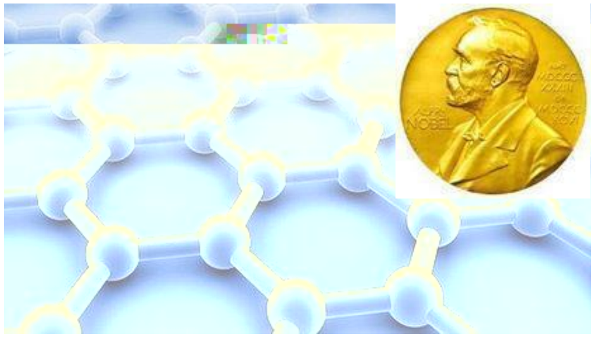
Email:yshi@nju.edu.cn

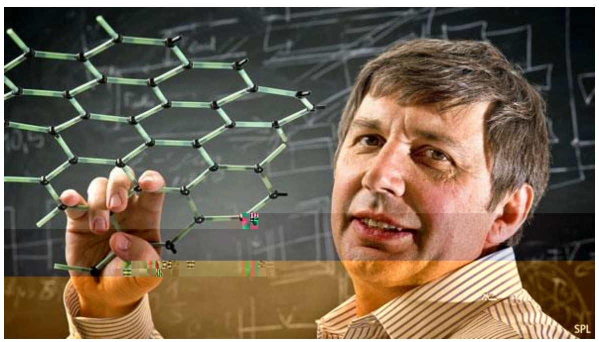
提　纲

到

——光探测器件

石墨烯的发现

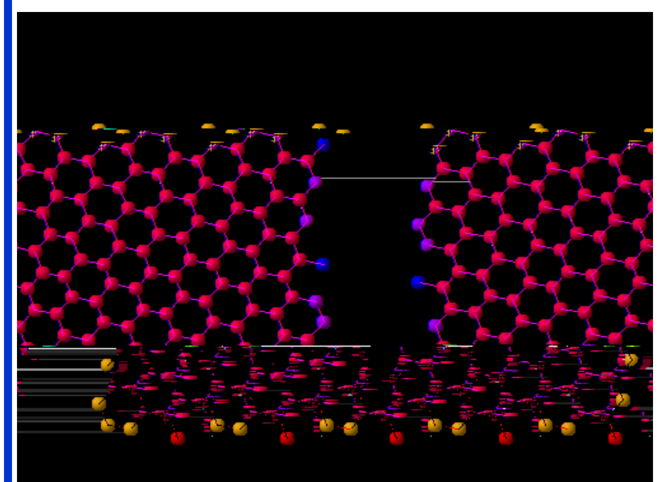


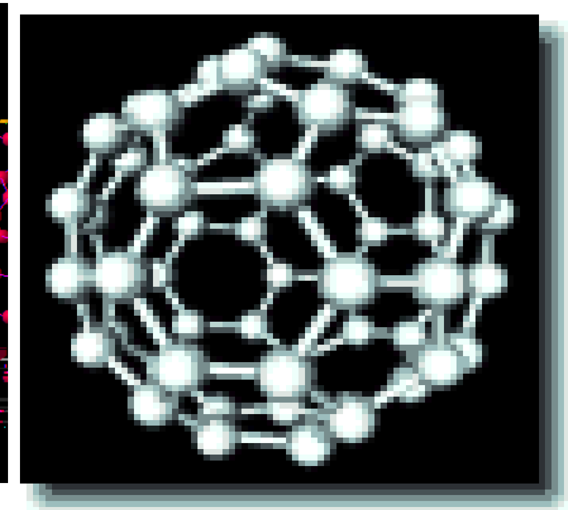


Andre Geim

Kostya Novoselov

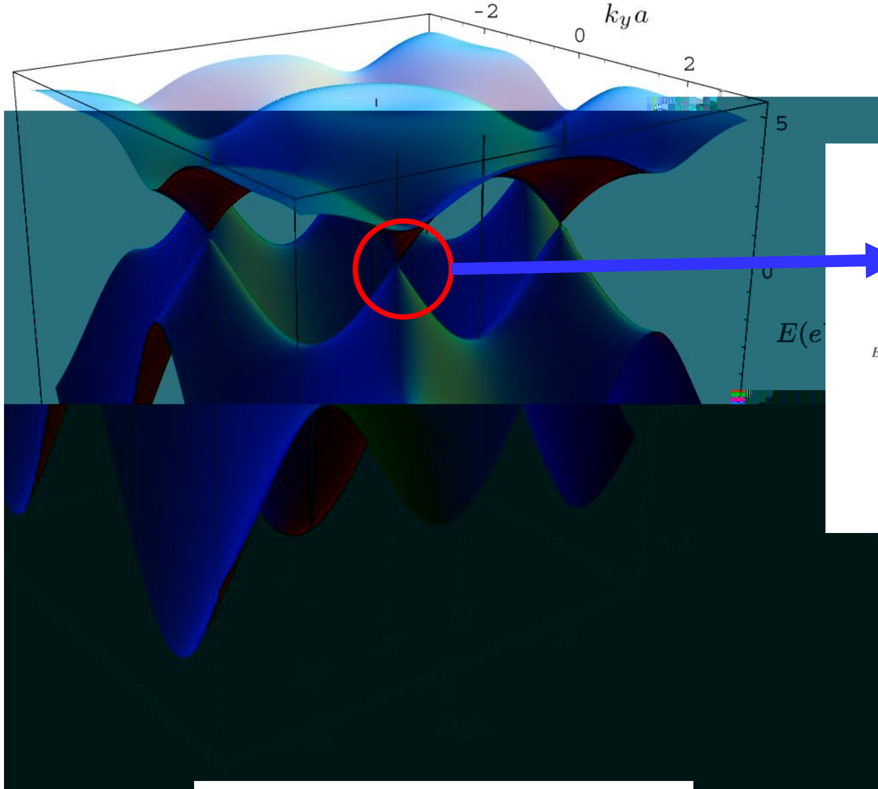
Novoselov KS, Geim A K, *et al.* **Science** 2004, **306**, 666
Zhang YB *et al.* **Nature** 2005, **438**, 201
Geim AK and Novoselov KS **Nature Materials** 2007, **6**, 183

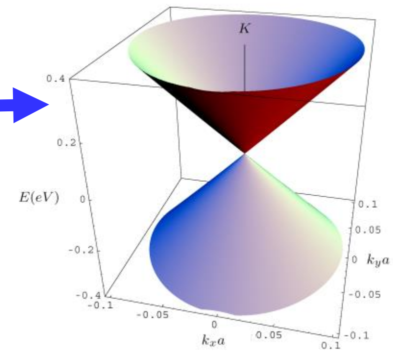


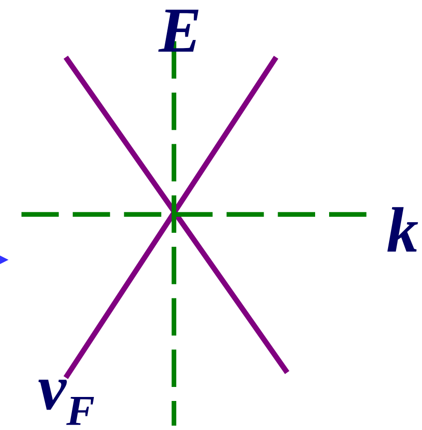


60

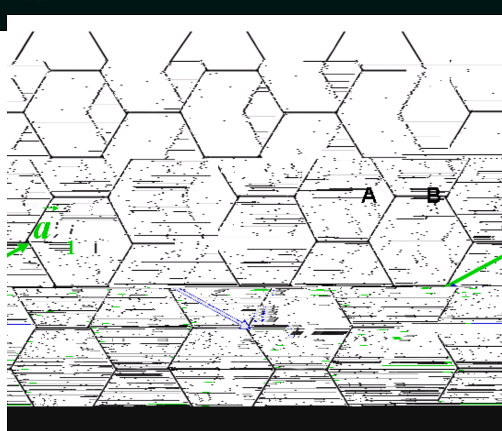
石墨烯能带结构







$v_F \approx 10^6\ ms^{-1} = c/300$



$2x10^5 cm^2/Vs$

石墨烯能带结构

$$H = H_{at} + H_{\text{int}}(\vec{k})$$

Tight-binding calculation on π bands:

$$H\begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} E_p, & f(\vec{k}) \\ f^*(\vec{k}), & E_p \end{pmatrix}\begin{pmatrix} u_1 \\ u_2 \end{pmatrix}$$

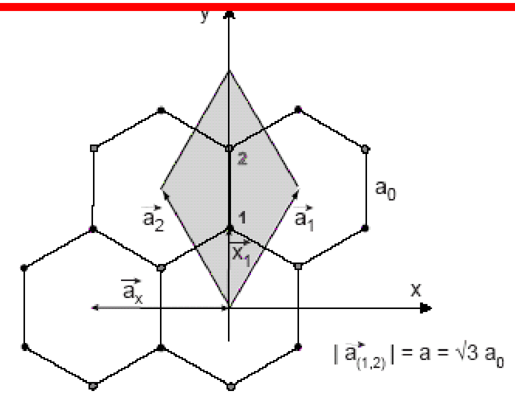
$$f(\vec{k}) = \gamma[1 + e^{i\vec{k}\cdot\vec{a}_1} + e^{i\vec{k}\cdot\vec{a}_2}]$$

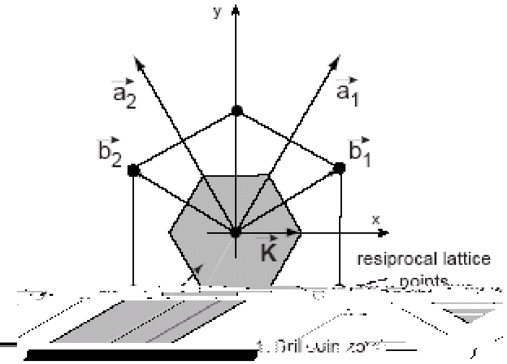
$$E_\pi(\vec{k}) = E_p \pm |\, f(\vec{k})\,|$$

$$= E_p \pm \sqrt{3 + 2\cos\vec{k}\cdot\vec{a}_1 + 2\cos\vec{k}\cdot\vec{a}_2 + 2\cos k(\vec{a}_2 - \vec{a}_1)}$$

$$= E_p \pm \sqrt{1 + 4\cos^2(\sqrt{3}k_x a/2) + 4\cos(\sqrt{3}k_x a/2)\cos(3k_y a/2)}$$

$$= E_p \pm v_F k' \qquad \text{near K points}$$





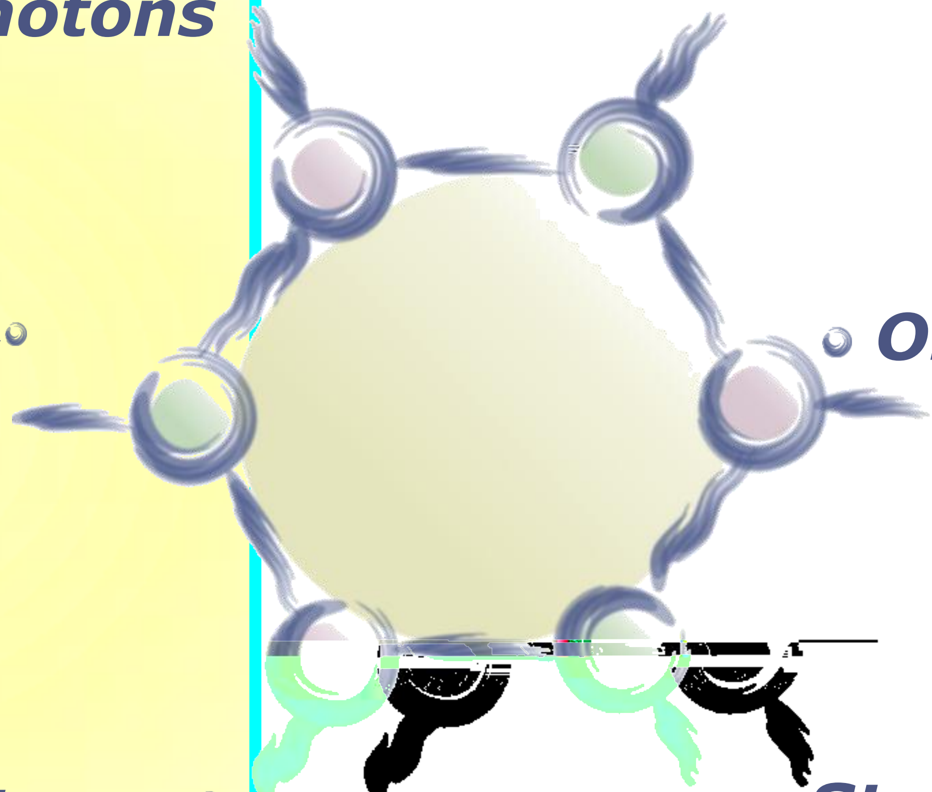
P.R.Wallace, Phys.Rev.71,(1947)

