WYDZIAŁ FIZYKI
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UNIVERSITAS VARSOVIENSIS

Electronic and optical properties of graphene and other 2D materials

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University of Warsaw

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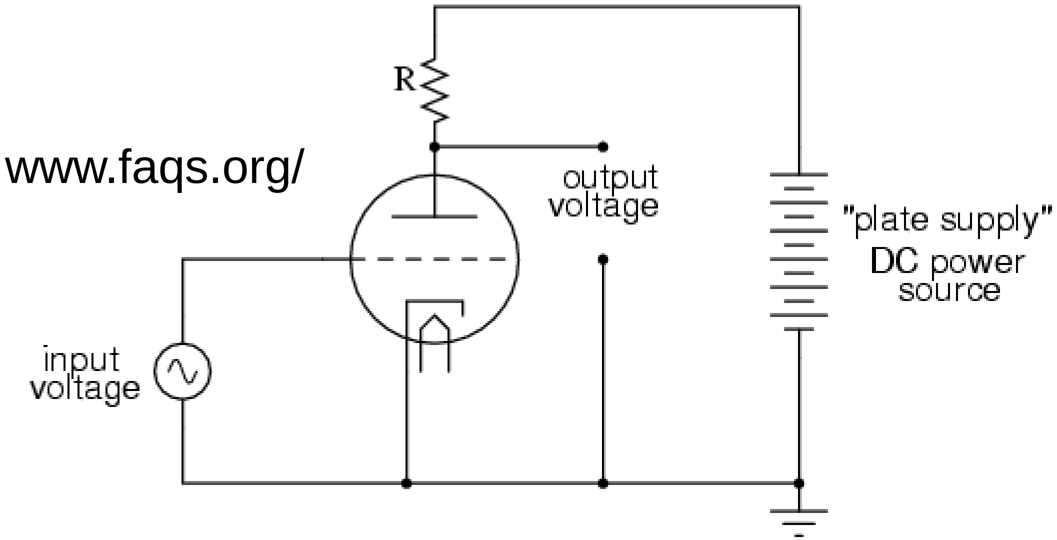
Vacuum electron tubes

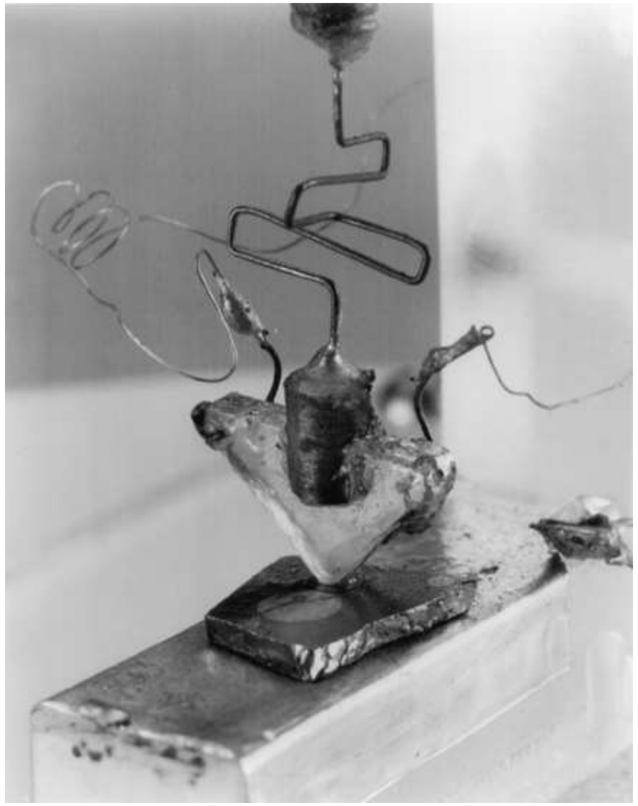
Triode amplifier circuit

www.faqs.org/



First transistor…

Julius Edgar Lilienfeld (born in Lwów) – field effect transistor Canada, 1925

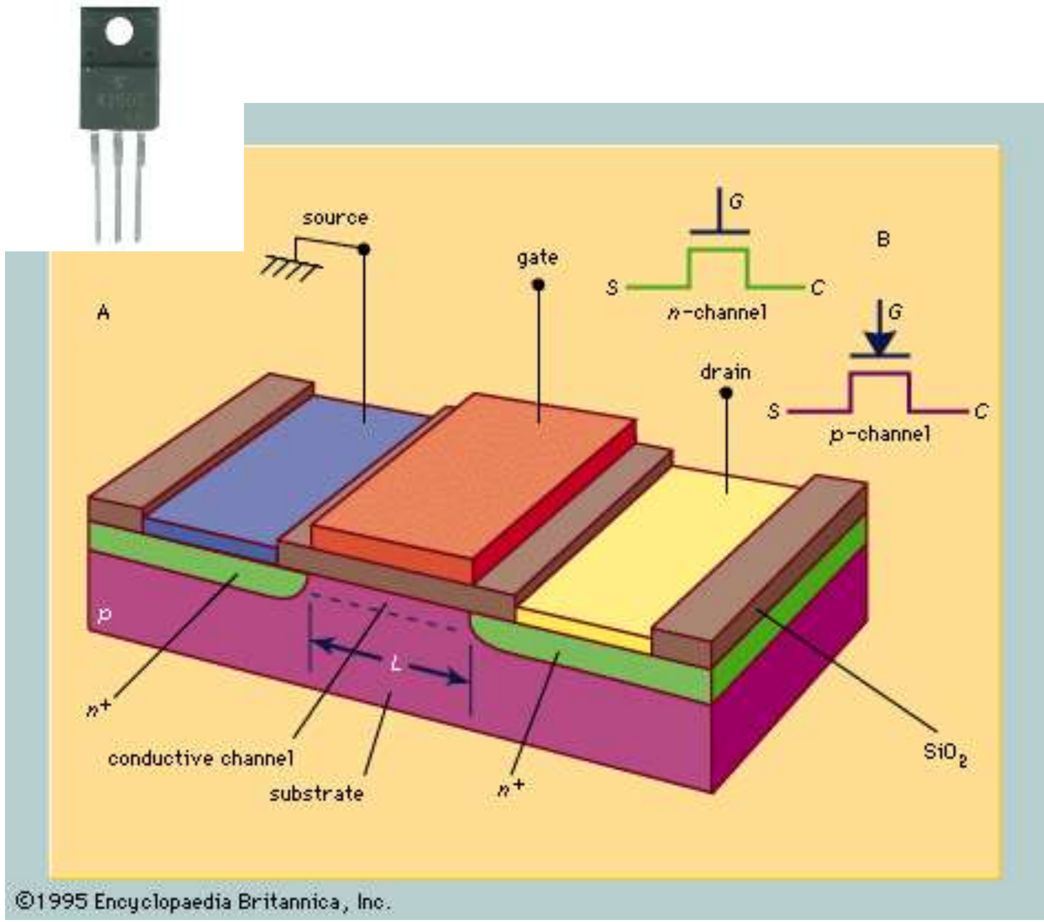


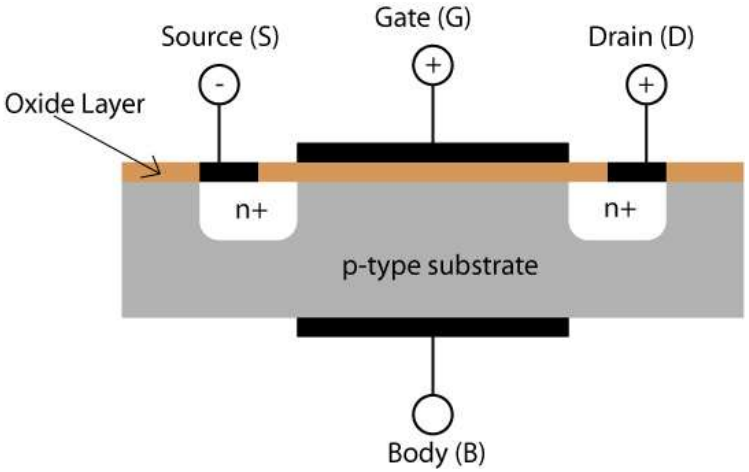
First point-contact transistor

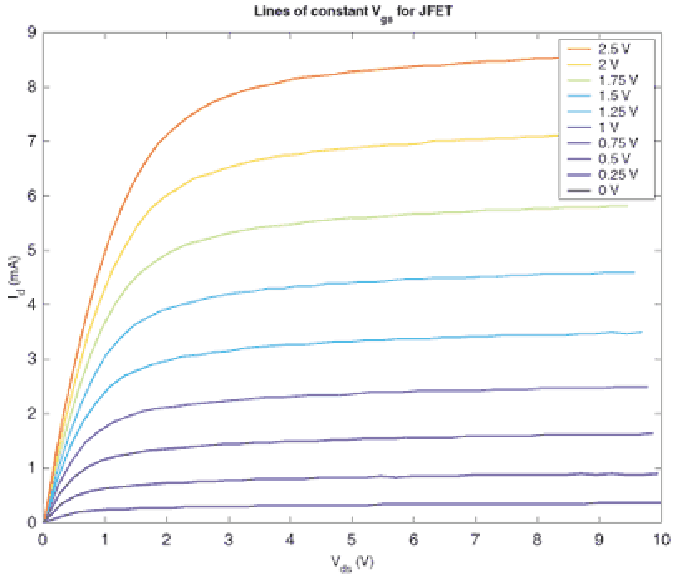
John Bardeen, William Shockley, Walter Brattain
Bell Labs, 1948
(Nobel Prize in Physics 1956)

http://en.wikipedia.org/wiki/Transistor#History

Field effect transistors







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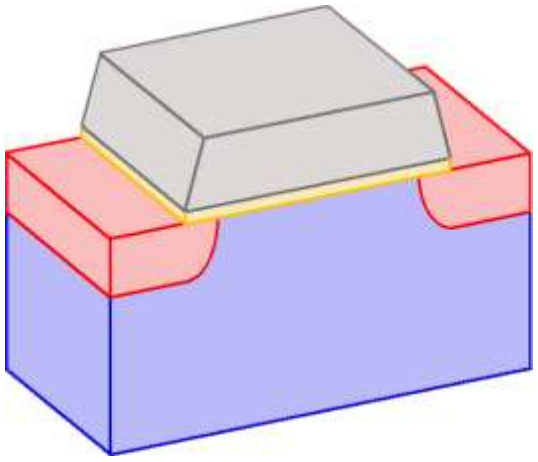
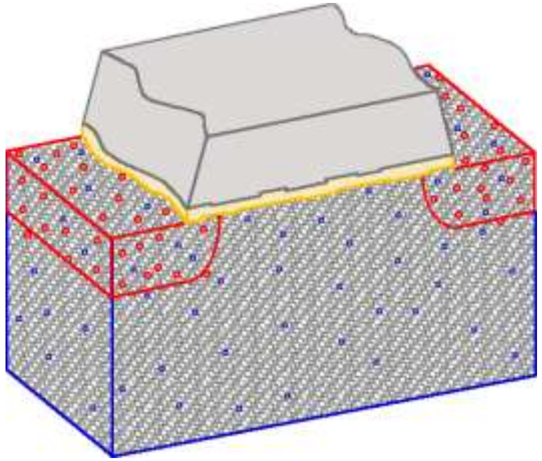
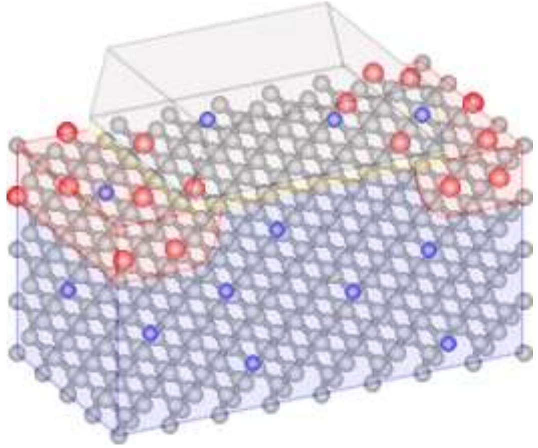
Miniaturization limits



we think that single
transistor looks like this



25 nm MOSFET
Production since 2008



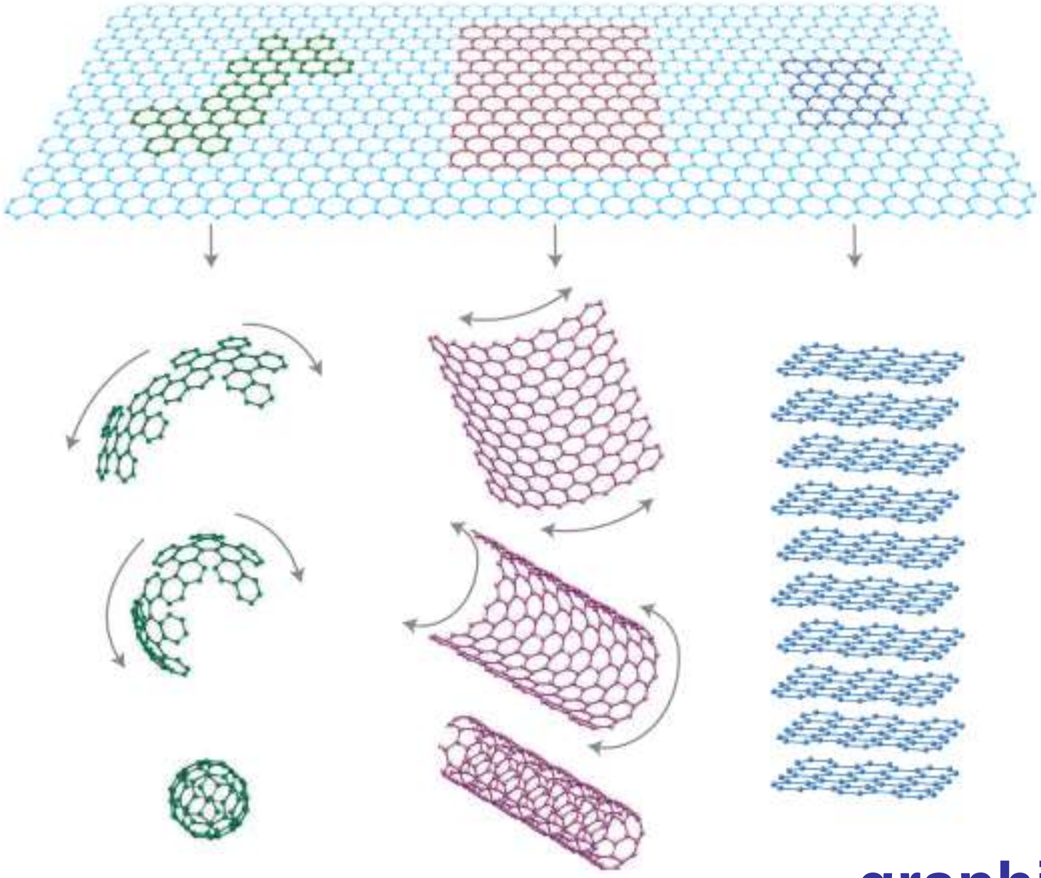
Asen Asenov, Glasgow

David Williams *Hitachi-Cambridge*

4,2 nm MOSFET ?

New ideas?

Graphene – a single layer of graphite…



fullerenes (0D)

nanotubes (1D)

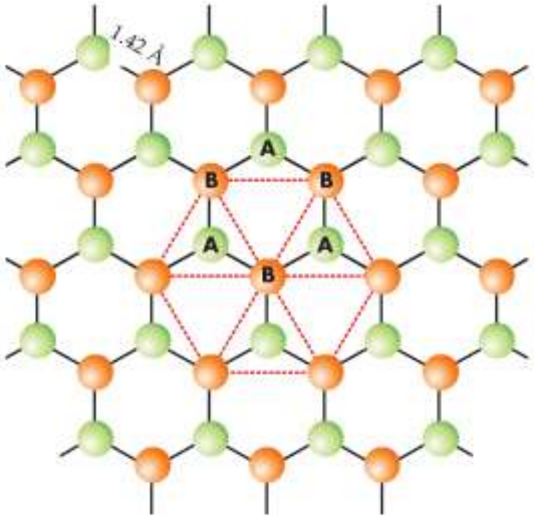
graphite (3D)

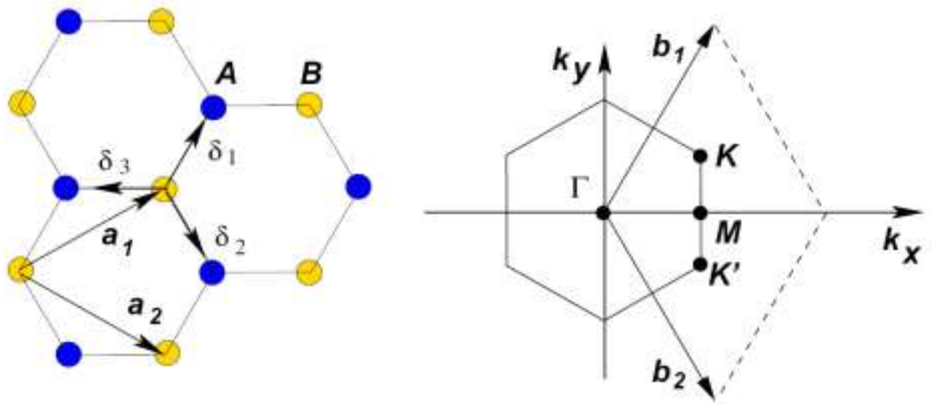
Basic block of different carbon allotropes….

A.K. Geim and K.S. Novoselov,Nature 6, 183 (2007)

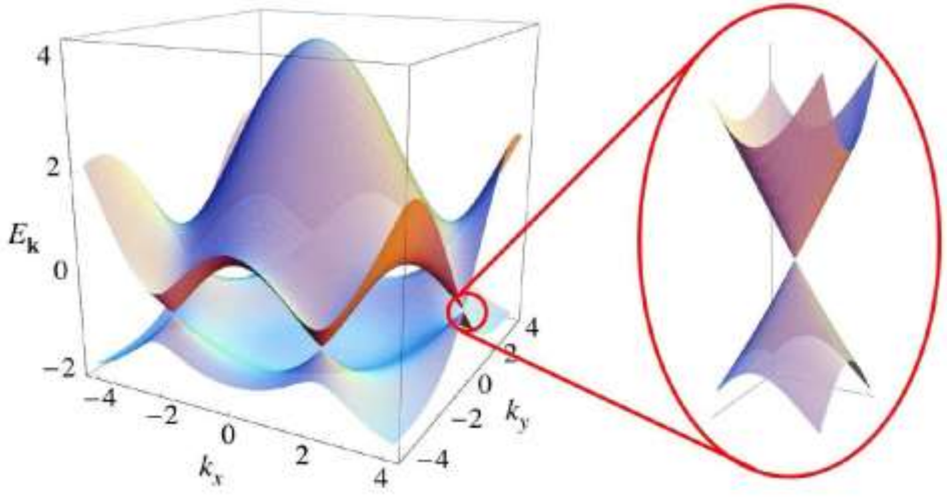
Band structure of graphene

…known since years: (*P.R. Wallace, Phys. Rev. (1947)*)





$$\mathbf{a}_1 = \frac{a}{2}(3, \sqrt{3}), \quad \mathbf{a}_2 = \frac{a}{2}(3, -\sqrt{3}) \quad \mathbf{b}_1 = \frac{2\pi}{3a}(1, \sqrt{3}), \quad \mathbf{b}_2 = \frac{2\pi}{3a}(1, -\sqrt{3})$$



$$E_\pm(\mathbf{k}) = \pm t\sqrt{3 + f(\mathbf{k})}\,.$$

$$f(\mathbf{k}) = 2\cos\left(\sqrt{3}k_y a\right) + 4\cos\left(\frac{\sqrt{3}}{2}k_y a\right)\cos\left(\frac{3}{2}k_x a\right)$$

$$\mathbf{K} = \left(\frac{2\pi}{3a}, \frac{2\pi}{3\sqrt{3}a}\right), \qquad \mathbf{K}' = \left(\frac{2\pi}{3a}, -\frac{2\pi}{3\sqrt{3}a}\right)$$

A.H. Castro Neto et al., Rev. Mod. Phys. (2009)

The Nobel Prize in Physics 2010
Andre Geim, Konstantin Novoselov

Photo: Sergeom, Wikimedia Commons

Andre Geim

Photo: University of Manchester, UK

Konstantin Novoselov

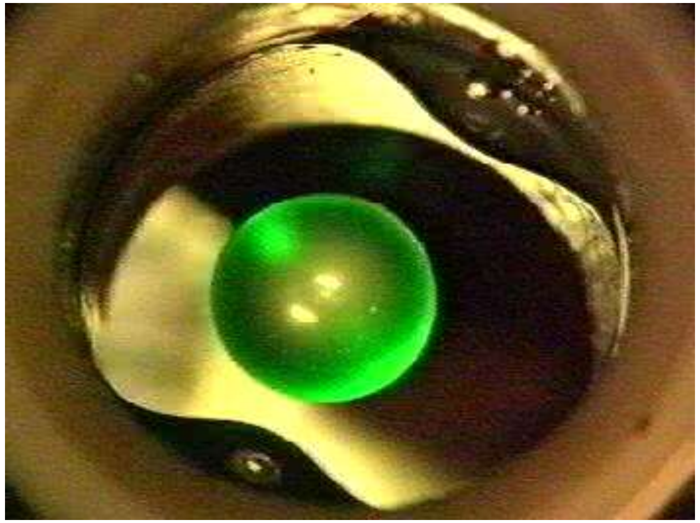
The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov *"for groundbreaking experiments regarding the two-dimensional material graphene"*

Ig Nobel Prize 2000

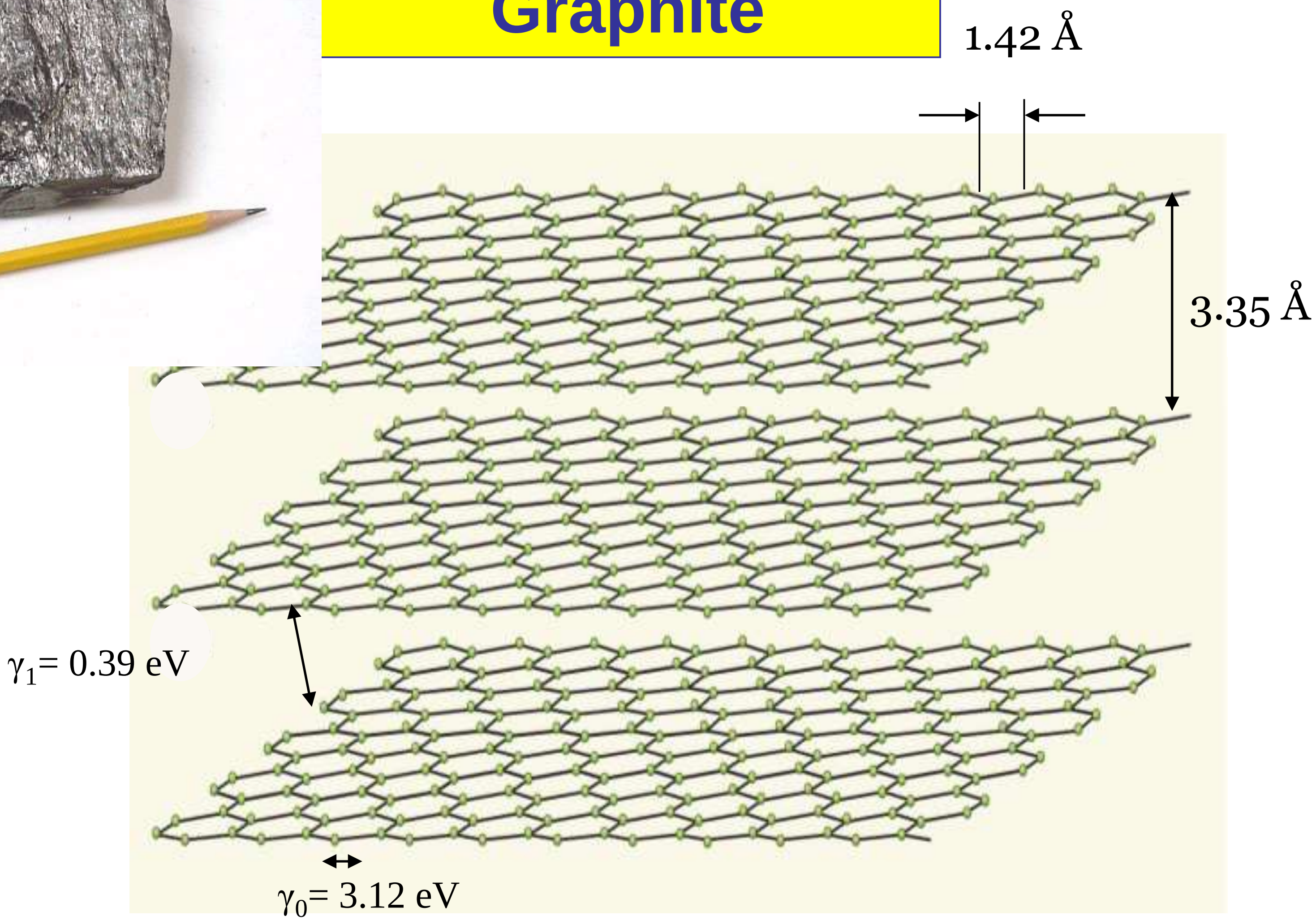
Andre Geim, University of Nijmegen (Netherlands)
Sir Michael Berry, Bristol University (UK),
„for using magnets to levitate a frog"

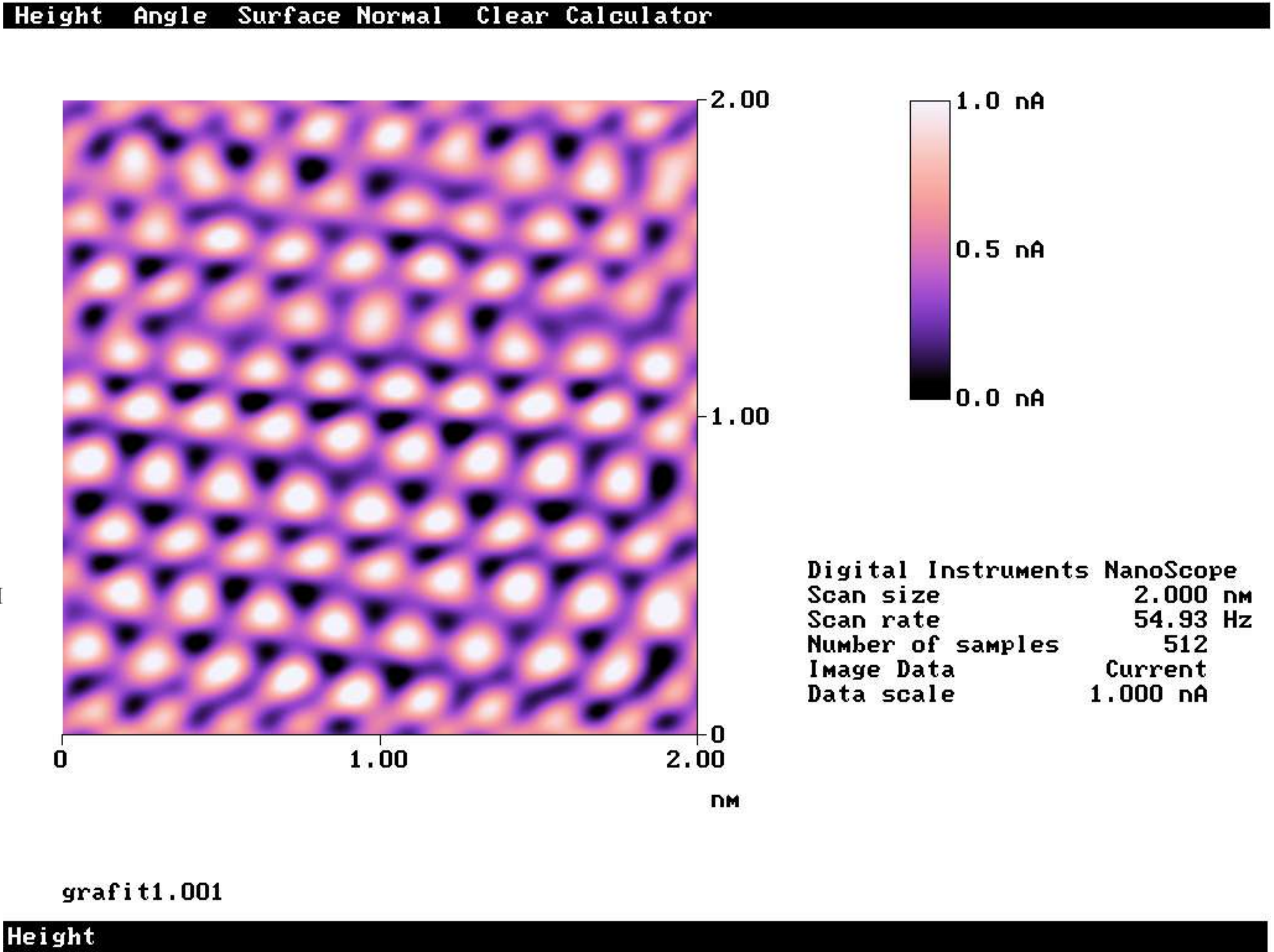
The motto of the Ig Nobel Prize is to „honour the achievements that first make people laugh, and then think…"

M.V. Berry and **A.K. Geim**,
"Of Flying Frogs and Levitrons"
European Journal of Physics, v. 18, 1997, p. 307-13.



Graphite




Height Angle Surface Normal Clear Calculator
2.00
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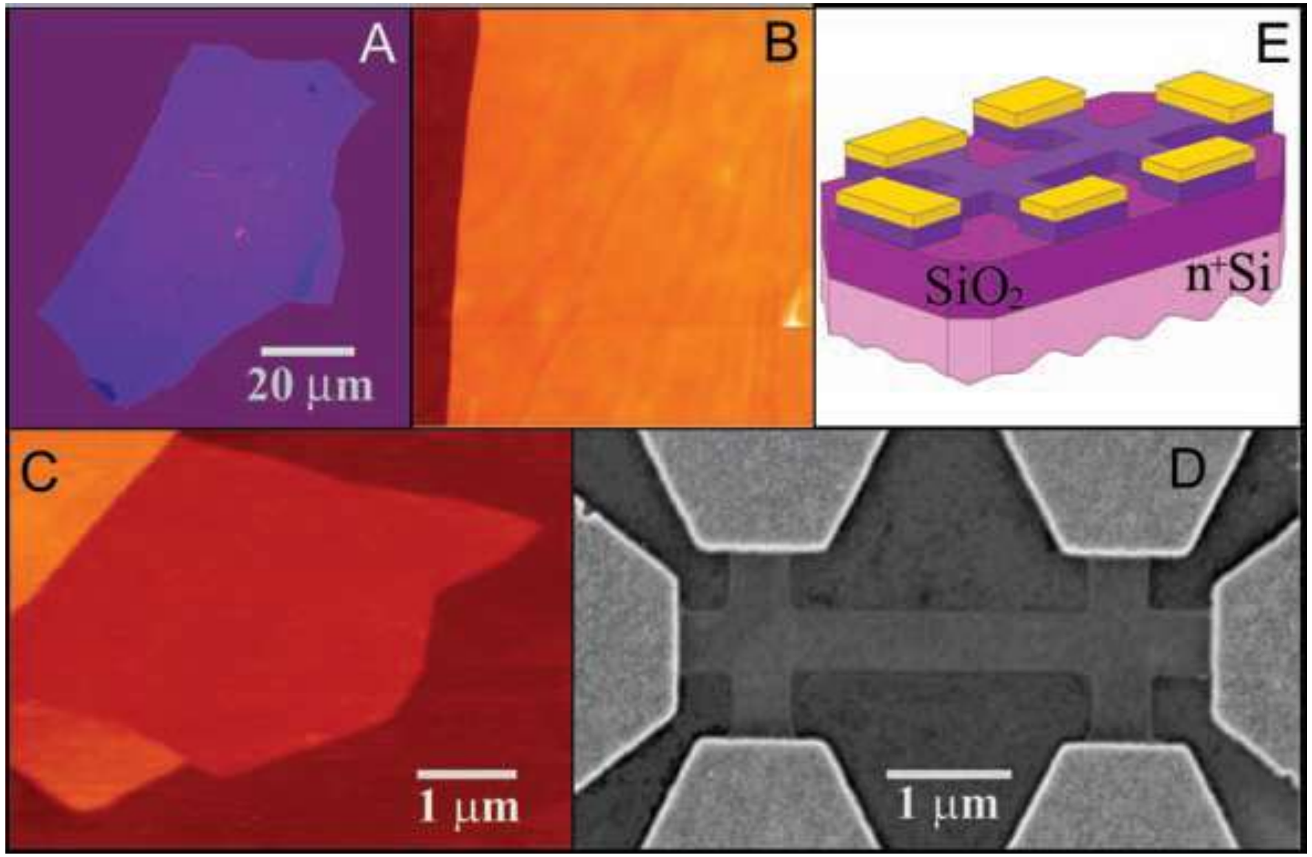
nm
1.0 nA
0.5 nA
0.0 nA
Digital Instruments NanoScope
Scan size 2.000 nm
Scan rate 54.93 Hz
Number of samples 512
Image Data Current
Data scale 1.000 nA
grafit1.001
Height

FI

Mechanical exfoliation from graphite



K. Novoselov, A. Geim *et al.* Science (2004)

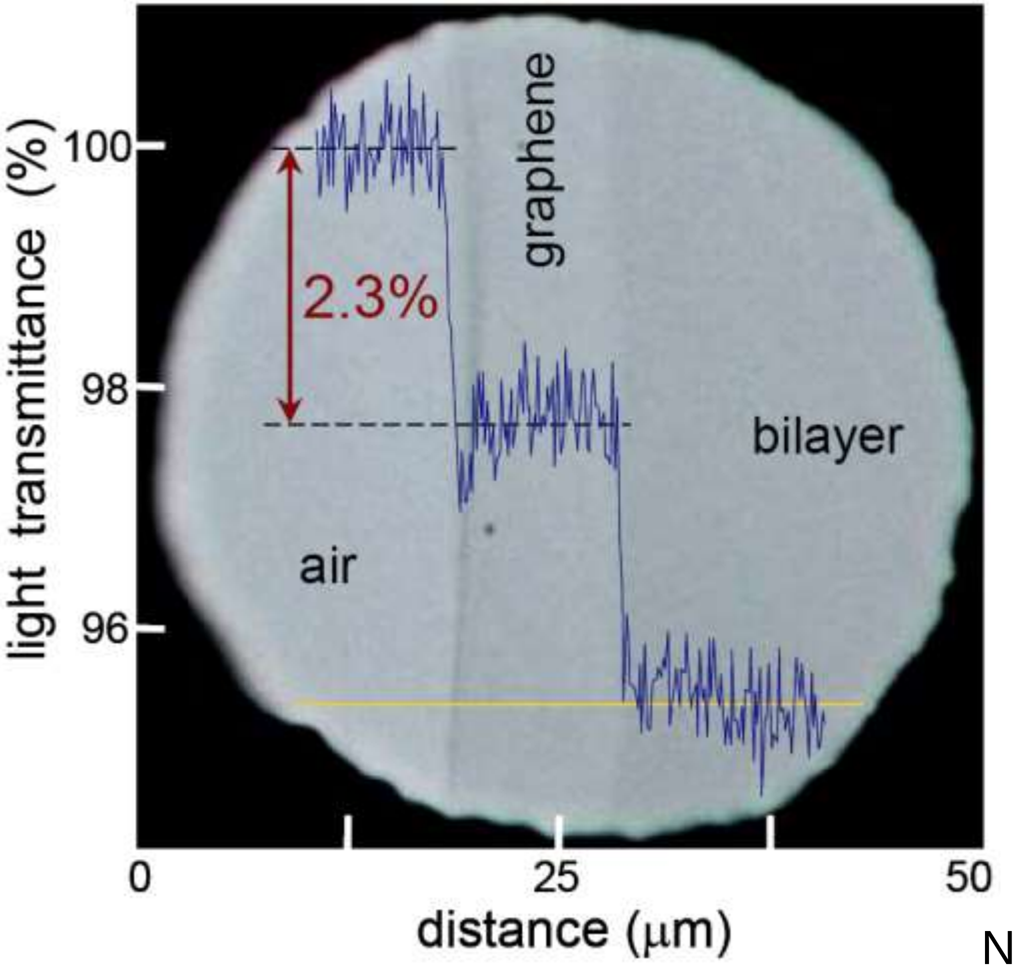
flake size ~10 μm

Graphene…

- high electron mobility (200000 cm^2/Vs)
- high critical density of carriers ~10^8 A/cm^2
- very high thermal conductivity
- excellent mechanical properties
- optical transparency…
- ….

