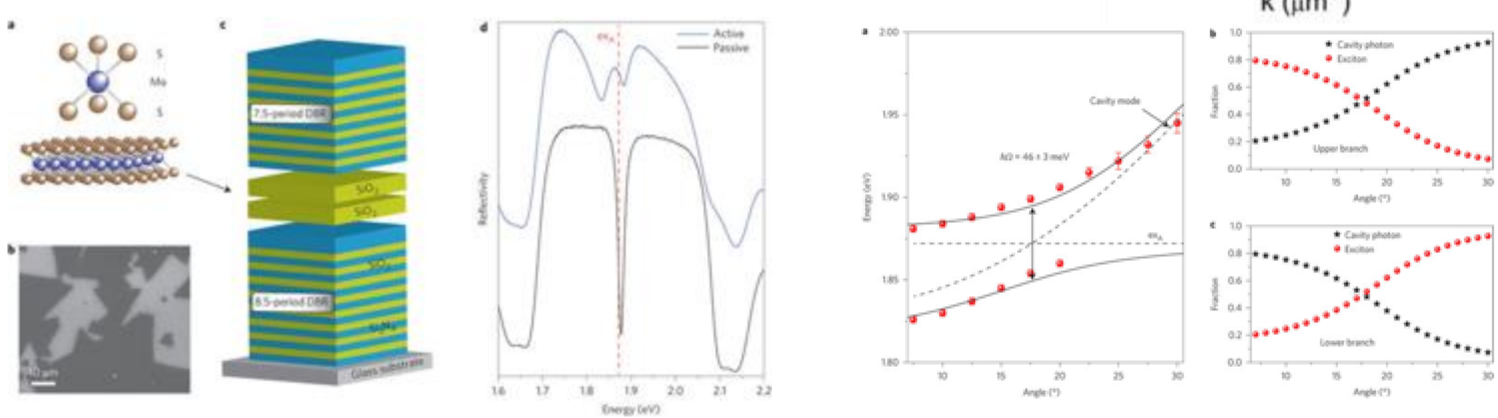
Exciton-Polariton in 2D Semiconductors



Strong coupling regime



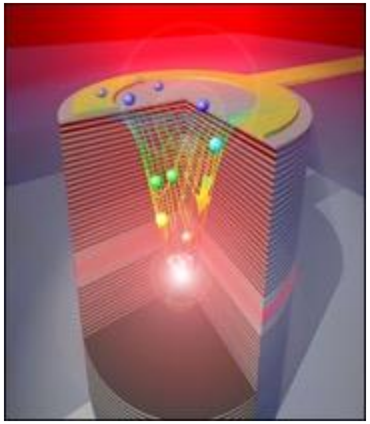
Exciton-Polariton in MoS_2

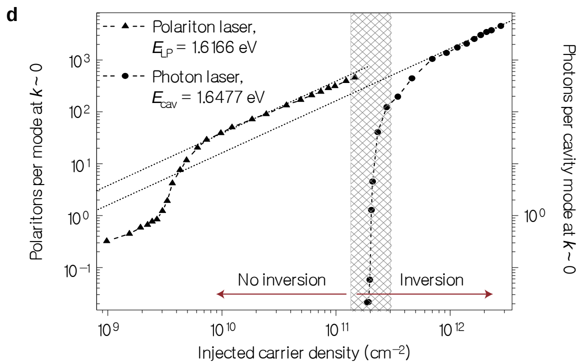


X. Liu *et al*, Nature Photonics. *(2015).*

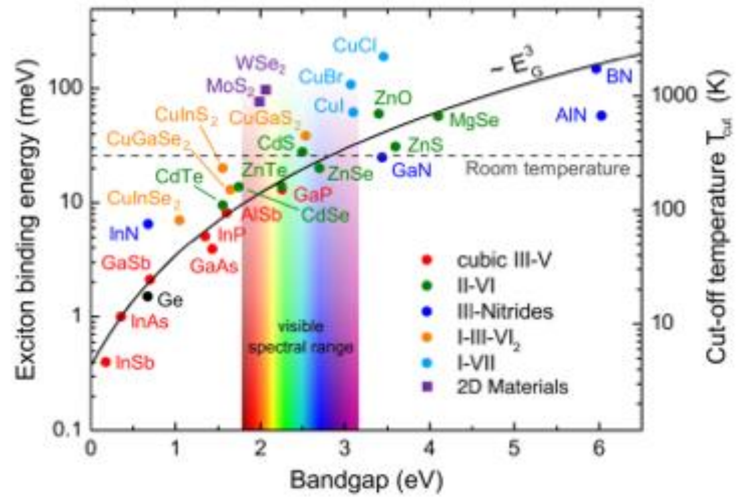
Exciton-Polariton Applications

Polariton laser: Thresholdless nano-lasers



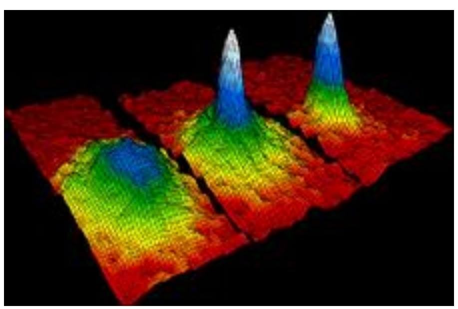


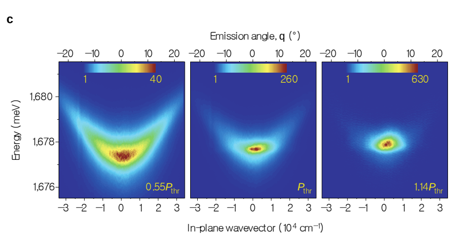
C. Schneider *et al*, Nature *(2013).*



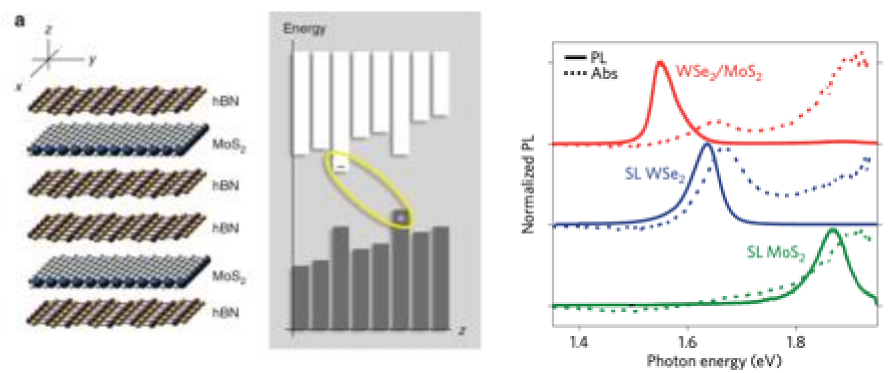