石墨烯的优异特性

Strong interaction with photons

High Mobility

Linear Spectrum

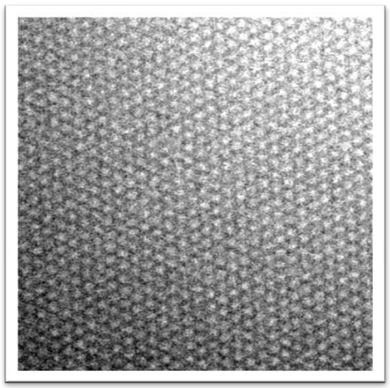


Highly Stretchable

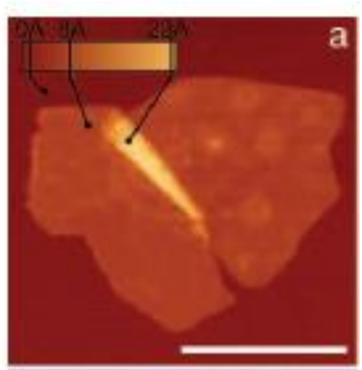
One Atom Thin

Strength

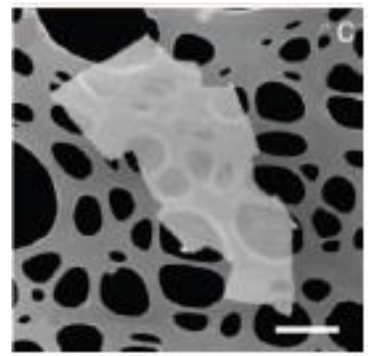
二维原子晶体材料



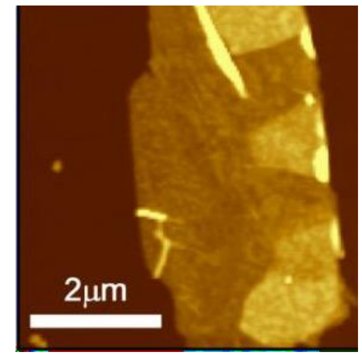
Graphene



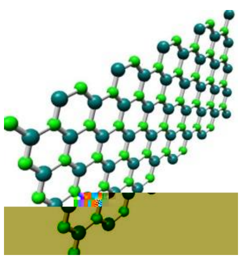
$NbSe_2$

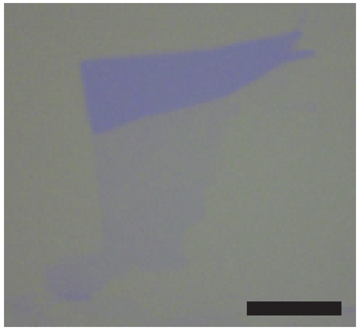


BiSrCaCuO

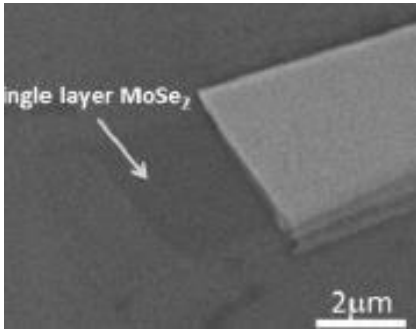


Black phosphorus

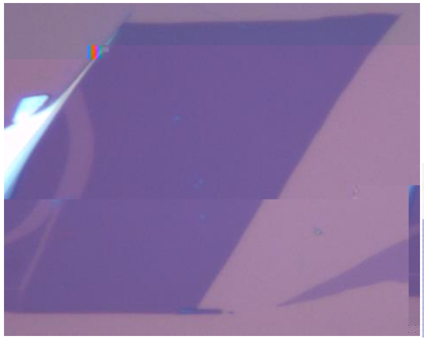


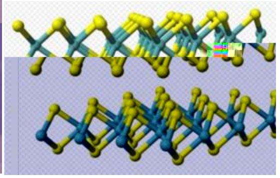


BN



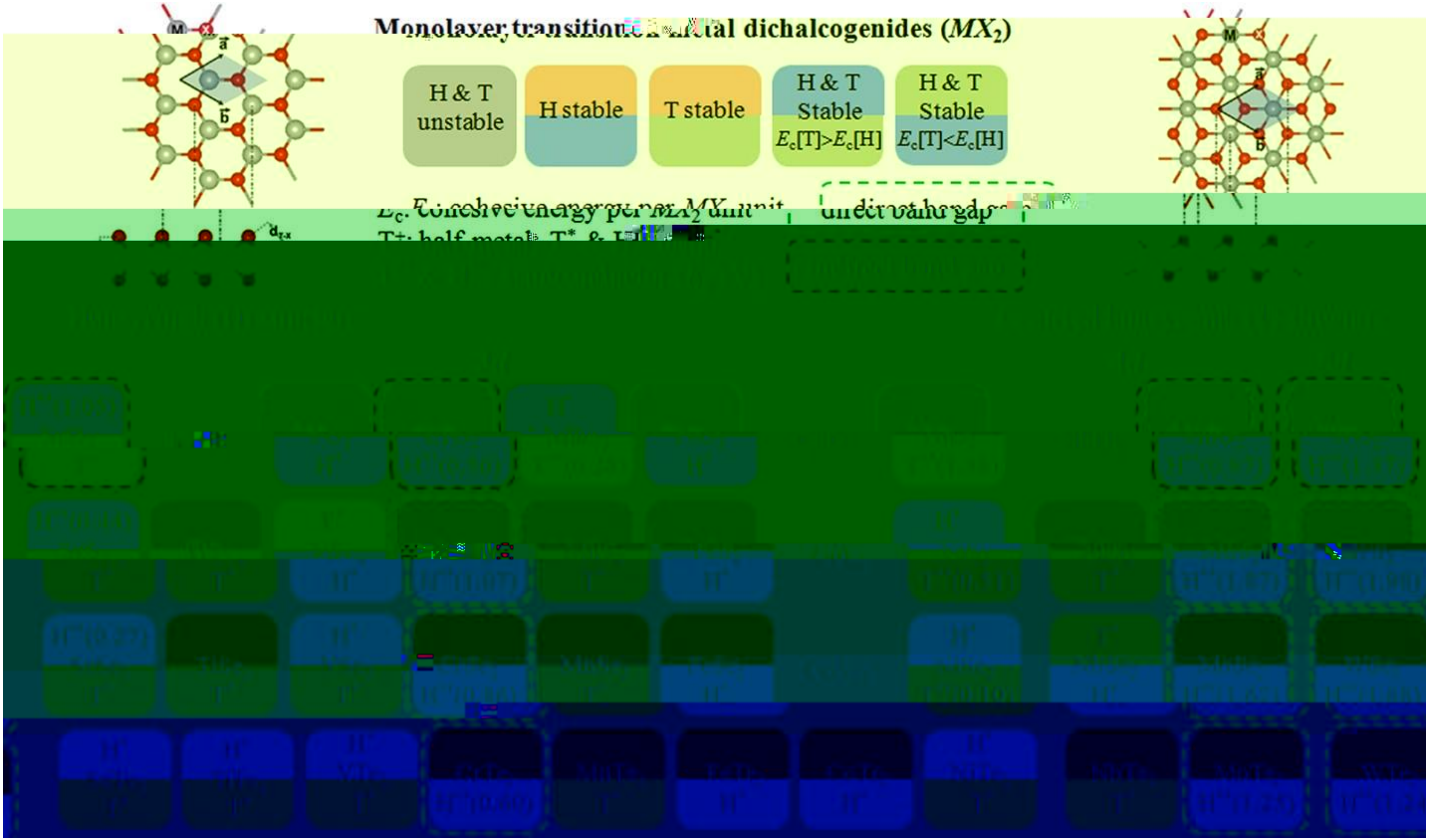
$MoSe_2$





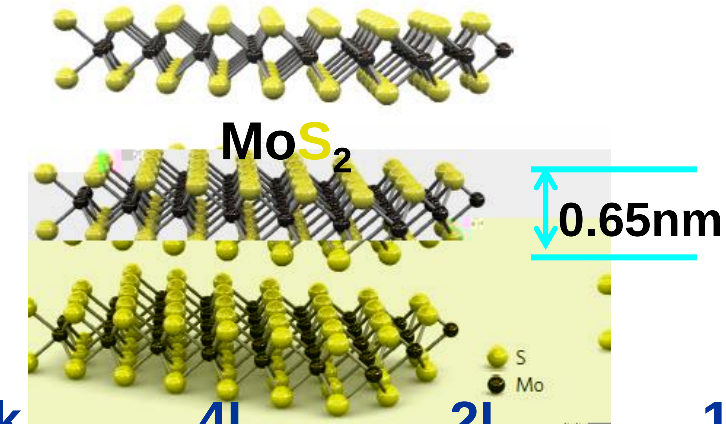
MoS_2

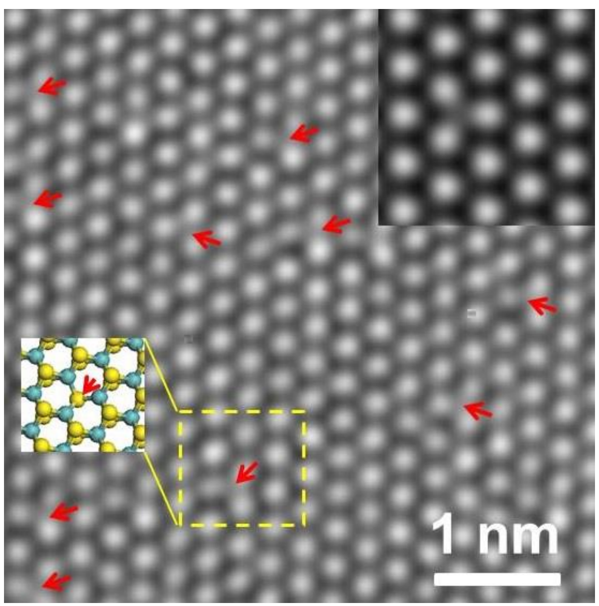
层状过渡金属二硫属化物

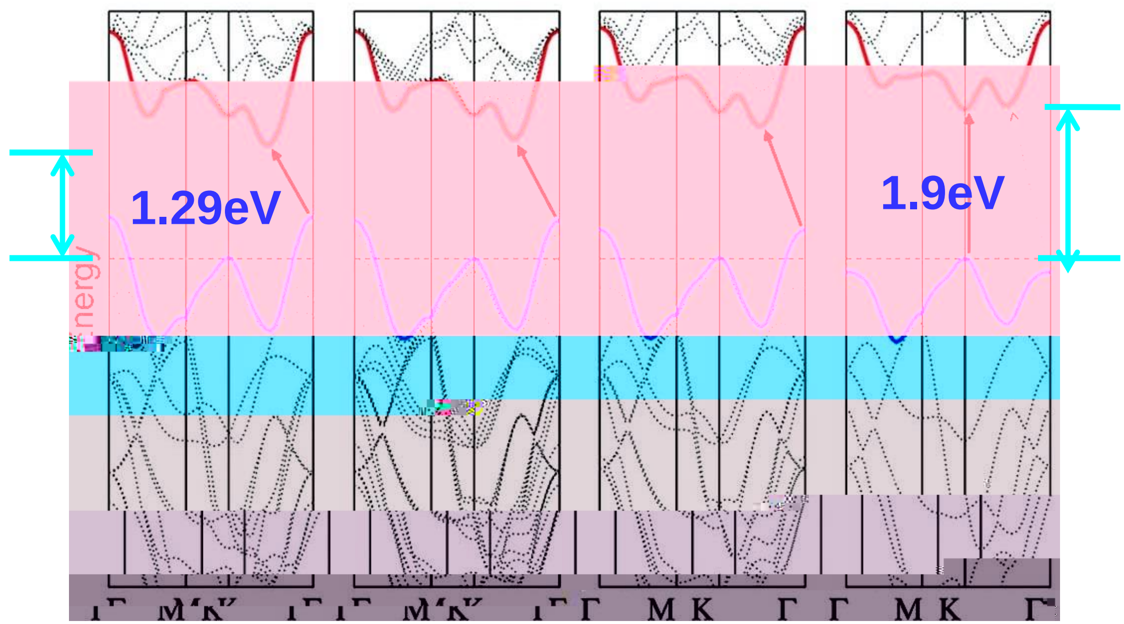


MoS$_2$

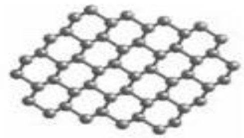
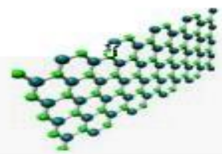
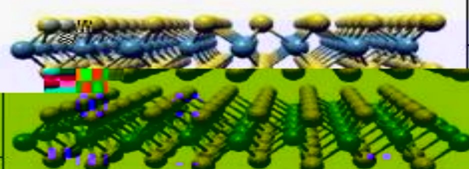

Natural MoS2 crystal,
Canada


MoS2
0.65nm
S
Mo

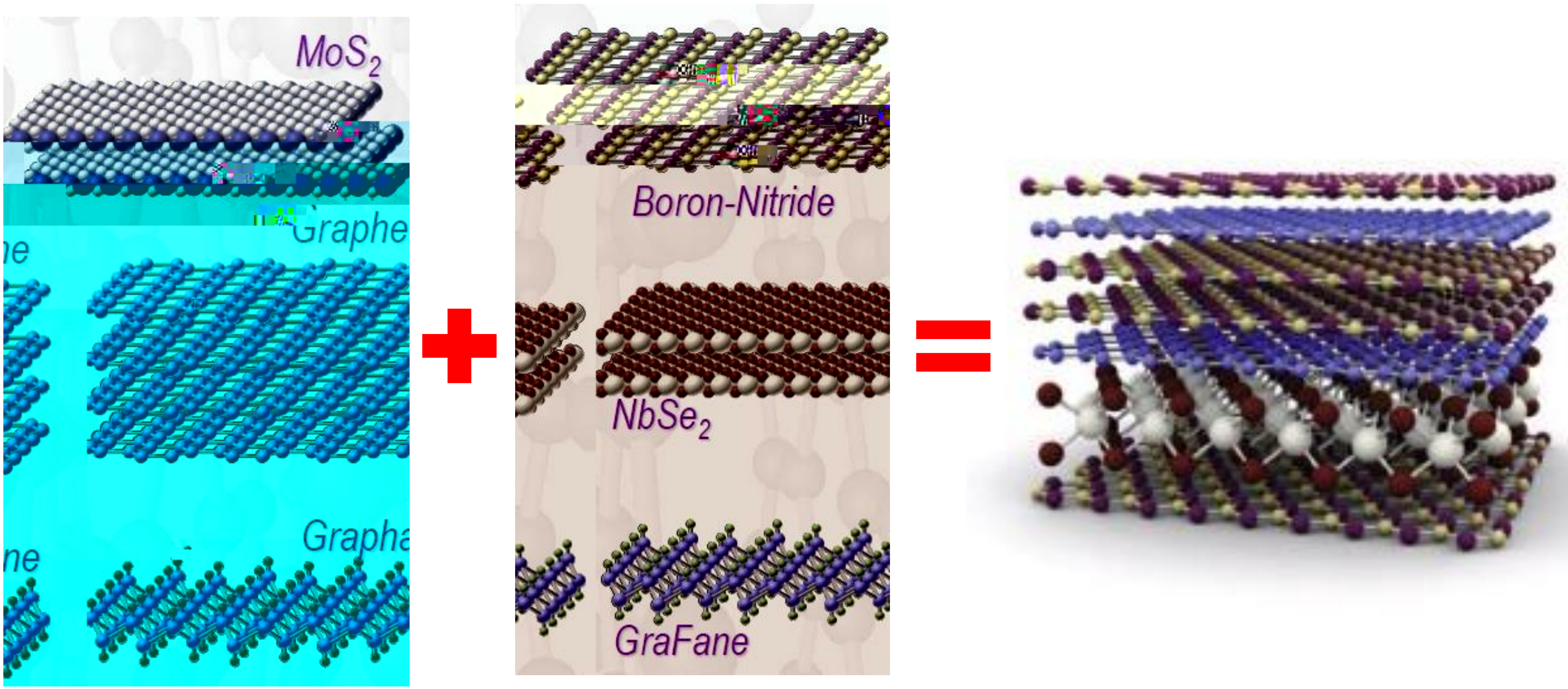

1 nm


Bulk
4L
2L
1L
1.29eV
1.9eV
Γ M K Γ

二维原子晶体材料的能带结构

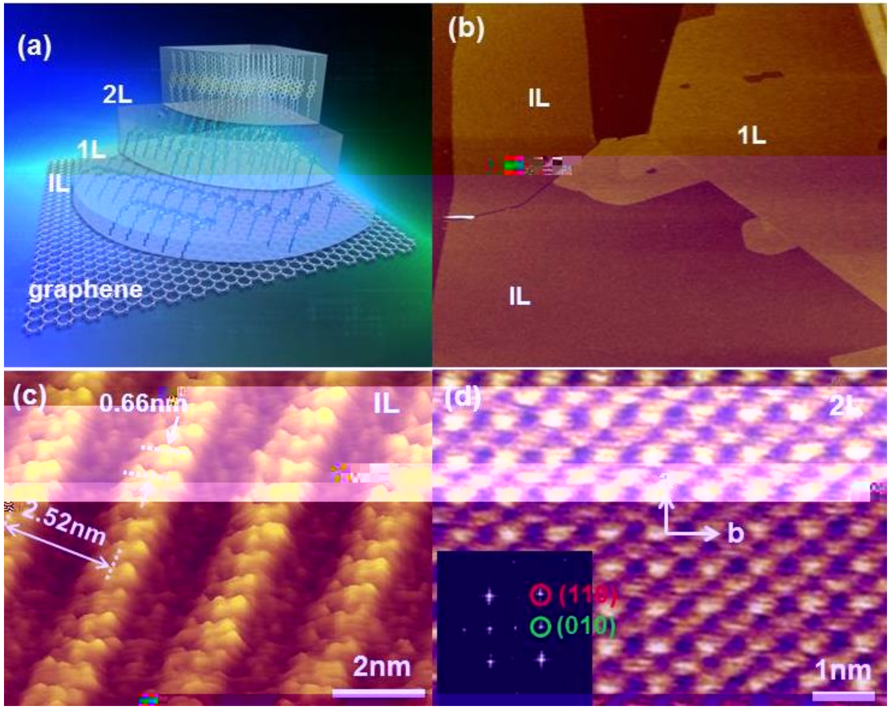
二维原子晶体材料	结构模型	能带隙 (eV)	载流子迁移率
单层石墨烯 (C)		0	超高
单层 *h*氮化硼 (BN)		~ 6.07	低
单层硫化钼 (MoS_2)		~1.90 (直接带隙)	
单层硫化钨 (WS_2)		~2.10 (直接带隙)	低
单层硒化钨 (WSe_2)		~1.44 (直接带隙)	
单层碲化钼 (WTe_2)		~1.07 (直接带隙)	
单层硫化镓 (GaS)		~ 3.04(直接带隙) ~ 2.59(间接带隙)	低
单层硒化镓 (GaSe)		~ 2.1(直接带隙) ~ 2.0(间接带隙)	

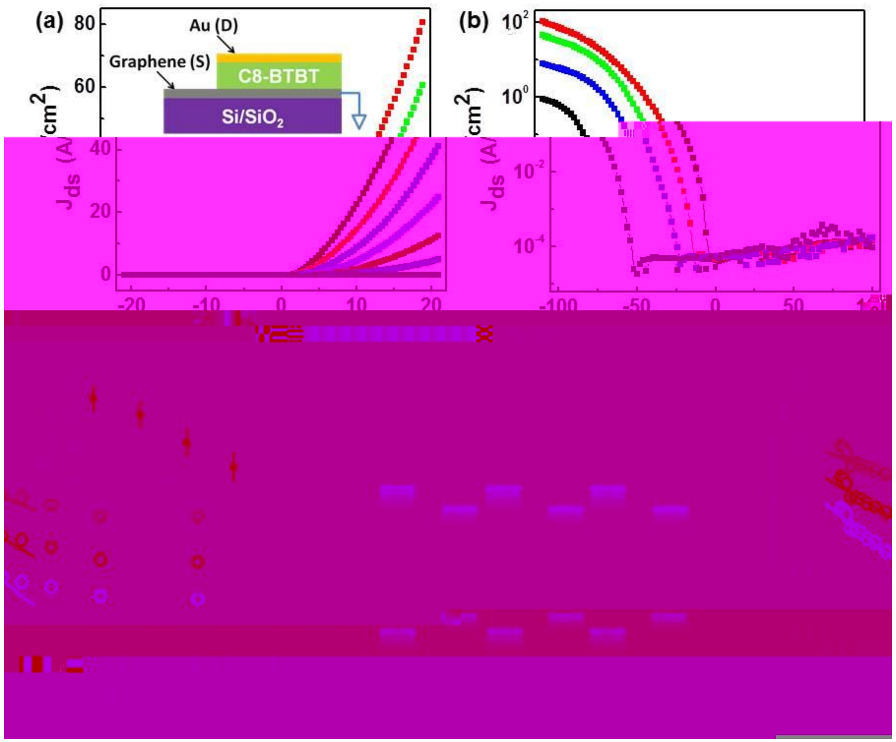
范德瓦尔斯（Van der Waals）异质结构



S.K.Novoselov, Nobel Prize Lecture (2010)