… very promising for electronic and optoelectronic applications!

Graphene is transparent…



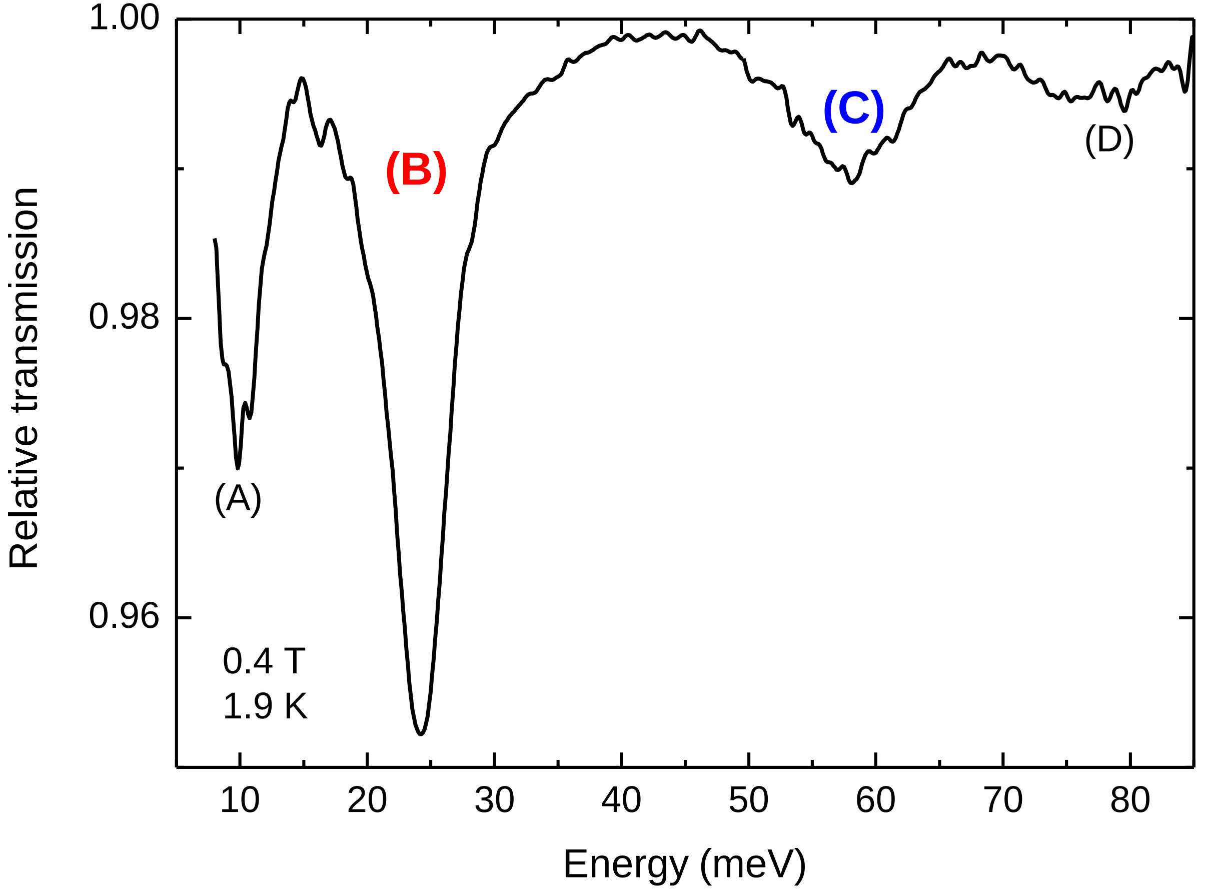
$$T = (1 + \tfrac{1}{2}\pi\alpha)^{-2}$$

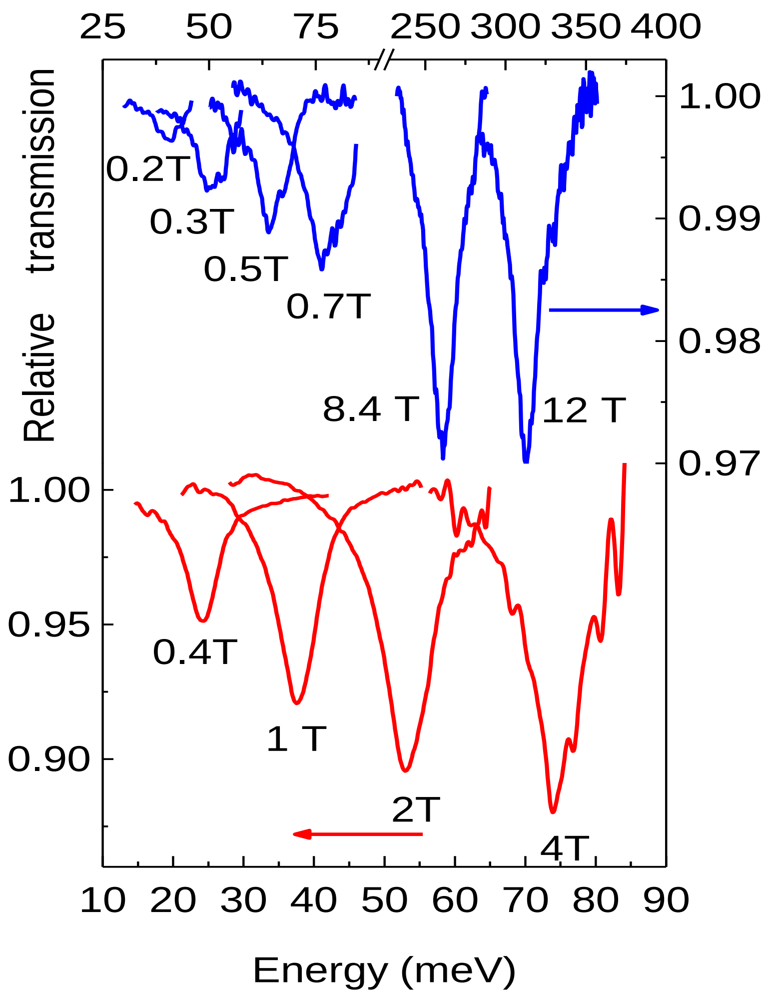
$$\alpha = e^2/\hbar c = 1/137{,}036\ !$$

Nair *et al.*, *Science* **320**, 1308 (2008)

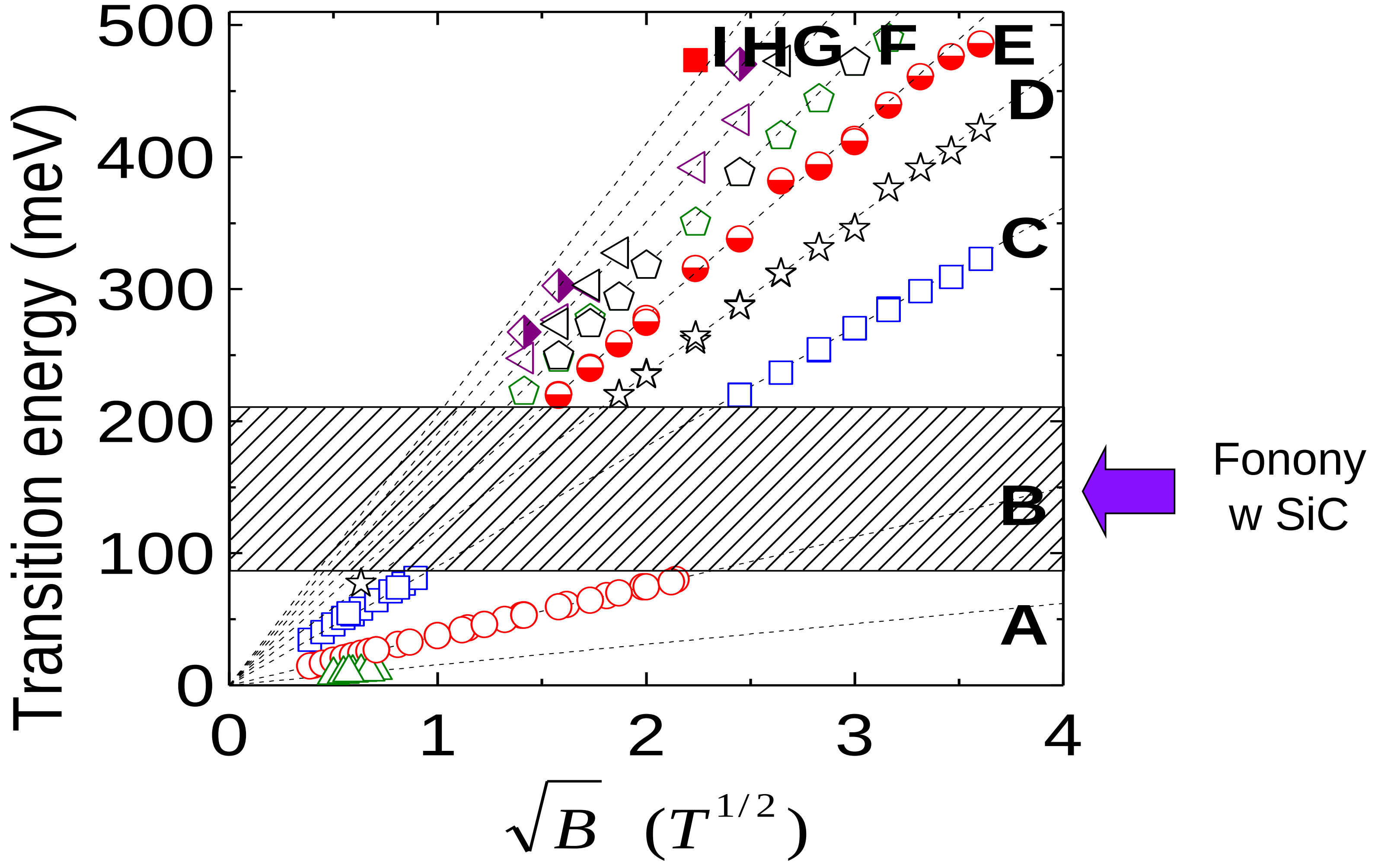
Applications: touch screens, solar cells…

Infrared magnetotransmission

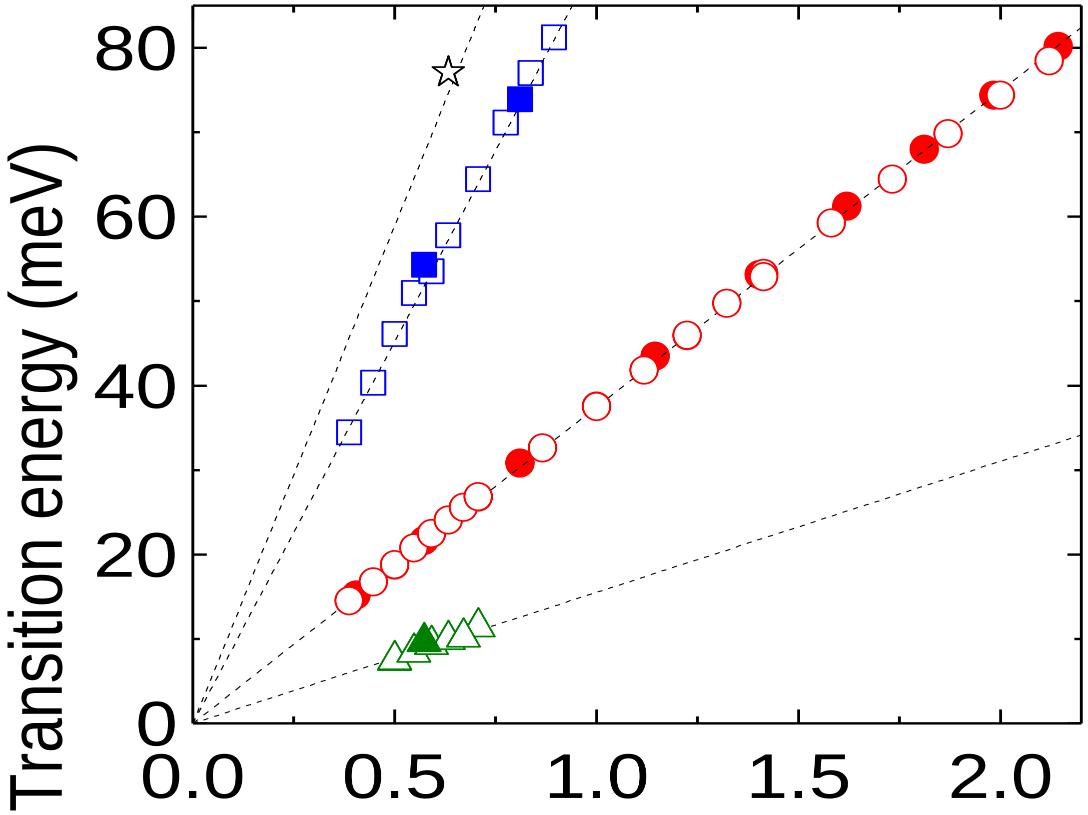




M. Sadowski et al., Phys. Rev. Lett. **97**, 266405 (2006)



M. Sadowski, Grenoble (2006)



open symbols
<(**B**,**n**) = 0°

solid symbols
<(**B**,**n**) = 50°

$(B_\perp)^{1/2}$

2D system !

M. Potemski et al. (Grenoble)

Solar cells

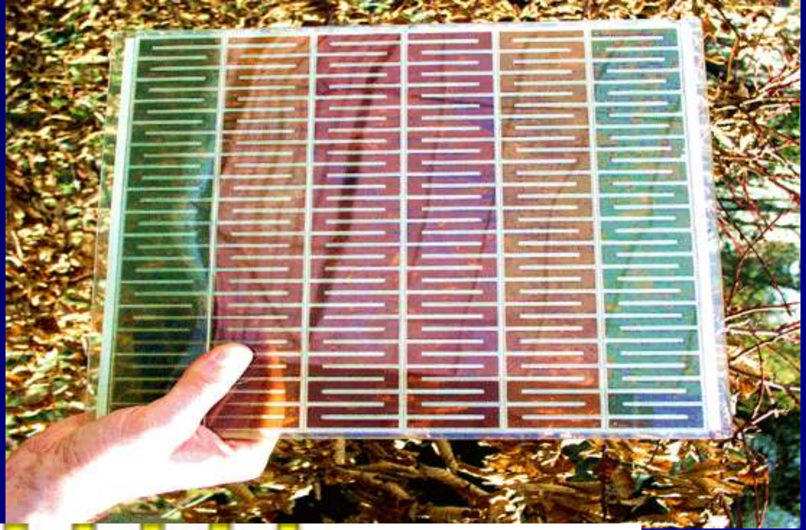

Kosuzume, Japan – 50 kW

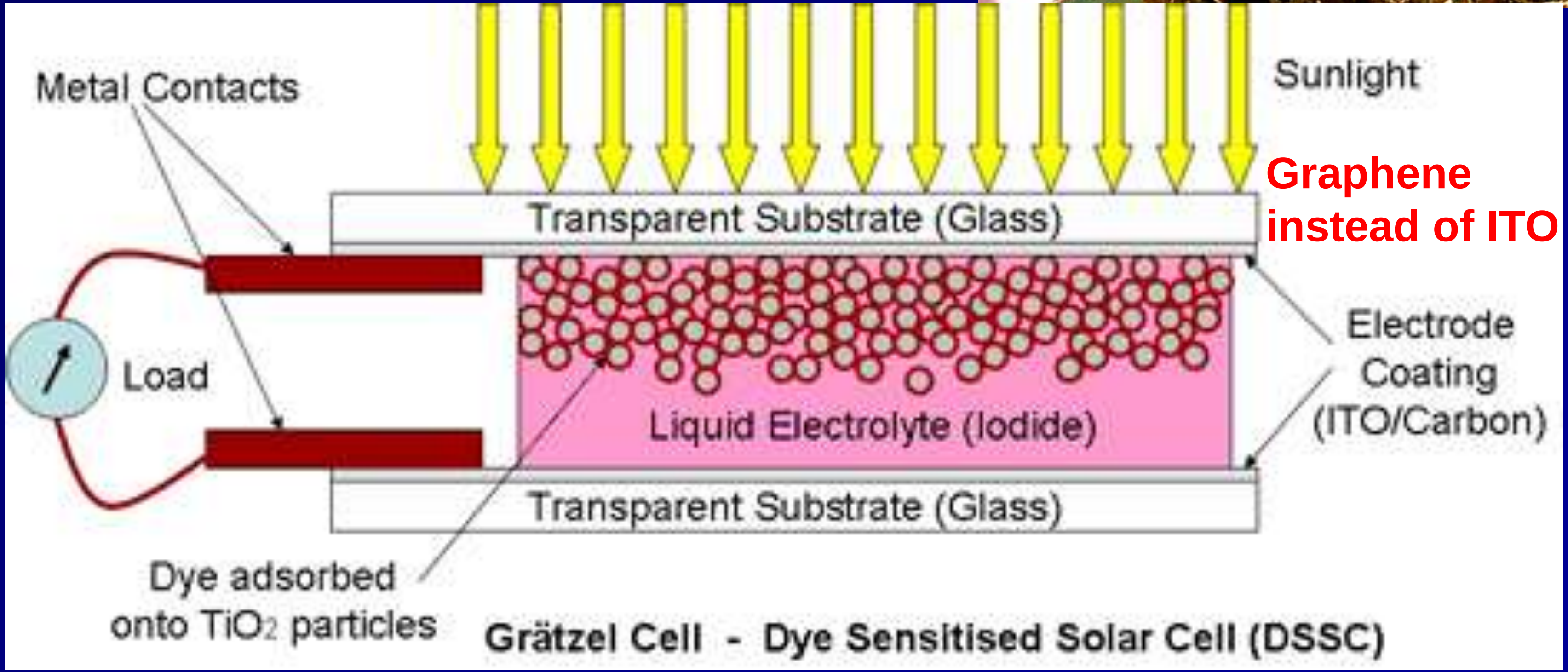

Geneva, Switzerland – 100 kW


Cudrefin, Switzerland -9.7 kW


Flotzheim, Germany – 8.4 kW

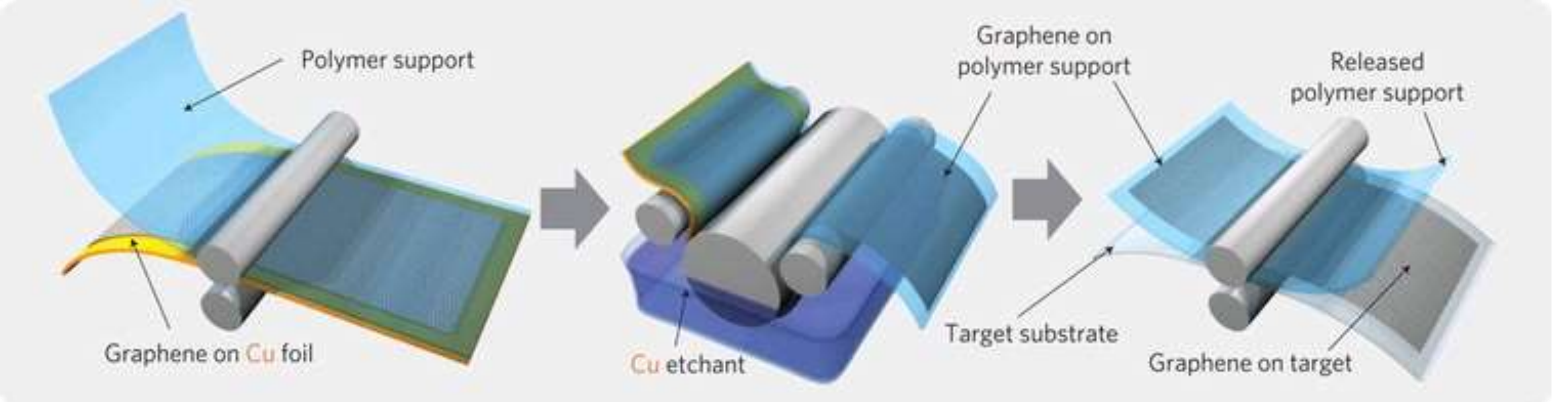
Improved Grätzel cells…



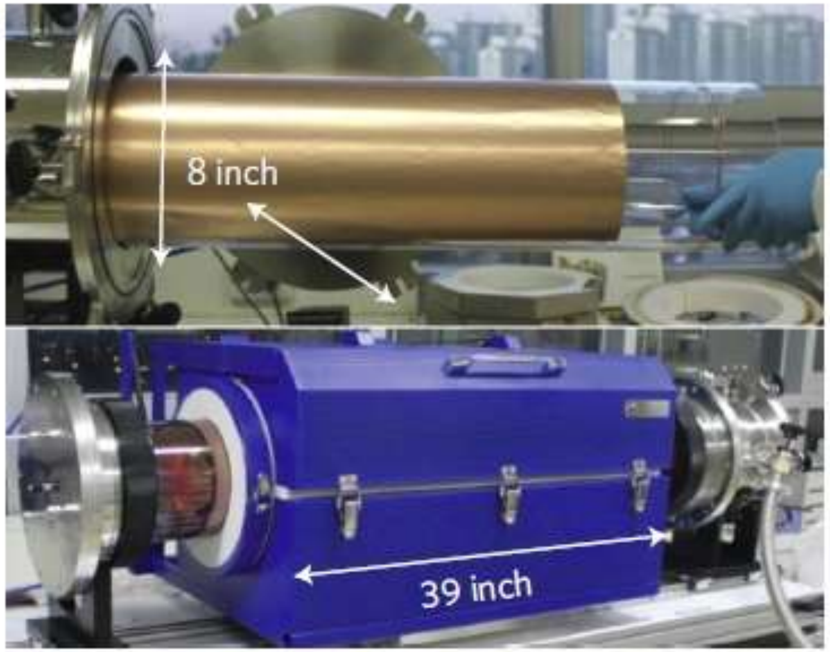


http://www.solarisnano.com/
http://www.mpoweruk.com/semiconductors.htm

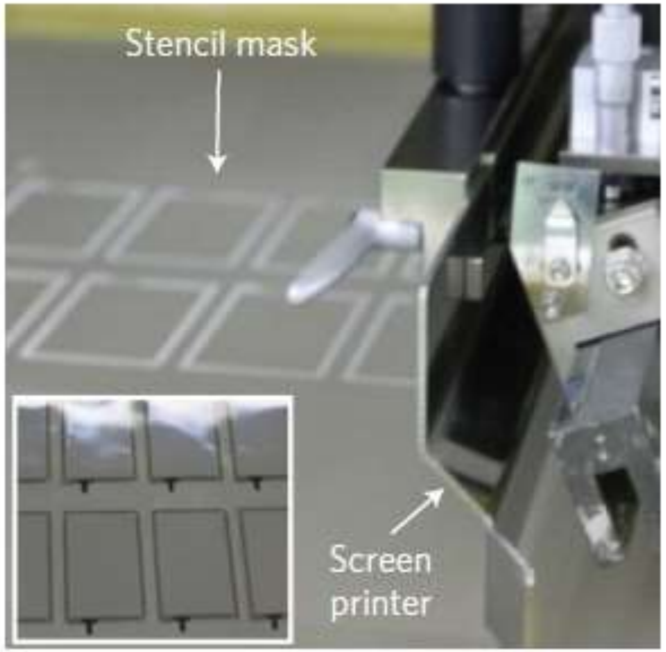
Graphene „roll-to-roll”



a



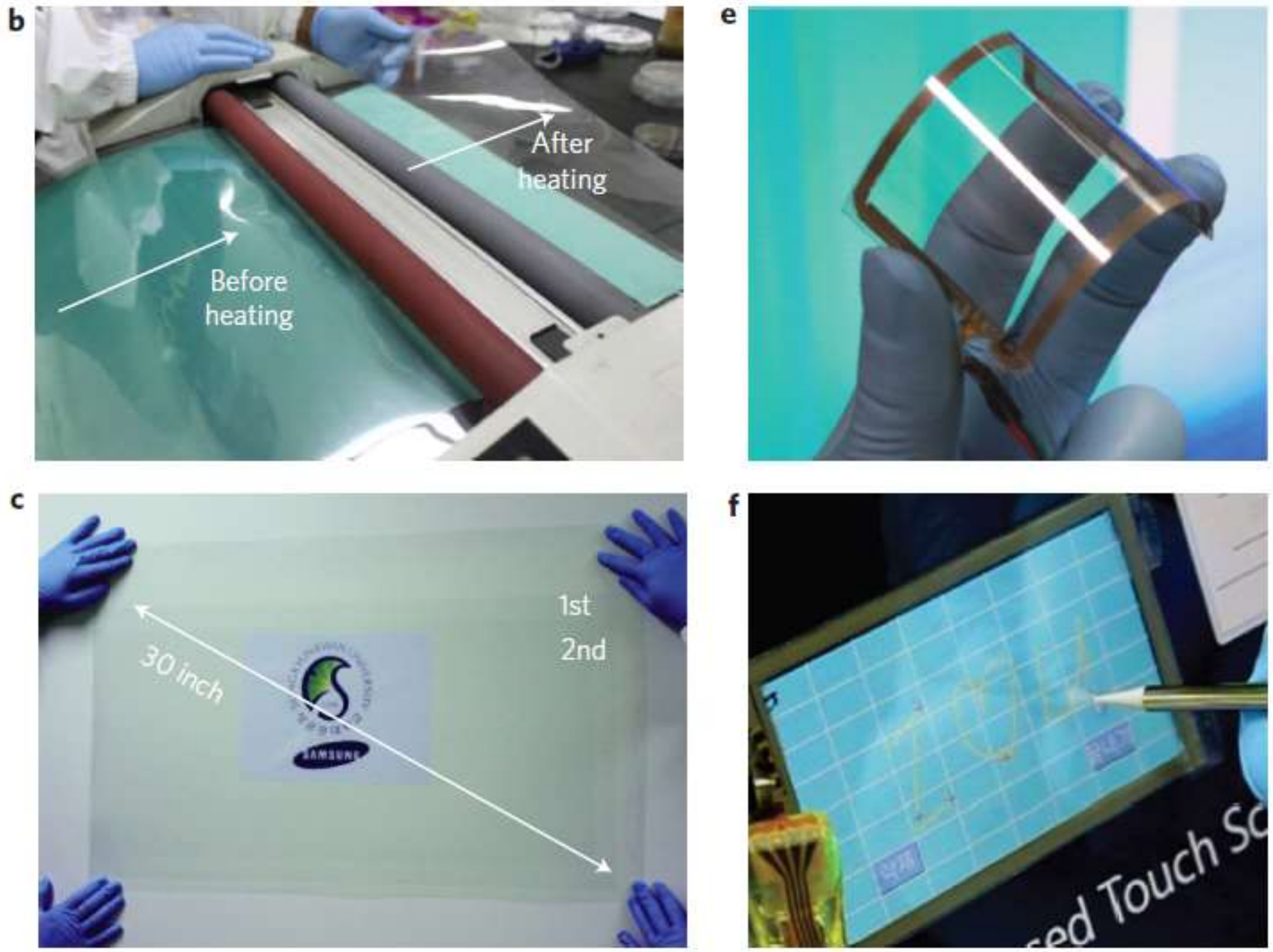
d



Bae et al. NATURE NANOTECHNOLOGY 5,574 (2010)

NATURE NANOTECHNOLOGY

Transparent and elastic touch screens



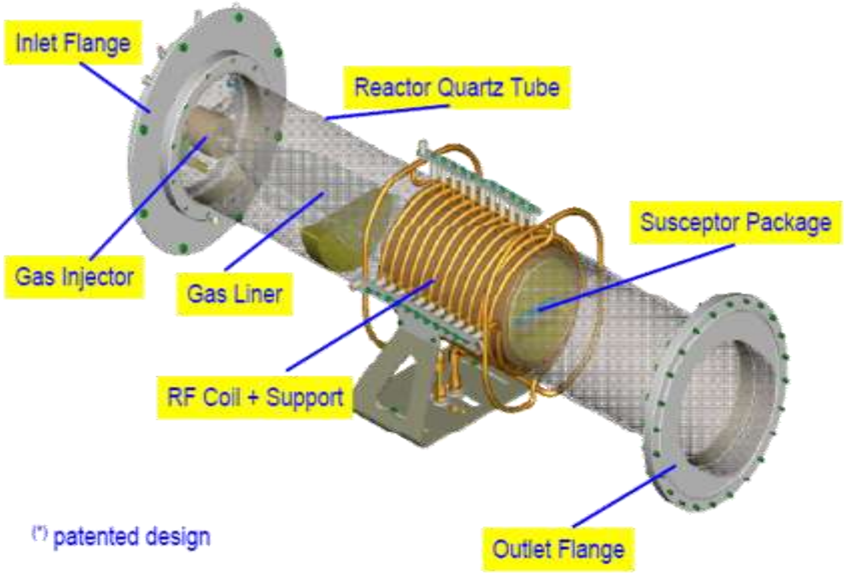
Bae et al. NATURE NANOTECHNOLOGY 5,574 (2010)

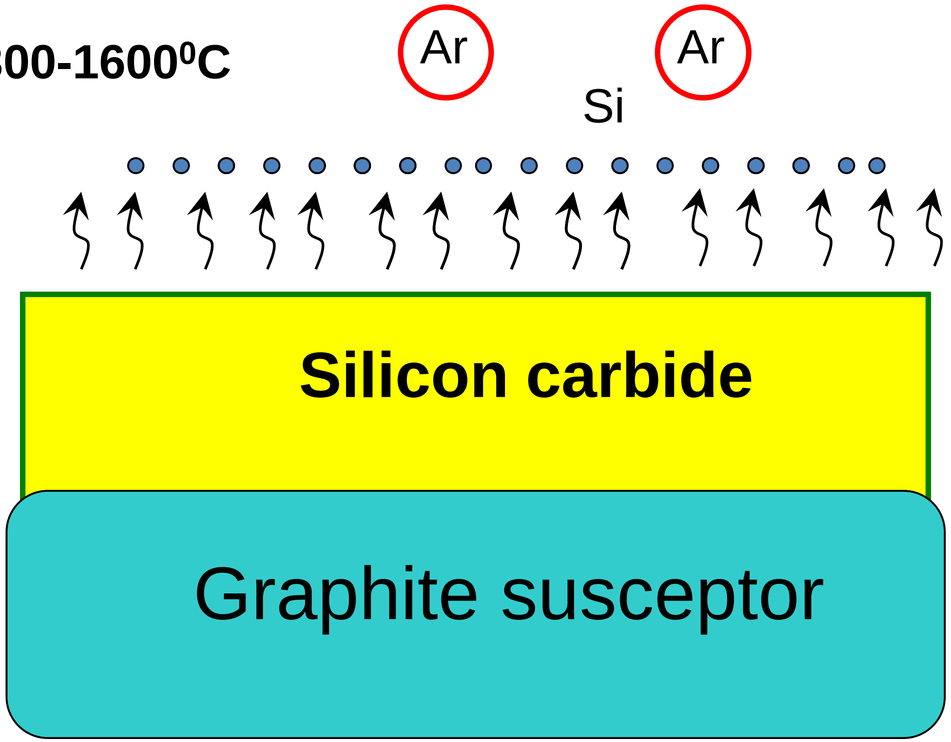
Sublimation method

(in Warsaw ~2006/2007)

First step: etching in H_2 at 1300-1600^{0}C

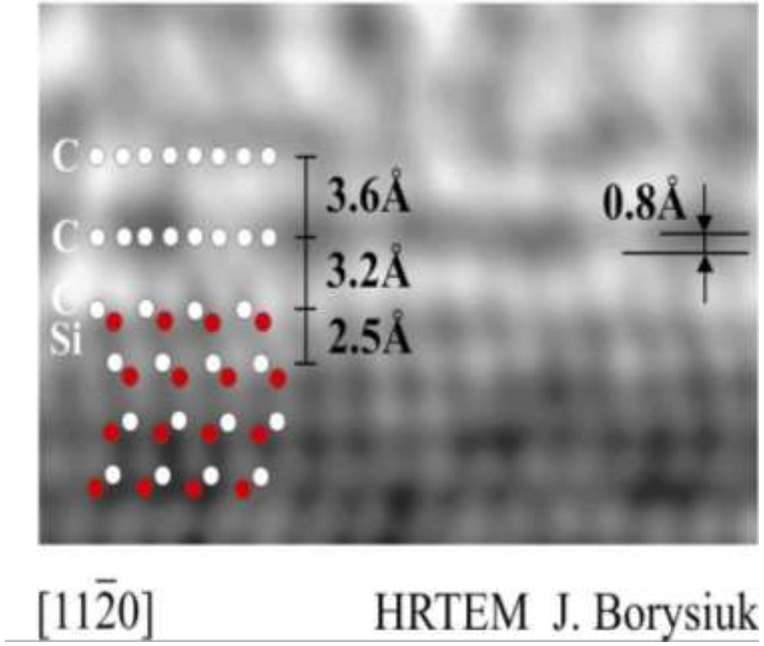
Graphitization at 1300-1600^{0}C

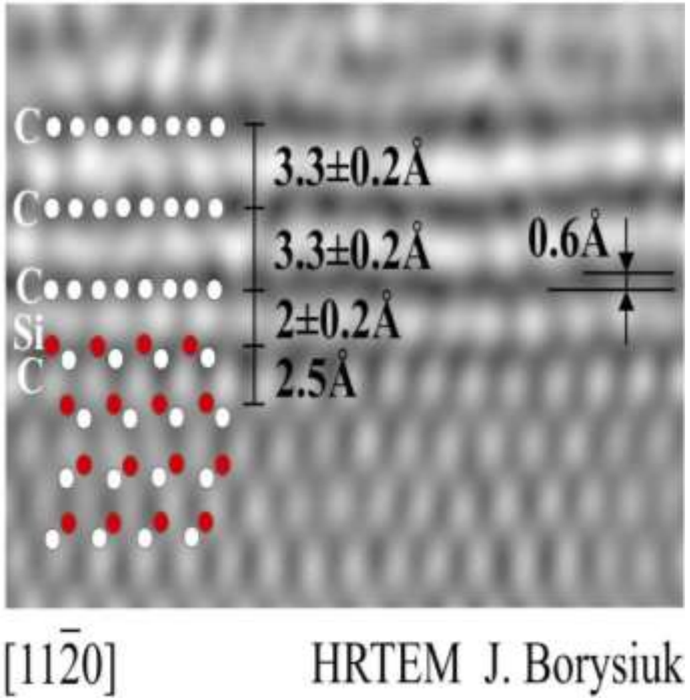




Aixtron VP508 CVD reactor (for SiC growth)