2D materials: large exciton binding energy

Bose-Einstein condensation in solid





Interlayer exciton: room temperature BEC



M. M. Fogler *et al*, Nature Comm *(2014).*

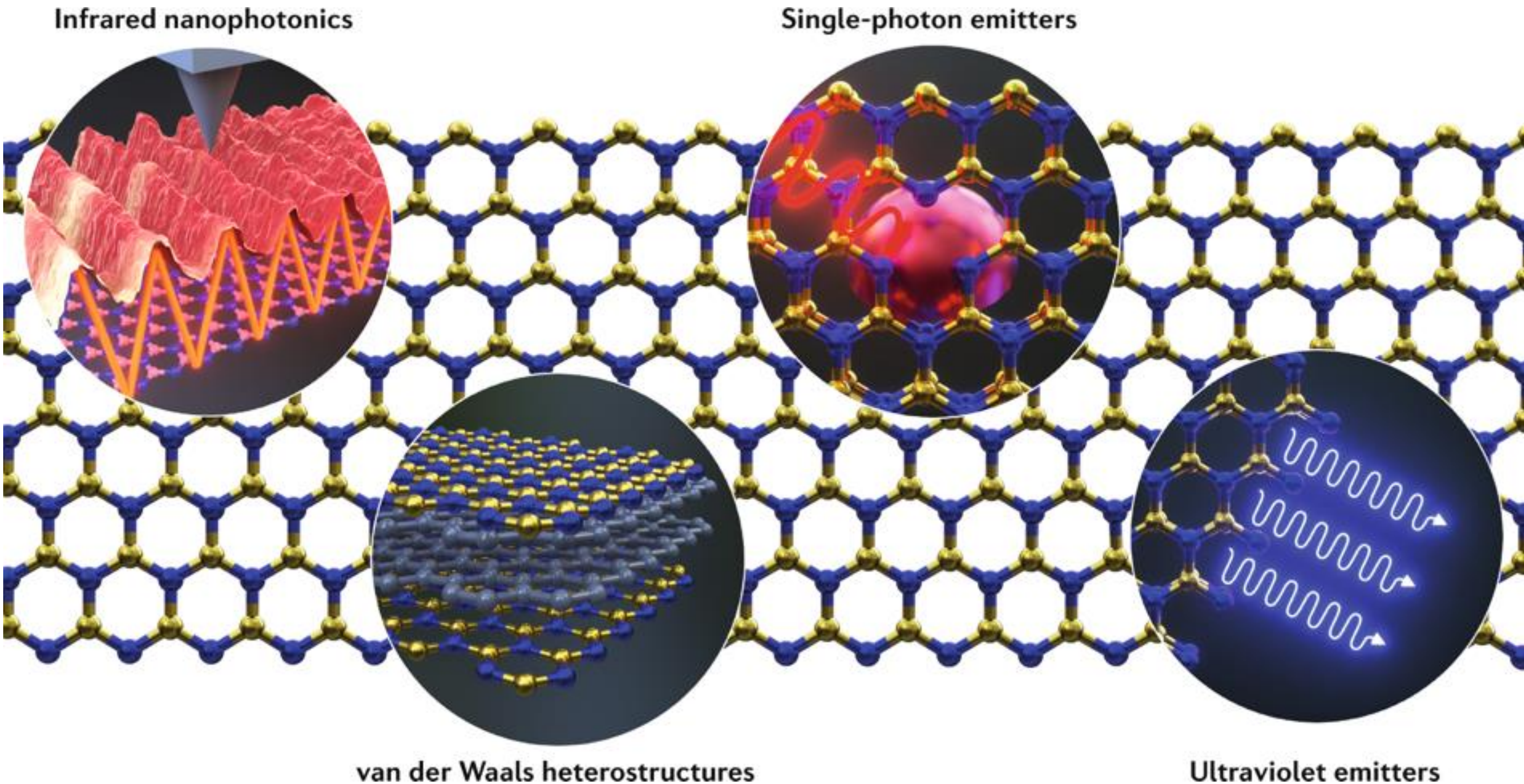
- Bosonic quasi particle
- High temperature superconductivity and superfluidity
- Quantum simulator and quantum information

GaAs: ~3.5 meV (15 nm Bohr radius)

MoS2: ~ 140 meV (1 nm Bohr radius)

Type II TMDC: >200 meV

2D Materials for Next-generation Light Source



J. D. Caldwell *et al*, Nature Reviews Materials. (2019)

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