范德瓦尔斯（Van der Waals）异质结构

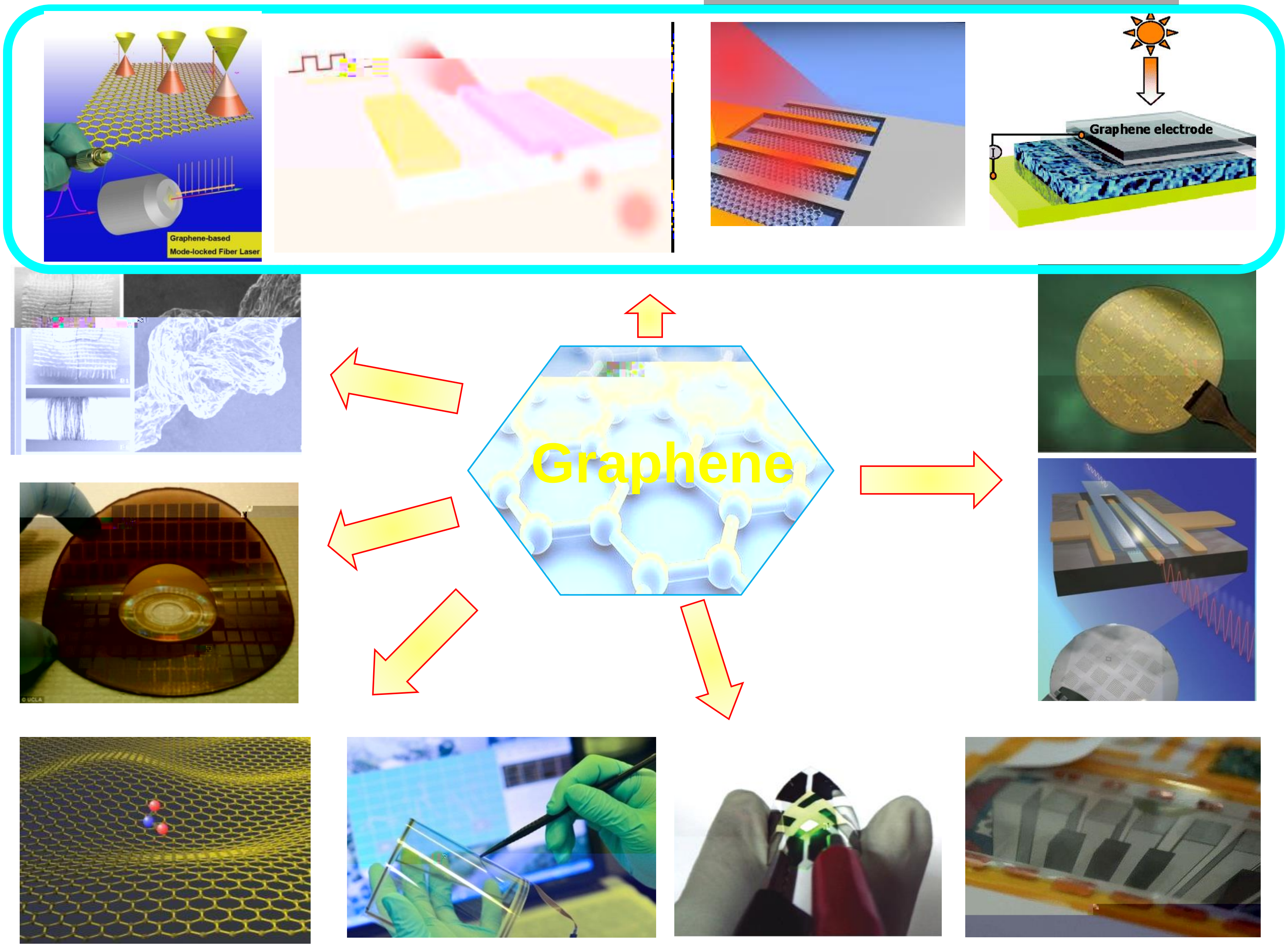




C8-BTBT

Nature Nano. under review

以石墨烯为代表的2D


Graphene-based
Mode-locked Fiber Laser
Graphene electrode
Graphene
© UCLA

A Roadmap for Graphene：光电子学

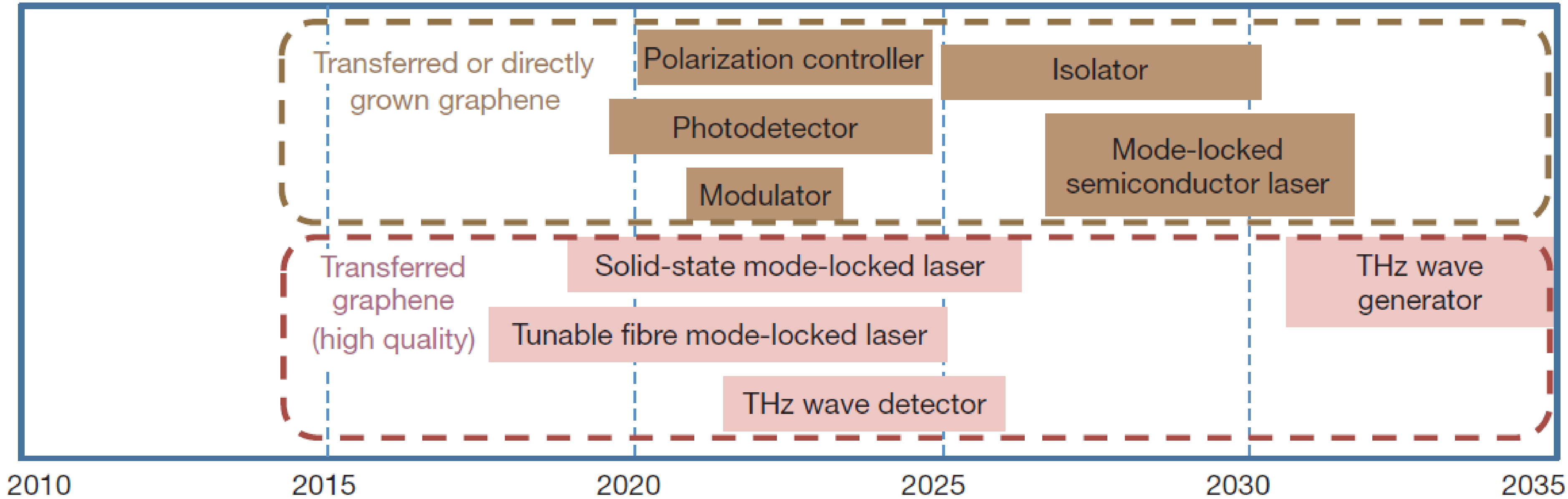


Table 3 | Photonic applications for graphene

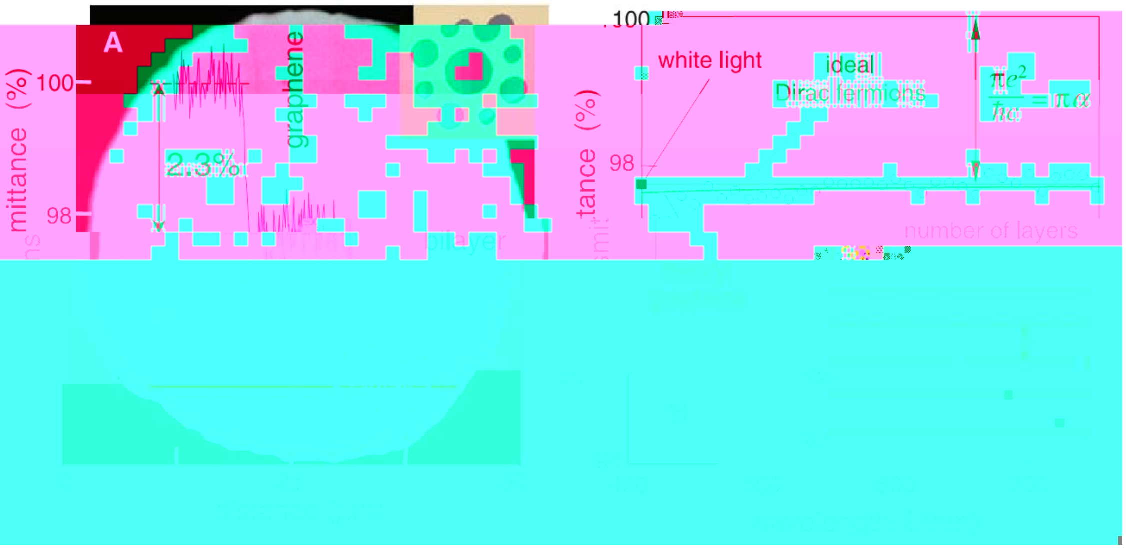
Application	Drivers	Issues to be addressed	
a cost-effective graphene-transferring technology	Solid-state mode-locked laser	Graphene saturable absorber would be cheaper and easy to integrate into the laser system	Requires
ncrease responsivity, which might require a ture and/or doping control, and the modulator h must follow suit	Photodetector	Graphene can supply bandwidth per wavelength of 640 GHz for chip-to-chip or intrachip communications (not possible with IV or III–V detectors)	Need to i new-struc bandwidt
ain full control of parameters of high-quality	Polarization controller	Current polarization controlling devices are bulky or difficult to integrate but graphene is compact and easy to integrate with Si	Need to g graphene
ty graphene with low sheet resistance is [illegible]	Optical modulator	Graphene could increase operating speed (Si operation [illegible] needed to increase bandwidth to over 100 GHz [illegible] the use of complicated III–V epitaxial growth or [illegible]	High-quali
act isolators tion	Decreasing magnetic field strength and optimization of process architecture are important for the products	Isolator	Graphene can provide both integrated and comp on a Si substrate, dramatically aiding miniaturiza
ease requires nterconnect	Competing technologies are actively mode-locked semiconductor lasers or external mode-lock lasers, but [illegible] interconnect architecture needs to consume low powe	Passively mode-locked semiconductor laser	Core-to-core and core-to-memory bandwidth incr a dense wavelength-division-multiplexing optical [illegible]

K. S. Novoselov *et al. Nature*, 2012

二维原子晶体材料应用的挑战

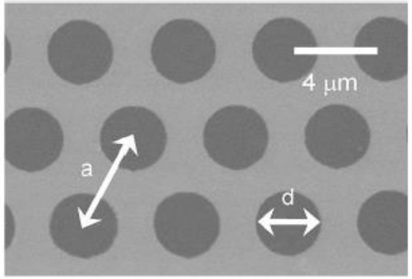
- **MATERIALS:**
  - Complete control: domain size, impurities, defects, number of layers, etc.
  - Low cost: low temperature, substrate re-use, etc.
  - Characterization: comprehensive information in large scale, in situ, high resolution.
- **PROCESSING:**
  - Transfer to arbitrary substrate at low cost without creating defects.
  - Create structures with controlled edge and orientation.
  - Compatibility with Si CMOS process.
- **STRUCTURES:**
  - Passive vs active components.
  - New devices structures that exploit the intrinsic properties of 2D materials is needed.

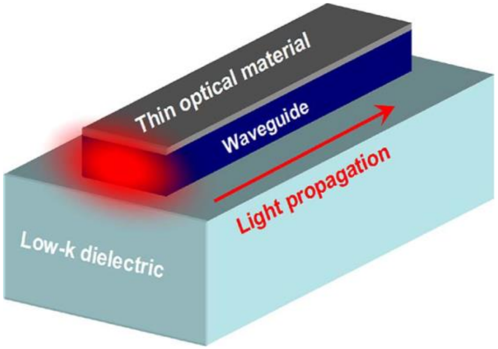
石墨烯与光相互作用特征



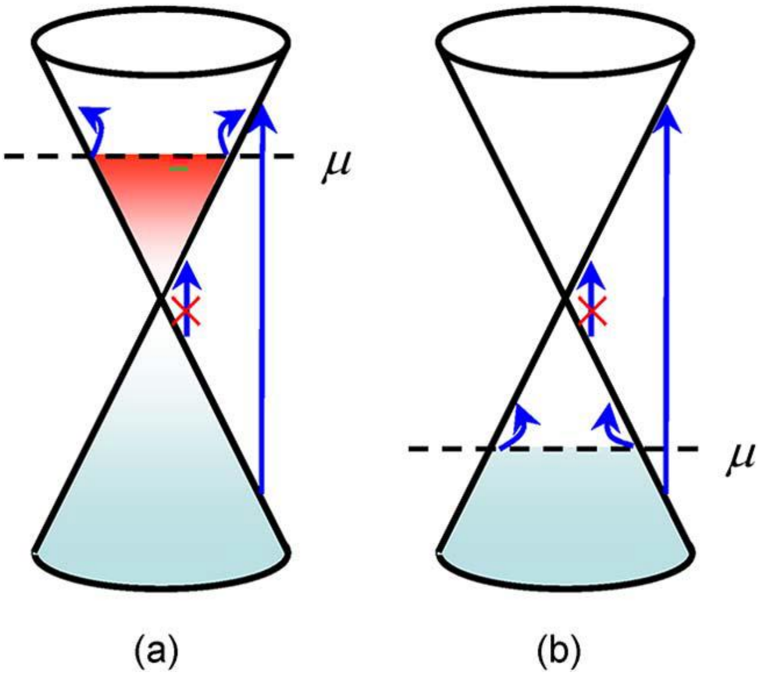
“强”？

强 (~2.3% per layer)



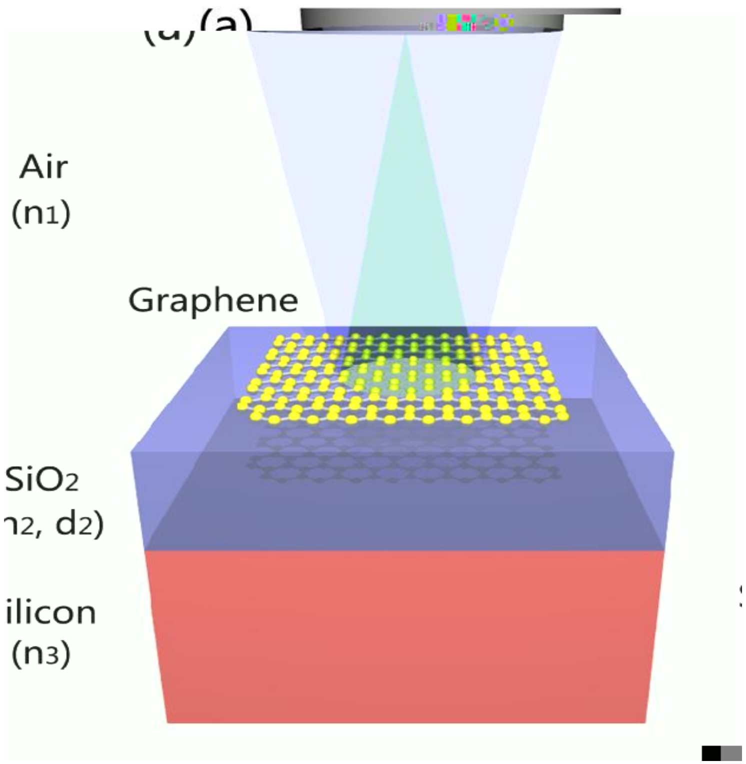


石墨烯与光相互作用特征

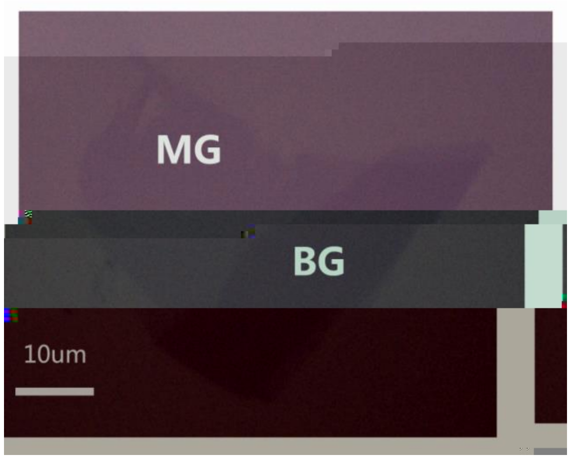


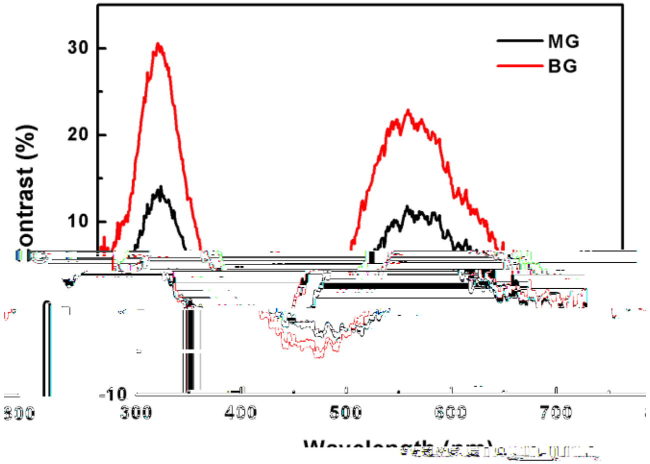
0.4-1.7ps
0.07-0.12ps

石墨烯与光相互作用特征



$$Contrast = \frac{R_{substrate} - R_{graphene}}{R_{substrate}}$$





Z.Fei, Phys. Rev. B (2008)