Graphene on SiC





Carbon face

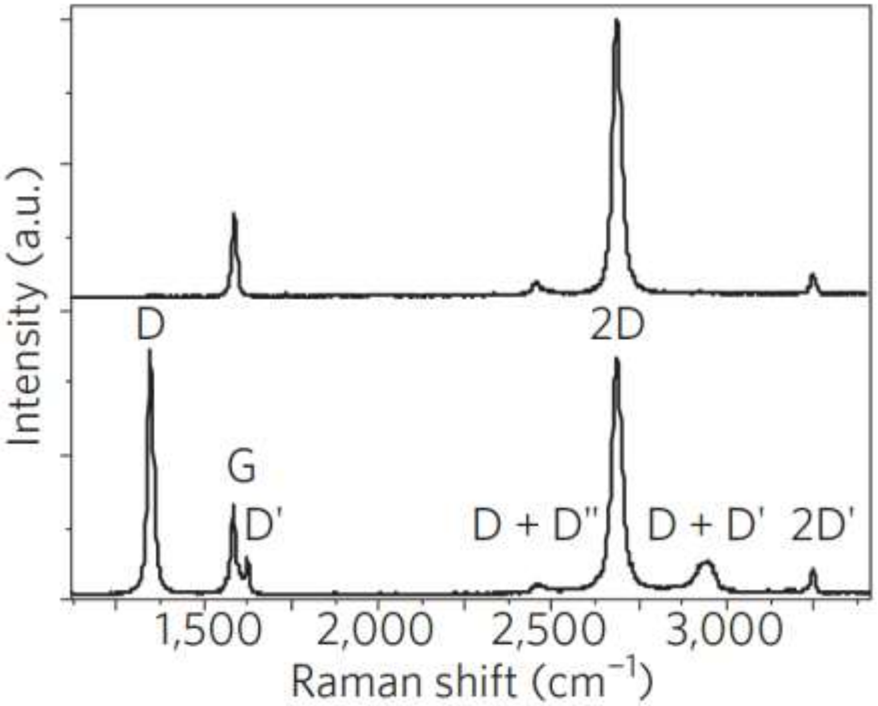
(usually low p-type)

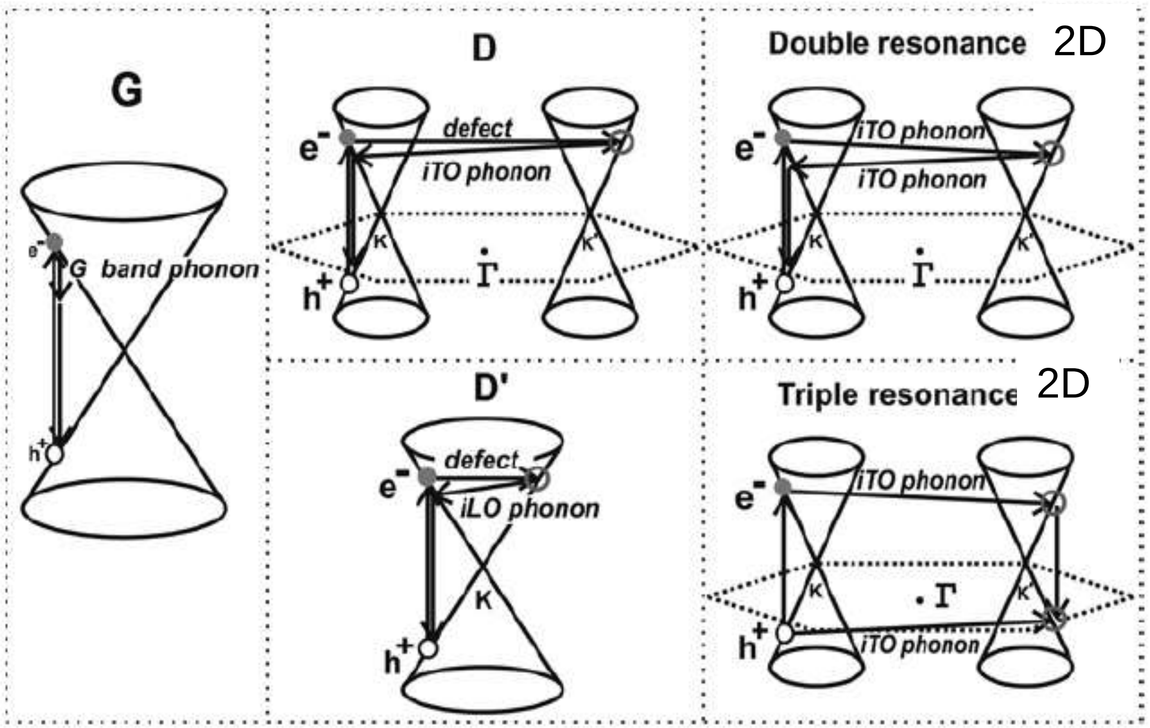
Silicon face

(usually highly n-type)

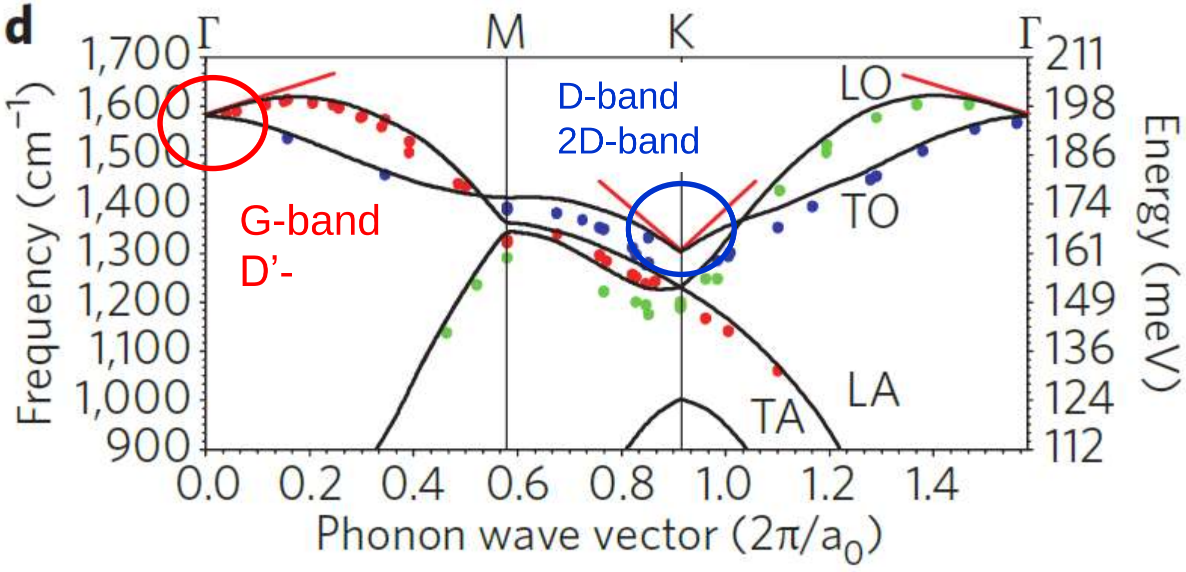
J. Borysiuk et al., J. Appl. Phys. **108,** 013518 (2010)

Raman spectra of graphene





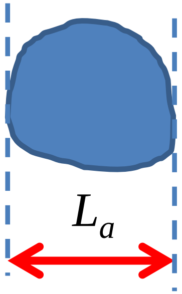
L. M. Malard et al. Phys. Rep. 473, 51 (2009)



A. C. Ferrari and D. M. Basco, Nature Nanotechnology 8, 235–246 (2013)

Defects in Graphene

D peak is produced only in a small region near a defect or an edge...



„Ideal" crystallites (flakes):

$I(D) \propto L_a$

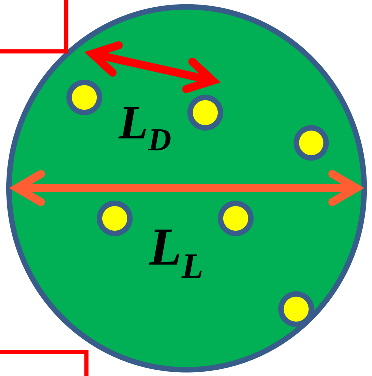
$I(G) \propto L_a^2$

L_a – flake size

$$\frac{I(D)}{I(G)} \propto 1/L_a$$

Flakes with rare defects

***I*(*D*)** $\propto$ number of defects within the laser spot…



$I(D) \propto (L_L/L_D)^2$

$I(G) \propto L_L^2$

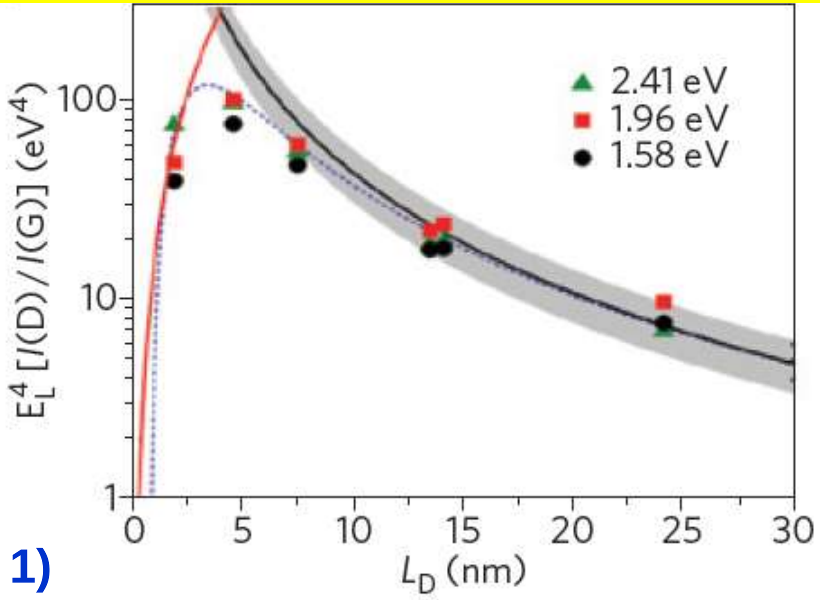
$$\frac{I(D)}{I(G)} \propto 1/L_D^2$$

High disorder

I (*D*) $\propto$ number of sp² rings

I (*G*) $\cong$ constant ($\propto$ relative motion of sp² carbons)

$$\frac{I(D)}{I(G)} \propto L_D^2$$



Low disorder (Stage 1)

$$n_D(cm^{-2}) = 7.3\times10^{-9} E_L^4(eV^4)\frac{I(D)}{I(G)}$$

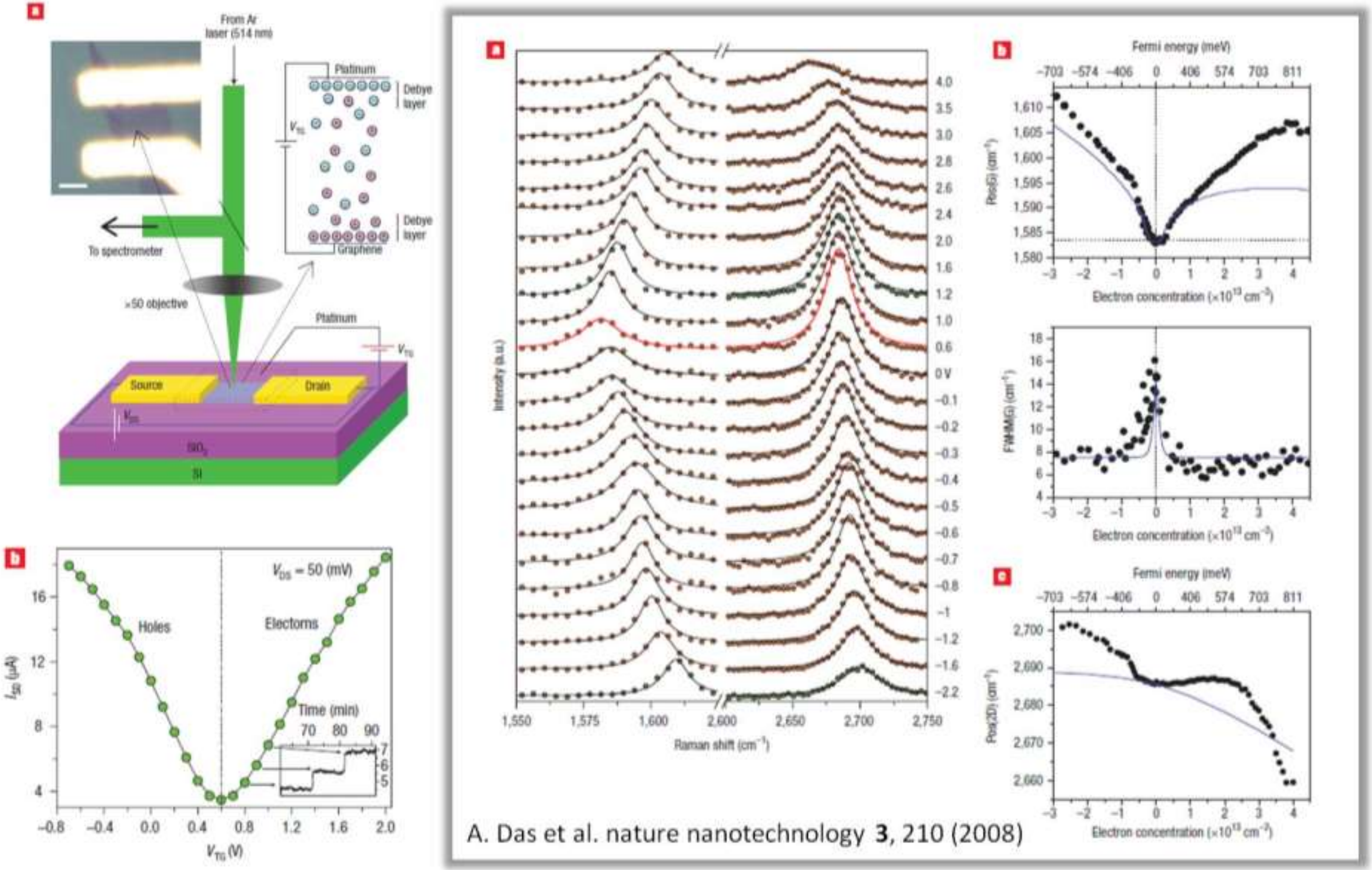
High disorder (Stage 2)

$$L_D^2(nm^2) = 5.4\times10^{-2} E_L^4(eV^4)\frac{I(D)}{I(G)}$$

$$n_D(cm^{-2}) = \frac{5.9\times10^{14}}{E_L^4(eV^4)}\left(\frac{I(D)}{I(G)}\right)^{-1}$$

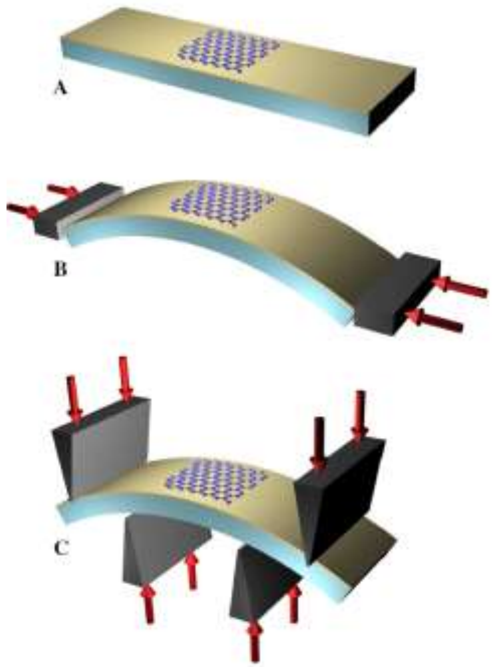
F. Tuinstra and J. L. Koenig, J. Chem. Phys. **53**, 1126 (1970)
L. G. Cancado et al., Nano Lett. **11** 3190 (2011)
A. C. Ferrari and D. M. Basco,Nature Nanotechn. 8, 235 (2013)

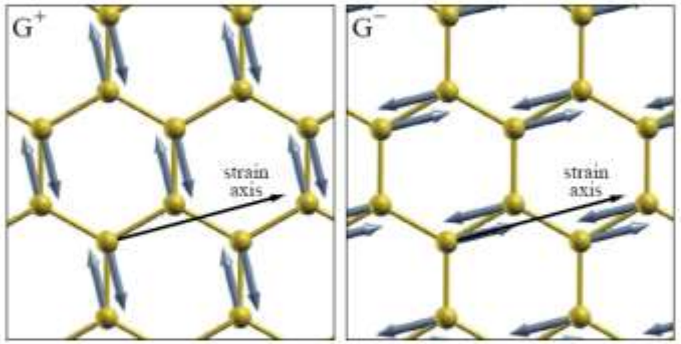
Doping reference - solid electrolyte top gated exfoliated graphene

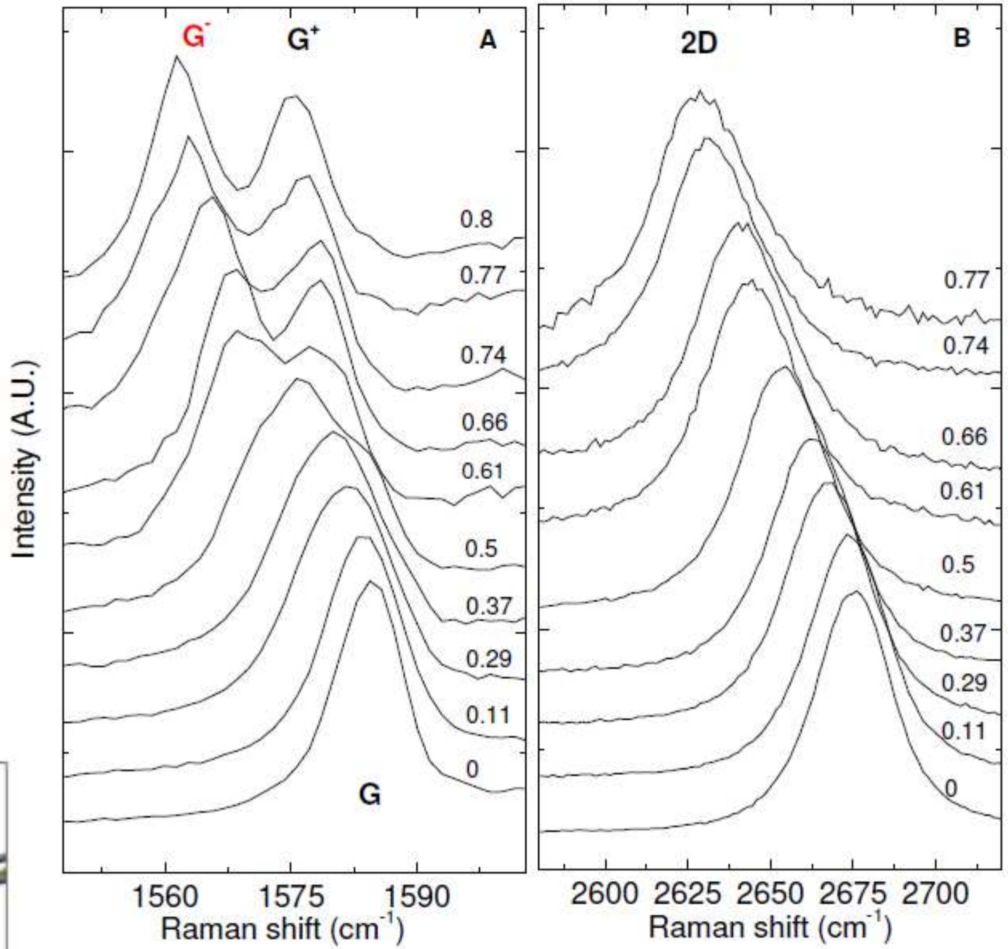


A. Das et al. nature nanotechnology **3**, 210 (2008)

Uniaxial strain influence on Raman spectra

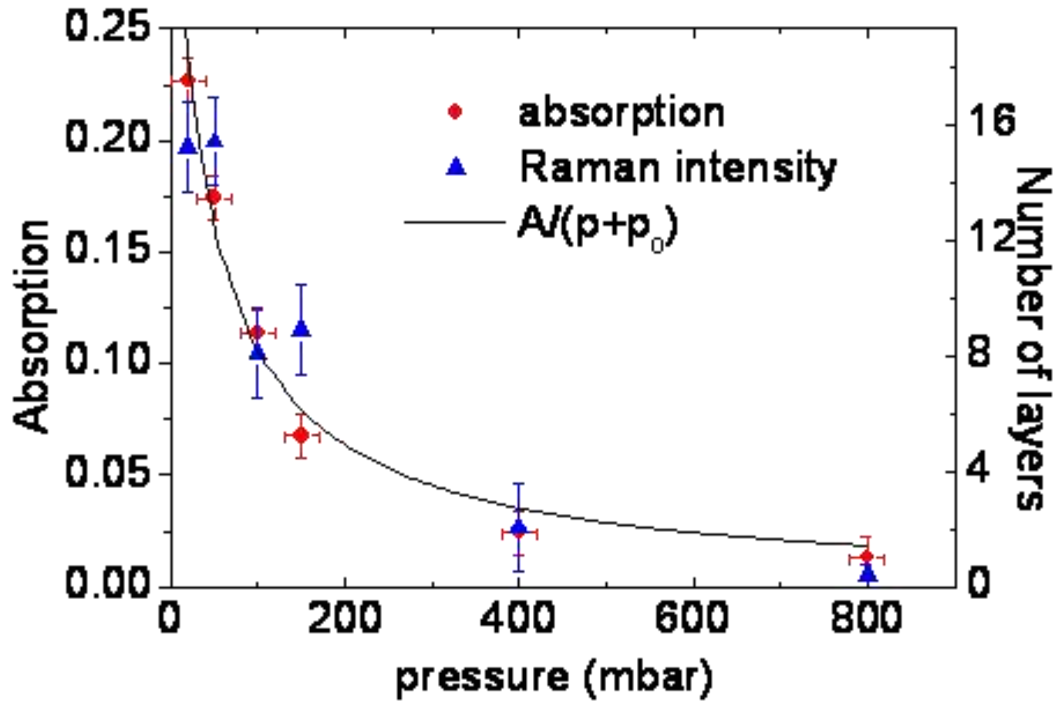


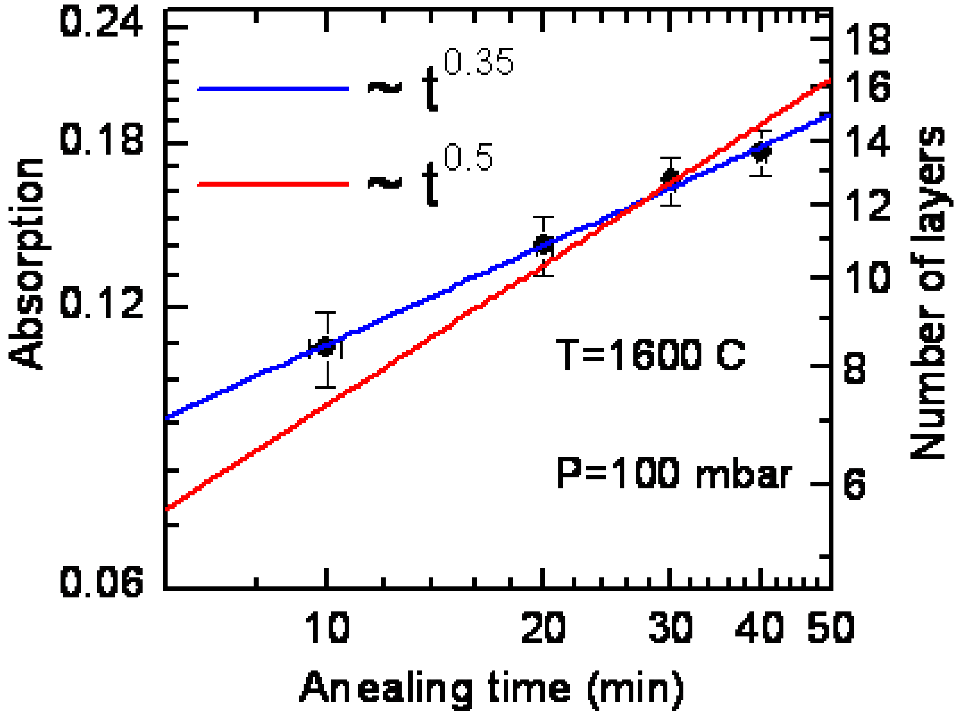




Mohiuddin et al. , Phys. Rev. B 79, 205433 (2009)

Graphene on SiC - sublimation growth kinetics (C-face)

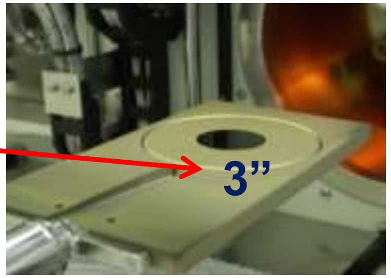


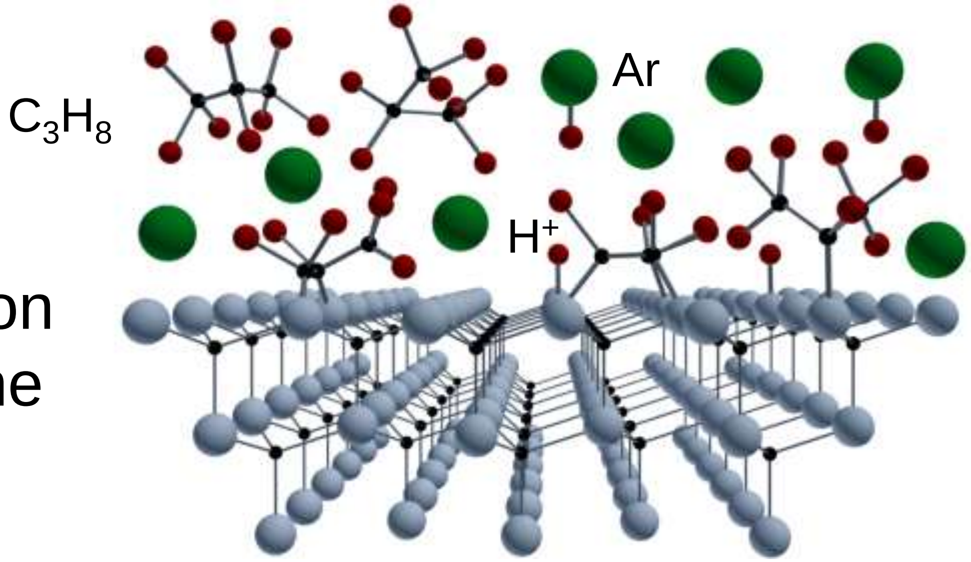


Growth kinetics driven by 2D – diffusion of Si!

A.Drabińska et al., Phys. Rev. B **81,** 245410 (2010)

Chemical Vapour Deposition





- suppression of sublimation
- decomposition of propane in Ar atmosphere

Standard CVD

W. Strupinski et al. Nano Lett. 11, 1786 (2011)

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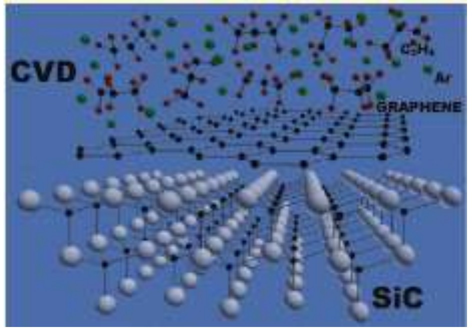
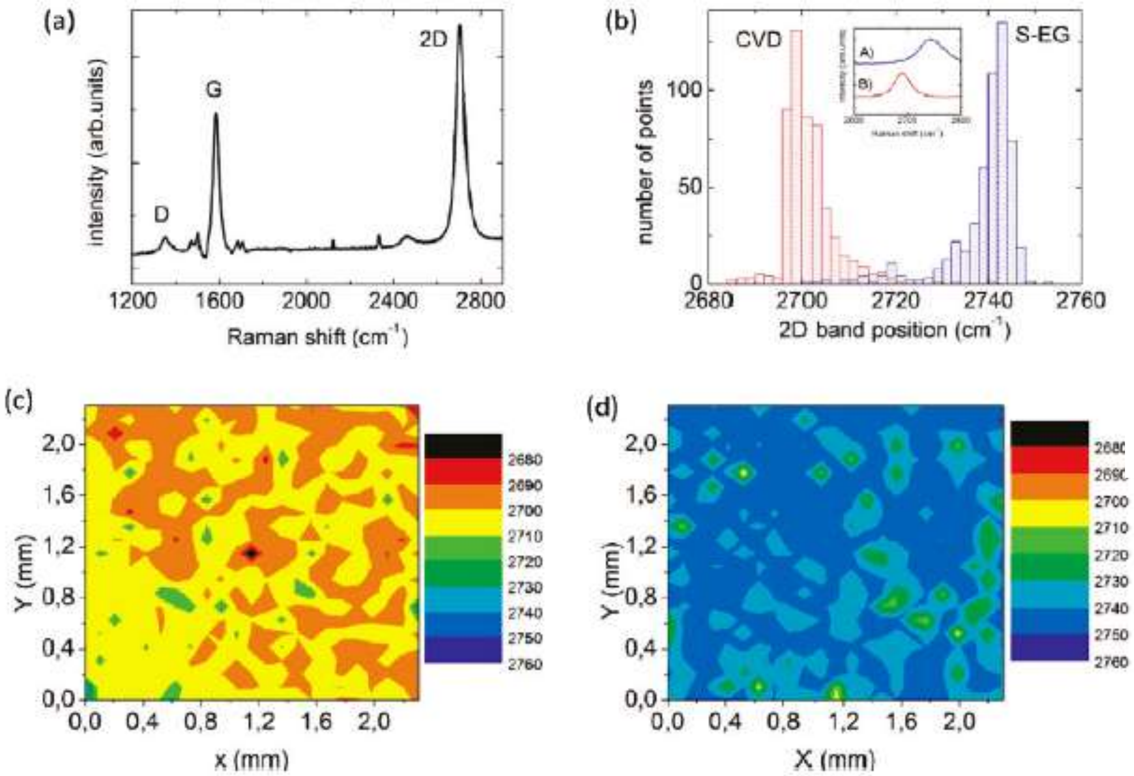
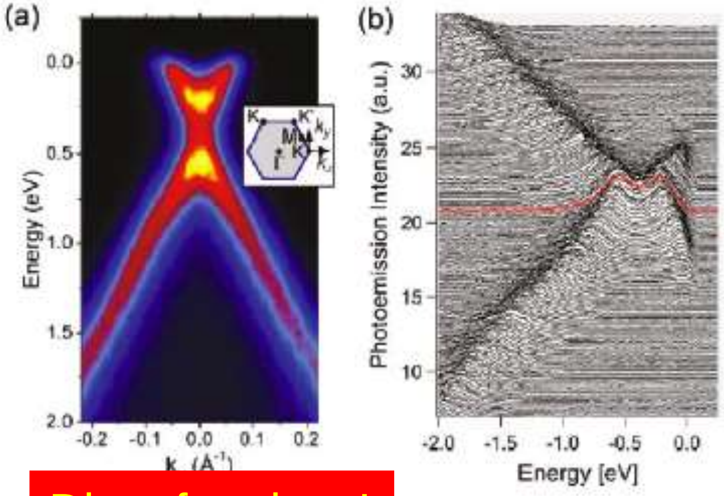
LETTER
pubs.acs.org/NanoLett



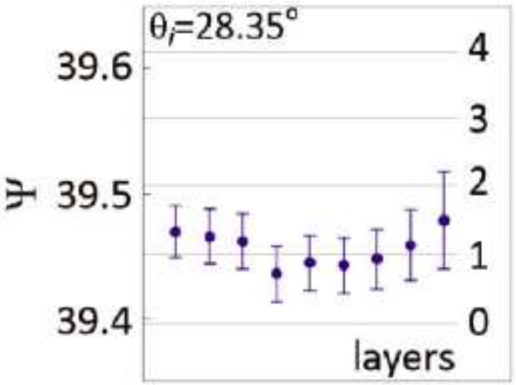
Graphene Epitaxy by Chemical Vapor Deposition on SiC

W. Strupinski,*[1] K. Grodecki,[1,2] A. Wysmolek,[2] R. Stepniewski,[2] T. Szkopek,[3] P. E. Gaskell,[3] A. Grüneis,[4,5] D. Haberer,[4] R. Bozek,[2] J. Krupka,[6] and J. M. Baranowski[1,2]



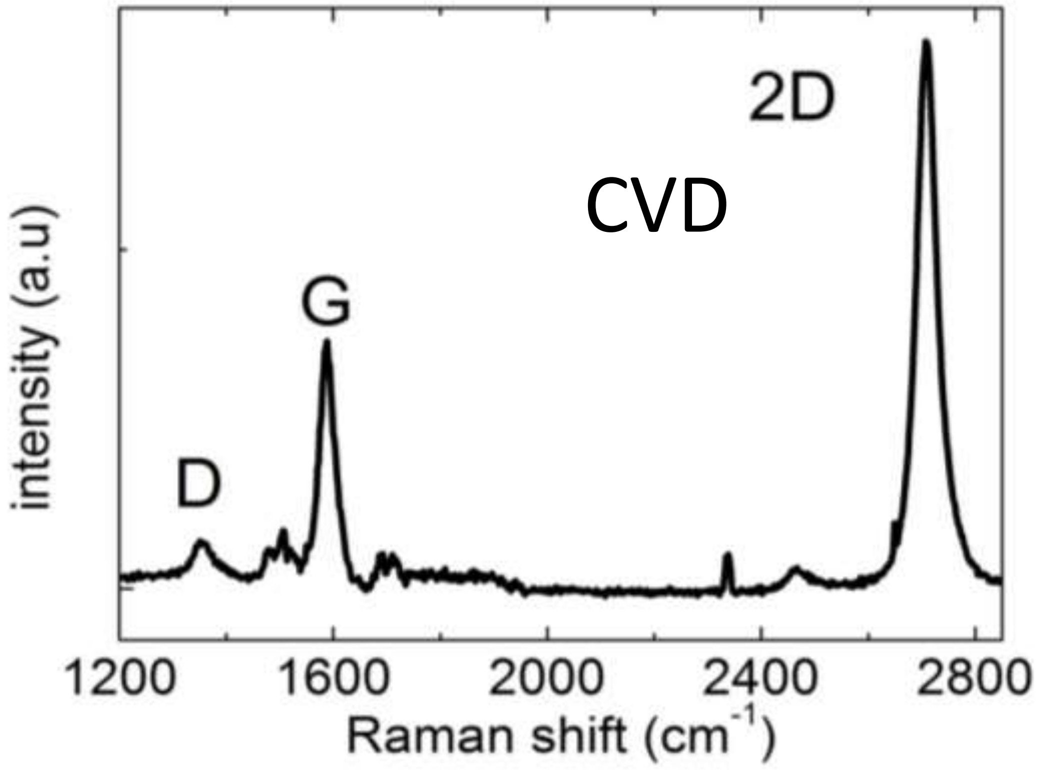


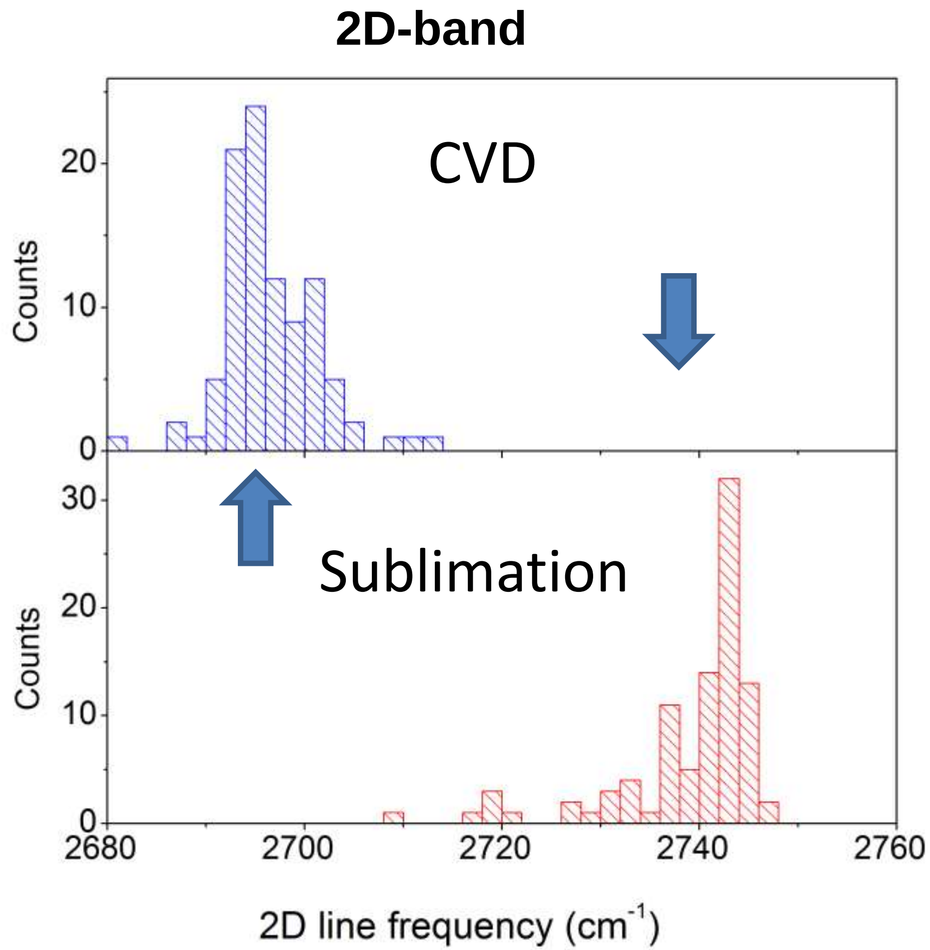
Dirac fermions!