石墨烯与光相互作用特征

A

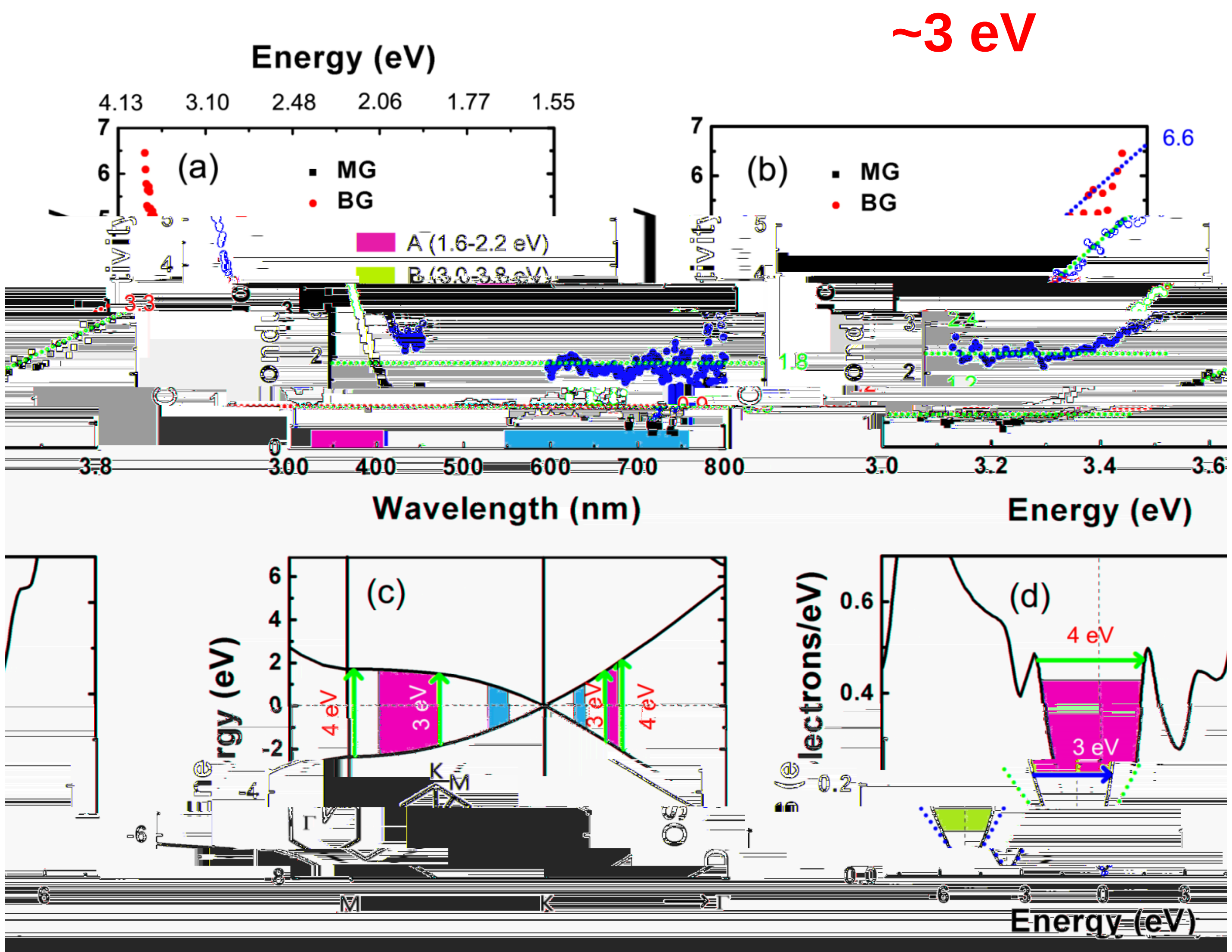
恒定的光电导

狄拉克色散关系
线形的态密度

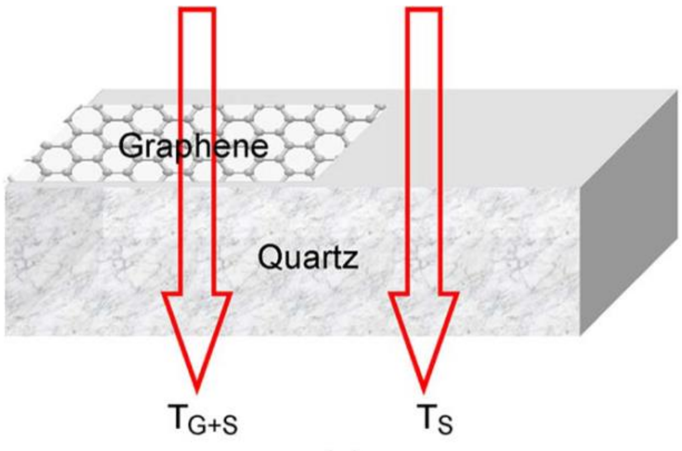
B

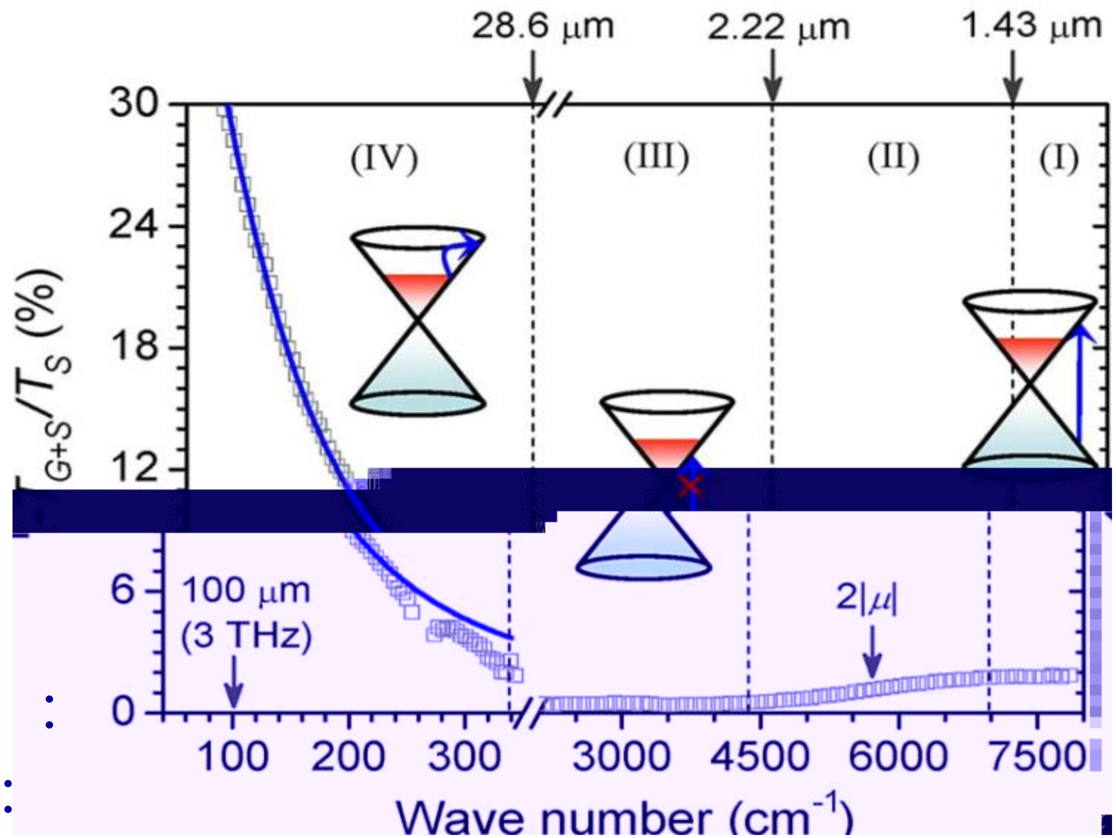
高速增长光电导

平的色散关系
快速增长的态密度



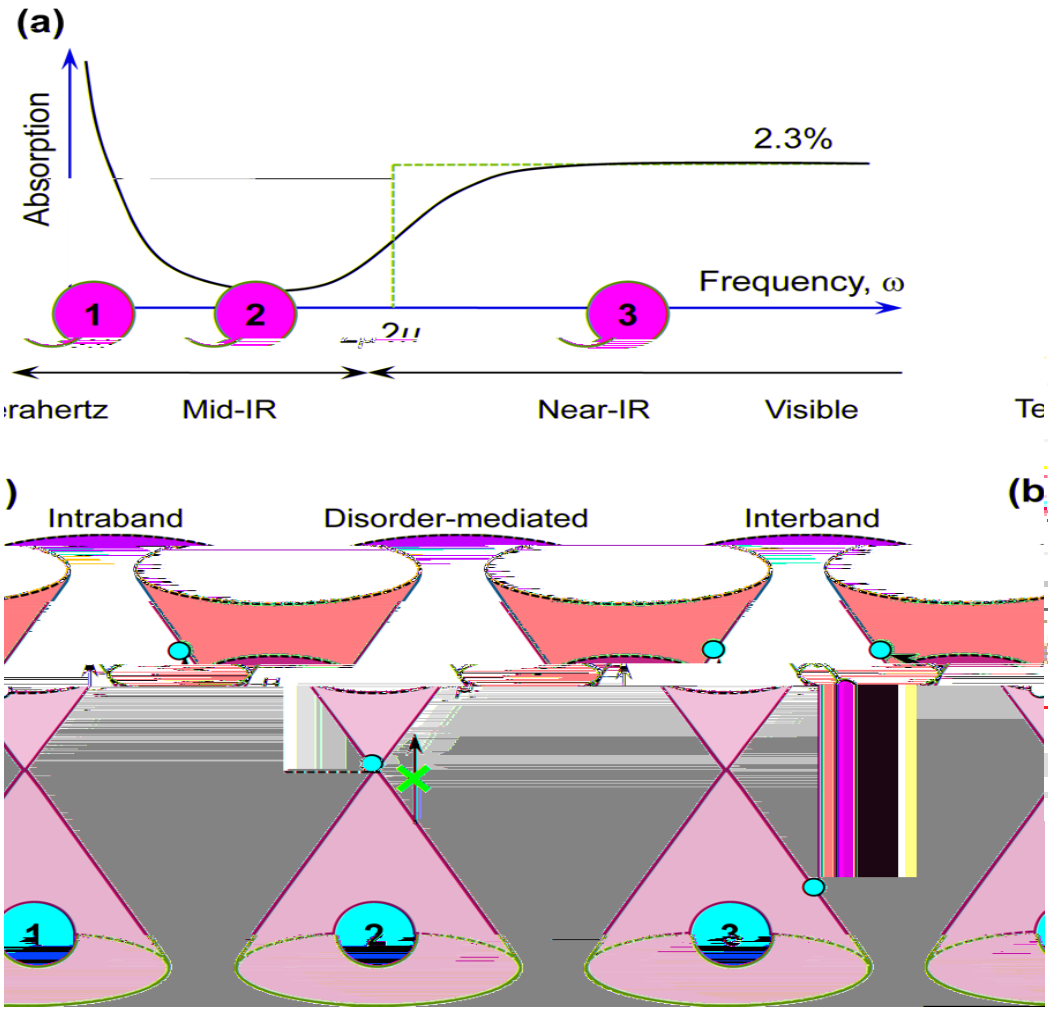
石墨烯与光相互作用特征

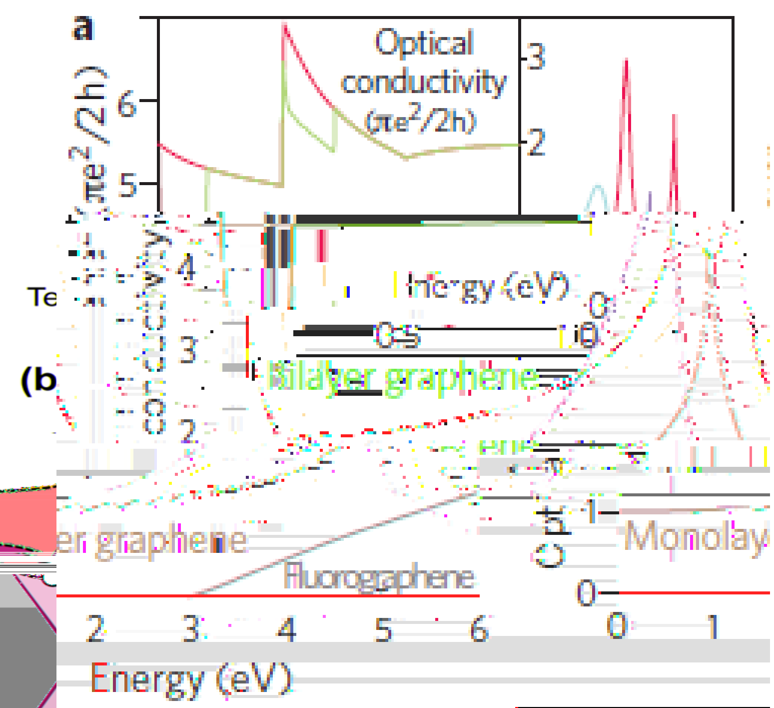




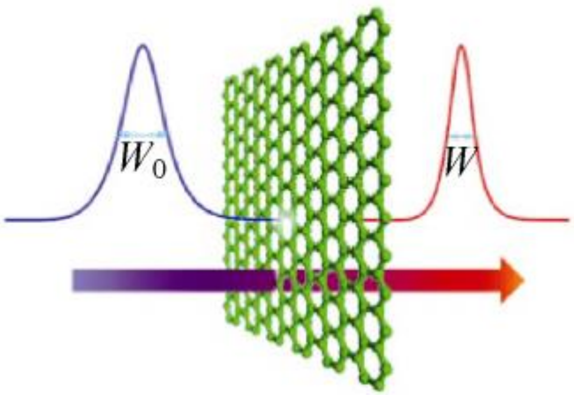
(:

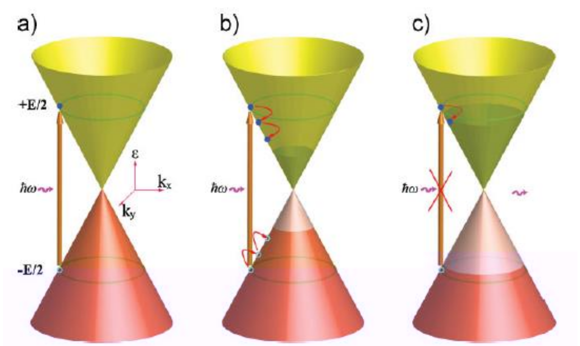
石墨烯与光相互作用特征



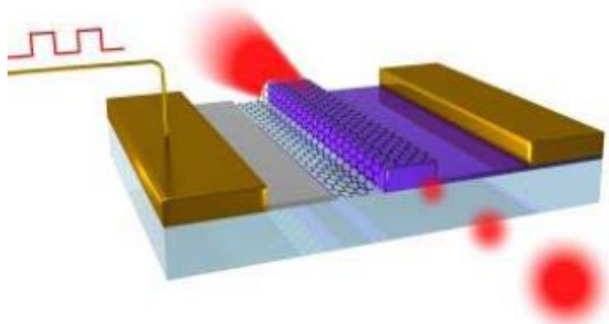


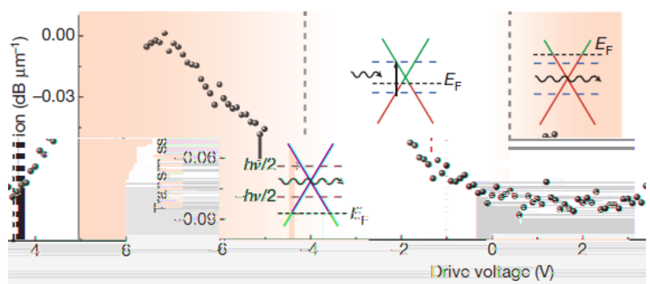
主要光电子器件



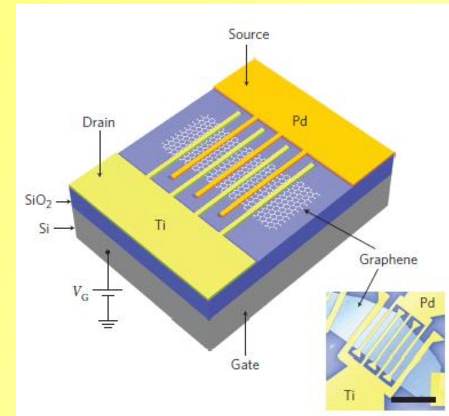


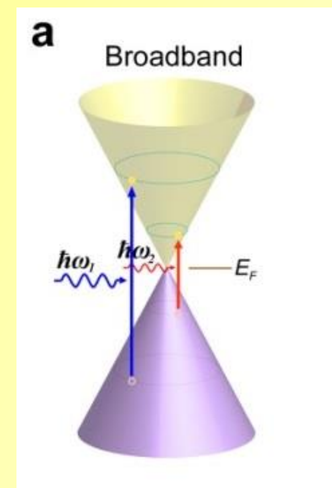
Adv Mater 19   (2009)





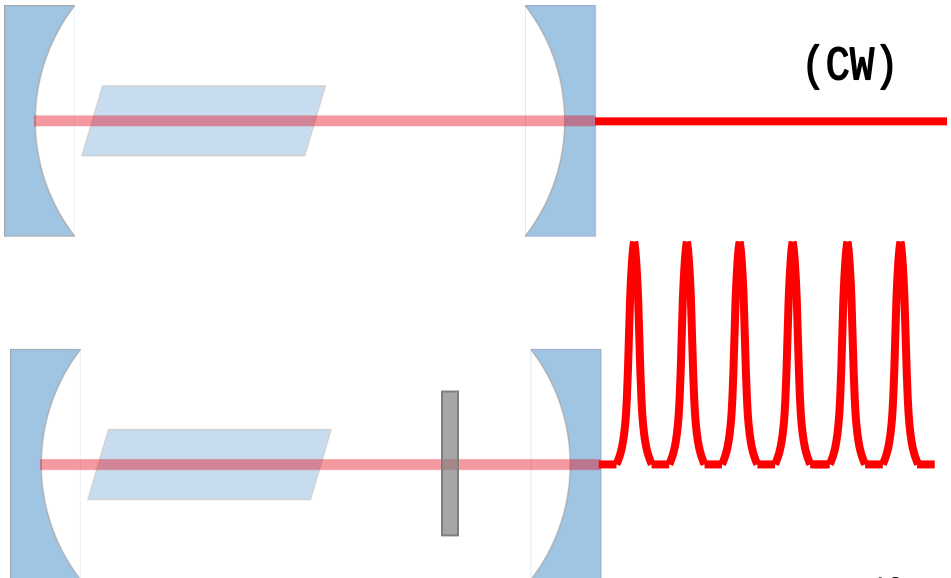
Nature 474, (2011)



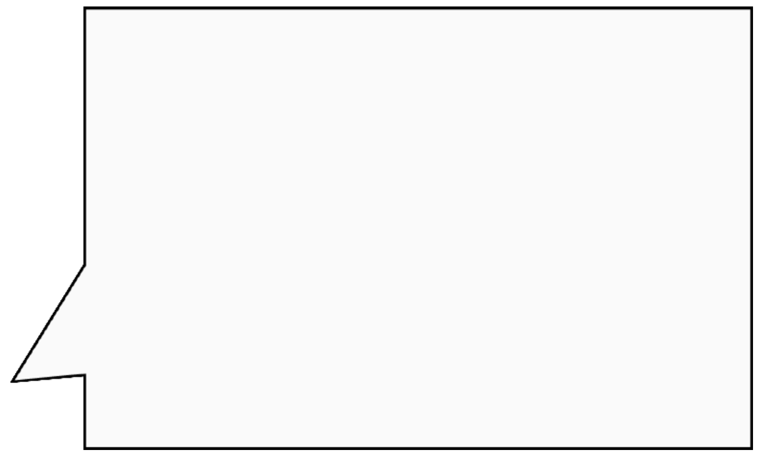


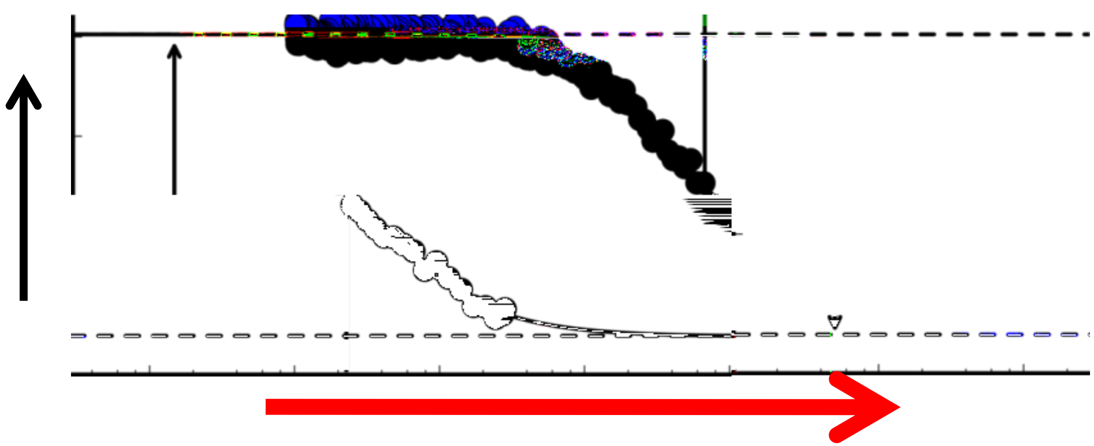
Nat Photonics 4, (2010)

石墨烯的可饱和吸收与激光锁模



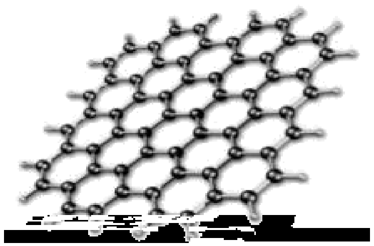
<1 = 10^{-12}

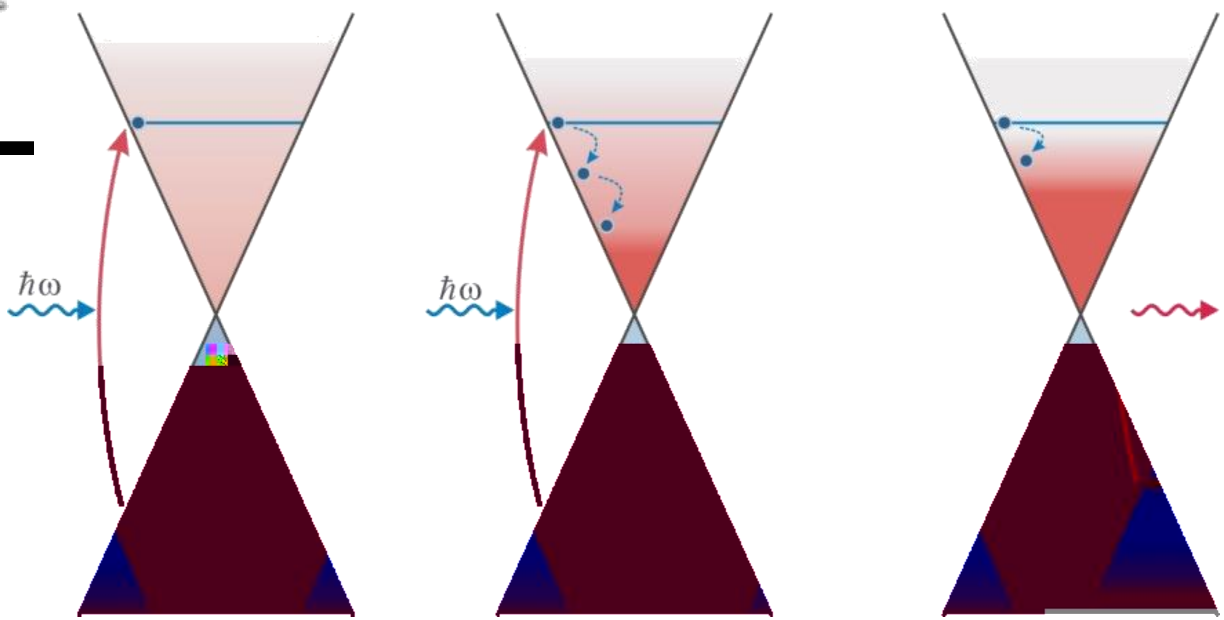




$$\alpha = \alpha_{ns} + \frac{\alpha_0}{1 + I / I_{sat}}$$

石墨烯的可饱和吸收与激光锁模





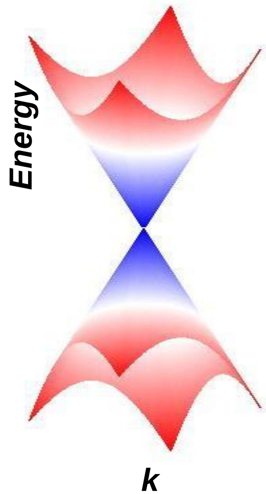
'

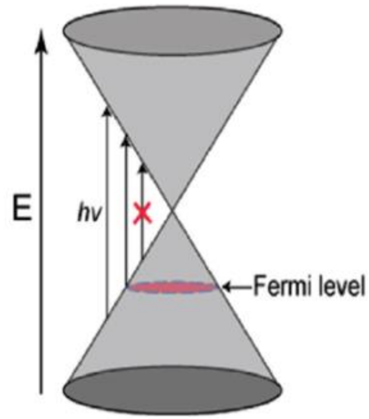
(Relaxation time) '

'

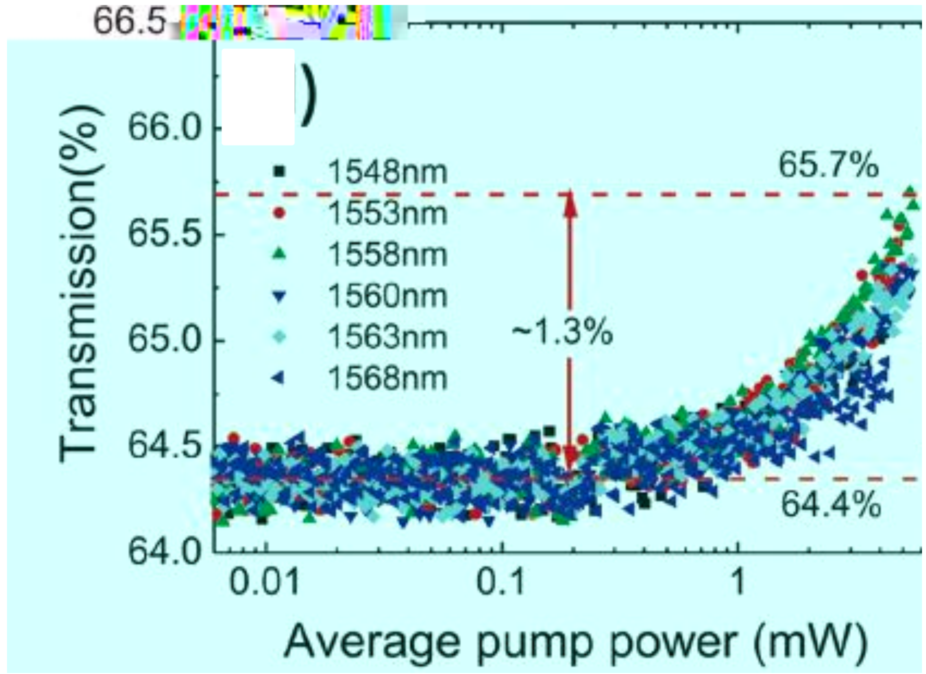
石墨烯的可饱和吸收与激光锁模

UV-to-FIR

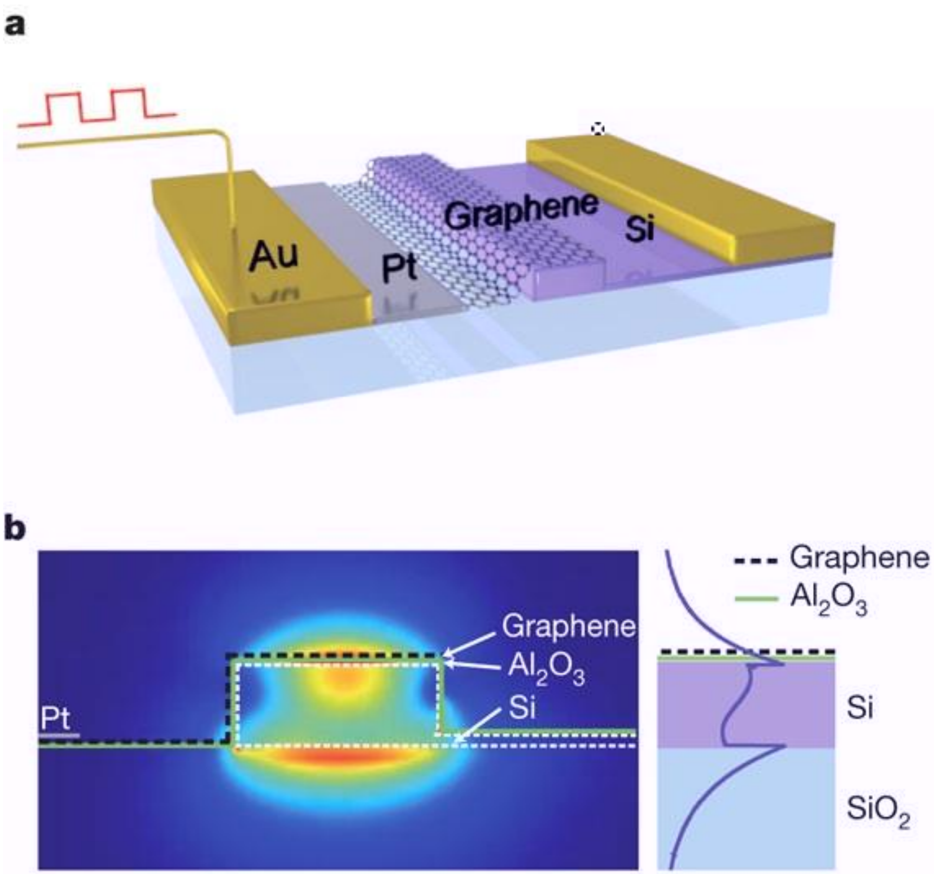


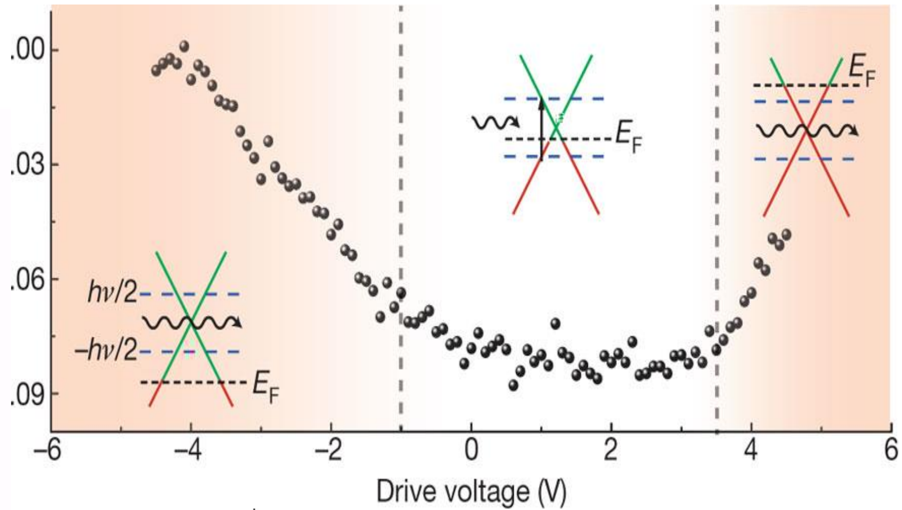


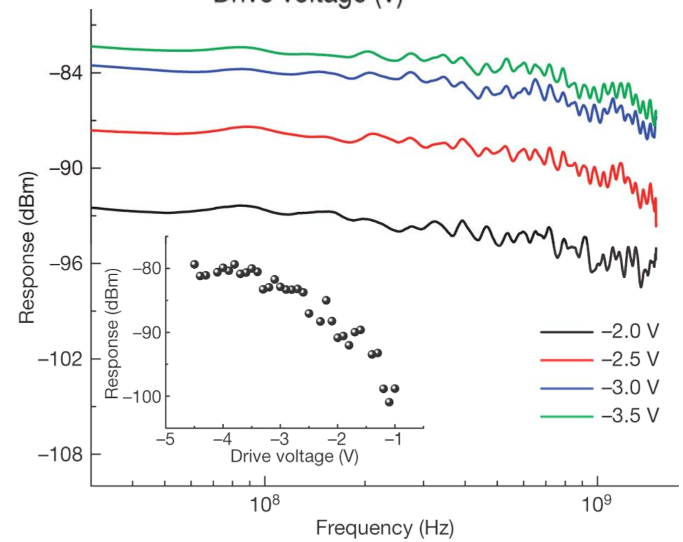
-



基于石墨烯的宽带光调制器

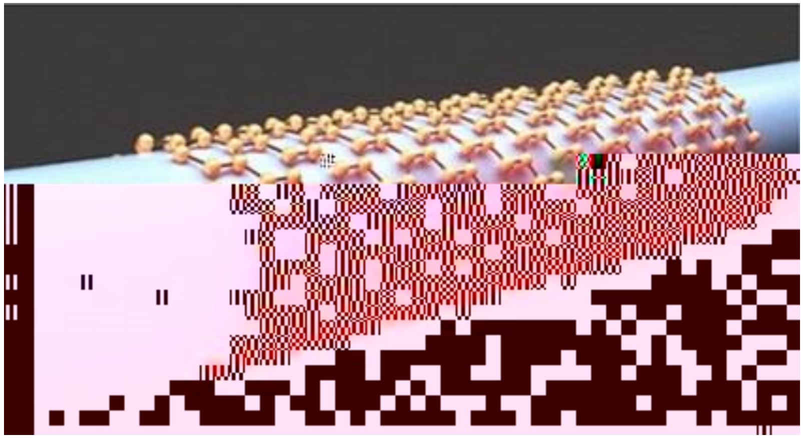


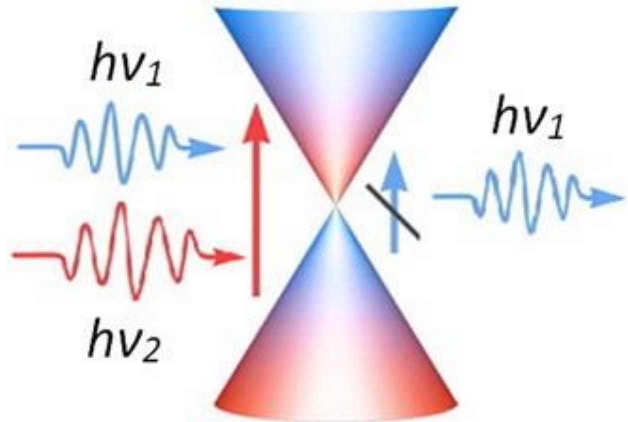


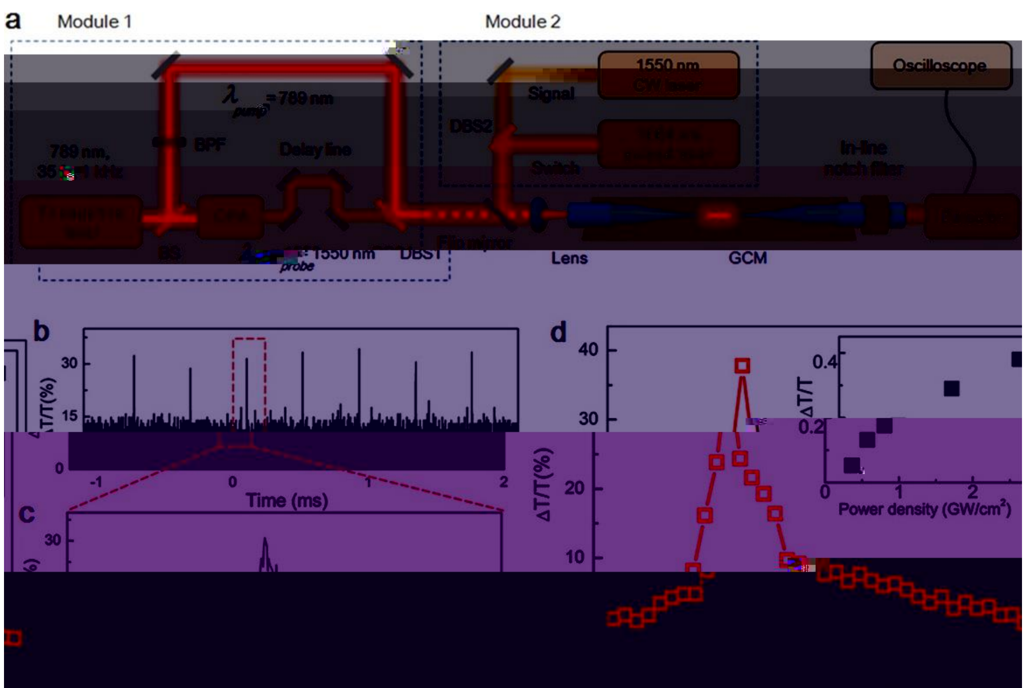


M.Liu, et al. Nature 474,(2011)

基于石墨烯的宽带光调制器

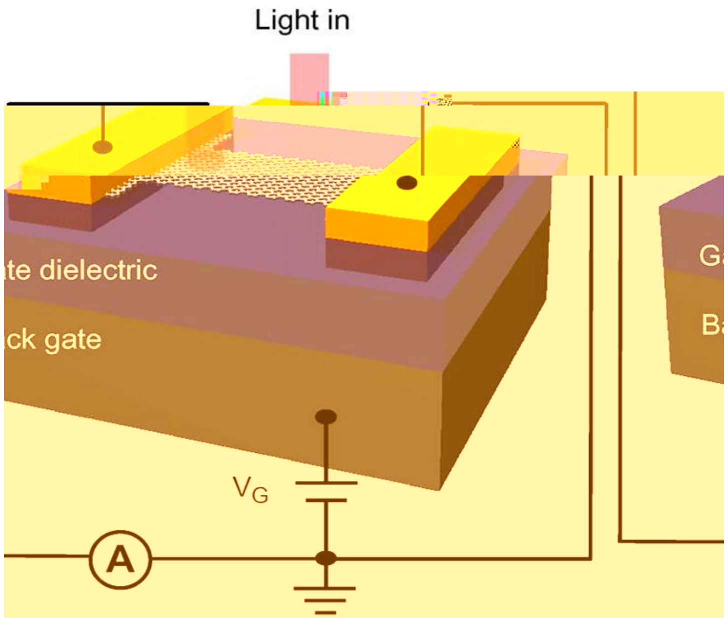


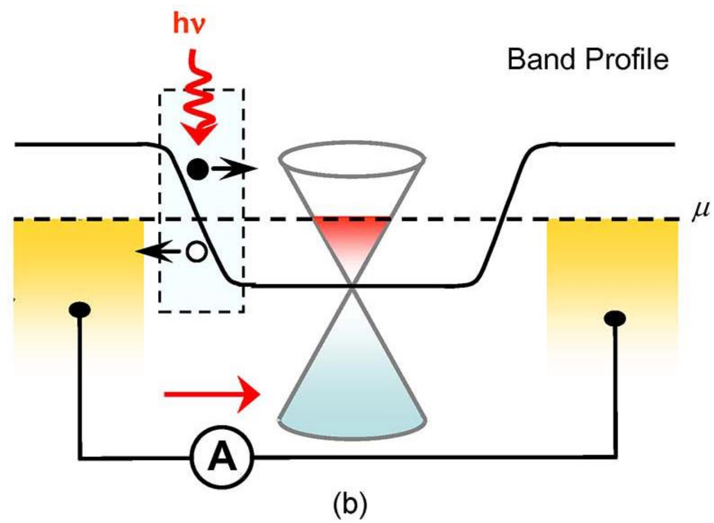




W.Li, et al. Nano Lett. 14,(2014)