W. Strupinski et al. Nano Lett. 11, 1786 (2011)

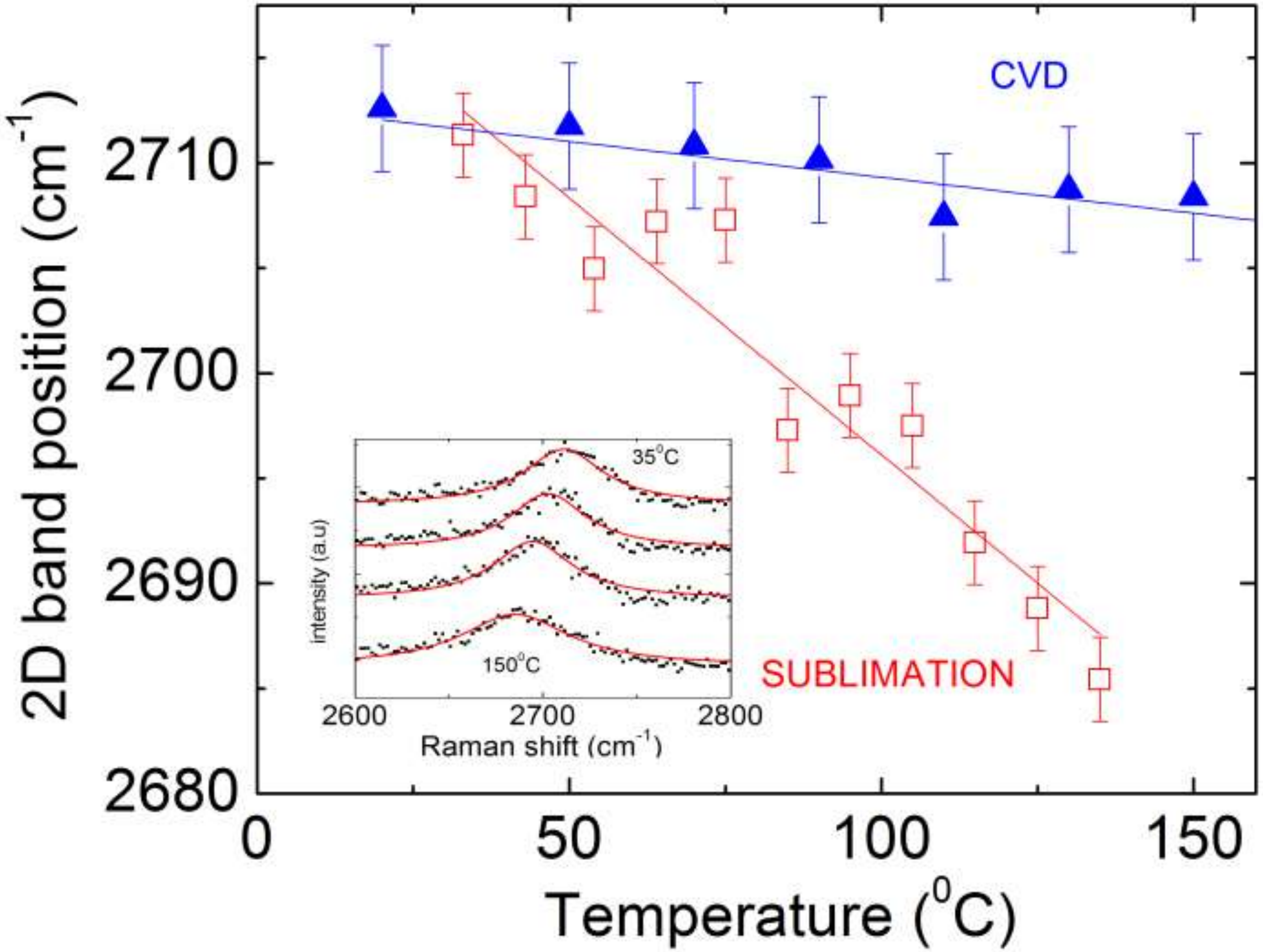
Interaction with the substrate





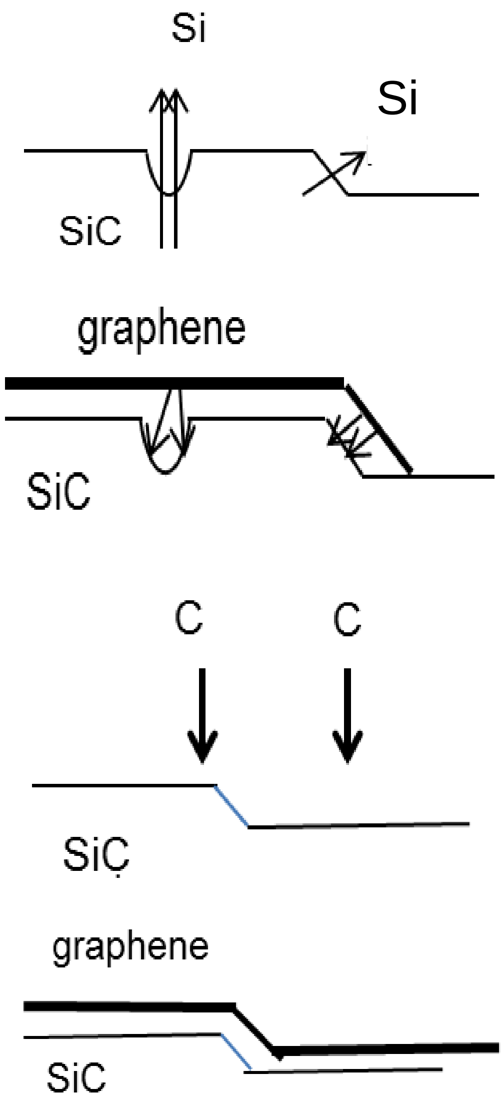
W. Strupinski et al. Nano Lett. 11, 1786 (2011)
K. Grodecki et al., J. Appl. Phys. 111, 114307 (2012)

Temperature dependence of 2D-band position

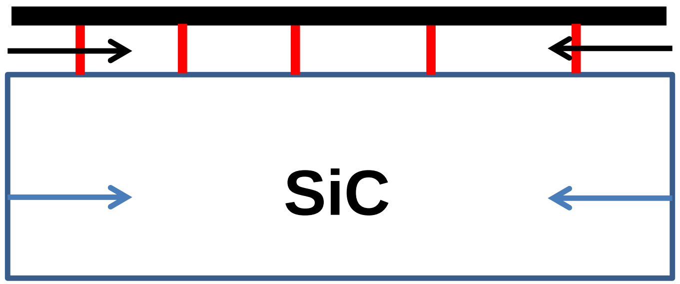


K. Grodecki et al., J. Appl. Phys. 111, 114307 (2012)

Interaction with the substrate



Sublimation

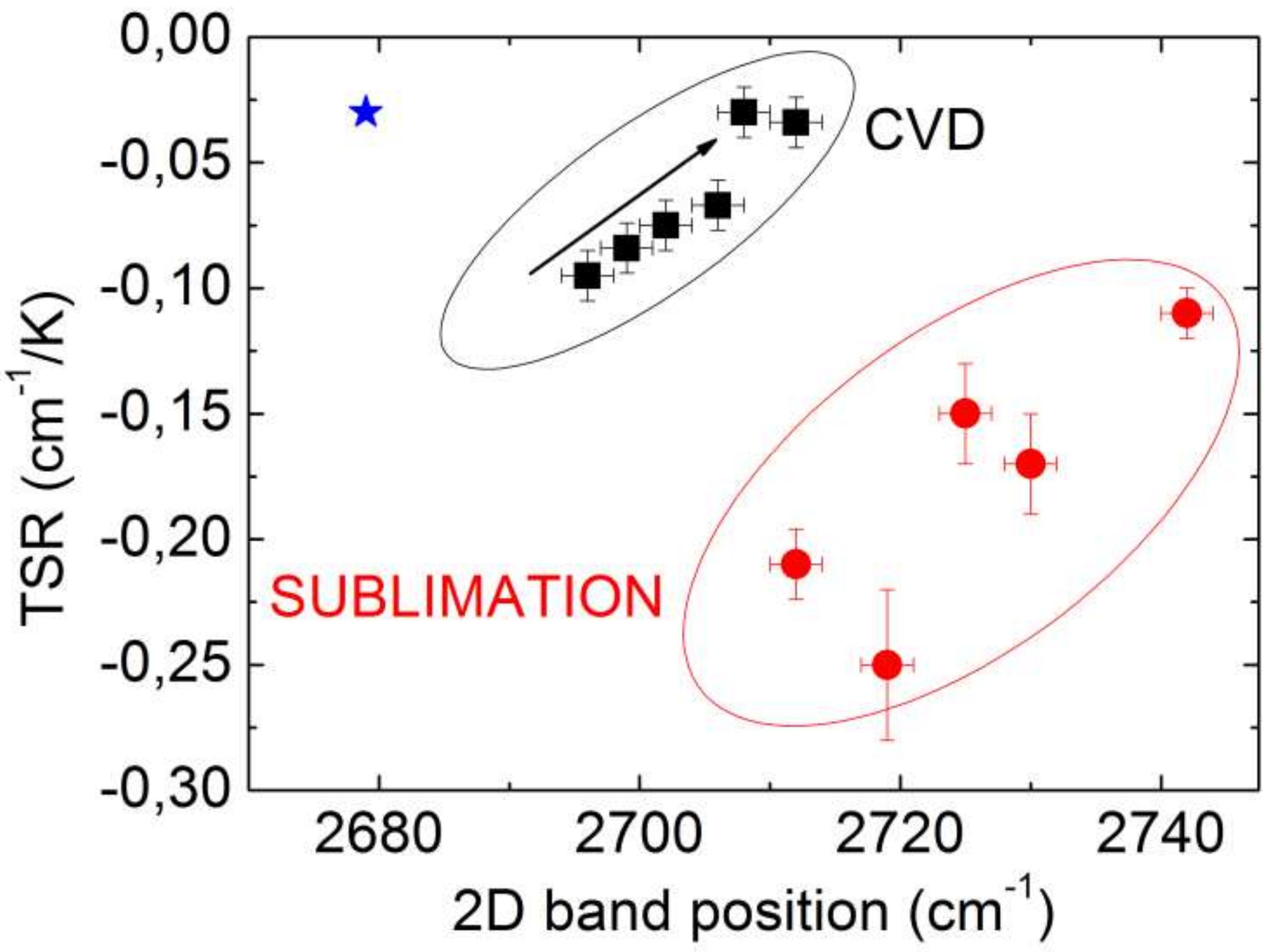


Graphene strongly **pinned** to the substrate (**defects**, step edges…)

CVD

Graphene can slide over the substrate…

„Phase diagram”

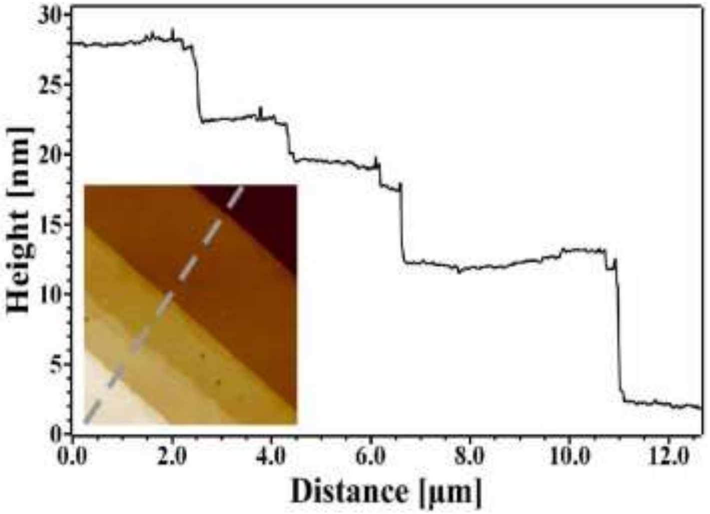


K. Grodecki et al., J. Appl. Phys. 111, 114307 (2012)

Microscale Raman experiments

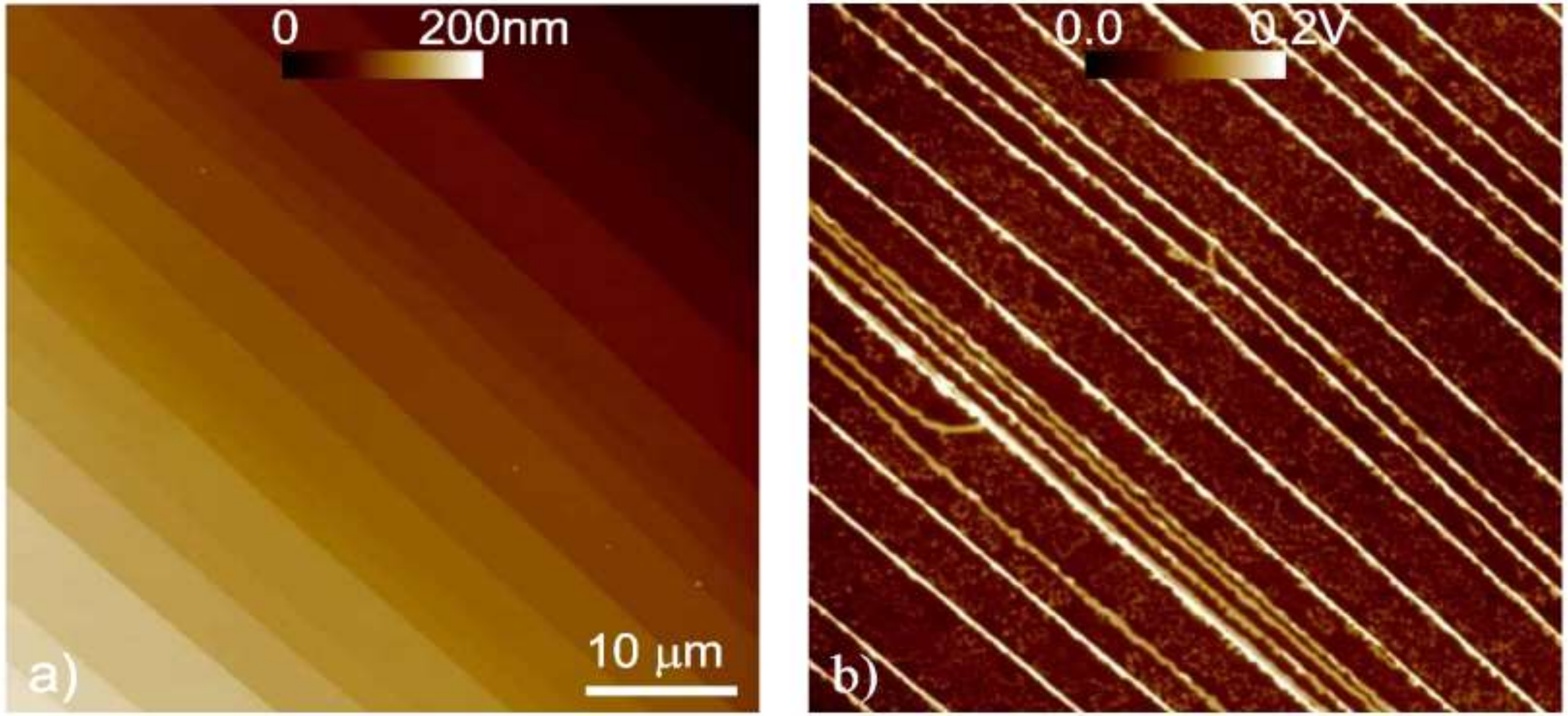
↓

steps play a role…

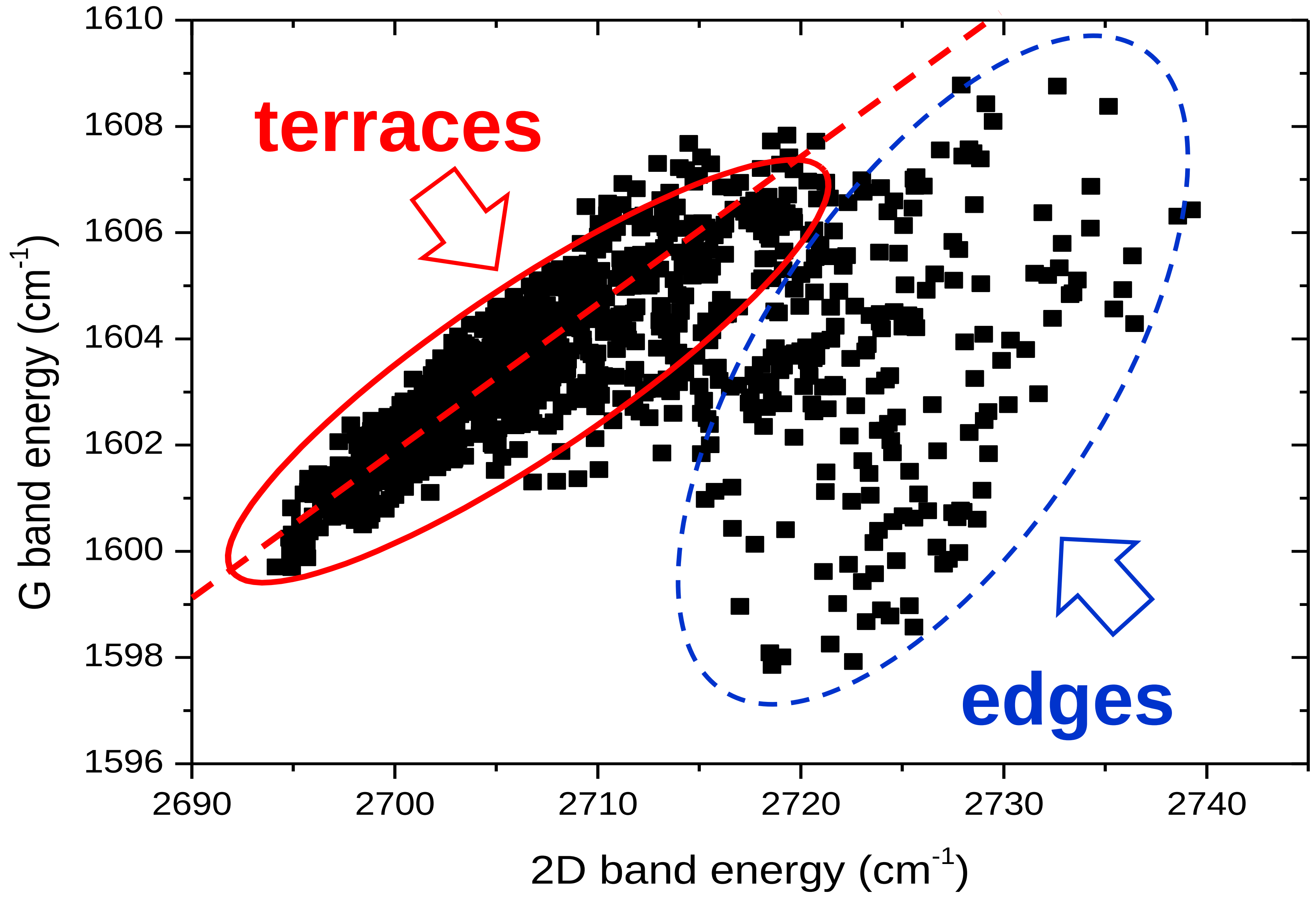


AFM &
Kelvin Probe Microscopy

CVD graphene
4H-SiC Si-face



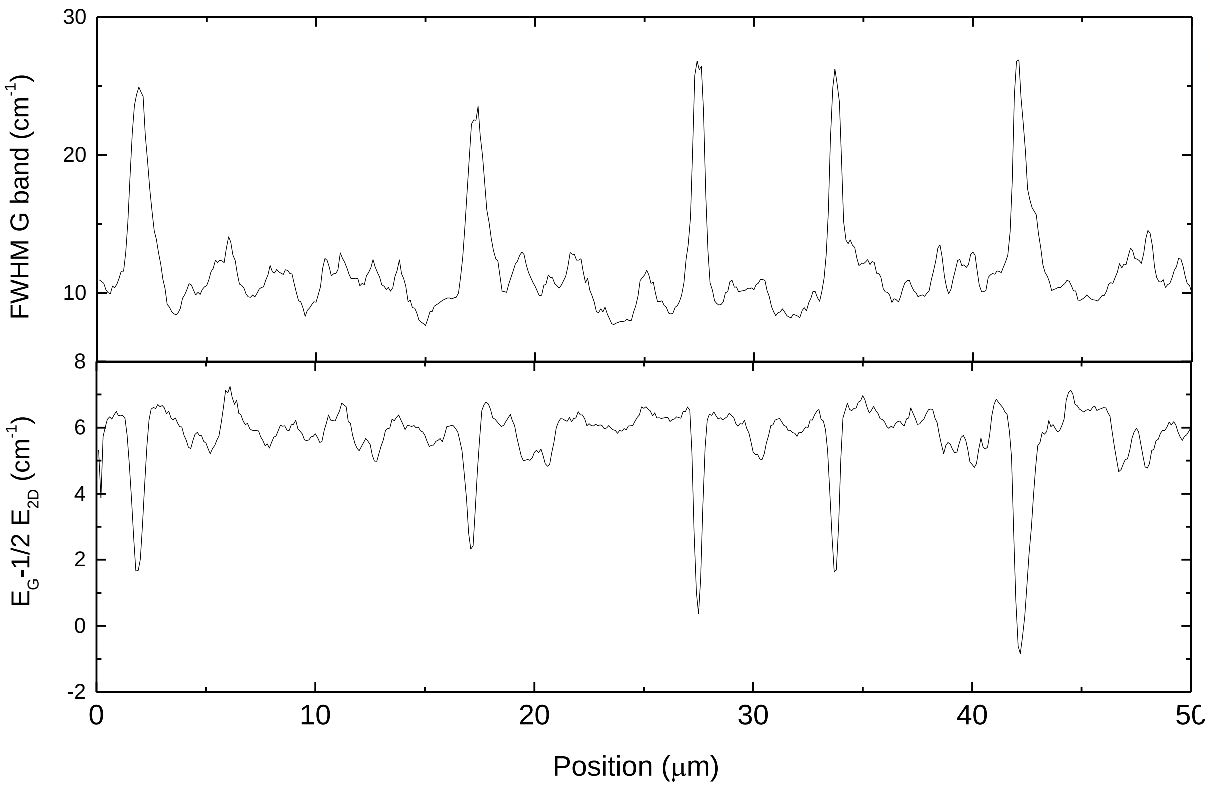
R. Bożek (2012)

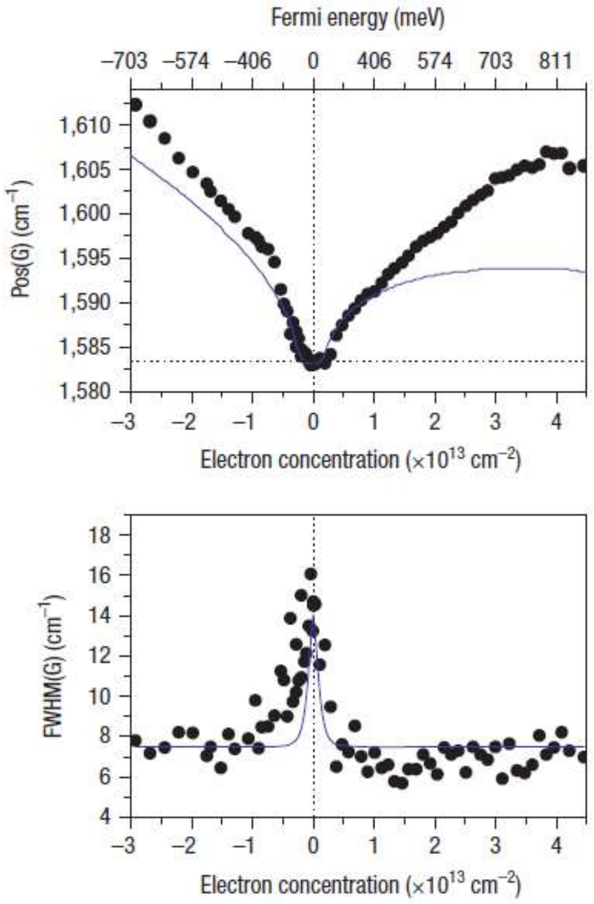


Grodecki et. al. APL , 100, 26 (2012)

FWHM vs. G-band position

CVD



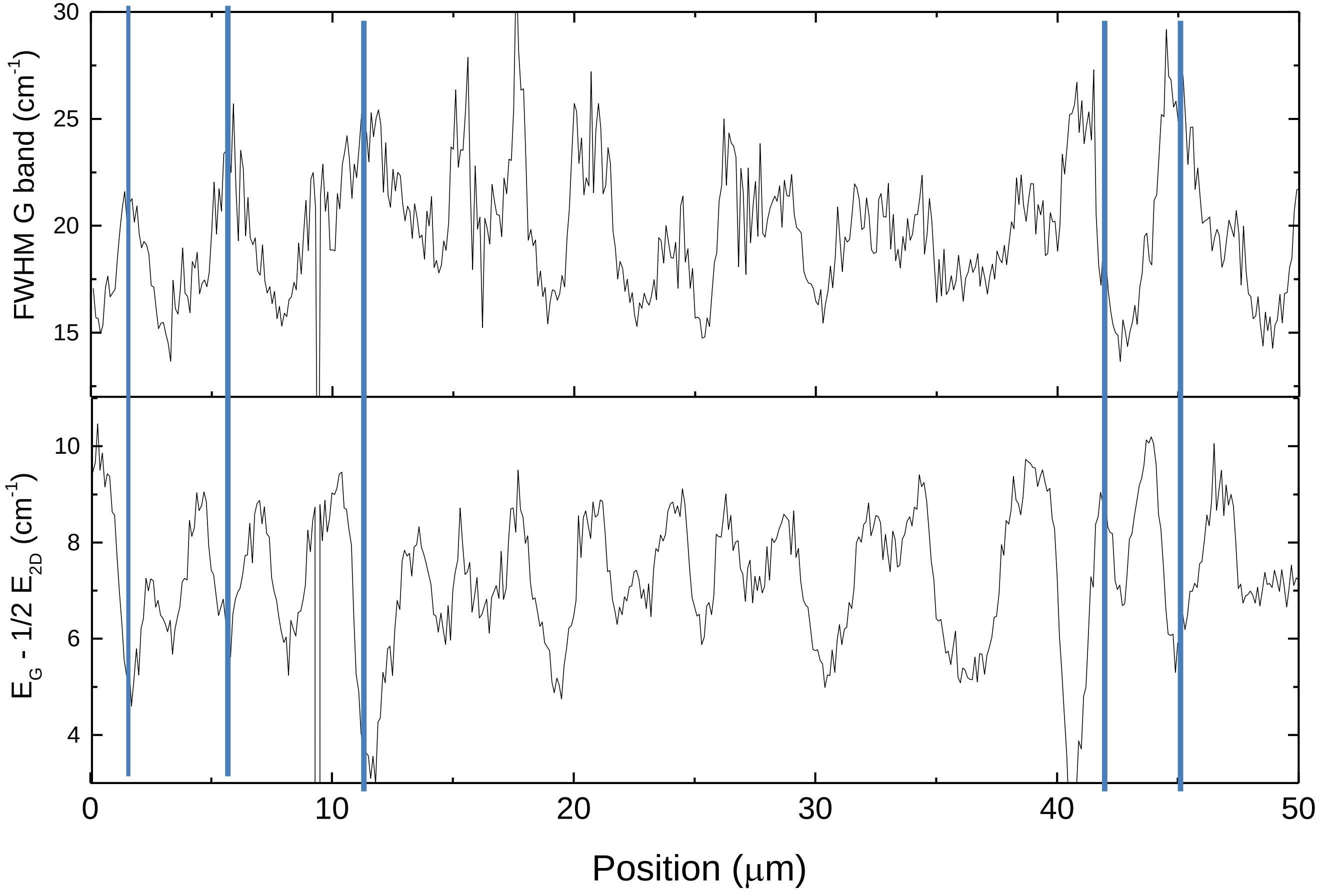


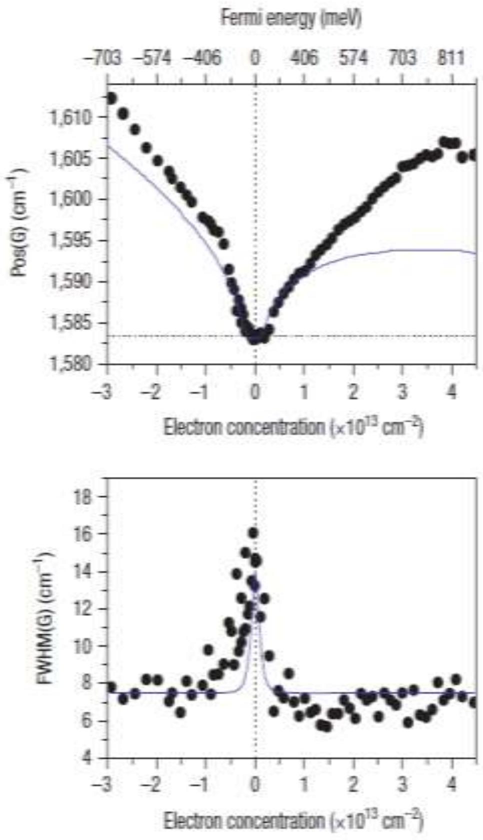
A. Das et al.
Nature Nan. 3, 210 (2008)

Well defined terraces!