基于石墨烯的光探测器

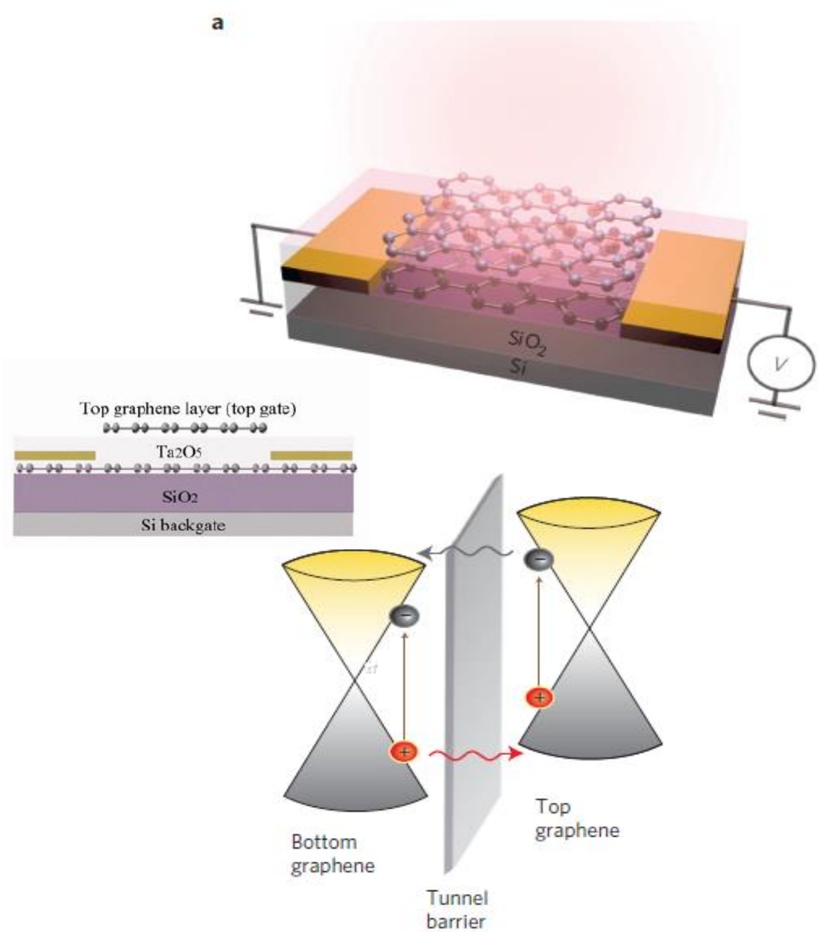


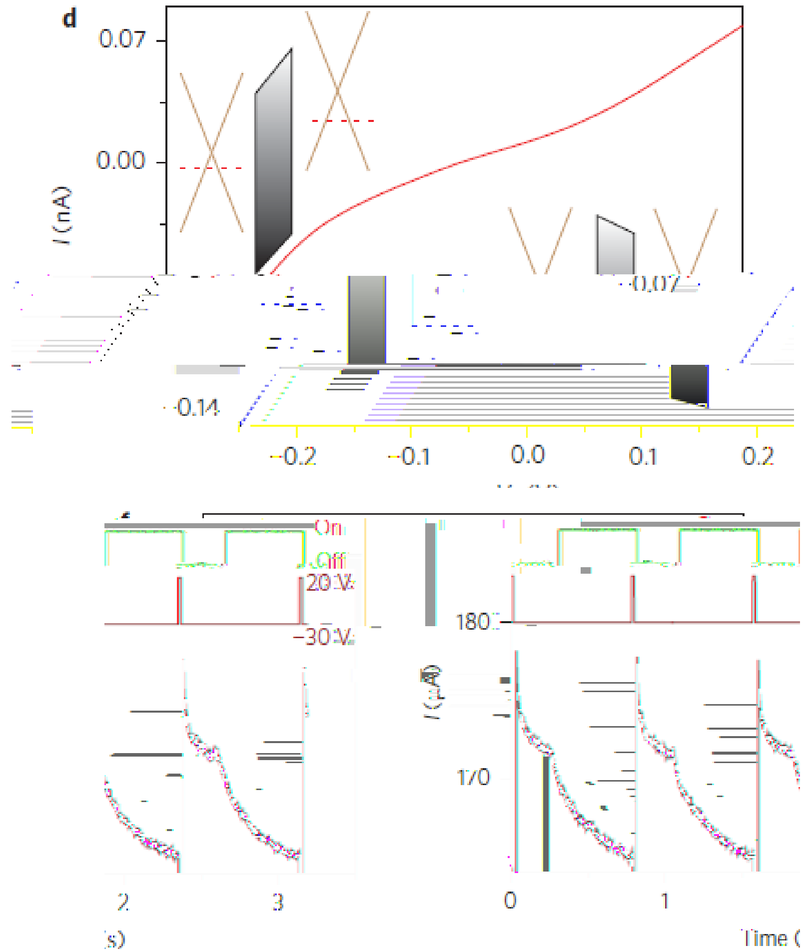


增 (

(

基于石墨烯的光探测器(超带宽）





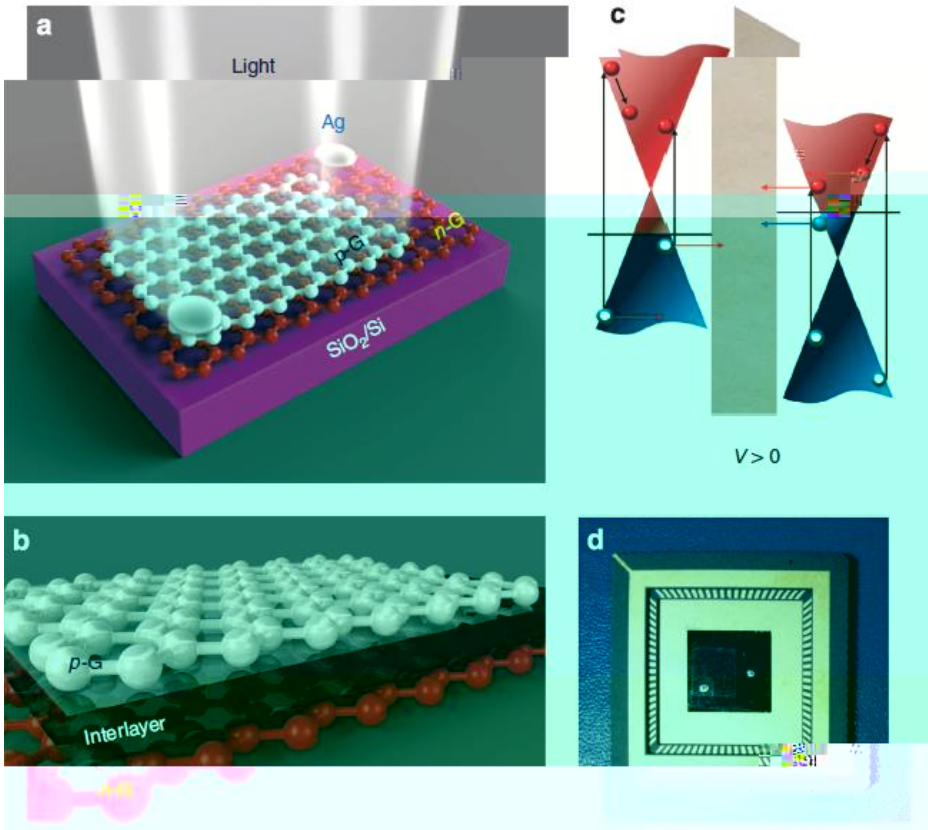
>1A/W

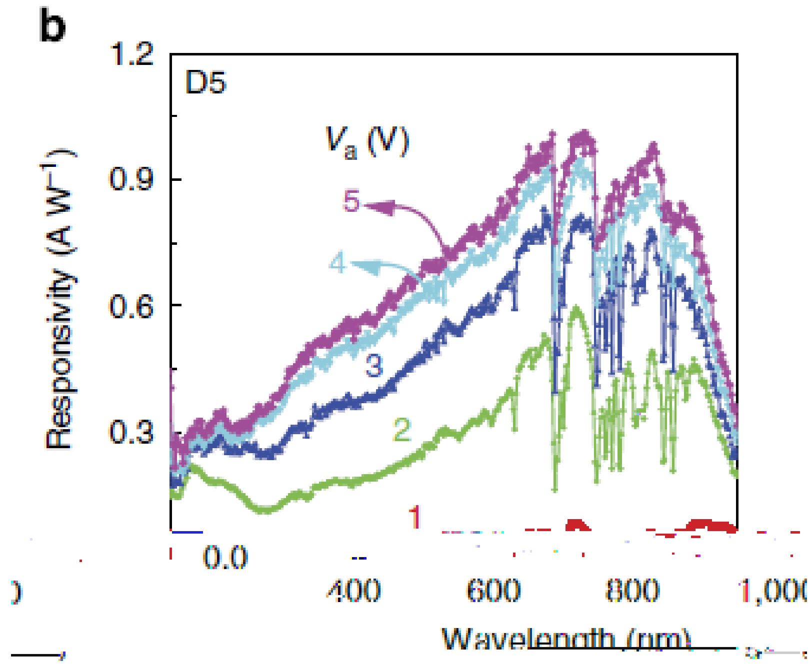
Photogating Effect

C.H..Liu, et al. Nature Nano.,(2014)

基于石墨烯的光探测器(超带宽）

High photoresponsivity in an all-graphene p–n vertical junction photodetector



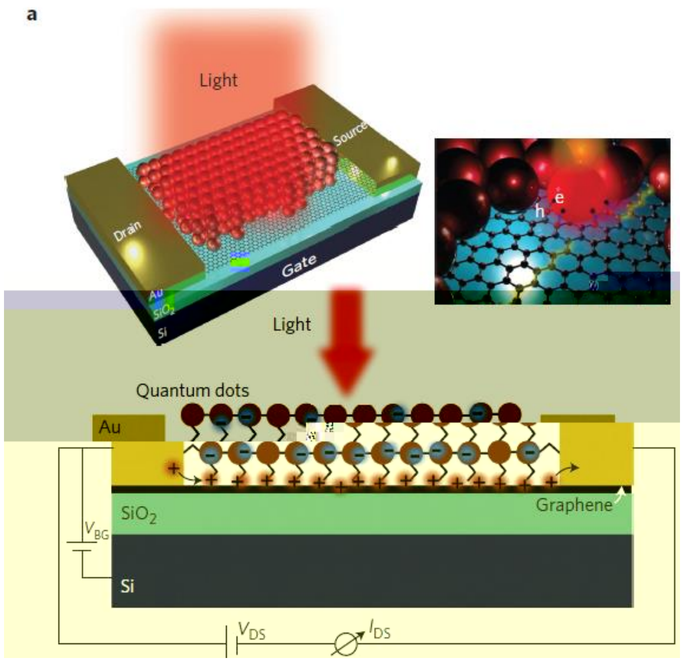


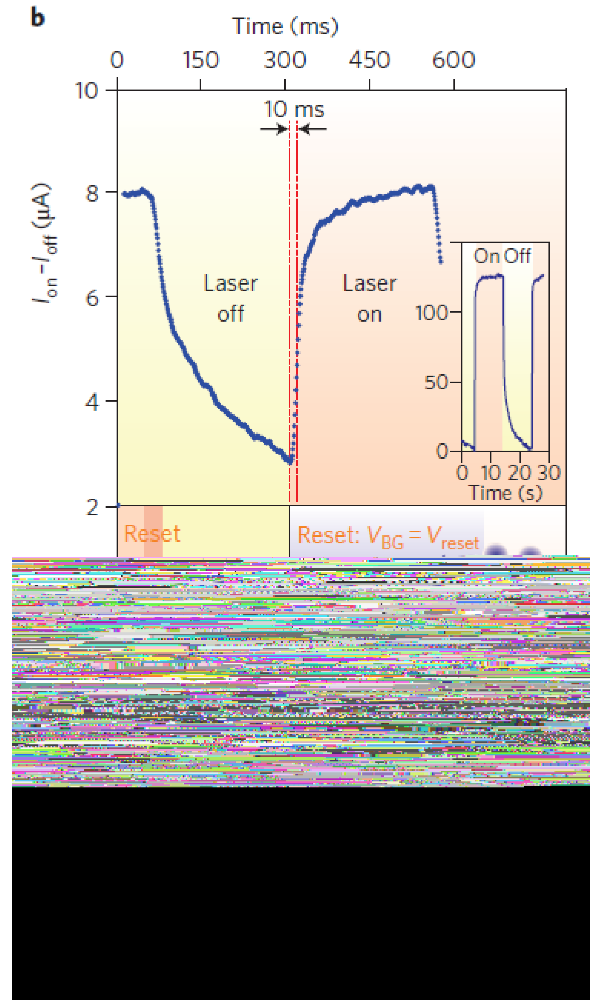
:0.4-1.0A/W

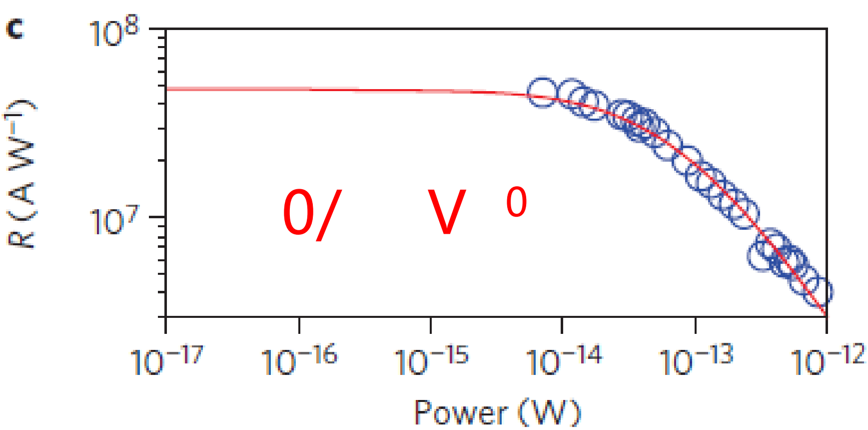
C.O.Kim, et al. Nature comm.,(2014)

基于石墨烯的光探测器（高增益）

PbS





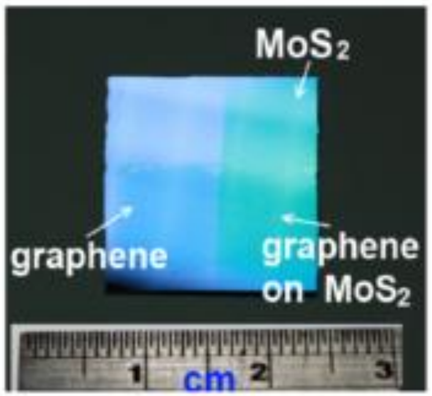


G. Konstantatos, et al. Nature nano (2012)

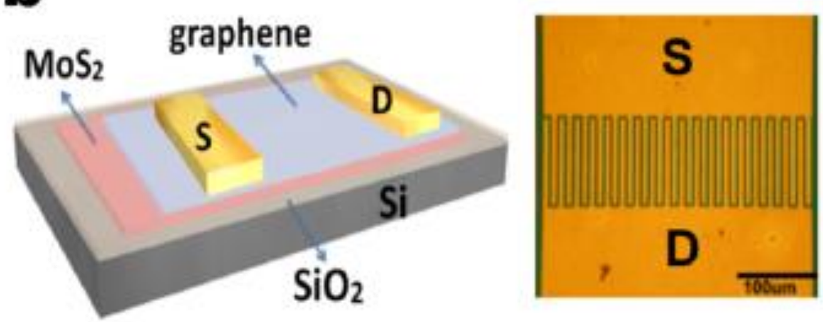
基于石墨烯的光探测器（高增益）

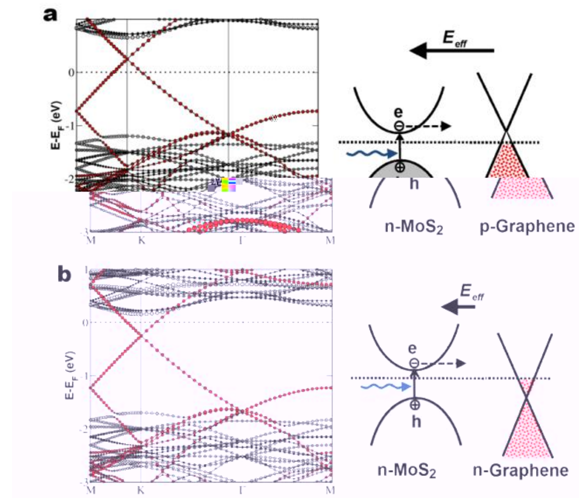
MoS2

a

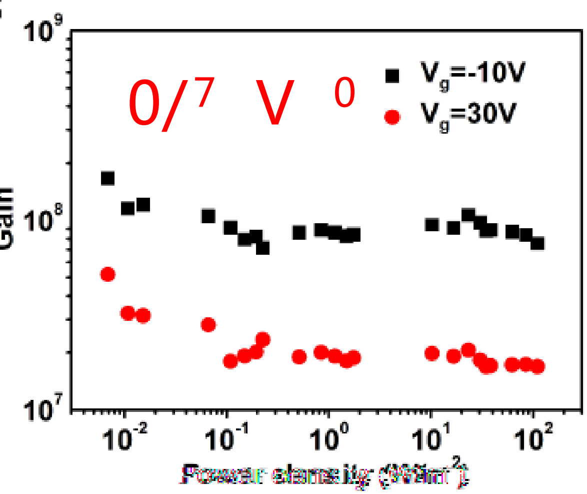


b



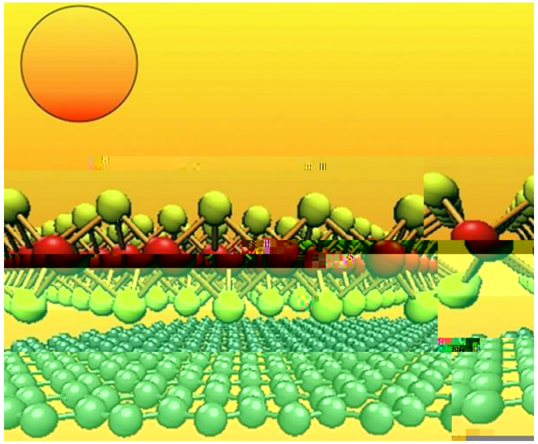


f

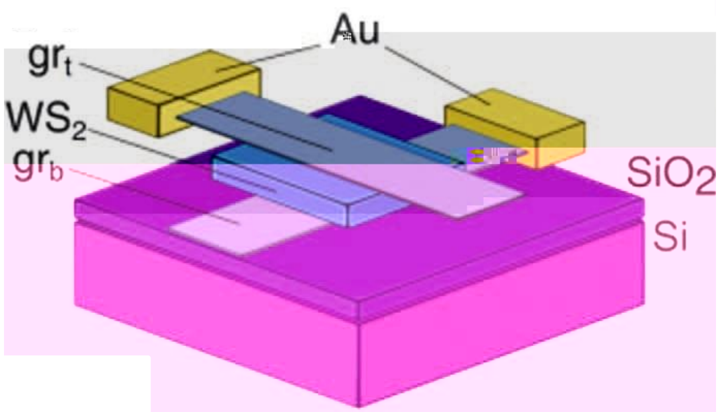


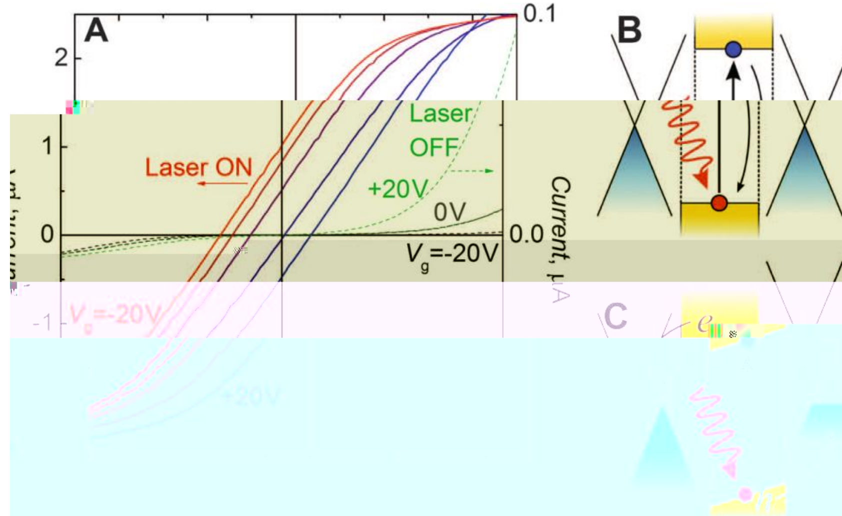
W.J.Zhang, et al. Sci.Rep. (2014)