G-band - FWHM vs. position

Sublimation





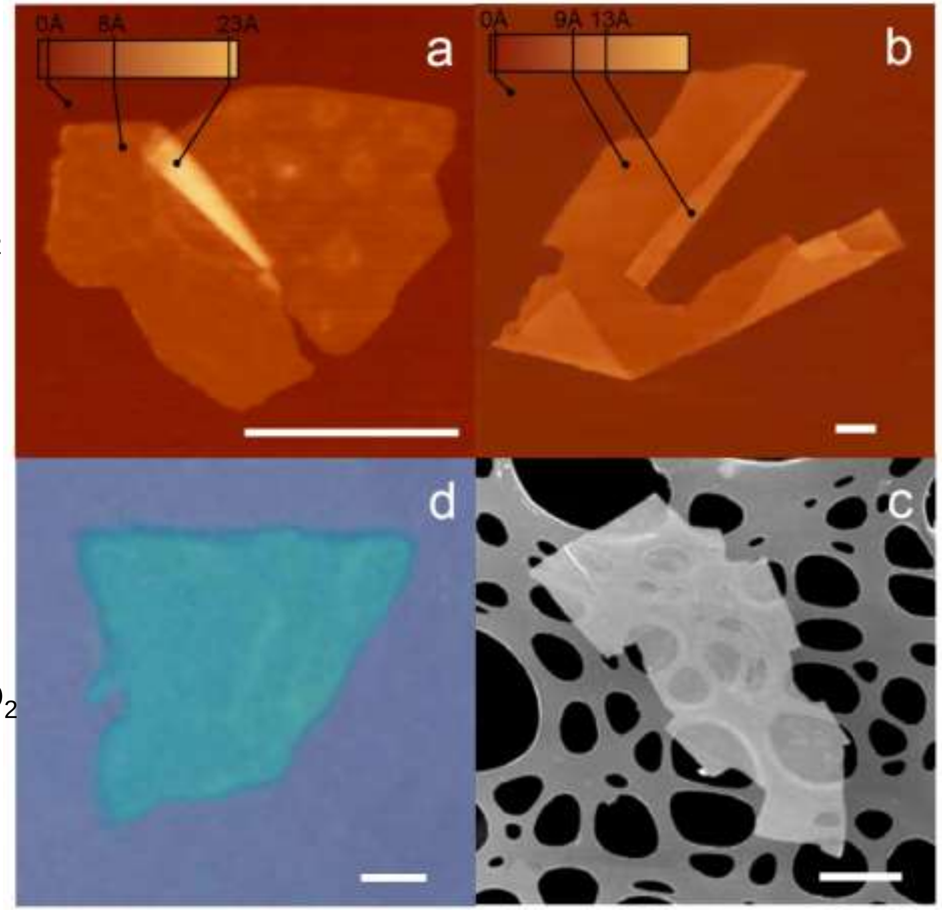
A. Das et al.
Nature Nan. 3, 210 (2008)

Erosion of steps…

Other 2D materials

Single layers

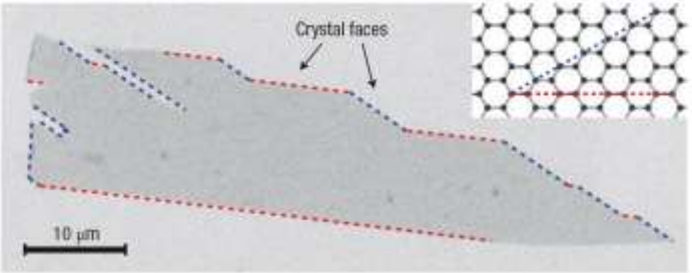
$NbSe_2$
on Si/SiO_2



MoS_2
on Si/SiO_2

graphite
on Si/SiO_2

graphene "big flake"



$Bi_2Sr_2CaCu_2O_x$
on carbon

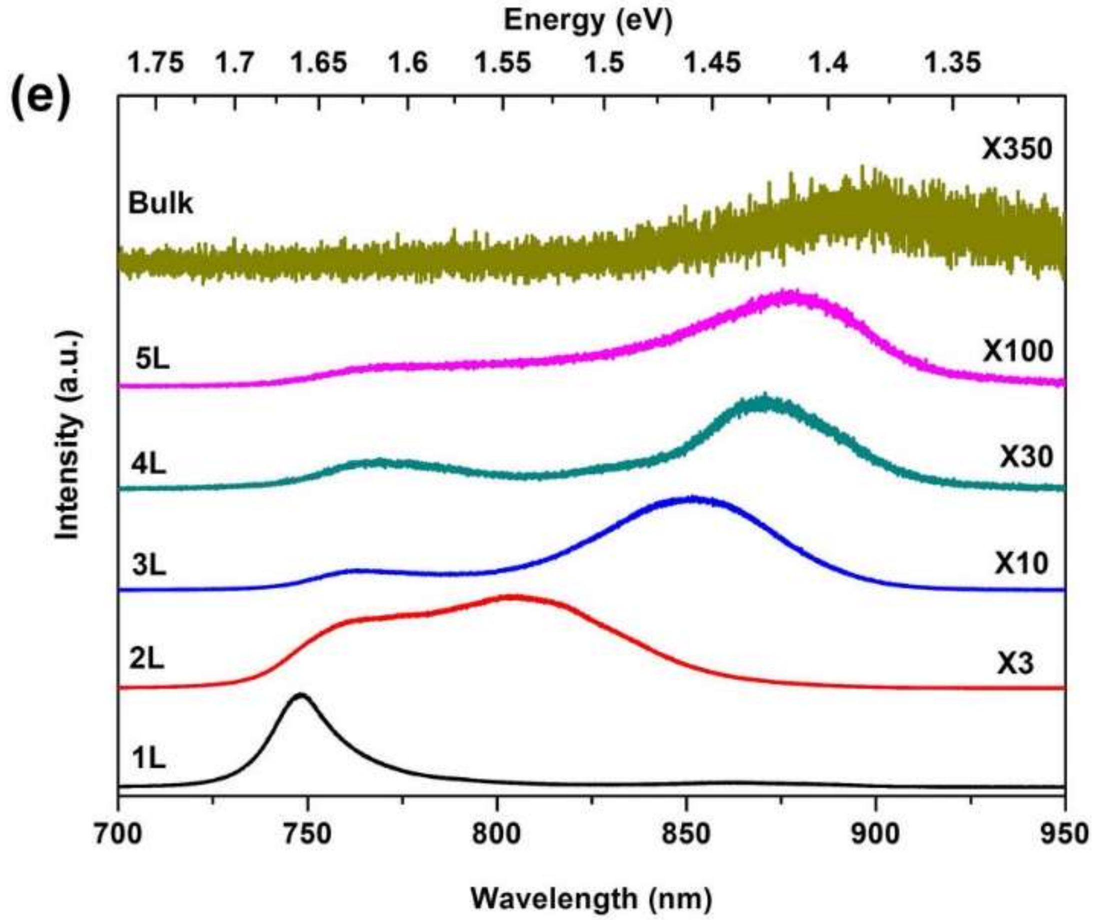
K.S. Novoselov, *et al.*, *Two-dimensional atomic crystals*, *Proc. Natl Acad. Sci. USA*, **102,** 10451–10453 (2005)
K.S. Novoselov and A.K. Geim,
The rise of graphene, Nature Materials, **6**, 183, (2007)

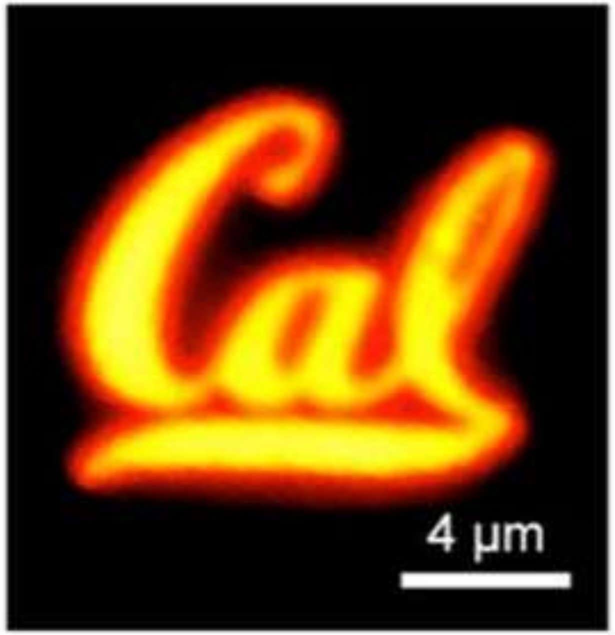
Van der Waals heterostructures – new possibilities

Graphene family	Graphene	hBN 'white graphene'	BCN	Fluorographene	Graphene oxide
2D chalcogenides	MoS_2, WS_2, $MoSe_2$, WSe_2		Semiconducting dichalcogenides: $MoTe_2$, WTe_2, ZrS_2, $ZrSe_2$ and so on	Metallic dichalcogenides: $NbSe_2$, NbS_2, TaS_2, TiS_2, $NiSe_2$ and so on Layered semiconductors: GaSe, GaTe, InSe, Bi_2Se_3 and so on	
2D oxides	Micas, BSCCO Layered Cu oxides	MoO_3, WO_3 TiO_2, MnO_2, V_2O_5, TaO_3, RuO_2 and so on	Perovskite-type: $LaNb_2O_7$, $(Ca,Sr)_2Nb_3O_{10}$, $Bi_4Ti_3O_{12}$, $Ca_2Ta_2TiO_{10}$ and so on	Hydroxides: $Ni(OH)_2$, $Eu(OH)_2$ and so on Others	

A. K. Geim & I. V. Grigorieva, Nature 499, 419 (2013)

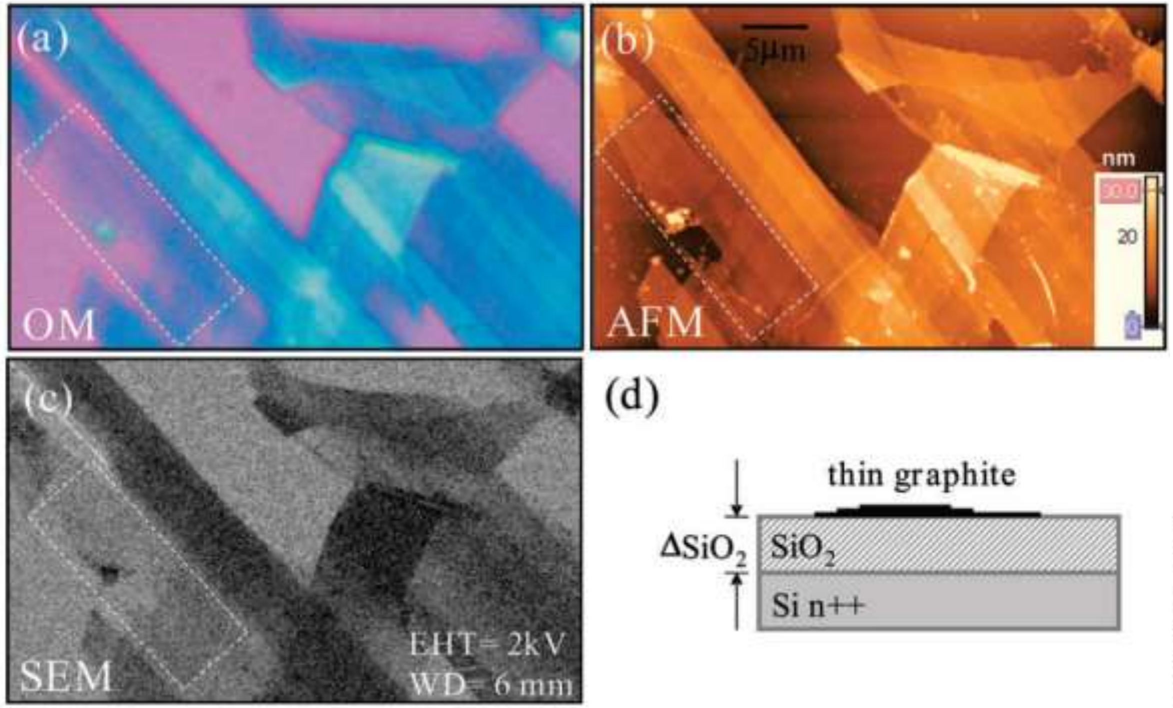
Unexpected behavior of the emission

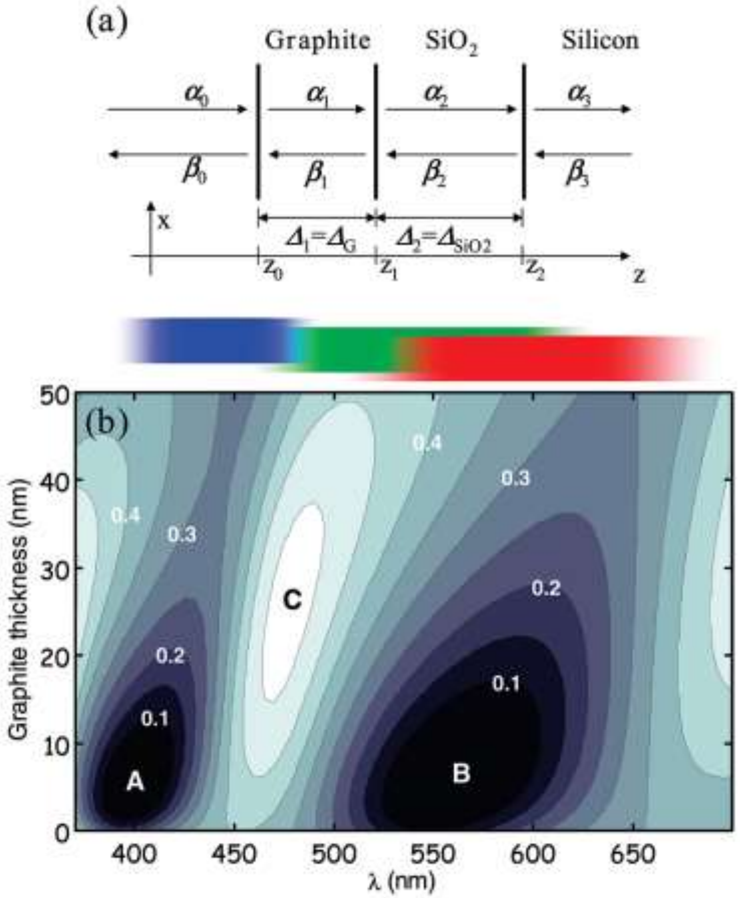




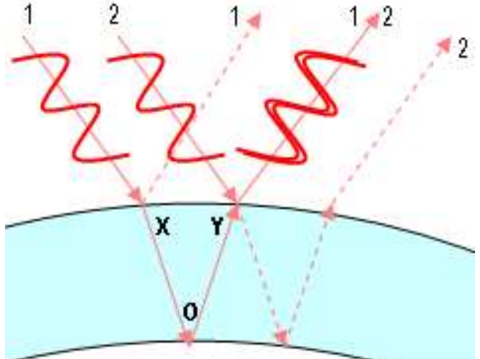
H. Terrones et al. Scientific Reports 4, 4215 (2014)   M. Amani et al. SCIENCE 350, 1065 (2015)

Interferences make 2D materials visible…



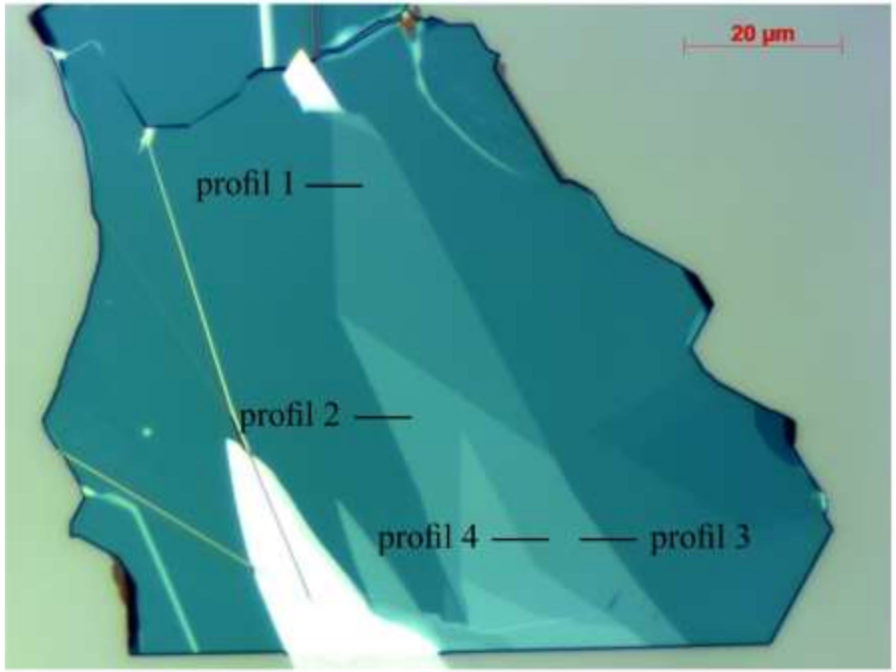


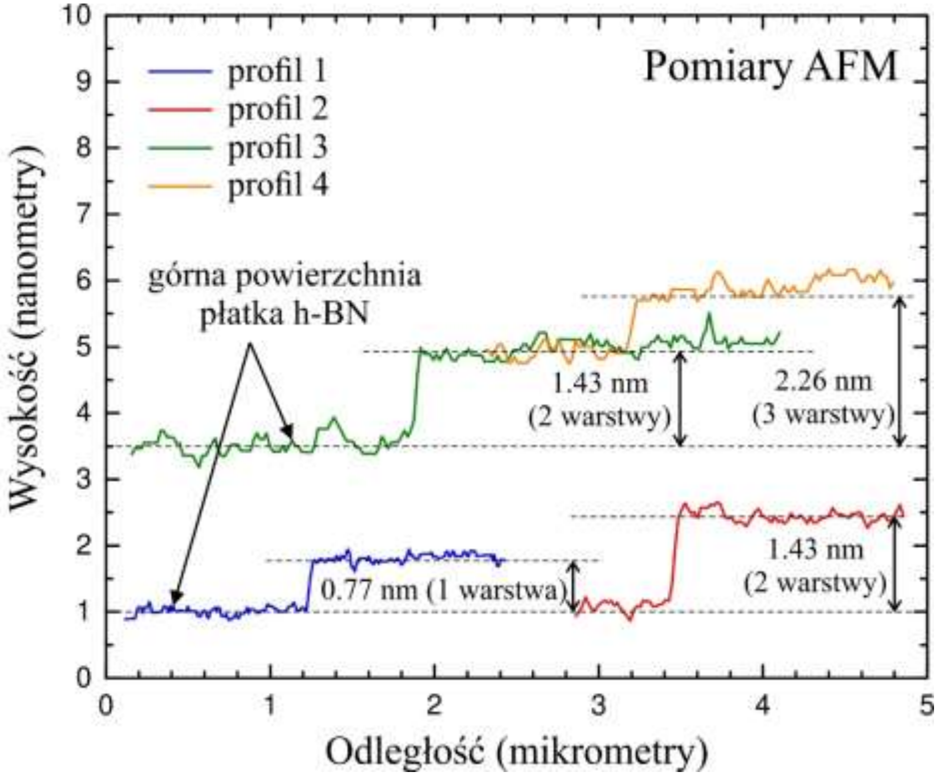
wikimedia.org



S. Roddaro et al. Nano Lett., 7, 2707 (2007)

Optical microscopy and Atomic Force Microscopy

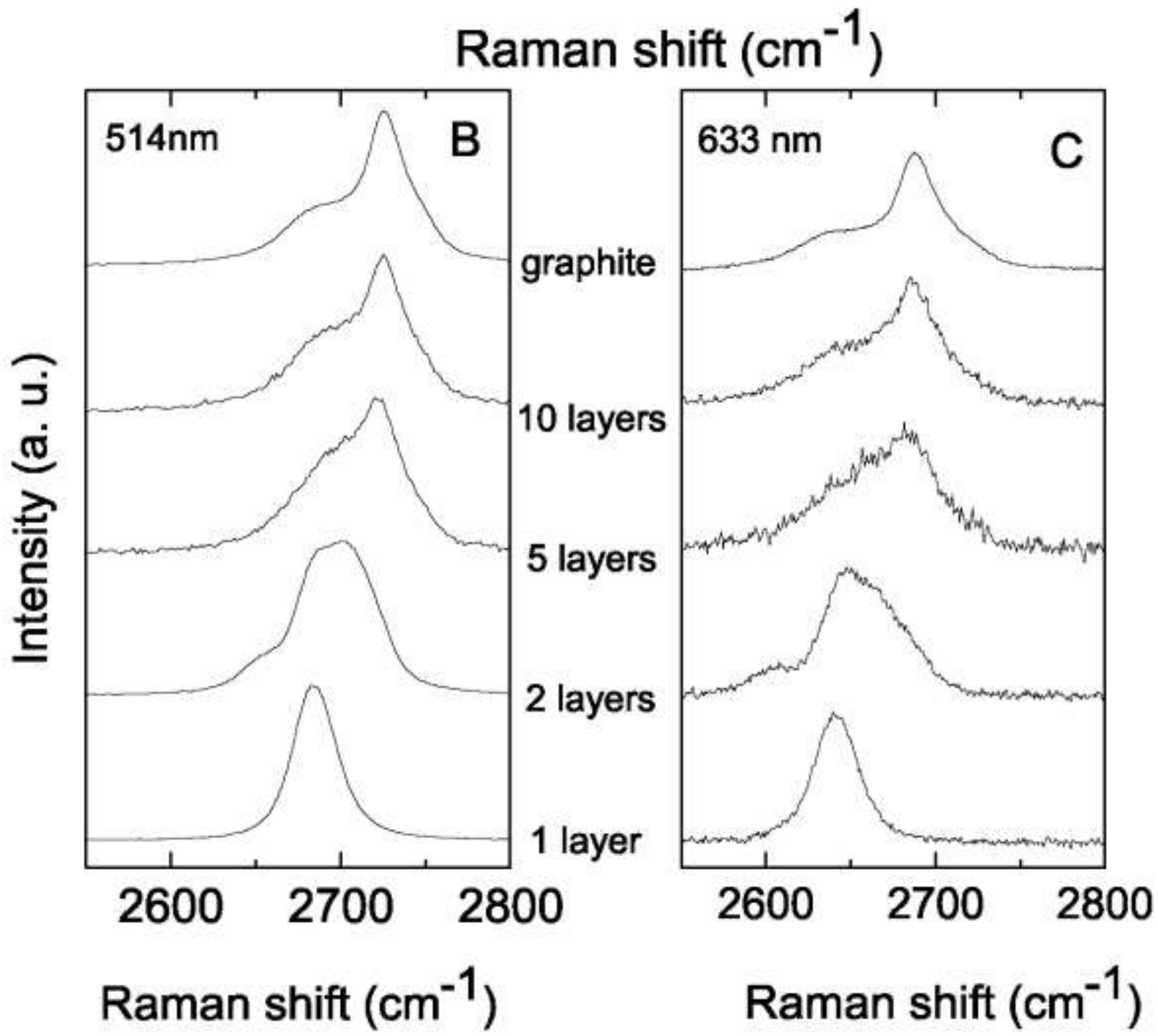




MoS2 on h-BN

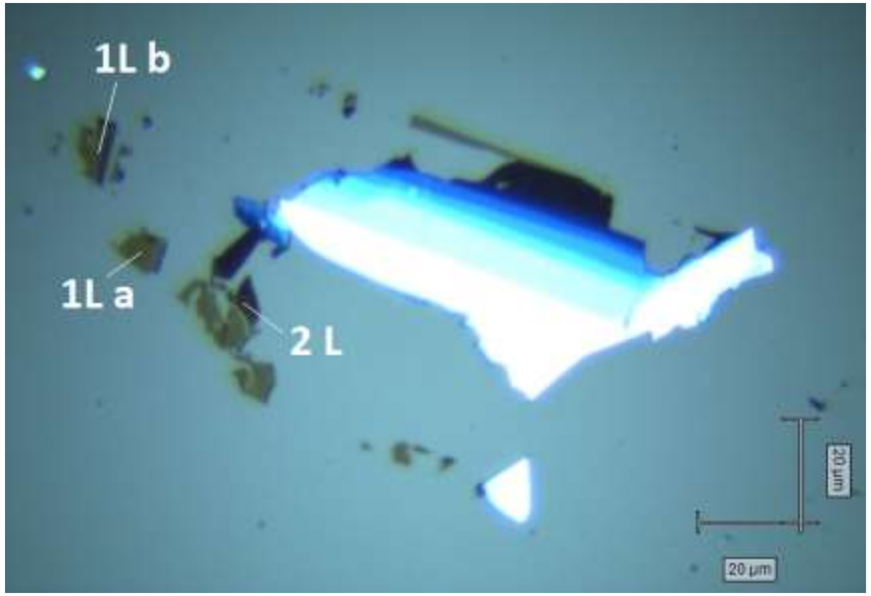
K. Nogajewski (2018)
Wydział Fizyki, NHMF Grenoble

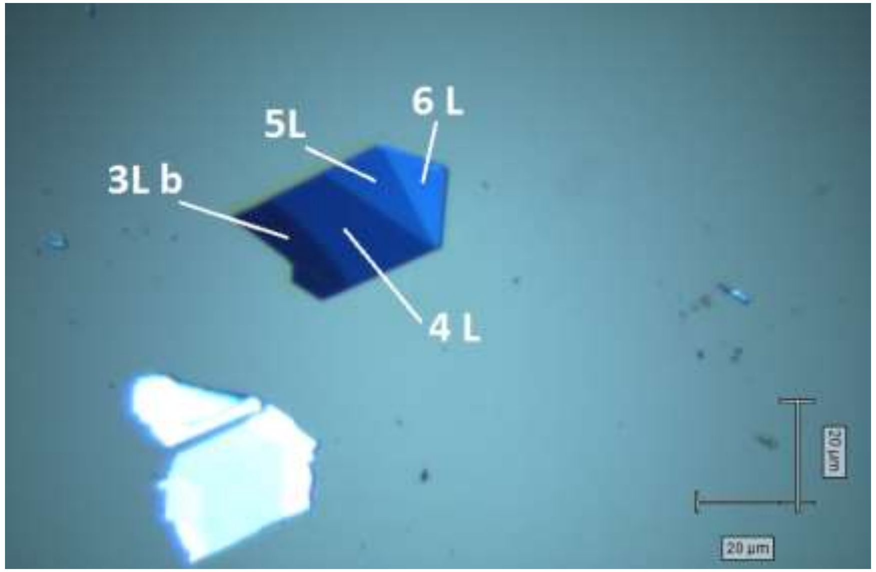
From graphite to graphene

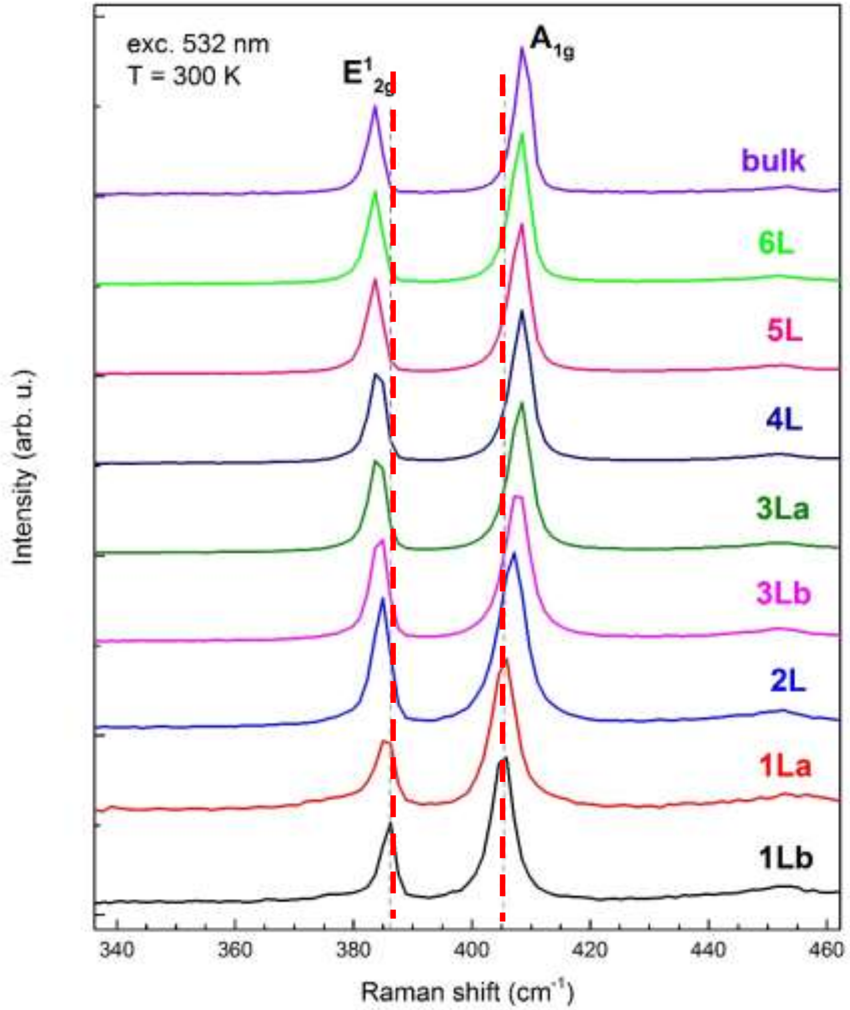


A.C. Ferrari et al.Phys. Rev. Lett. 97, 187401 (2006)

Number of layers – example: MoS_2

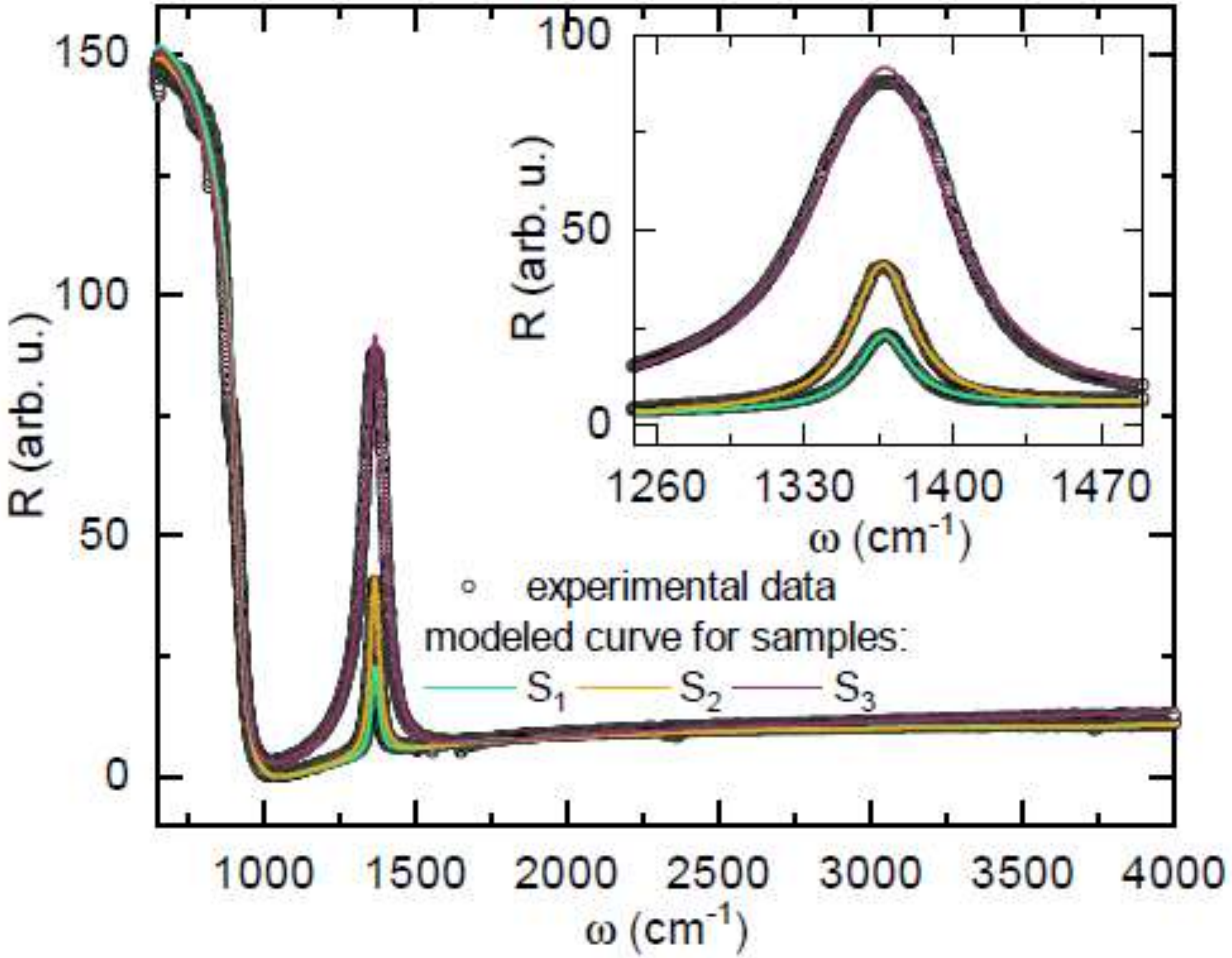






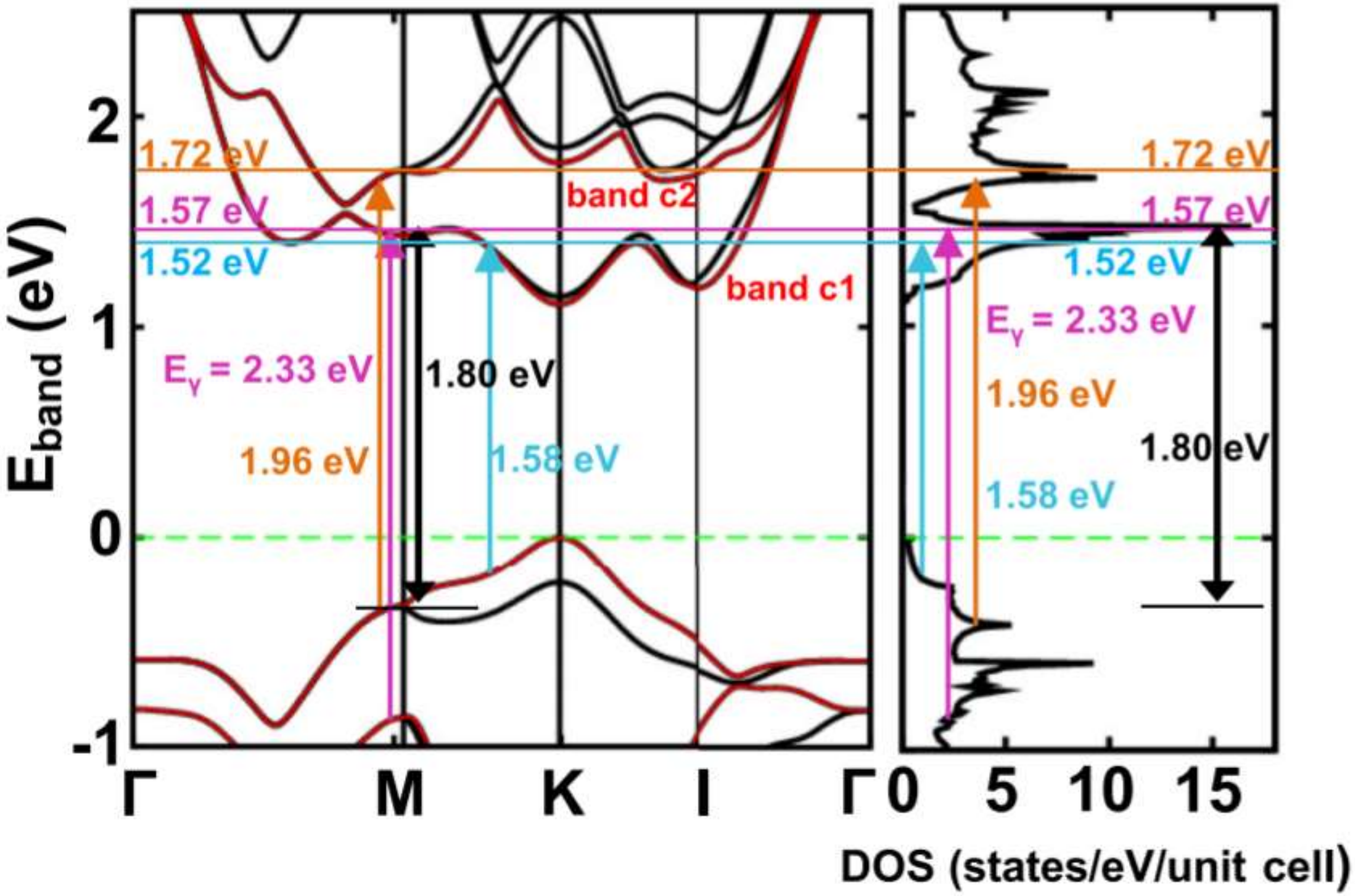
Ewa Łacińska (2017)
Wydział Fizyki UW

FTIR of BN layers



J. Iwanski et al (2022)

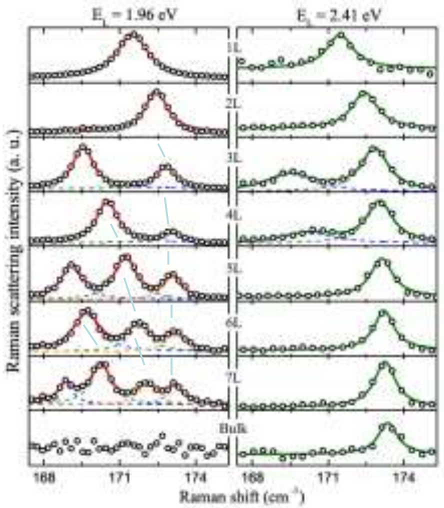
Raman Scattering of TMDC (examples)



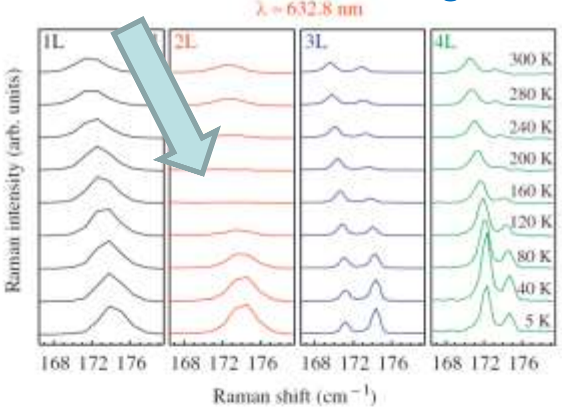
Huaihong Guo et al., Double resonance Raman modes in monolayer and few-layer $MoTe_2$, Physical Review B 91, 205415 (2015)

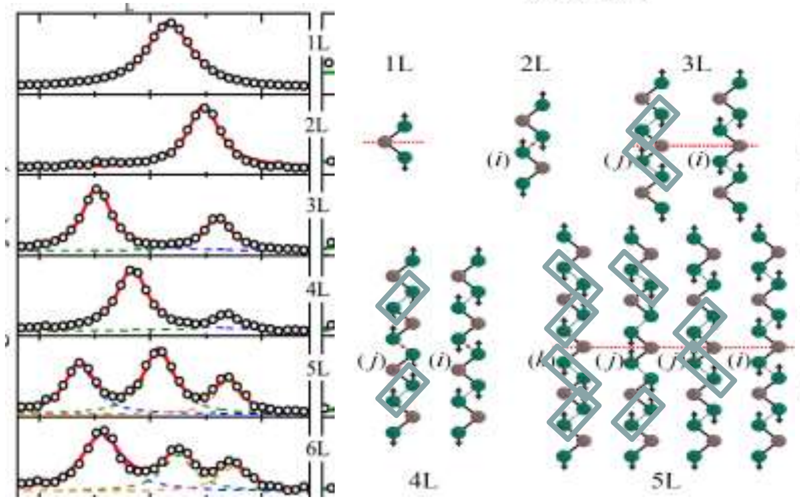
Raman Scattering of TMDC (examples)

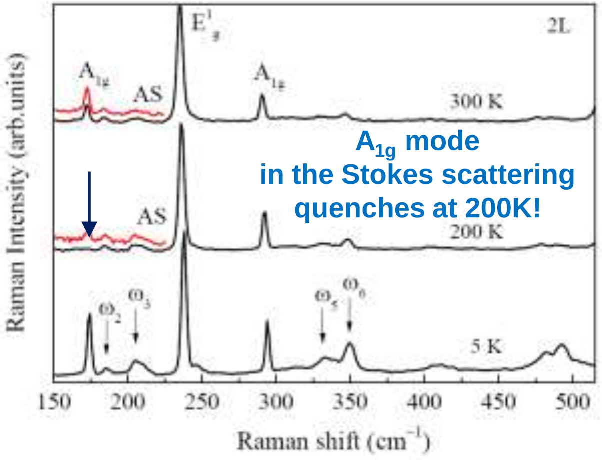
A_{1g}/A'_1 modes
in $MoTe_2$
Davydov splitting



Resonant quenching of
Raman scattering







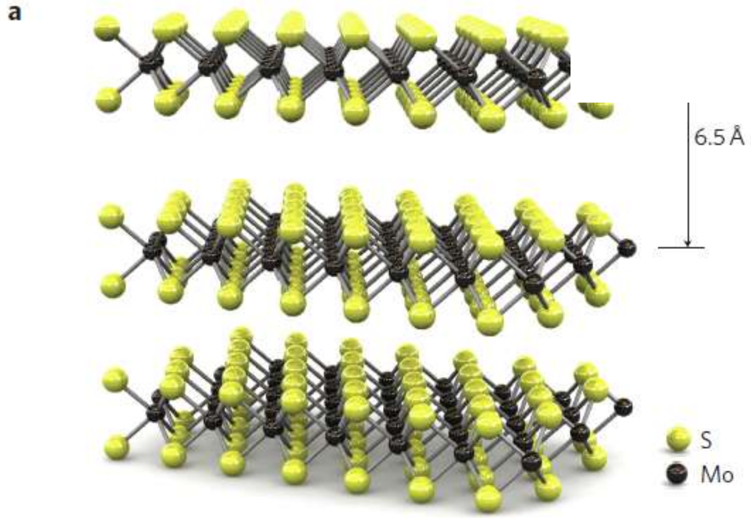
A_{1g} mode
in the Stokes scattering
quenches at 200K!

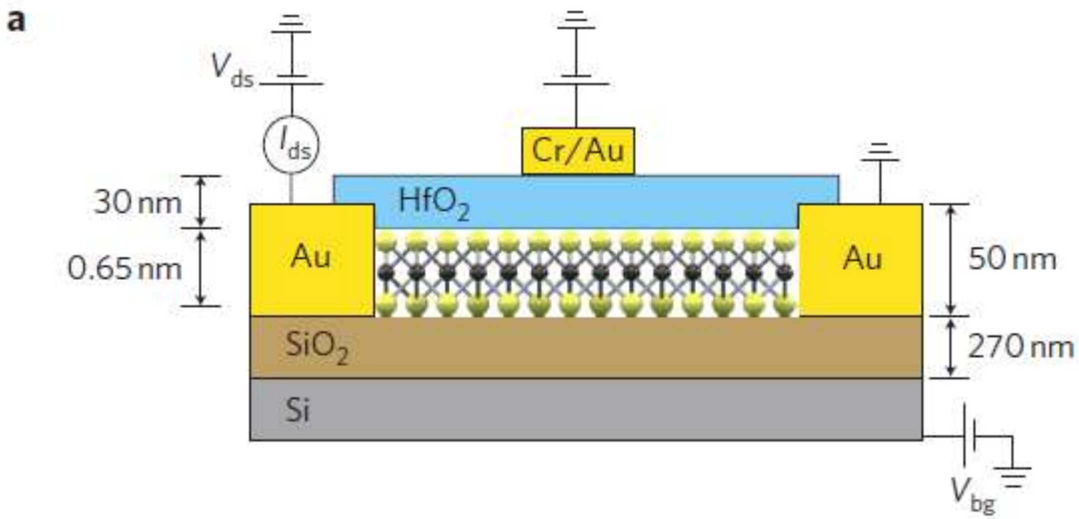
M.Grzeszczyk et al., *2D Materials* **3** 025010 (2016)

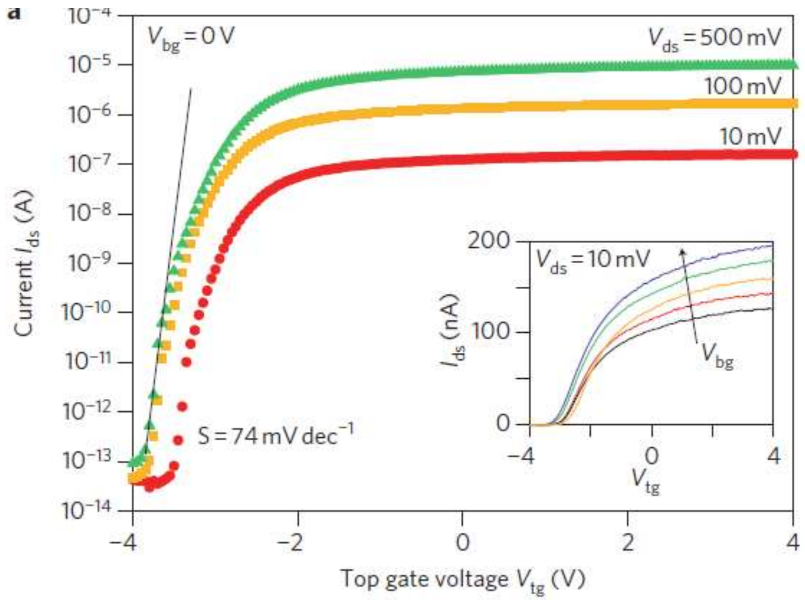
K. Gołasa et al, *Nanophotonics* **6**, 1281 (2017)

MoS_2 – silicon competitor?

Scotch tape method works!

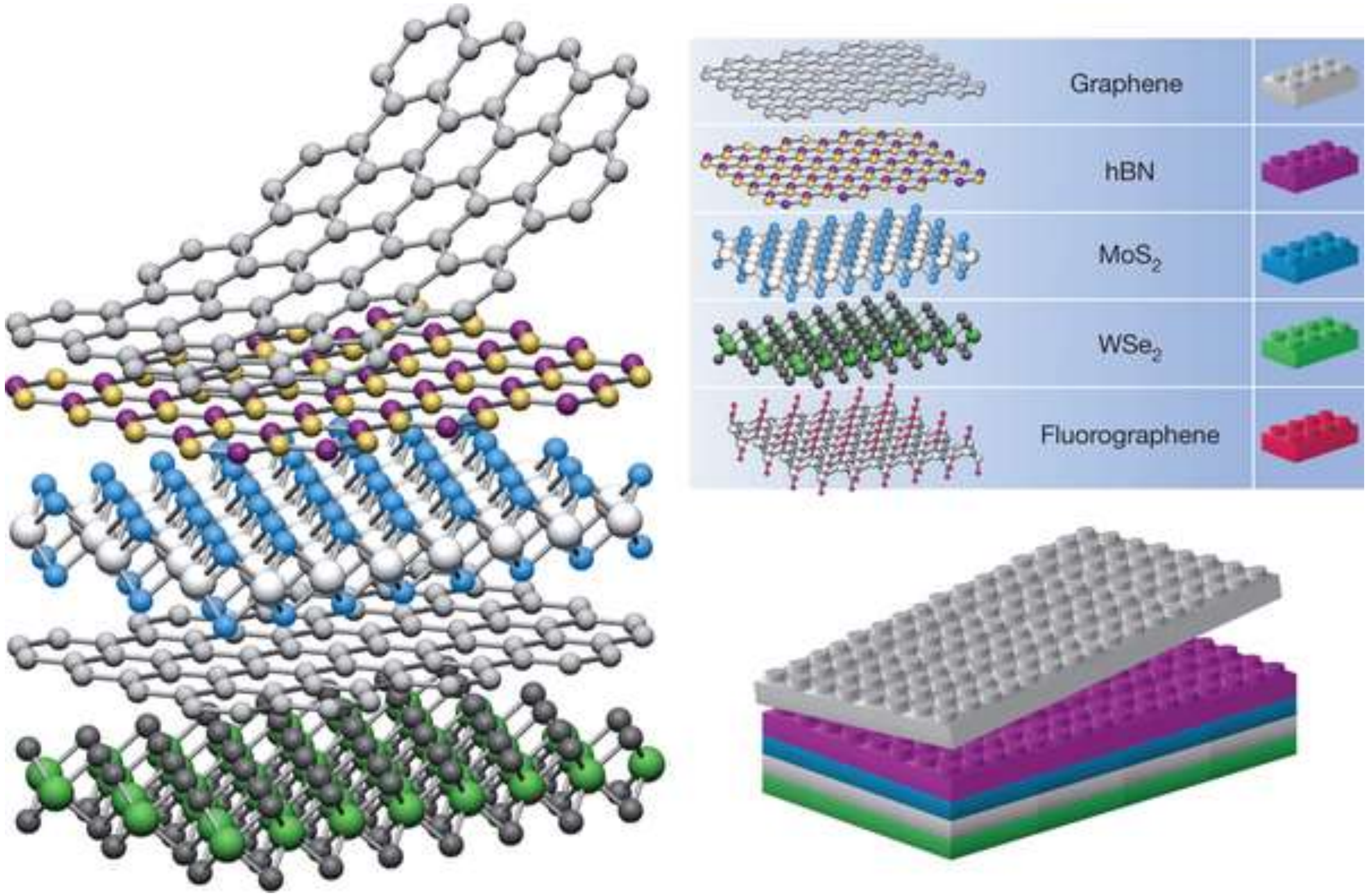






B. Radisavljevic et al., Nature naotechnology (2011)

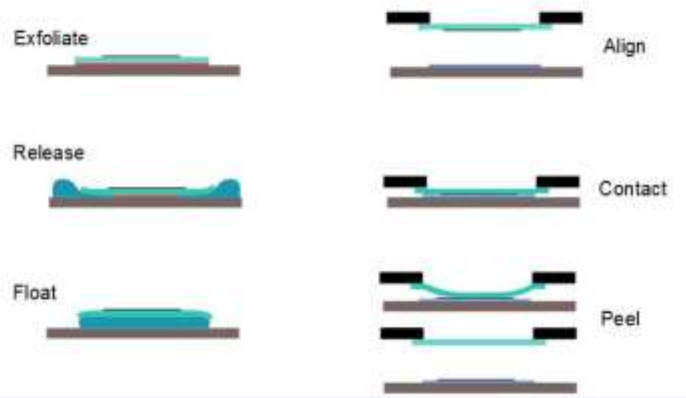
Nano-LEGO system



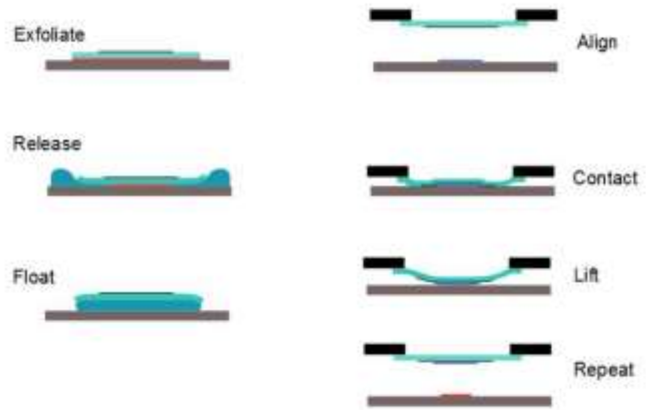
A. K. Geim & I. V. Grigorieva, Nature 499, 419 (2013)

Fabrication

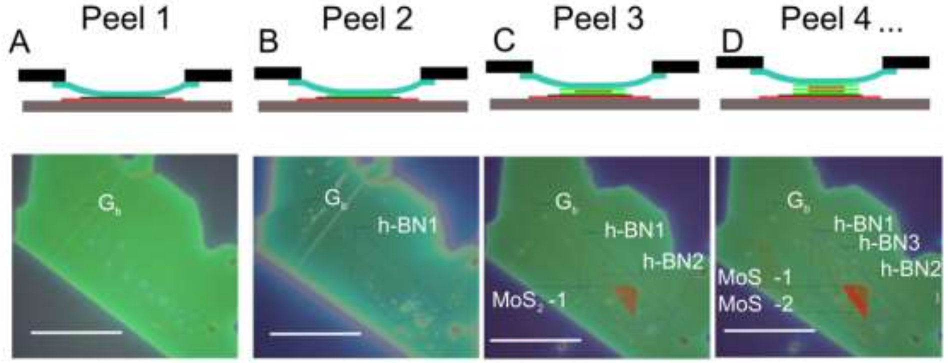
“Peel”



“Lift” or “pick-up”

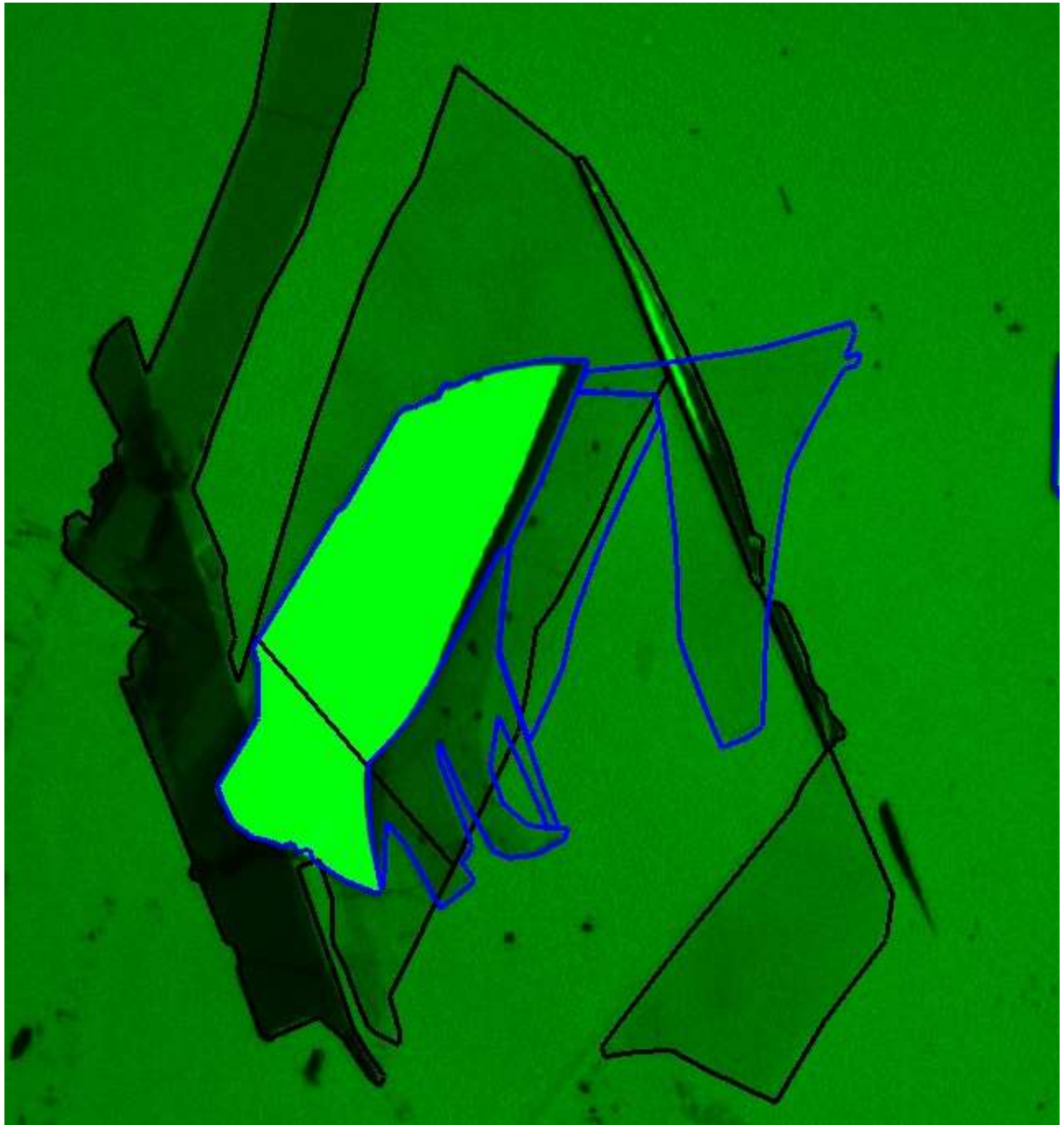


Multiple runs



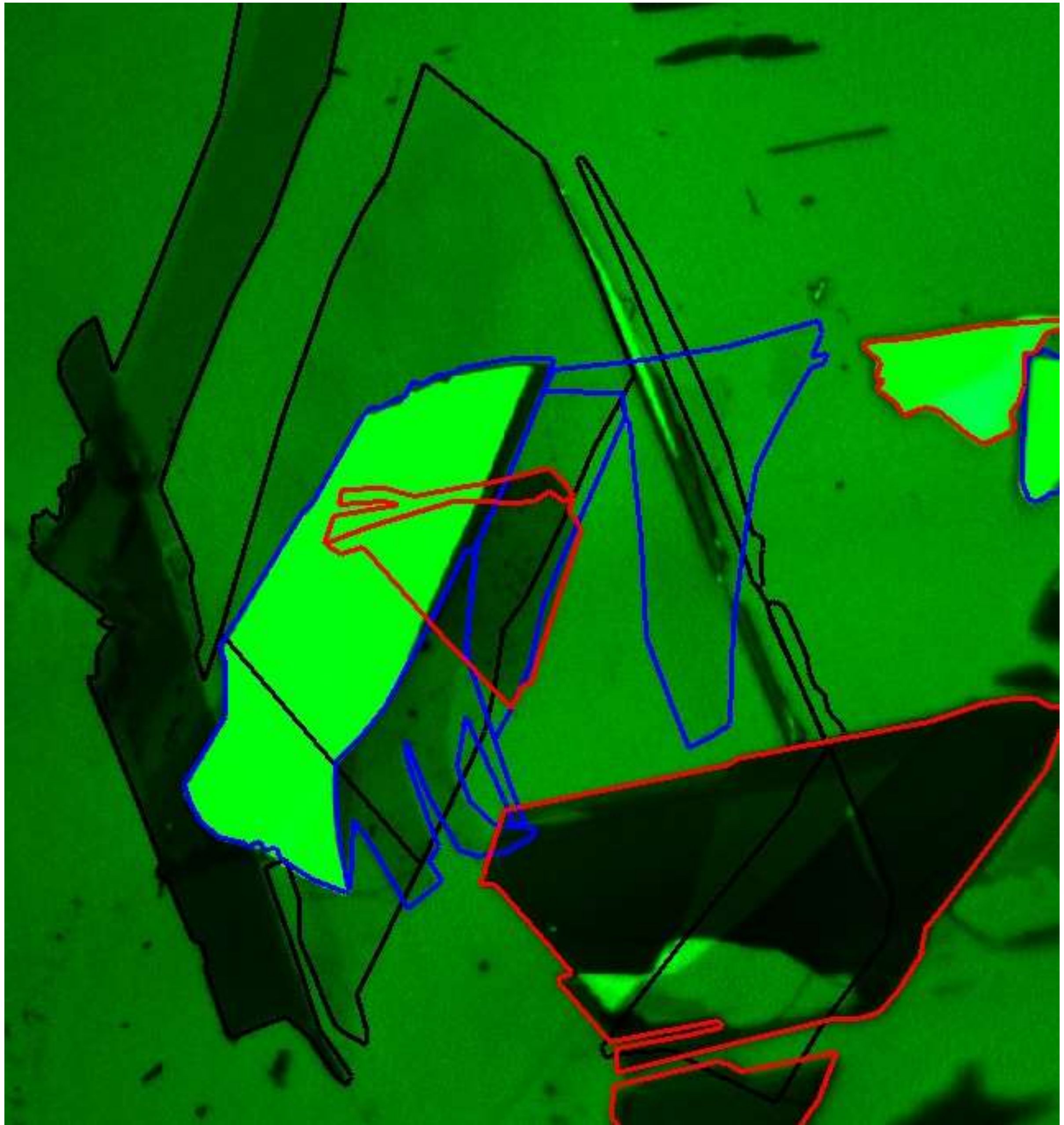
Supplementary information: F. Withers et al. Nature materials **14**, 302 (2015)