基于石墨烯的光探测器（高增益）



material	thickness	efficiency	power density (kW/L)
GaAs	1 μm	~29%[38]	290
Si	35 μm	20.6%[39]	5.9
graphene/MoS_2	0.9 nm	0.1−1.0%	1000−10 000
WS_2/MoS_2	1.2 nm	0.4−1.5%	[illegible]3-10 00[illegible]



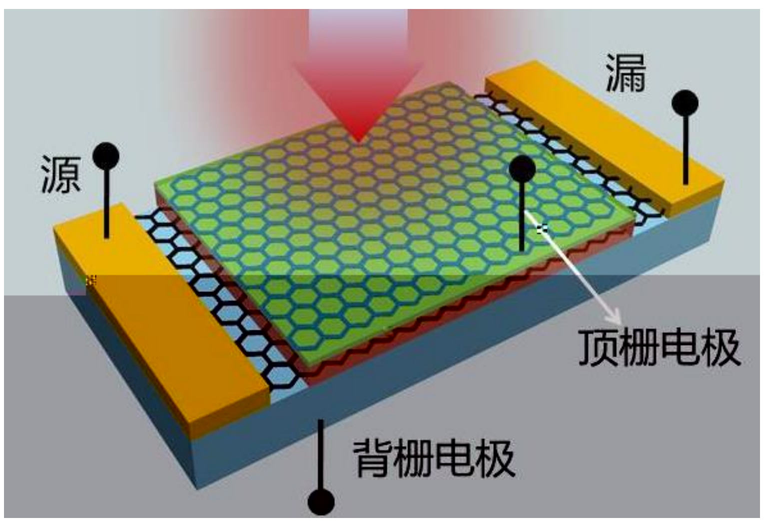


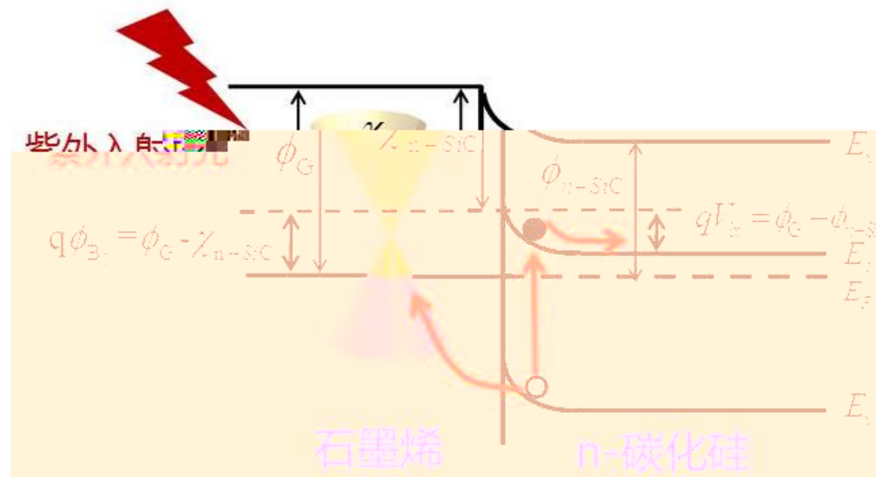
30% EQE achieved due to enhanced light-matter interaction

Bernardi et al. Nano Lett (2013); Britnell et al. Science (2013)

基于石墨烯的光探测器（高增益）

(SAM　Separate Absorption and Multiplication)





基于石墨烯的光探测器（硅基集成）

LETTERS | nature photonics

CMOS-compatible graphene photodetector covering all optical communication bands

LETTERS | nature photonics

PUBLISHED ONLINE: 15 SEPTEMBER 2013 | DOI: 10.1038/NPHOTON.2013.241

High-responsivity graphene/silicon-heterostructure waveguide photodetectors

nature photonics | LETTERS

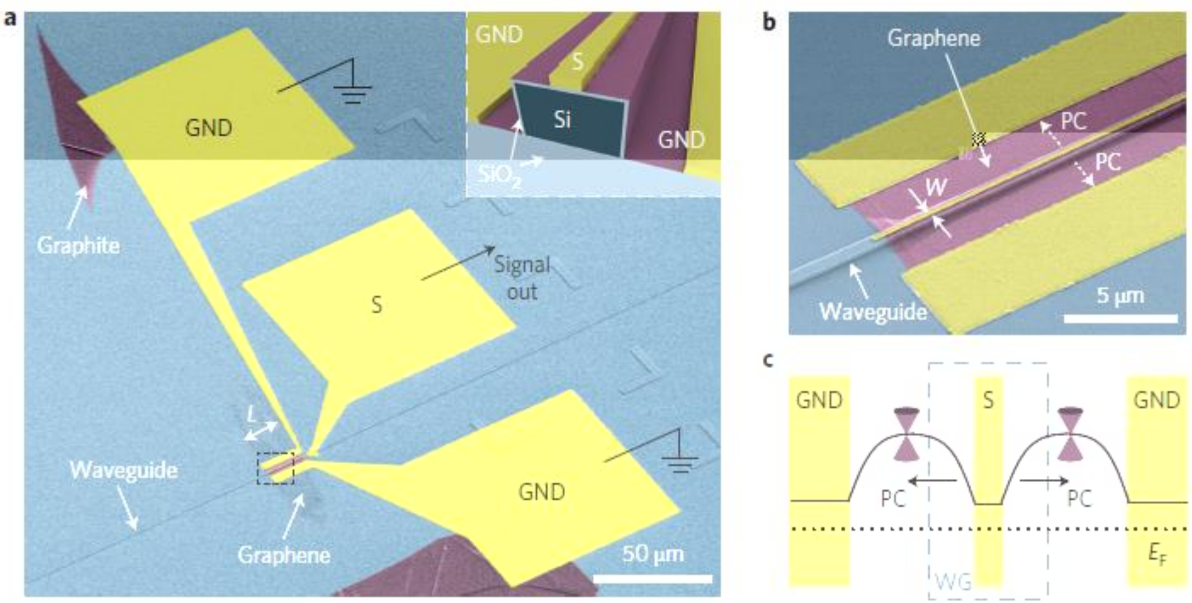
Chip-integrated ultrafast graphene photodetector with high responsivity

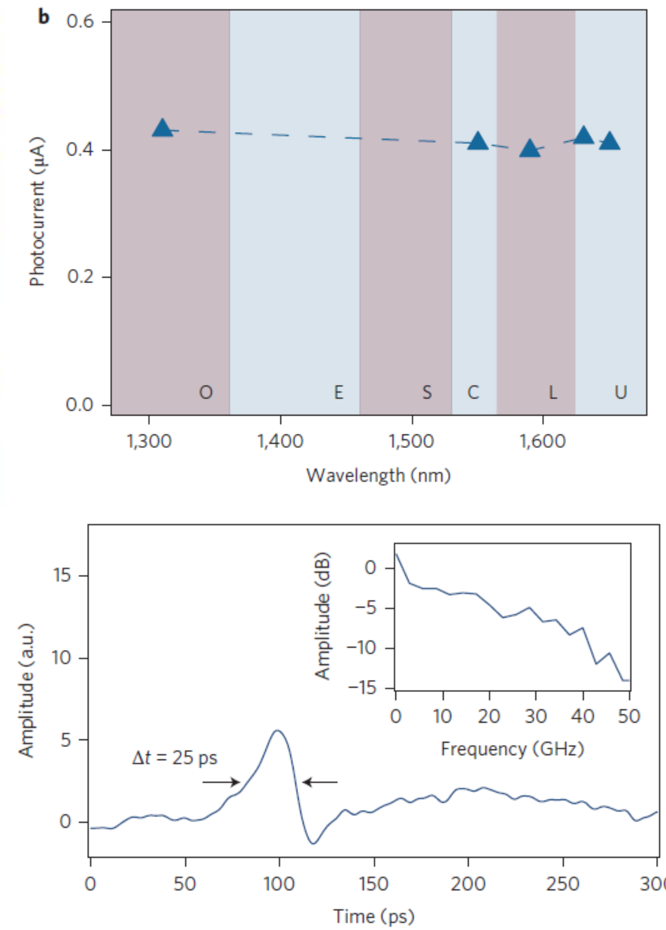
James Hone[3], Solomon Assefa[5] and Dirk Englund[1,2]*

2013 Nature Photonics

基于石墨烯的光探测器（硅基集成）

Chip-integrated ultrafast graphene photodetector with high responsivity



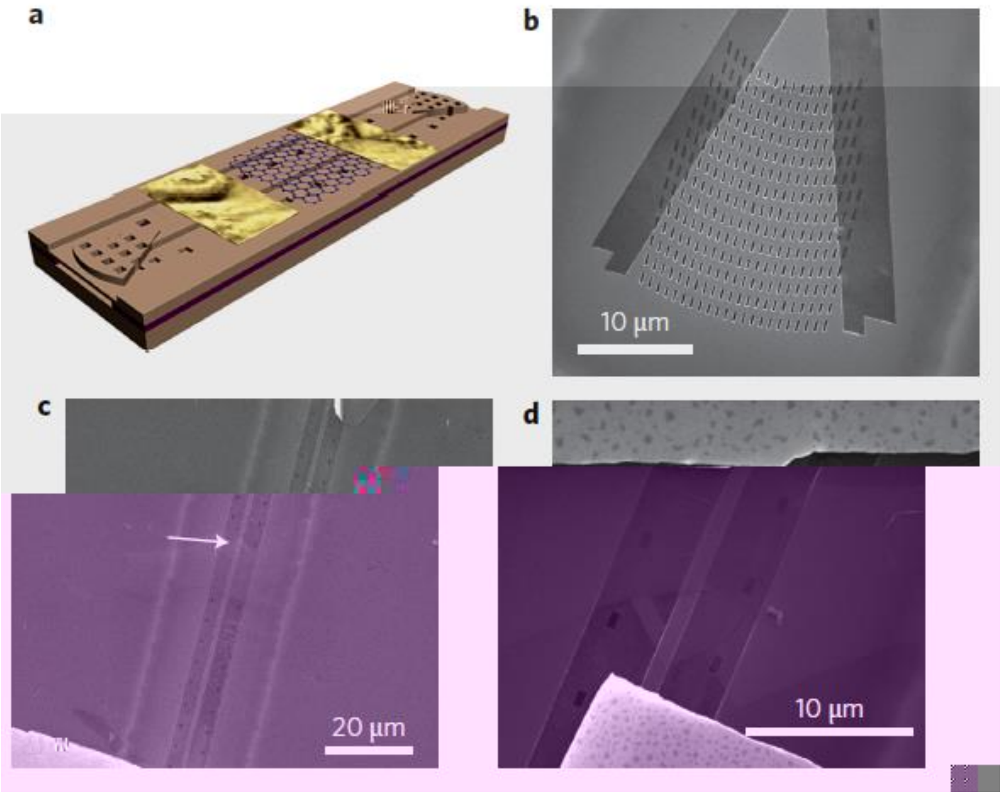


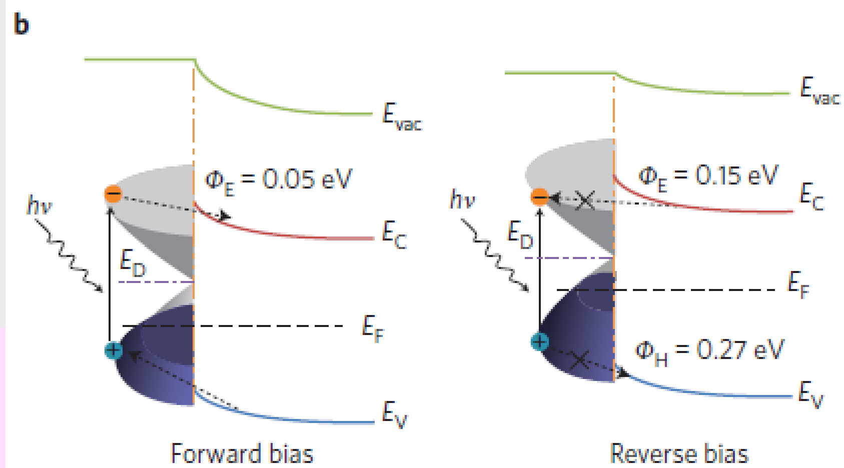
> 20GHz

Gan, X. *et al*. Nature Photon. 7,883 (2013).

基于石墨烯的光探测器（硅基集成）

High-responsivity graphene/silicon-heterostructure waveguide photodetectors



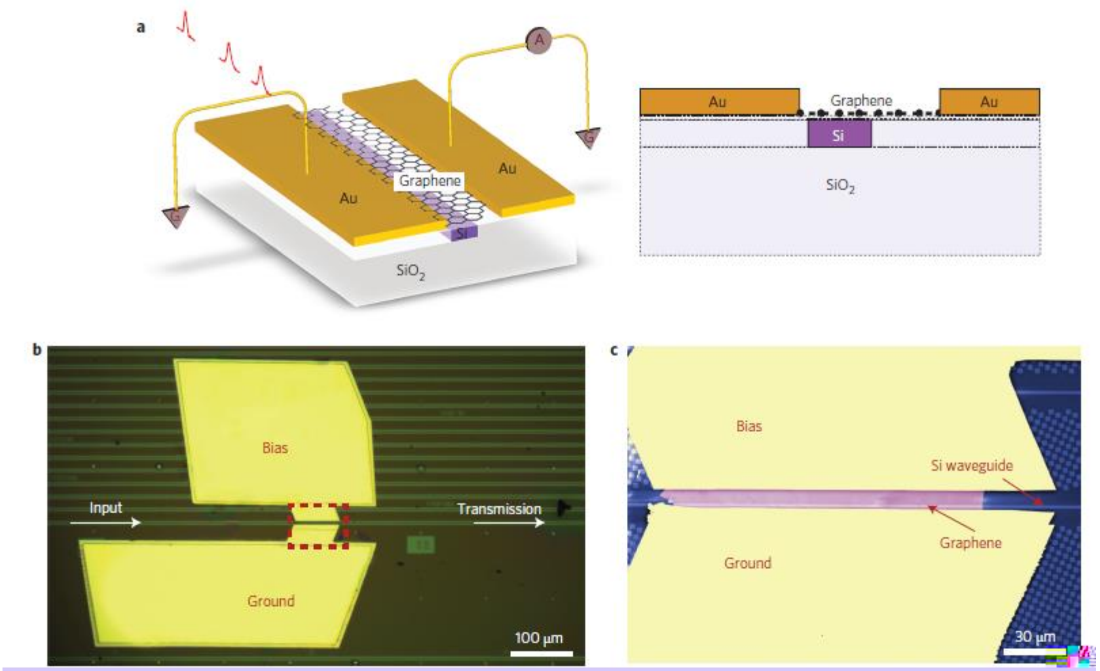


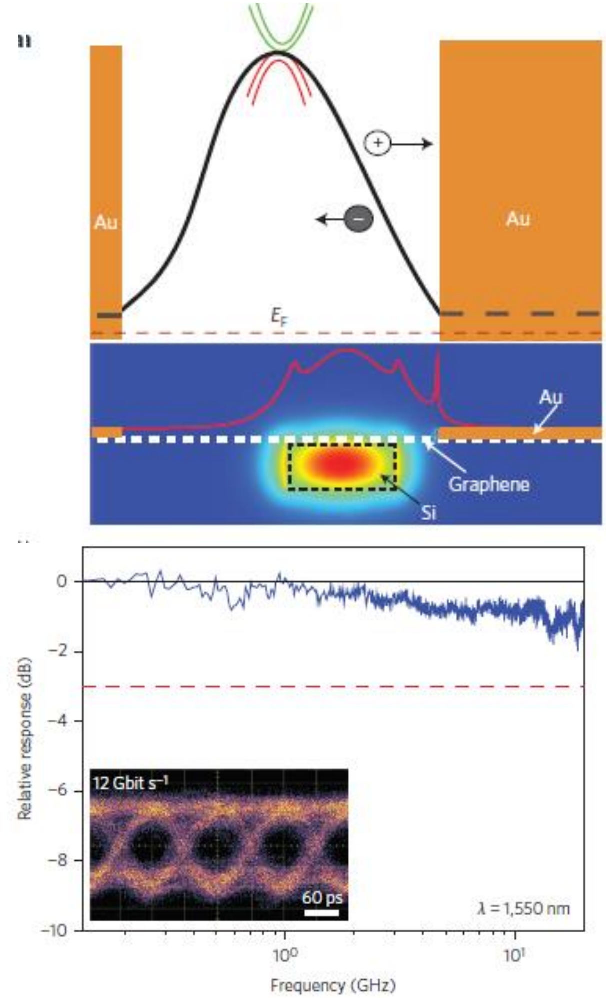
1.2~8um

Wang, X. *et al.* Nature Photon. 7,888 (2013).