Transfer



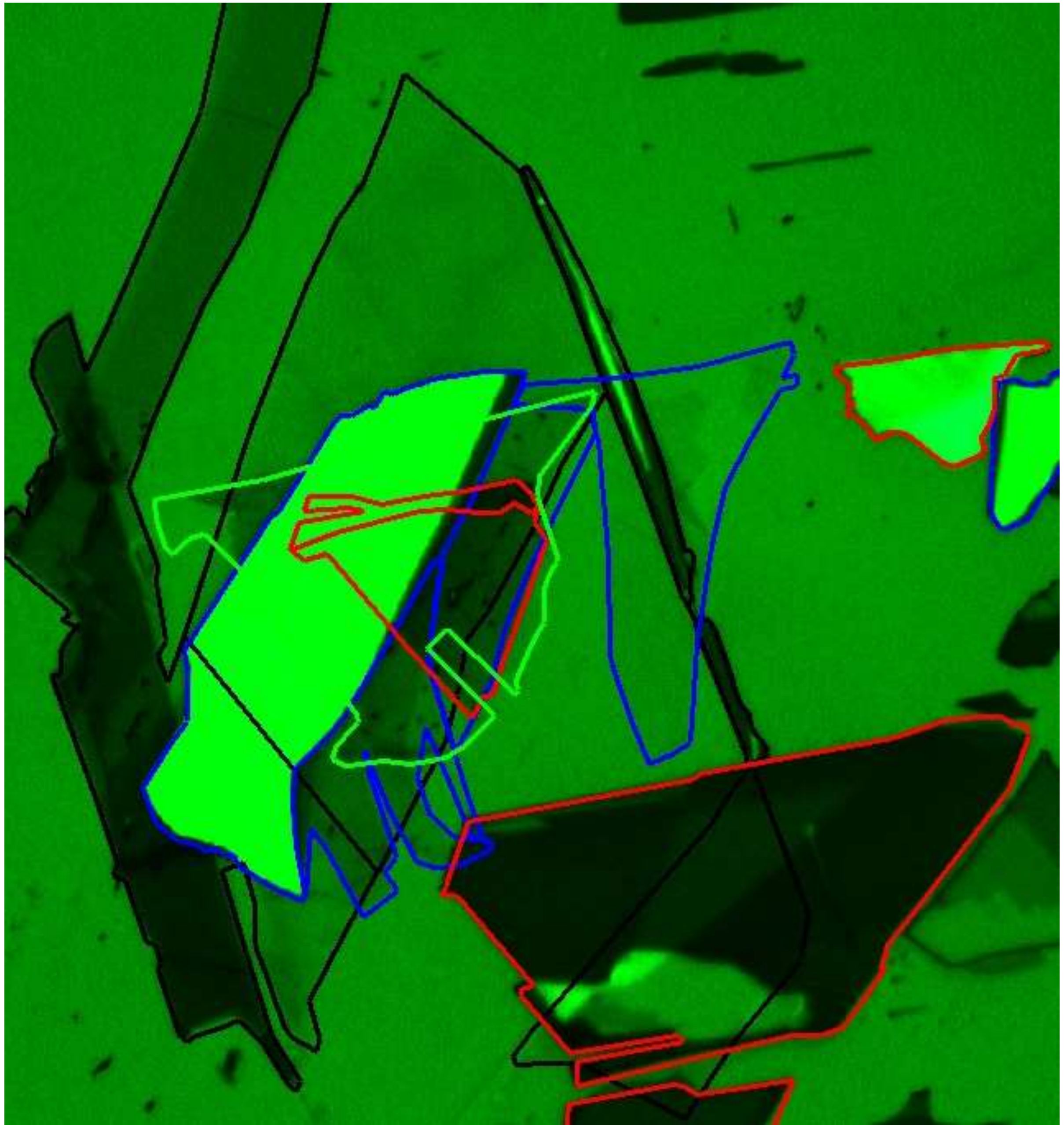
A. Kozikov
University of Manchester

Transfer



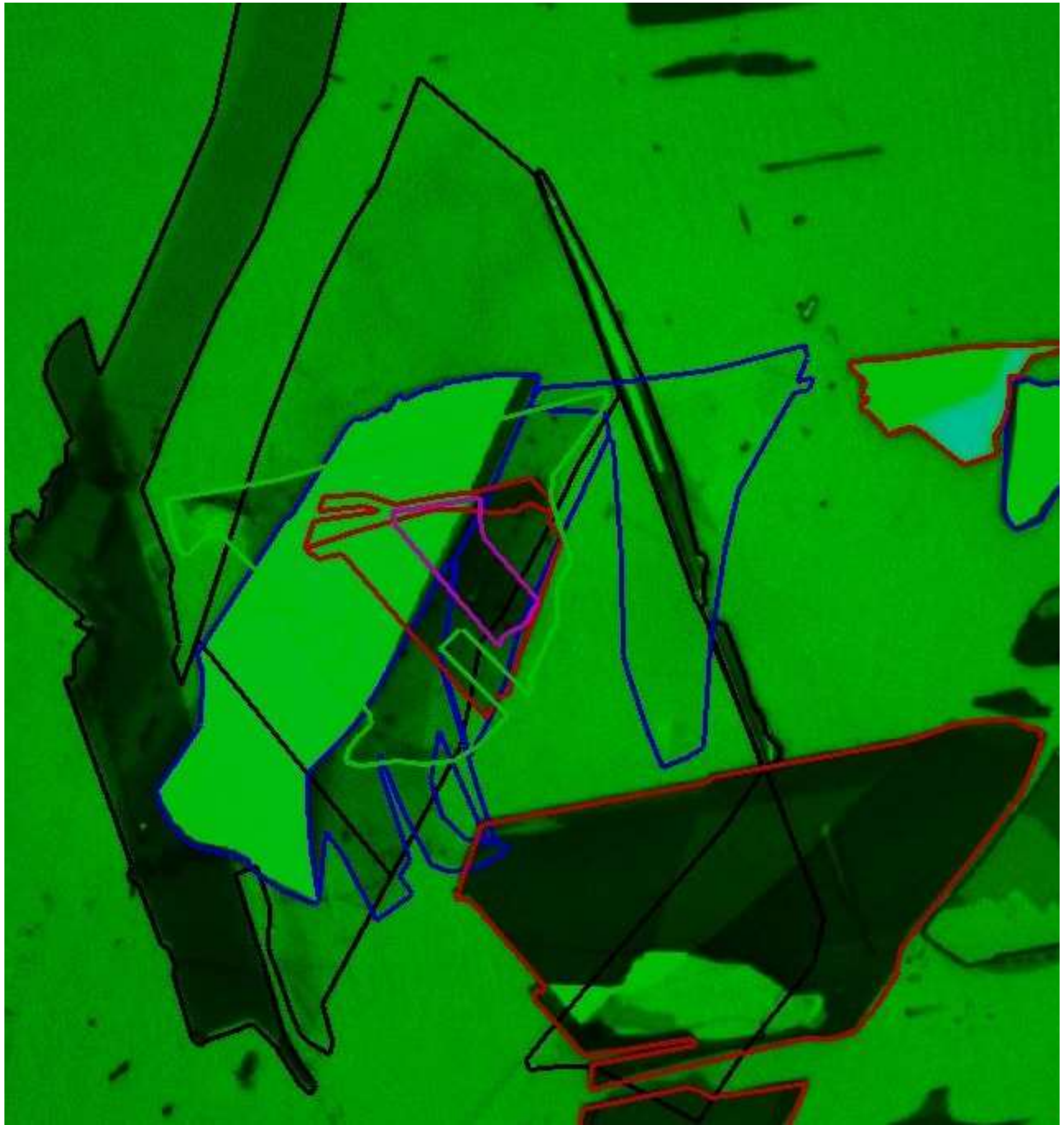
A. Kozikov
University of Manchester

Transfer



A. Kozikov
University of Manchester

Transfer



Gr

BN

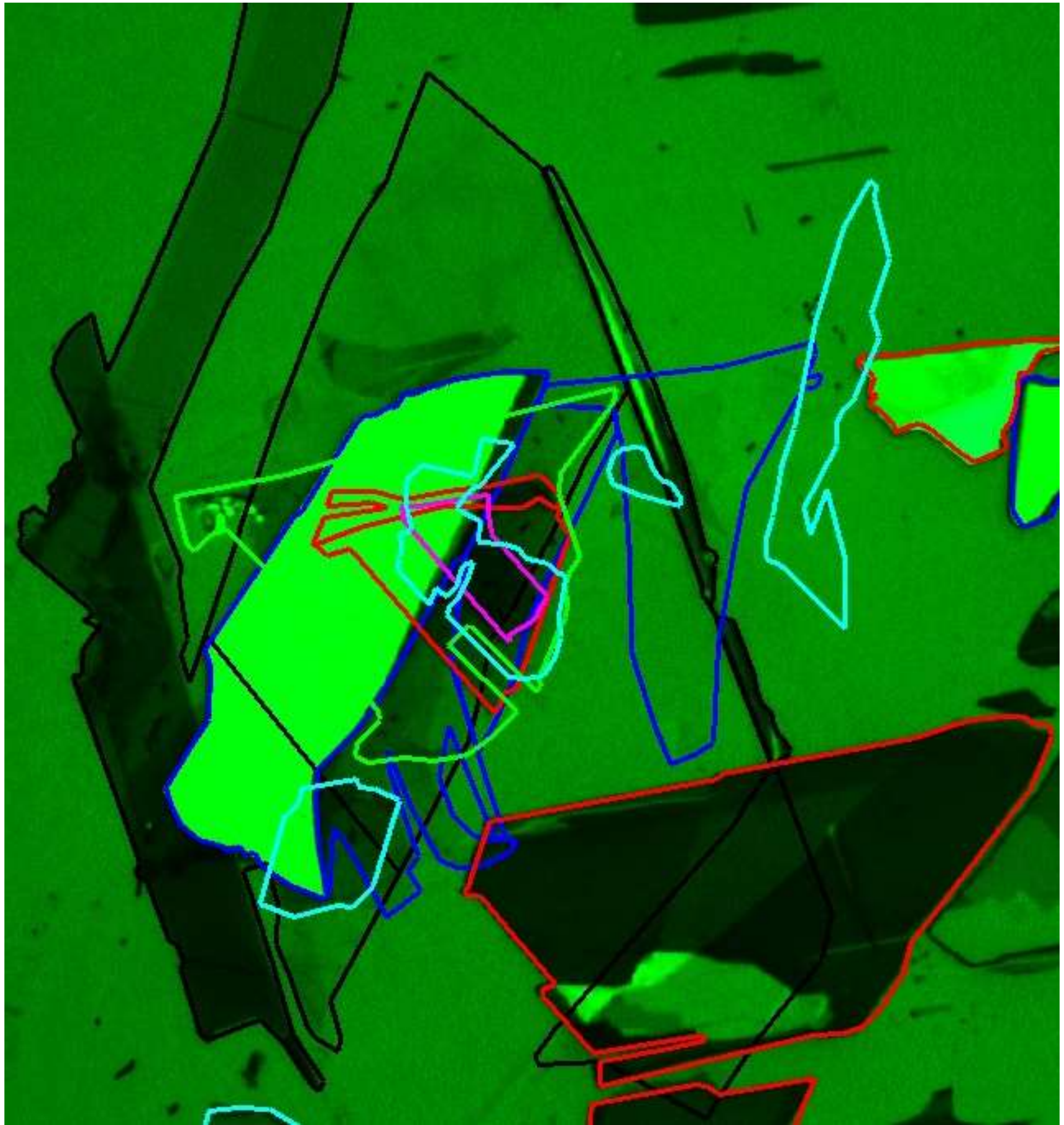
MoS_2

BN

WSe_2

A. Kozikov
University of Manchester

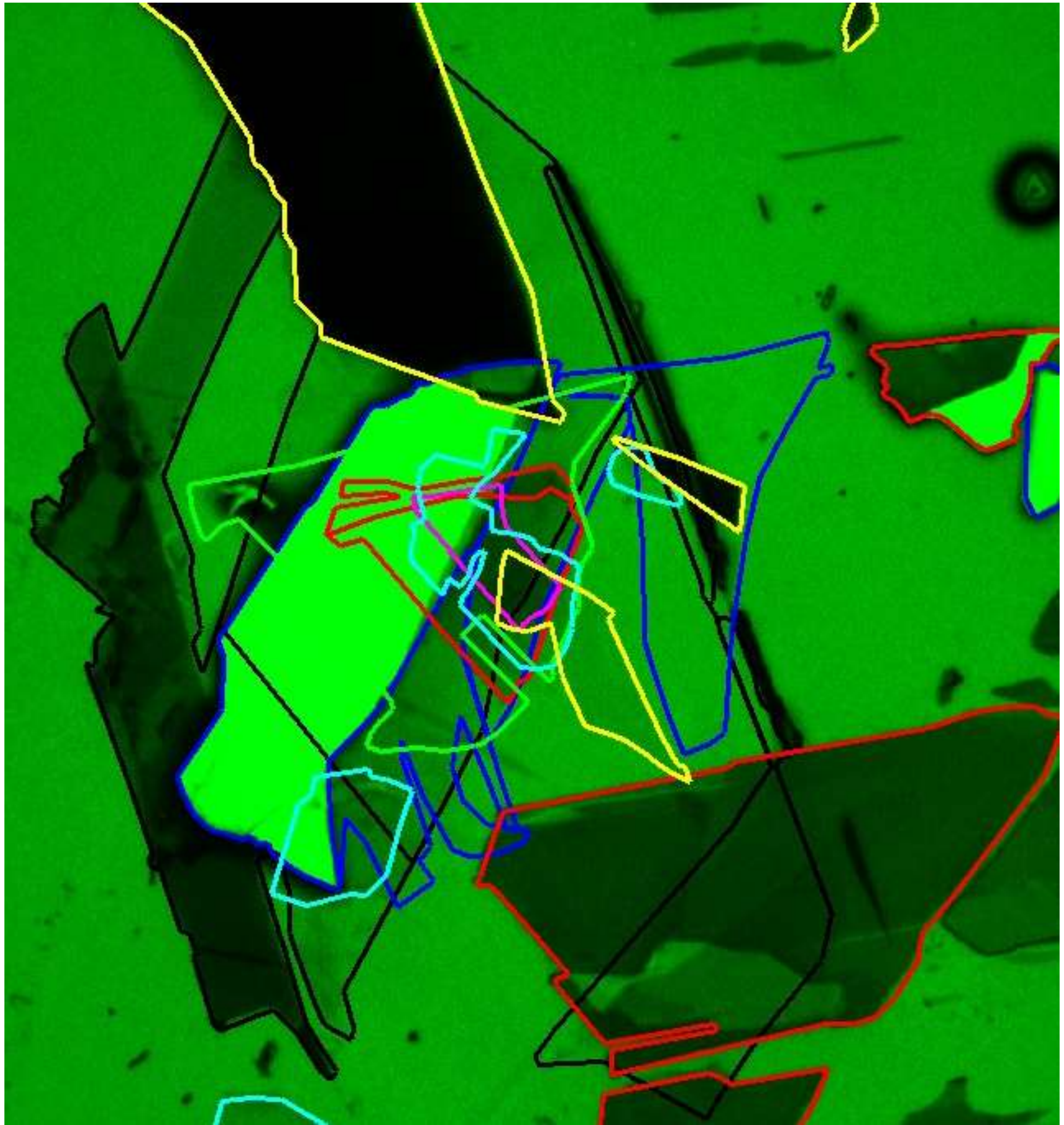
Transfer



- Gr
- BN
- MoS_2
- BN
- WSe_2
- BN

A. Kozikov
University of Manchester

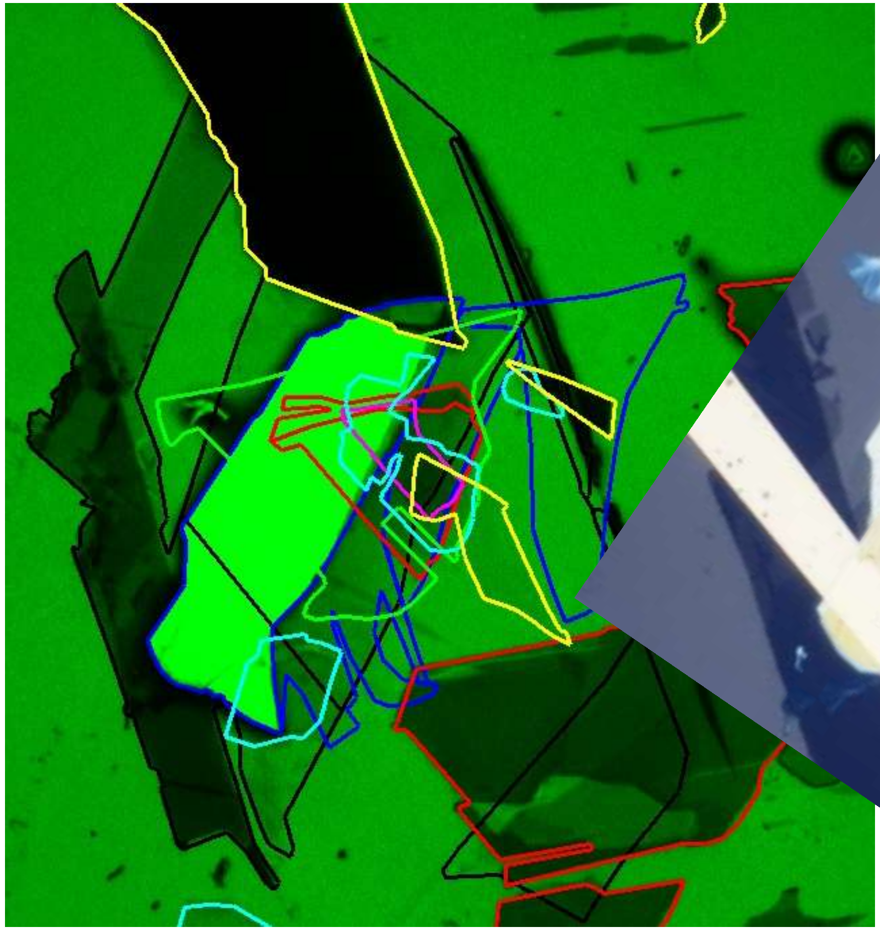
Transfer

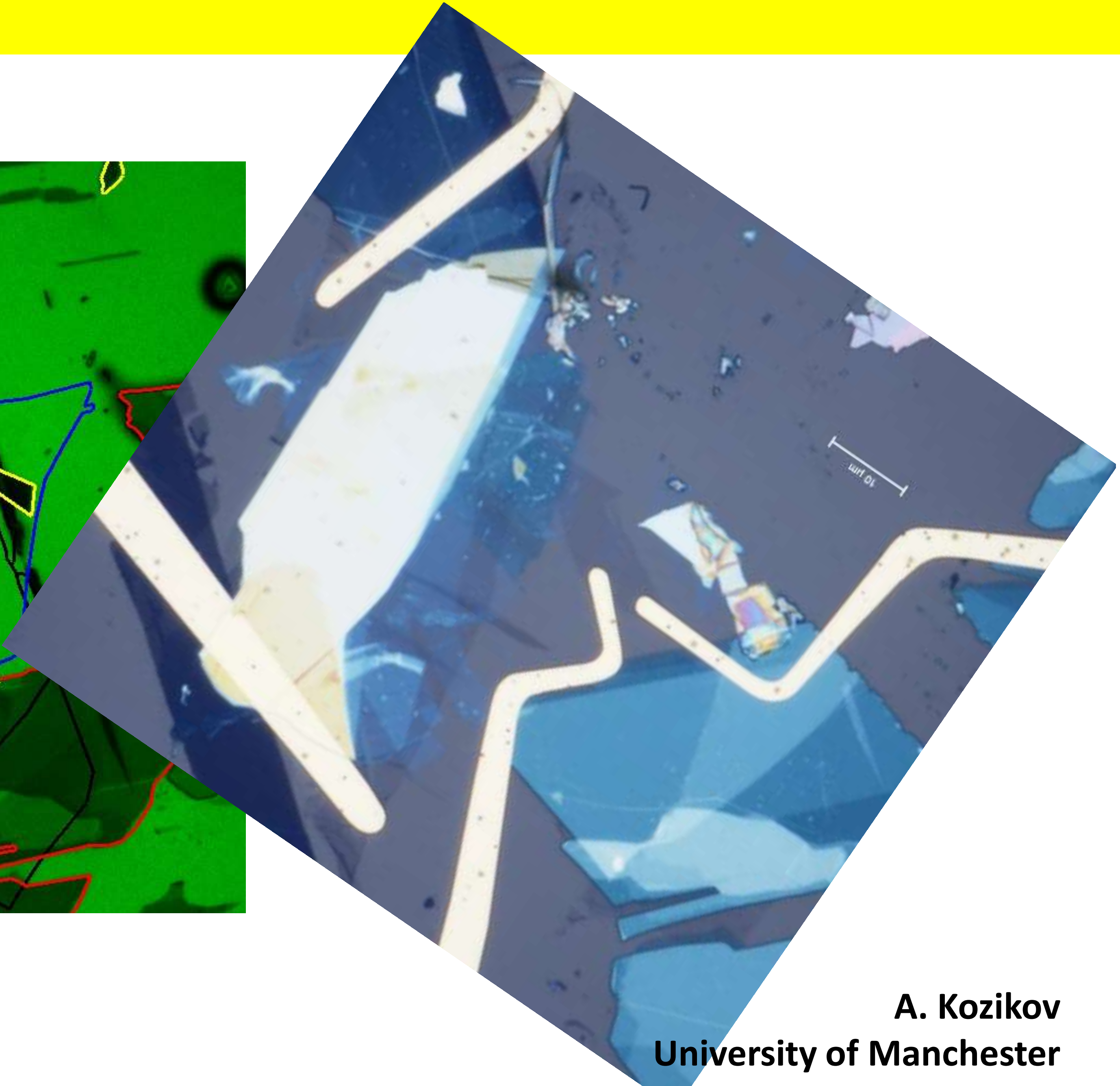


Black line	Gr
Blue line	BN
Red line	MoS_2
Green line	BN
Magenta line	WSe_2
Light blue line	BN
Yellow line	Gr

A. Kozikov
University of Manchester

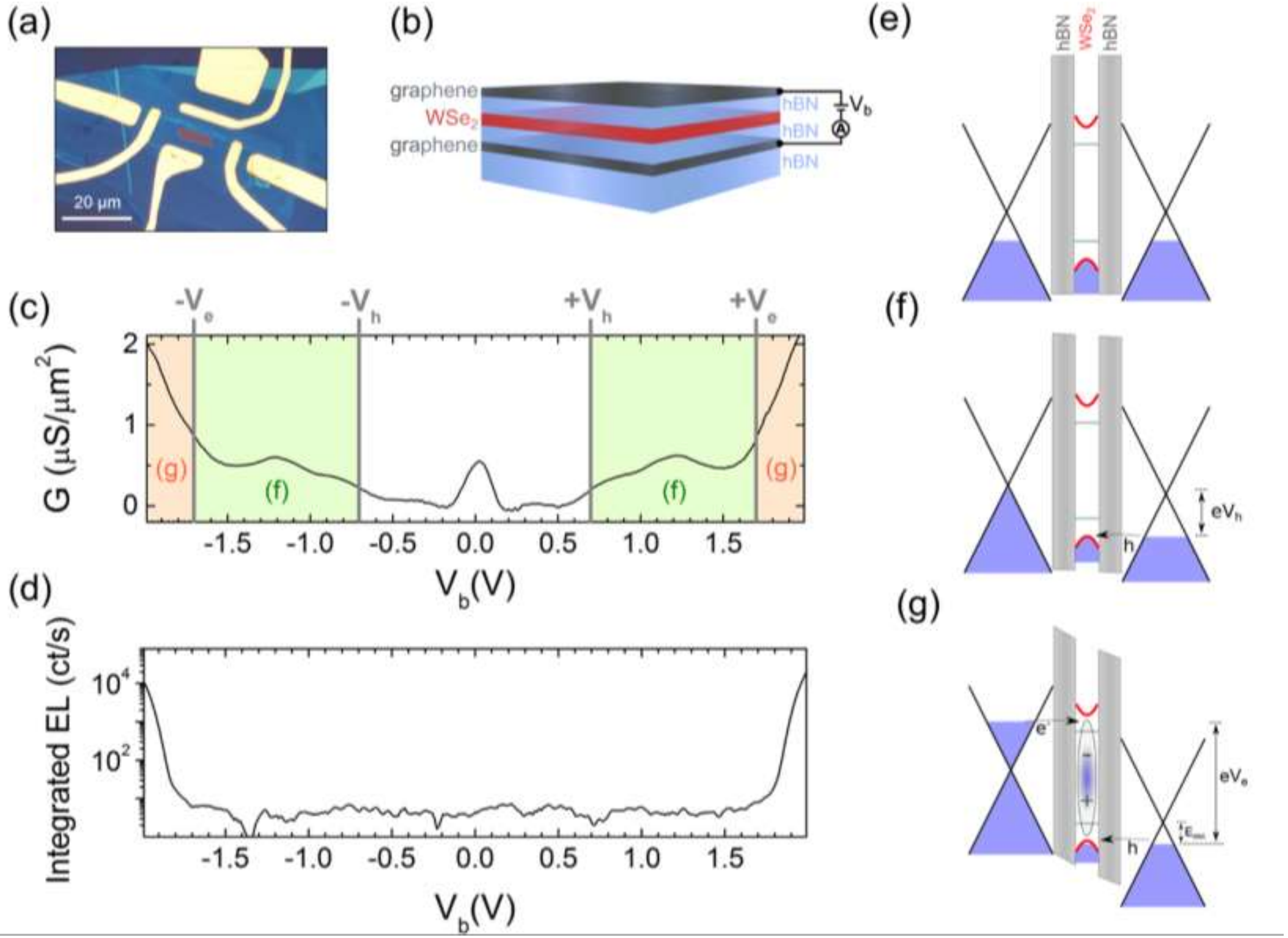
Transfer





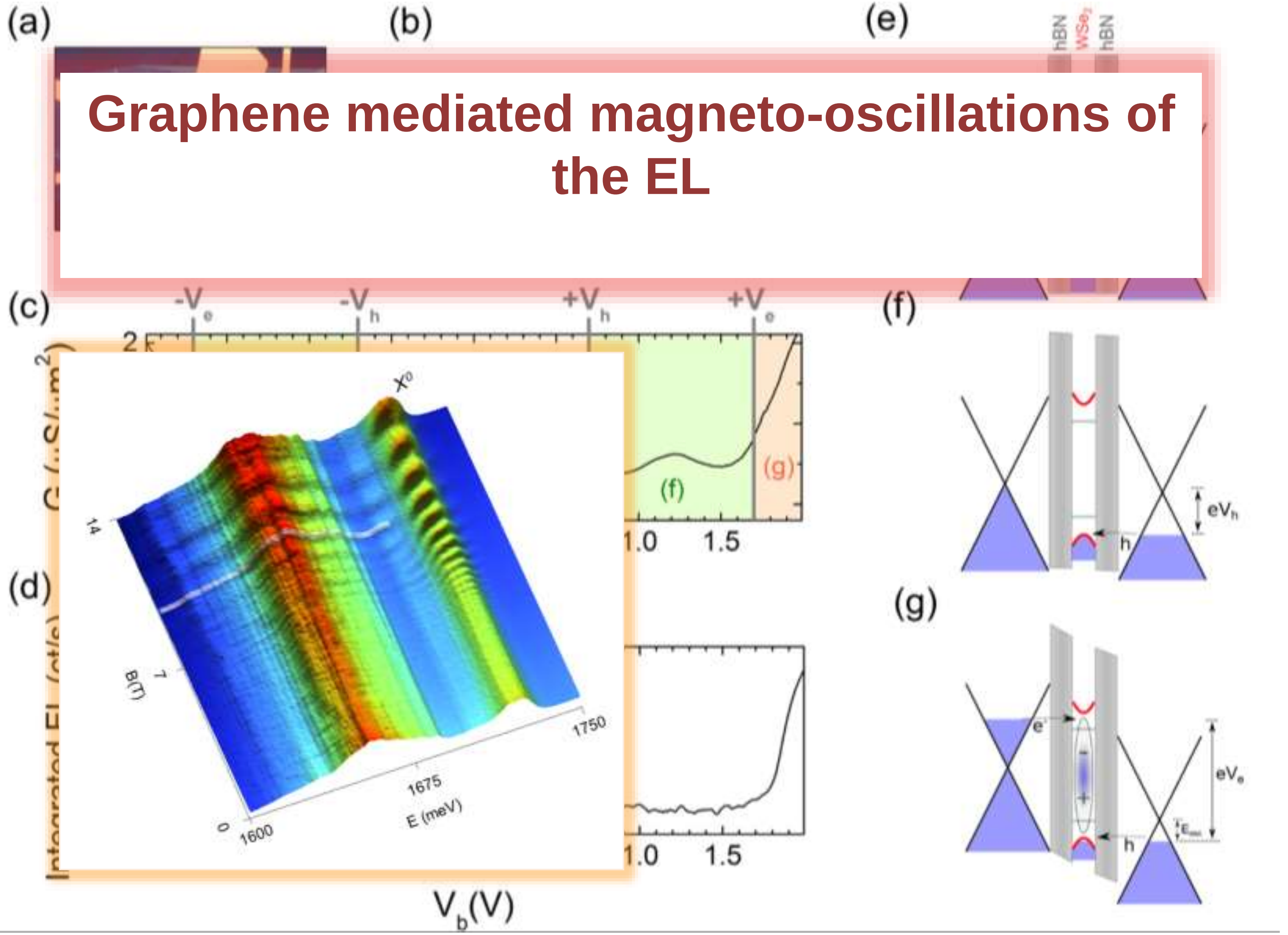
A. Kozikov
University of Manchester

Structures with a single TMDC



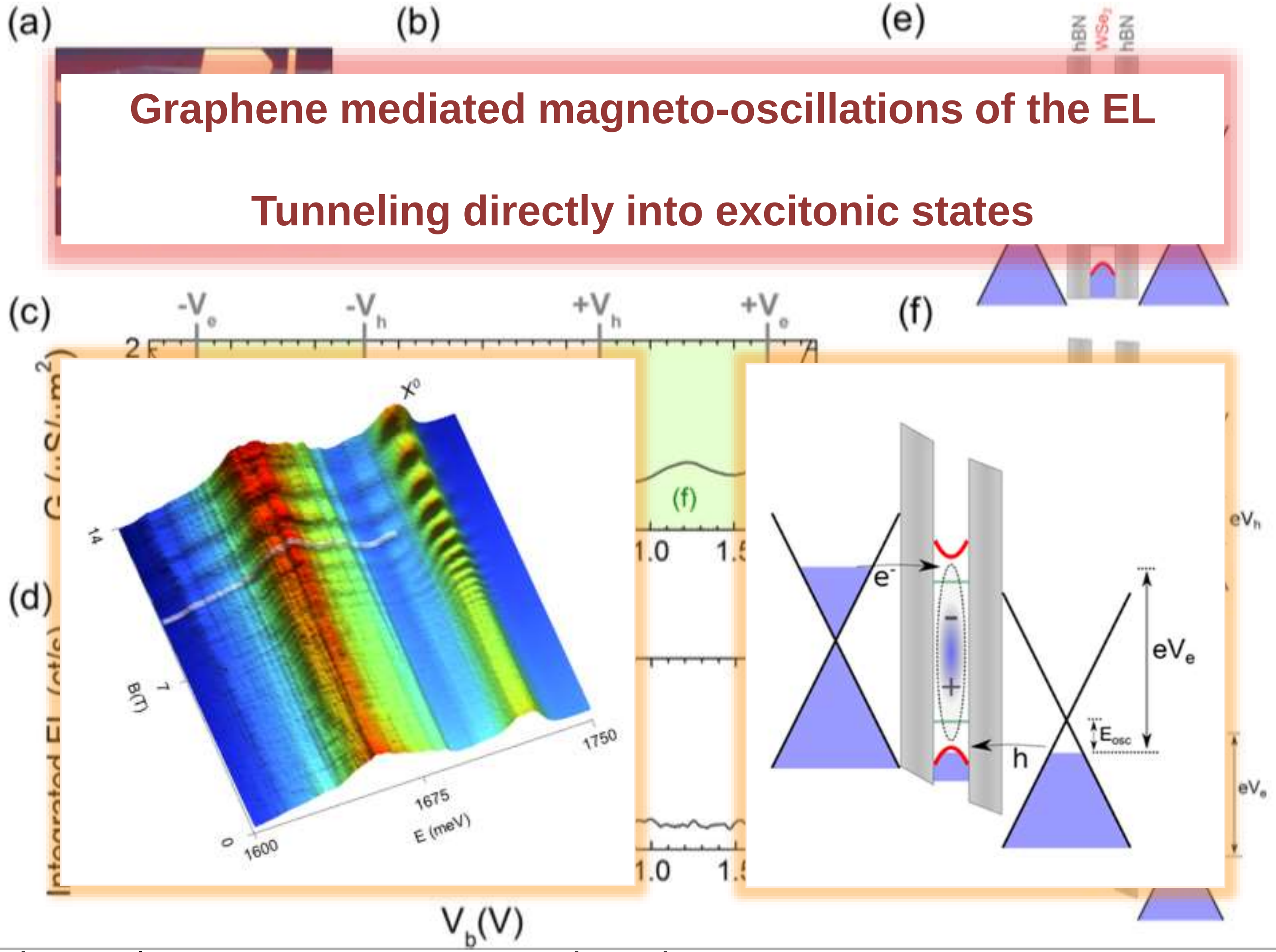
J. Binder et al. *Nano Letters* 17, 1425 (2017)

Structures with a single TMDC



J. Binder et al. *Nano Letters* 17, 1425 (2017)

Structures with a single TMDC



Graphene mediated magneto-oscillations of the EL

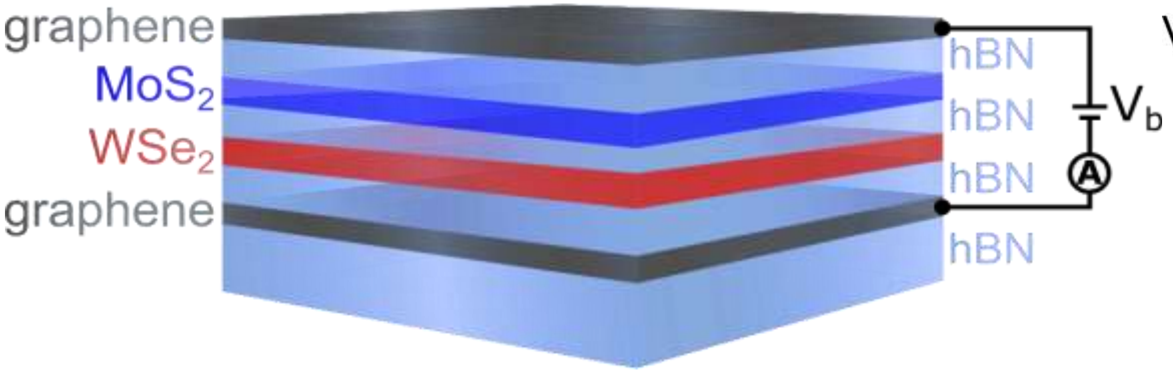
Tunneling directly into excitonic states

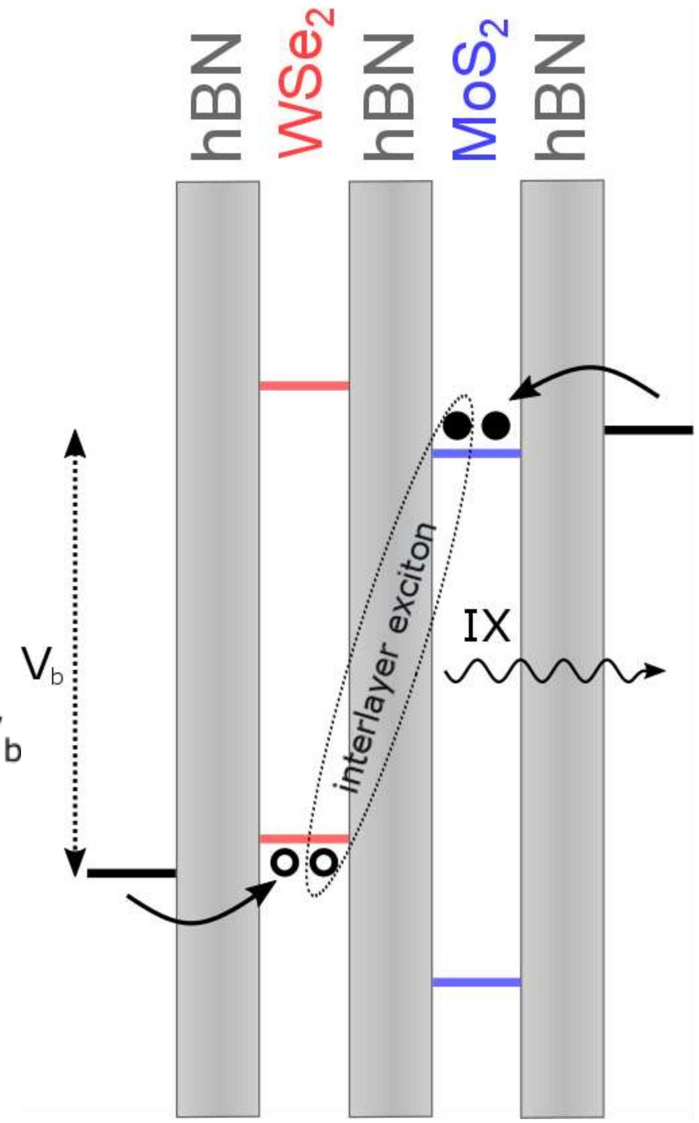
J. Binder et al. *Nano Letters* 17, 1425 (2017)

Two TMDCs in a vdW heterostructre

Increase in complexity:

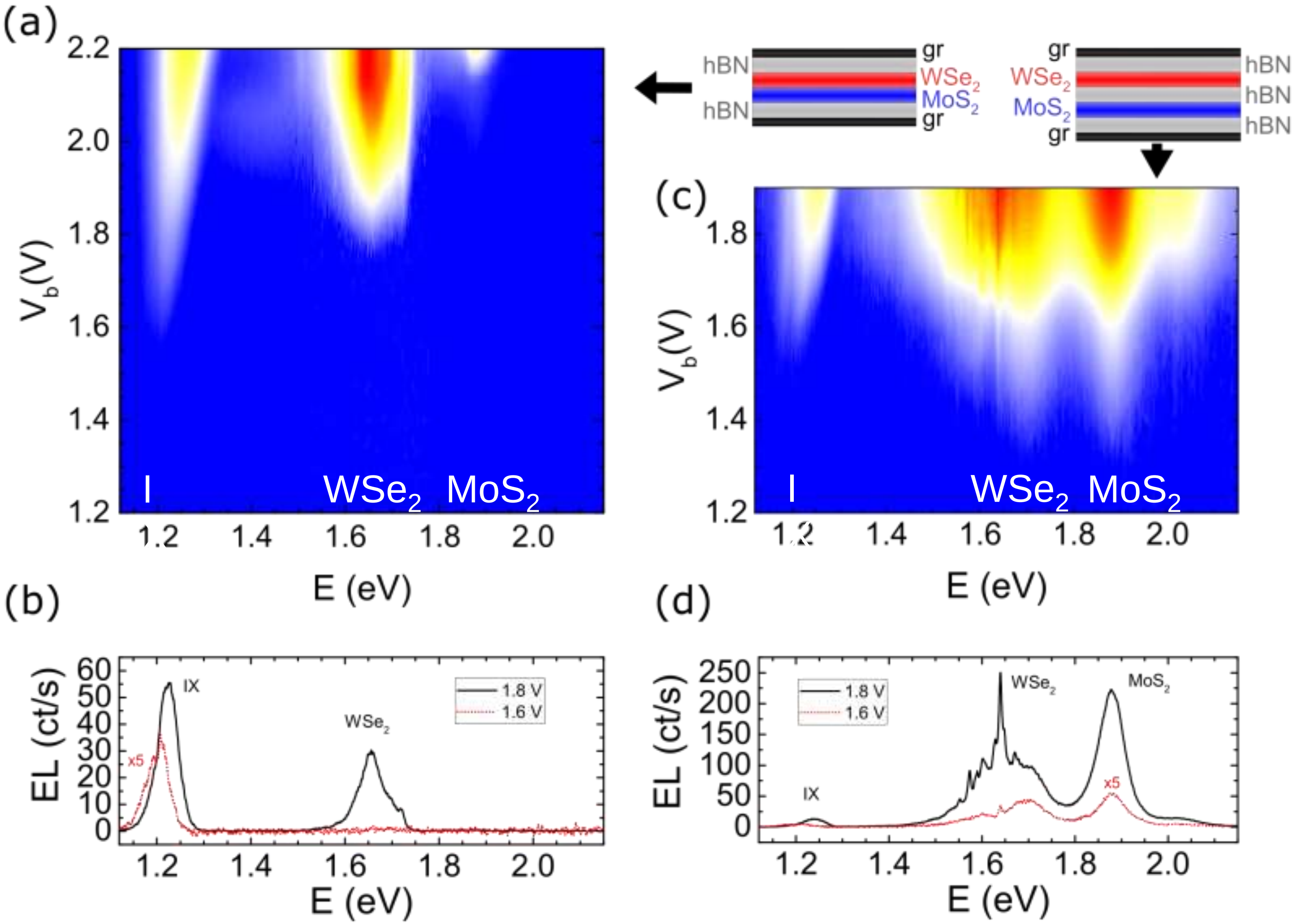
- ➢ Adding a 2nd TMDC monolayer
- ➢ Indirect (interlayer) excitons!