基于石墨烯的光探测器（硅基集成）

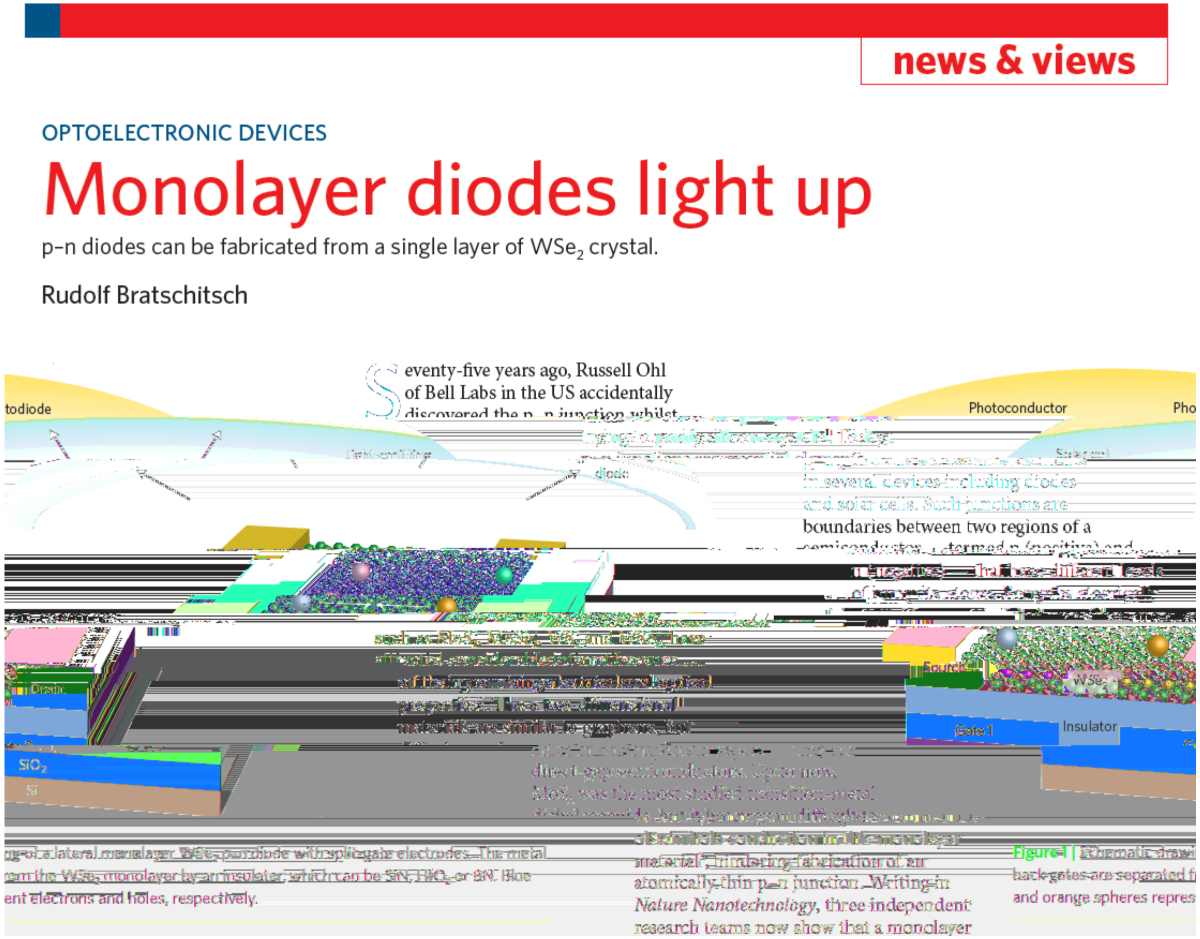
CMOS-compatible graphene photodetector covering all optical communication bands





>20GHz　　0.1A/W

二维原子晶体光发射器件



news & views

OPTOELECTRONIC DEVICES

Monolayer diodes light up

p–n diodes can be fabricated from a single layer of WSe_2 crystal.

Rudolf Bratschitsch

Seventy-five years ago, Russell Ohl of Bell Labs in the US accidentally

boundaries between two regions of a

Nature Nanotechnology, three independent research teams now show that a monolayer

4 Nature Nanotechonlogy PN

二维原子晶体光发射器件

nature nanotechnology
LETTERS

Solar-energy conversion and light emission in an atomic monolayer p–n diode

LETTERS
PUBLISHED ONLINE: 9 MARCH 2014 | DOI: 10.1038/NNANO.2014.25
nature nanotechnology

Optoelectronic devic… tunable p–n diodes i…

…es based on electrically …n a monolayer dichalcogenide

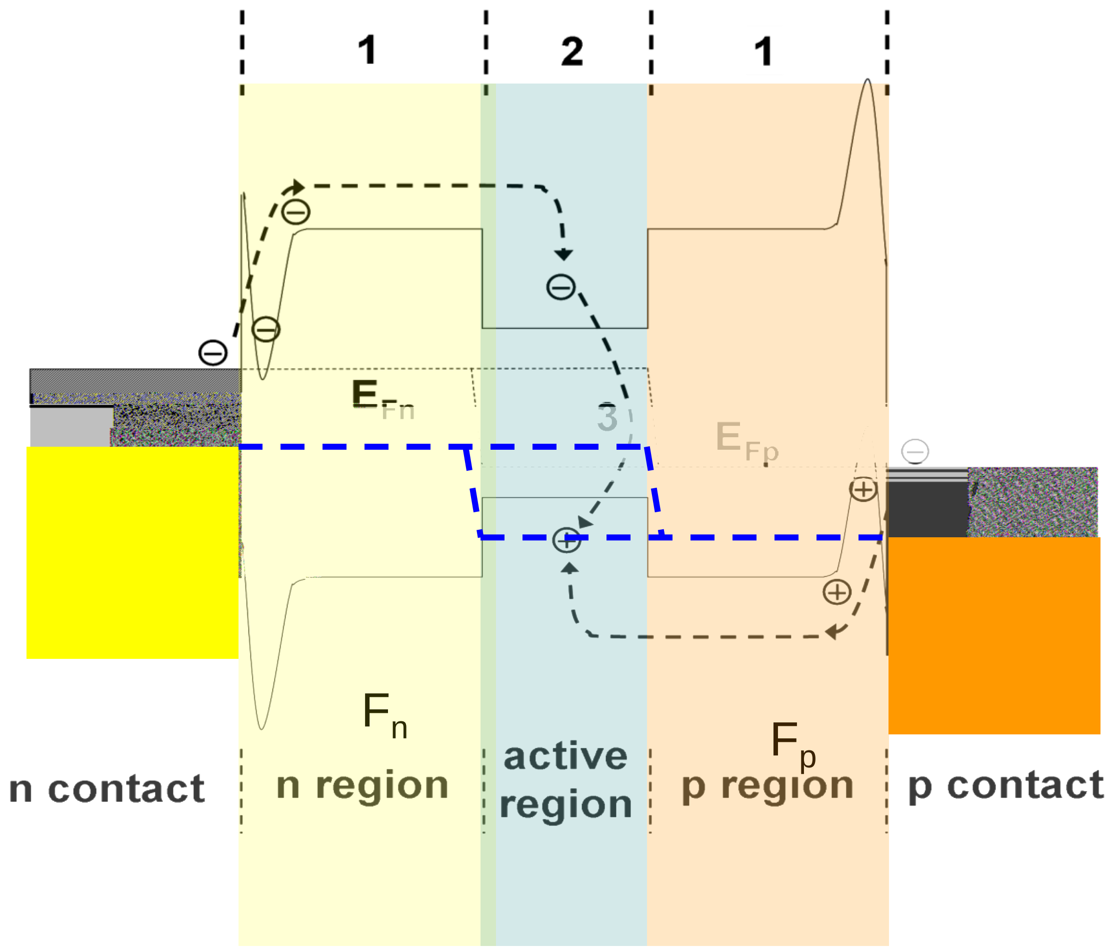
…hill†, Yafar…

LETTERS
PUBLISHED ONLINE: 9 MARCH 2014 | DOI: 10.1038/NNANO.2014.26
nature nanotechnology

Electrically tunable excitonic light-emitting diodes based on monolayer WSe_2 p–n junctions

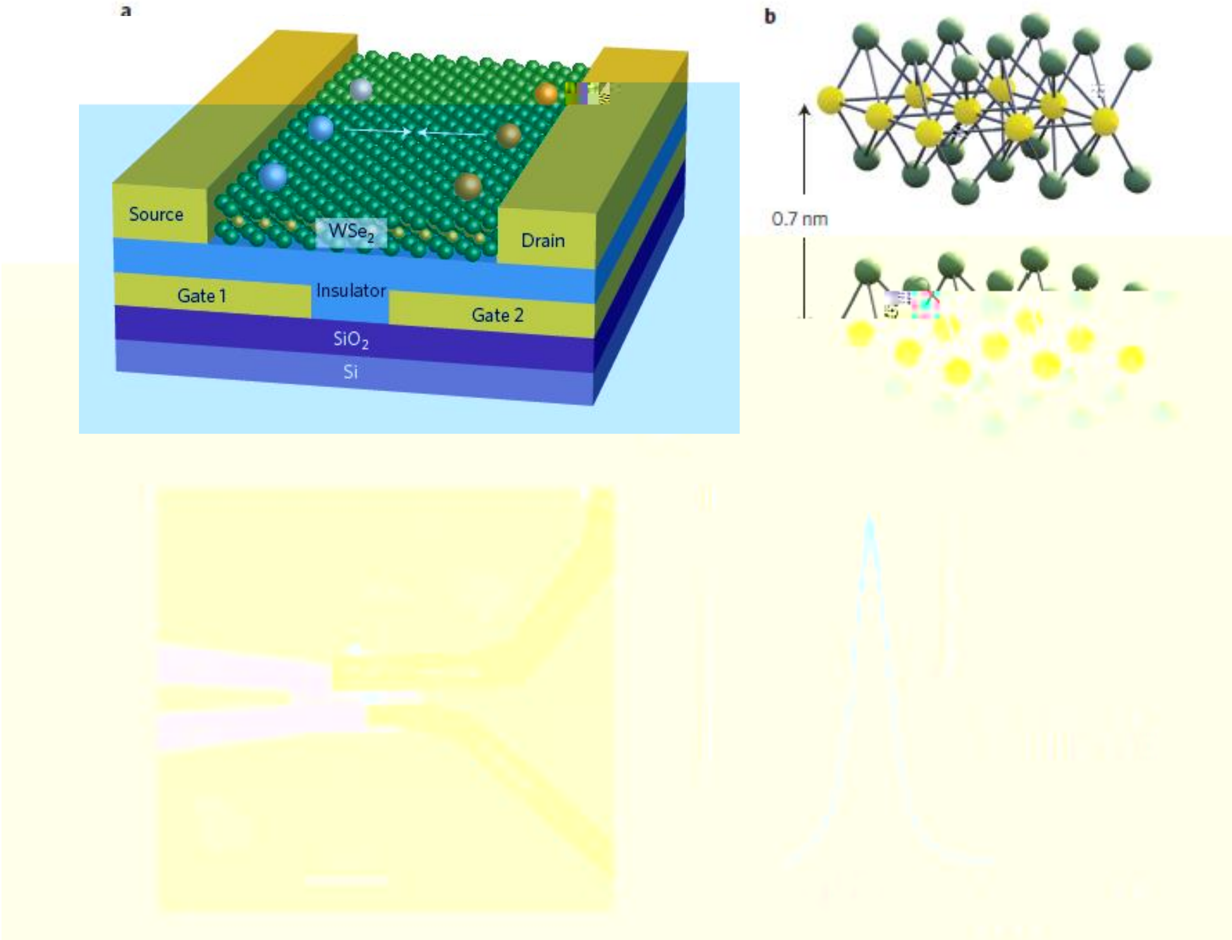
Jason S. Ross, Philip Klement, Aaron M. Jones, Nirmal J. Ghimire, Jiaqiang Yan,
D. G. Mandrus[4,5,6], Takashi Taniguchi[7], Kenji Watanabe[7], Kenji Kitamura[7], Wang Yao[8],
David H. Cobden[2] and Xiaodong Xu[1,2,3]

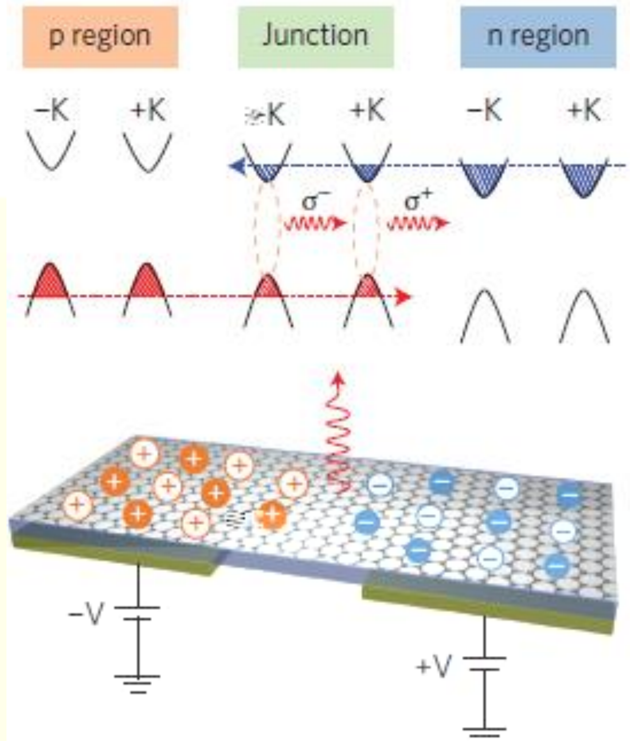
二维原子晶体光发射器件



二维原子晶体光发射器件

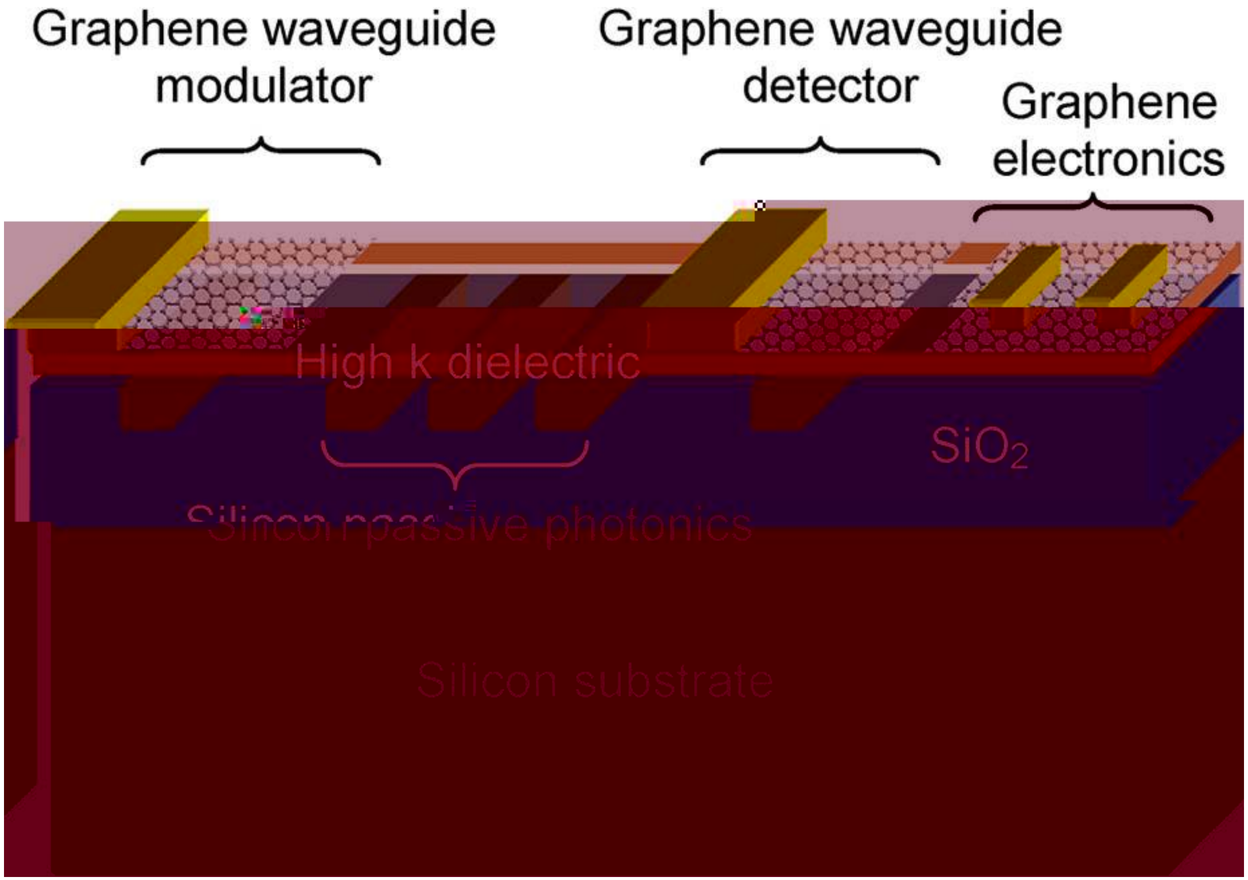
Optoelectronic devices based on electrically tunable p–n diodes in a monolayer dichalcogenide





WSe_2 p-n

展望


Graphene waveguide modulator
Graphene waveguide detector
Graphene electronics
High k dielectric
SiO2
Silicon passive photonics
Silicon substrate

/

展 望

K.S.Novoselov A.K.Geim

2D materials are promising system for optoelectronic applications.

Graphene based hybrid is believed to improve its optoelectronic performance.

The interactions between the materials in hybrid structures are important and deserved detail investigation.

谢谢大家！