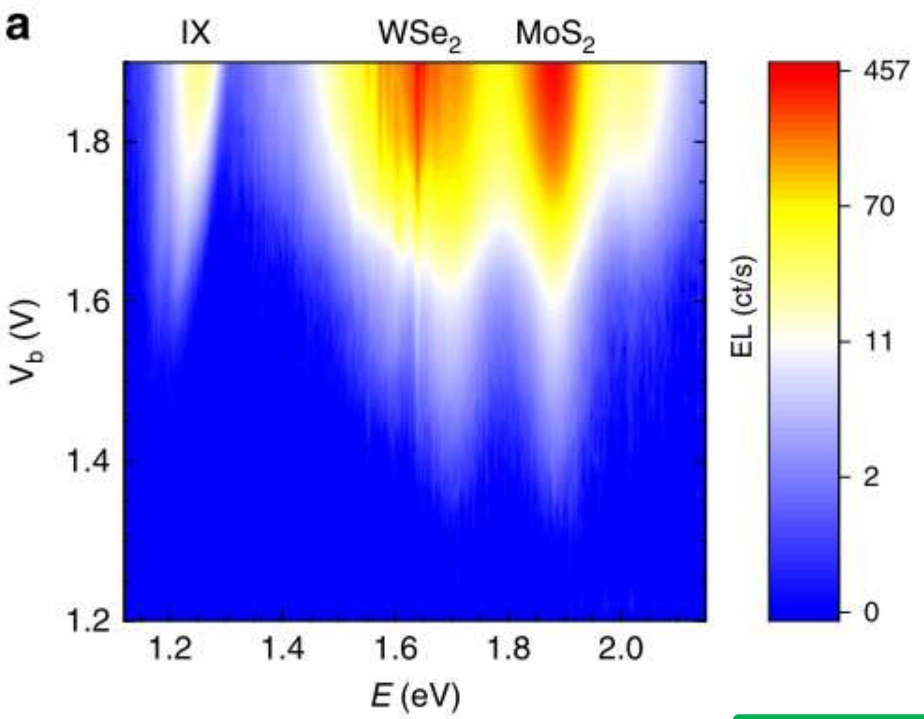


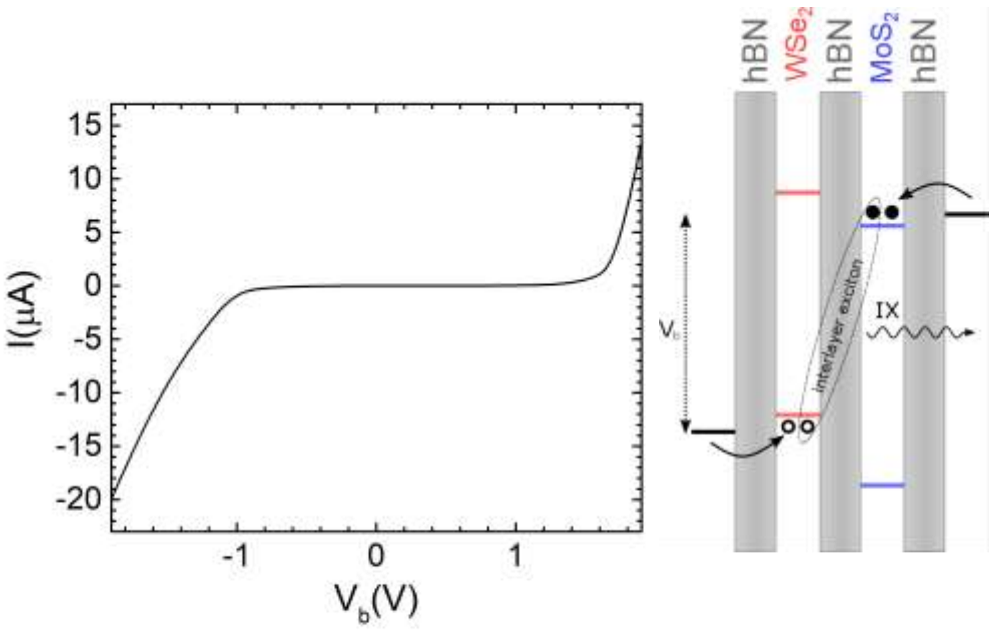
J. Binder et al. *Nature Communications* 10:2335 (2019)

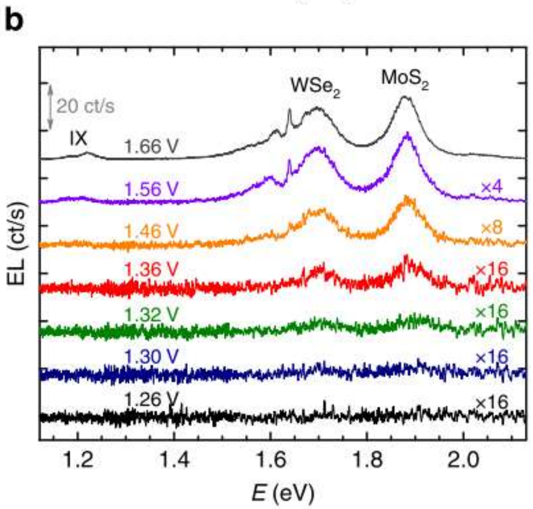
Electroluminescence



Electroluminescence





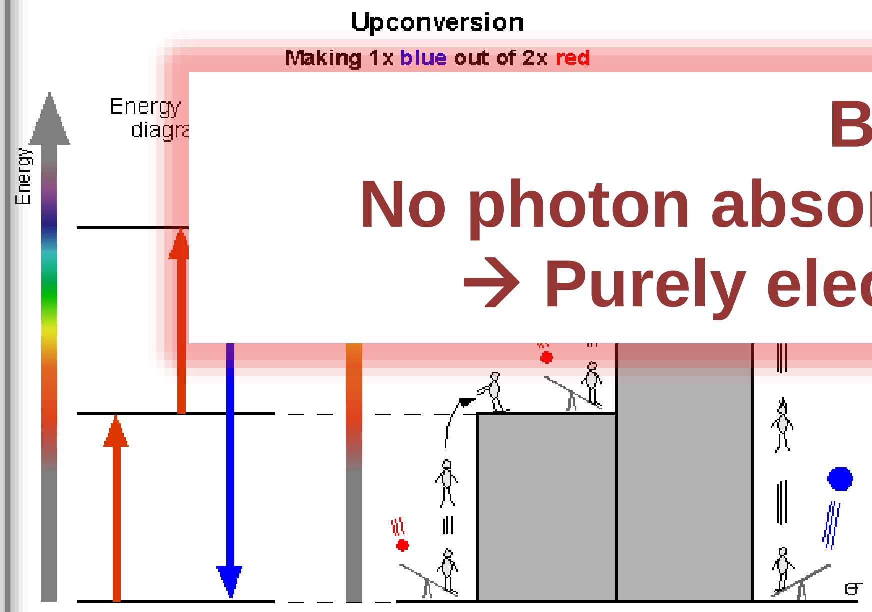


- EL of WSe_2 and MoS_2 appear at lower voltages than IX
- At a voltage of about 1.3 V we observe emission of WSe_2 and MoS_2 with an energy of ≈ 1.7 and 1.9 eV

UPCONVERSION of ≈ 0.6 eV

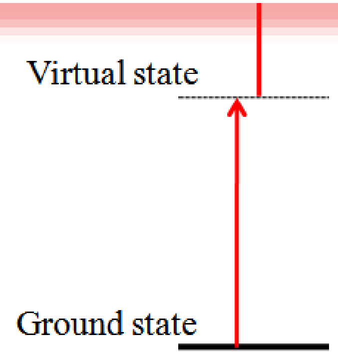
Upconversion (optical excitation)

Photon upconversion (e.g. ions)



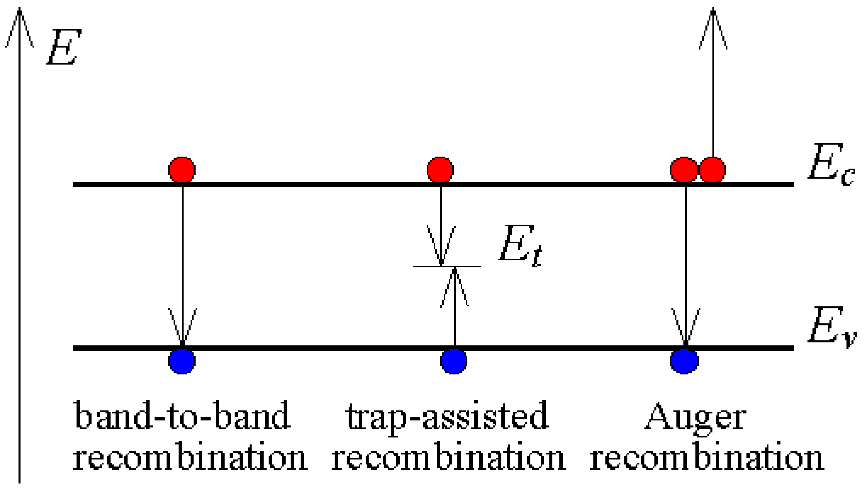
https://guedel.dcb.unibe.ch/research/hug_upc.htm

Nonlinear optical processes (second harmonic generation, two photon absorption

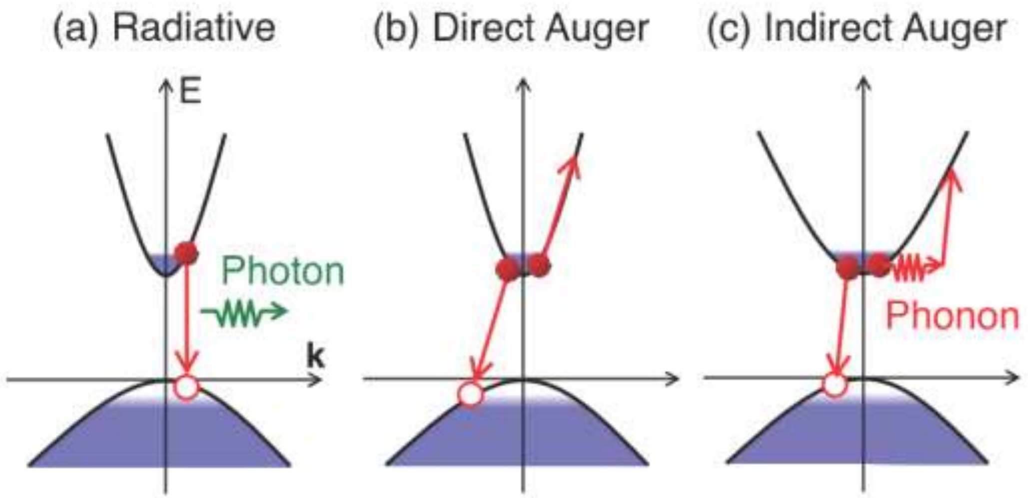


BUT:
No photon absorption in our case!
→ Purely electrical injection

Auger effect

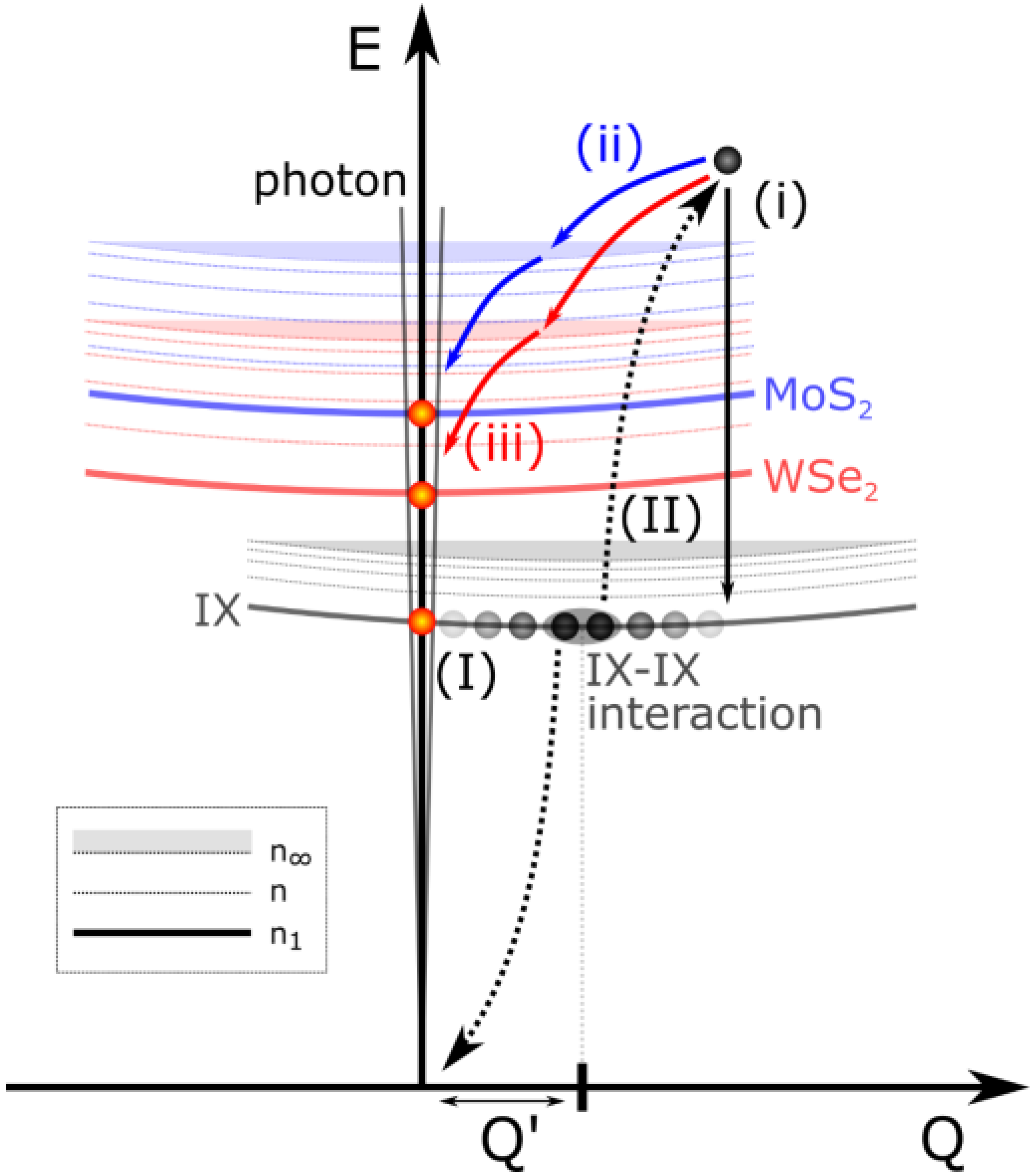


https://ecee.colorado.edu/~bart/book/book/chapter2/ch2_8.htm



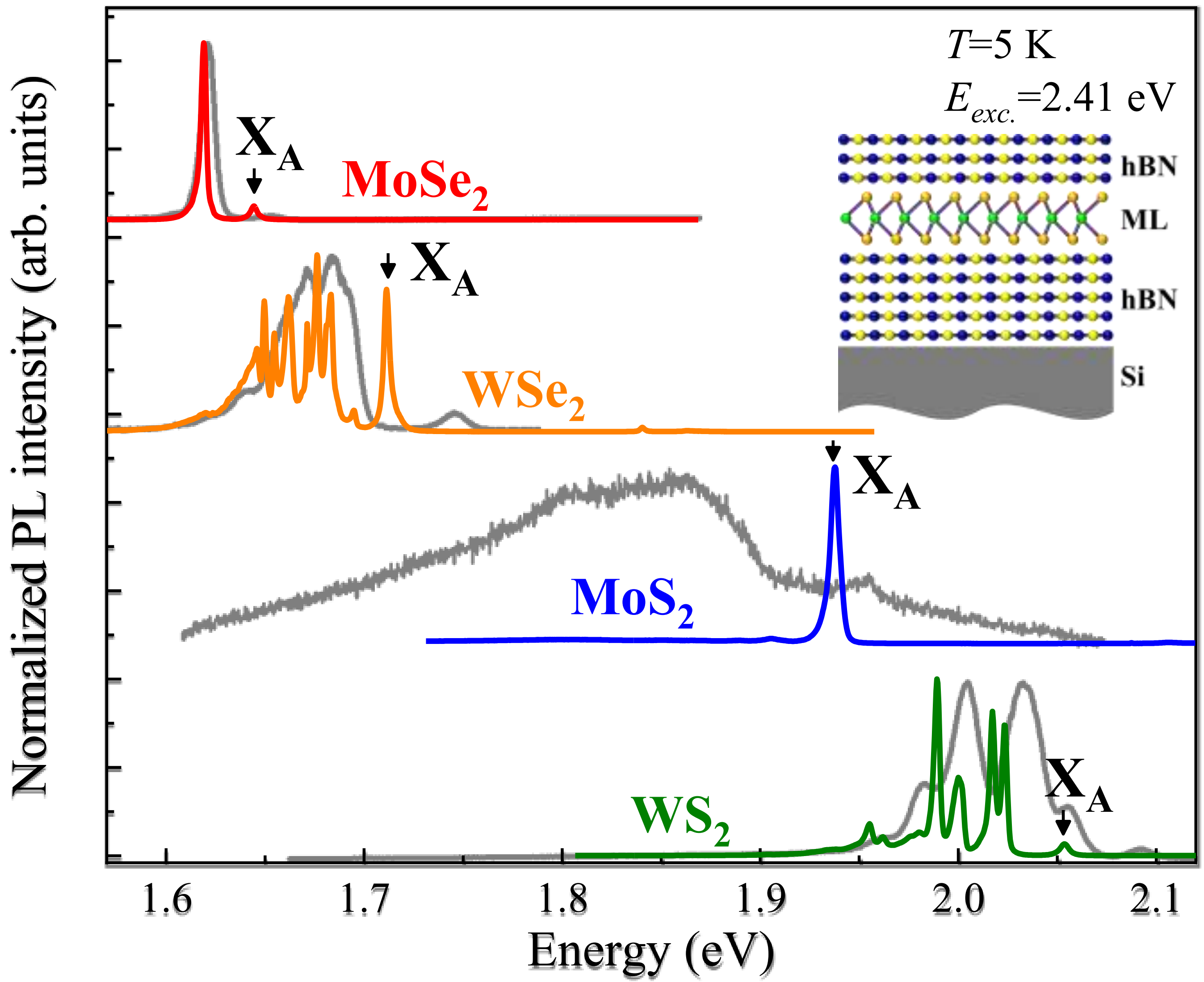
E. Kioupakis et al. New J. Phys. 15 125006 (2013)

Excitonic Auger Upconversion?



J. Binder et al. *Nature Communications* 10:2335 (2019)

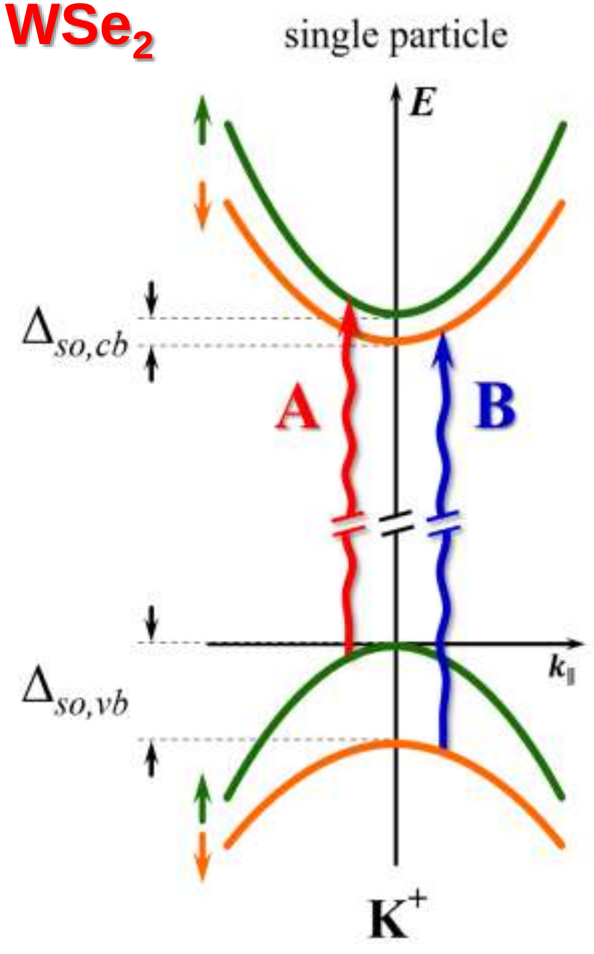
h-BN protective layers

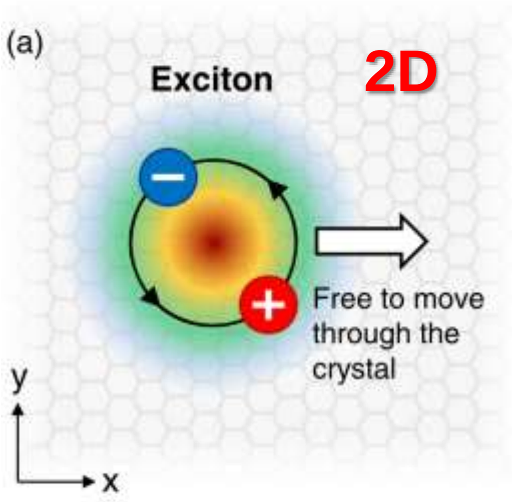


M. R. Molas et al..PRL 123, 136801 (2019).

Excitonic ladder in S-TMD monolayers

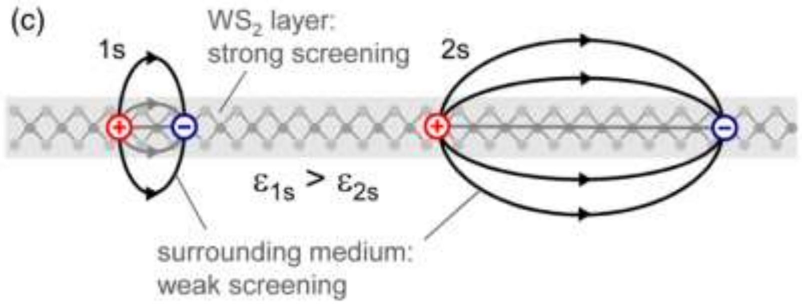
WSe_2





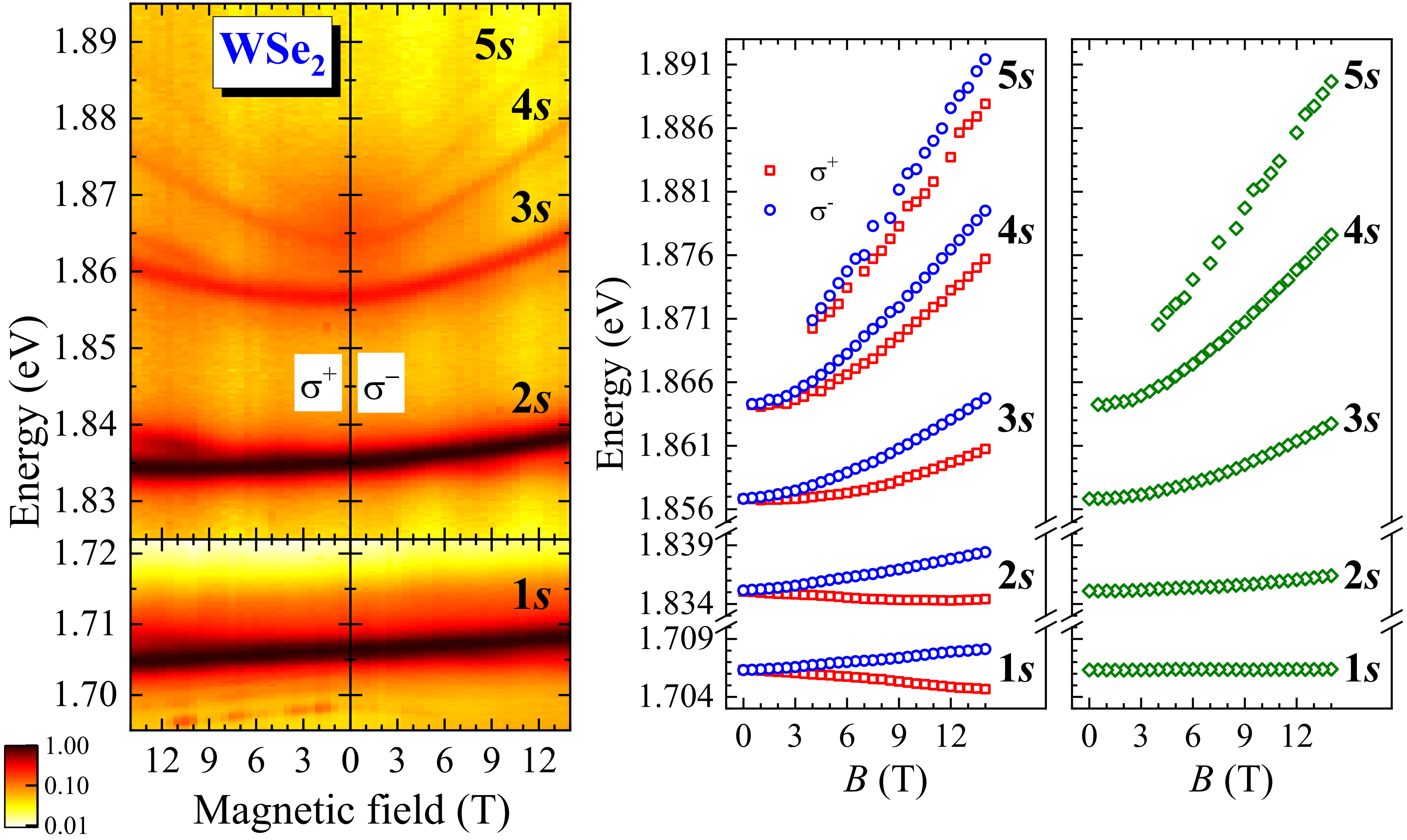
G. Wang et al., *Rev. Mod. Phys*. 90, 021001 (2018)

$$E_n = E_g - \frac{R^*}{(n-1/2)^2}$$



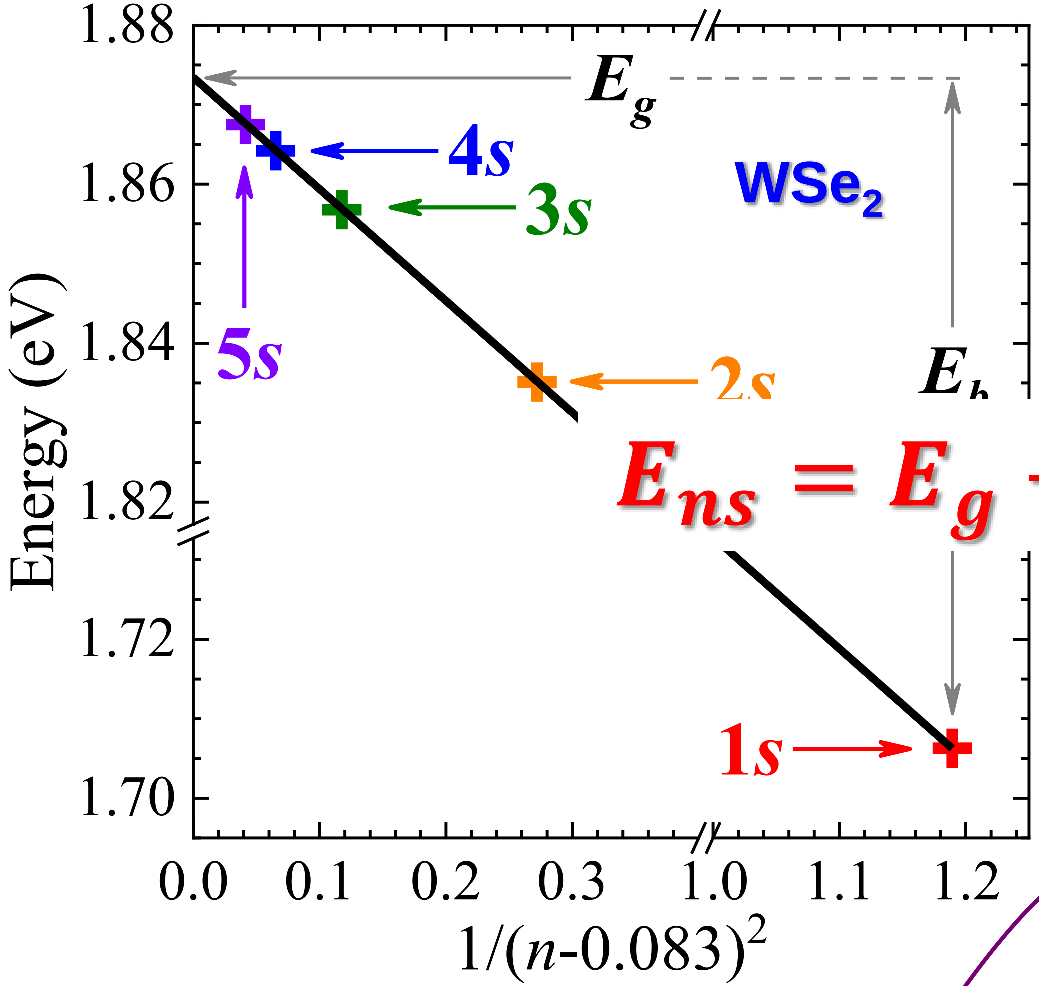
A. Chernikov et al., Phys. Rev. Lett. 113, 076802 (2014)

Example - energy spectrum of two-dimensional excitons WSe_2



M. R. Molas et al., Phys. Rev. Lett. 123, 136801 (2019)

Energy spectrum of two-dimensional excitons in a nonuniform dielectric medium

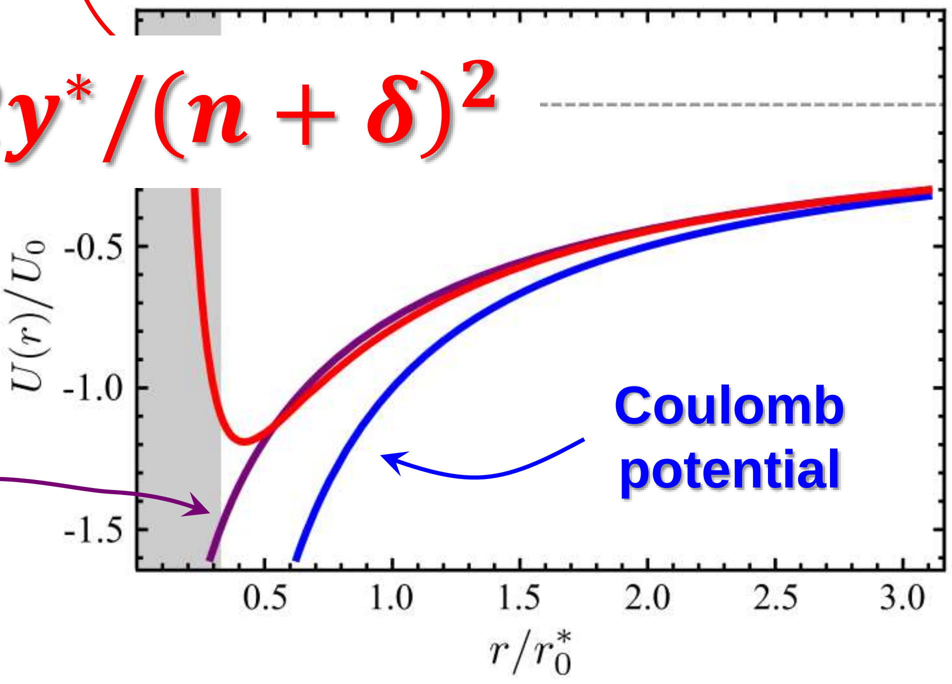


$$E_{ns} = E_g - Ry^*/(n+\delta)^2$$

Kratzer potential

$$U_{\text{ext}}(r) = -\frac{e^2}{r_0}\left(\frac{r_0^*}{r} - \frac{g^2 r_0^{*2}}{r^2}\right)$$

solvable analytically ☺



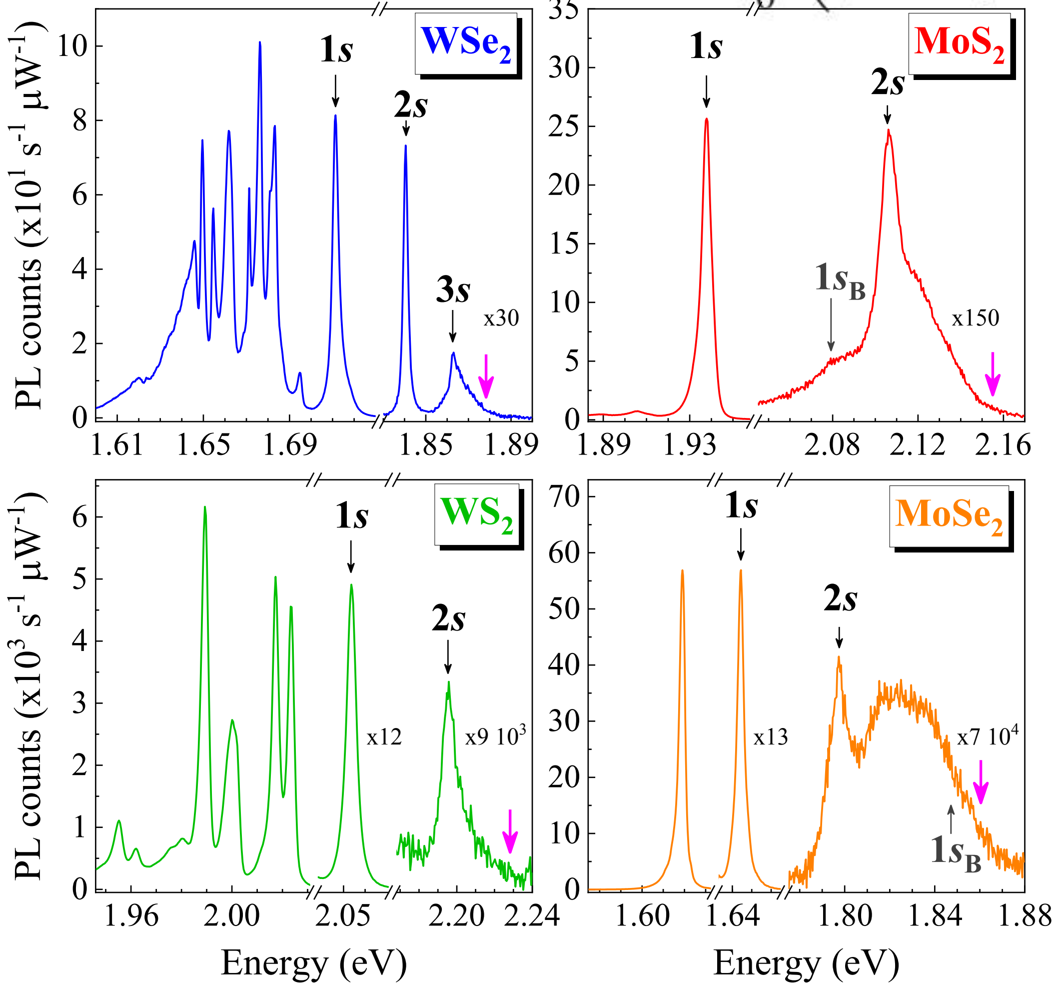
Keldysh potential

solvable numerically ☹

Energy spectrum of two-dimensional excitons in a nonuniform dielectric medium

Kratzer potential $U_{\text{ext}}(r) = -\frac{e^2}{r_0}\left(\frac{r_0^*}{r} - \frac{g^2 r_0^{*2}}{r^2}\right)$

$$E_{ns} = E_g - Ry^*/(n+\delta)^2$$



ML	E_b [1]
MoS_2	217 meV
$MoSe_2$	216 meV
WS_2	174 meV
WSe_2	167 meV

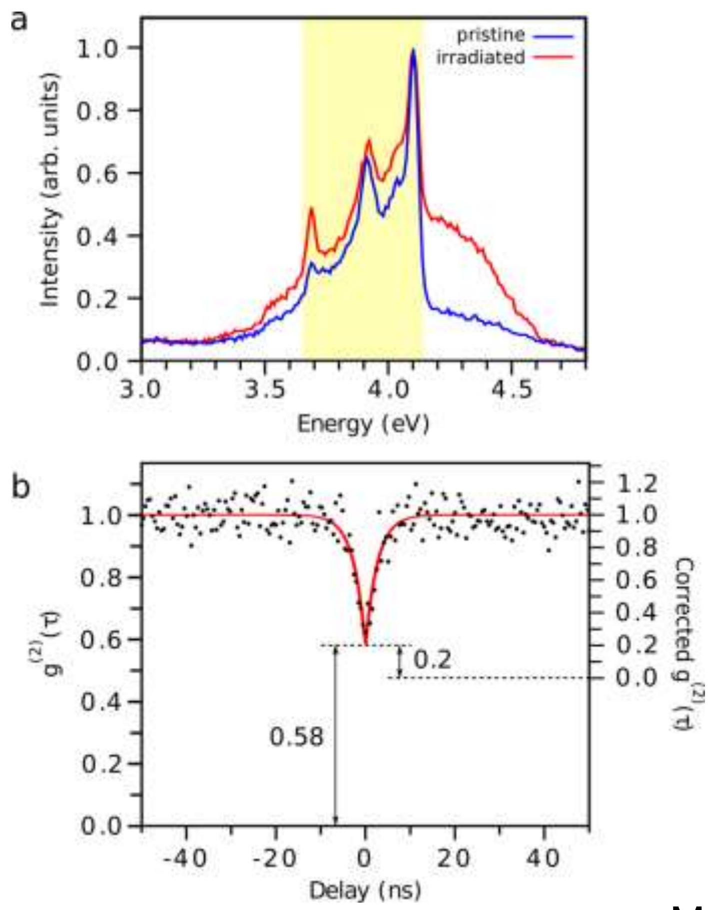
[1] Kratzer potential

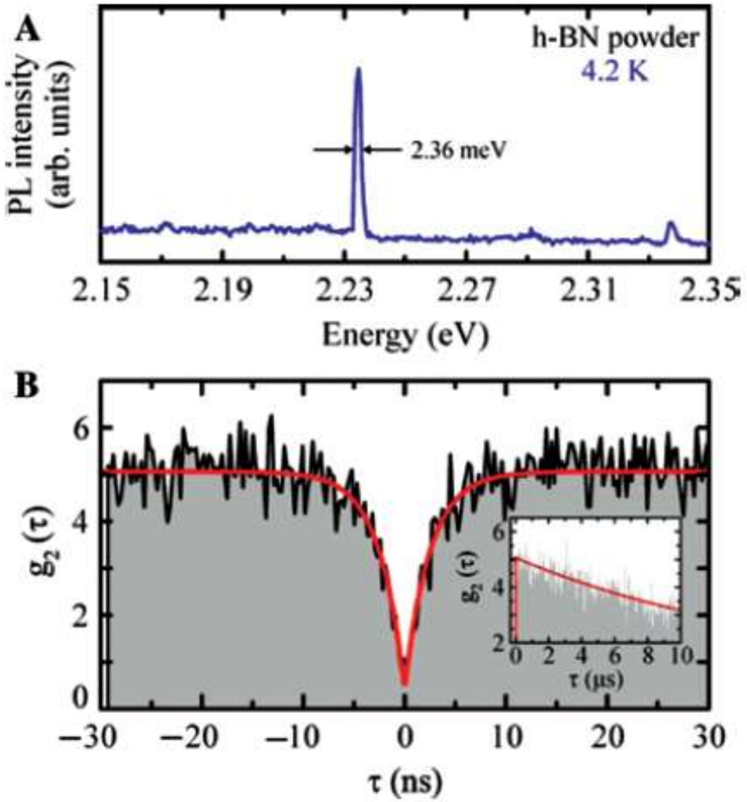
M. R. Molas et al., Phys. Rev. Lett. 123, 136801 (2019)

[2] Keldysh potential

M. Goryca et al., Nature Comm. 10, 4172 (2019)

Point defects in h-BN - single photon emitters



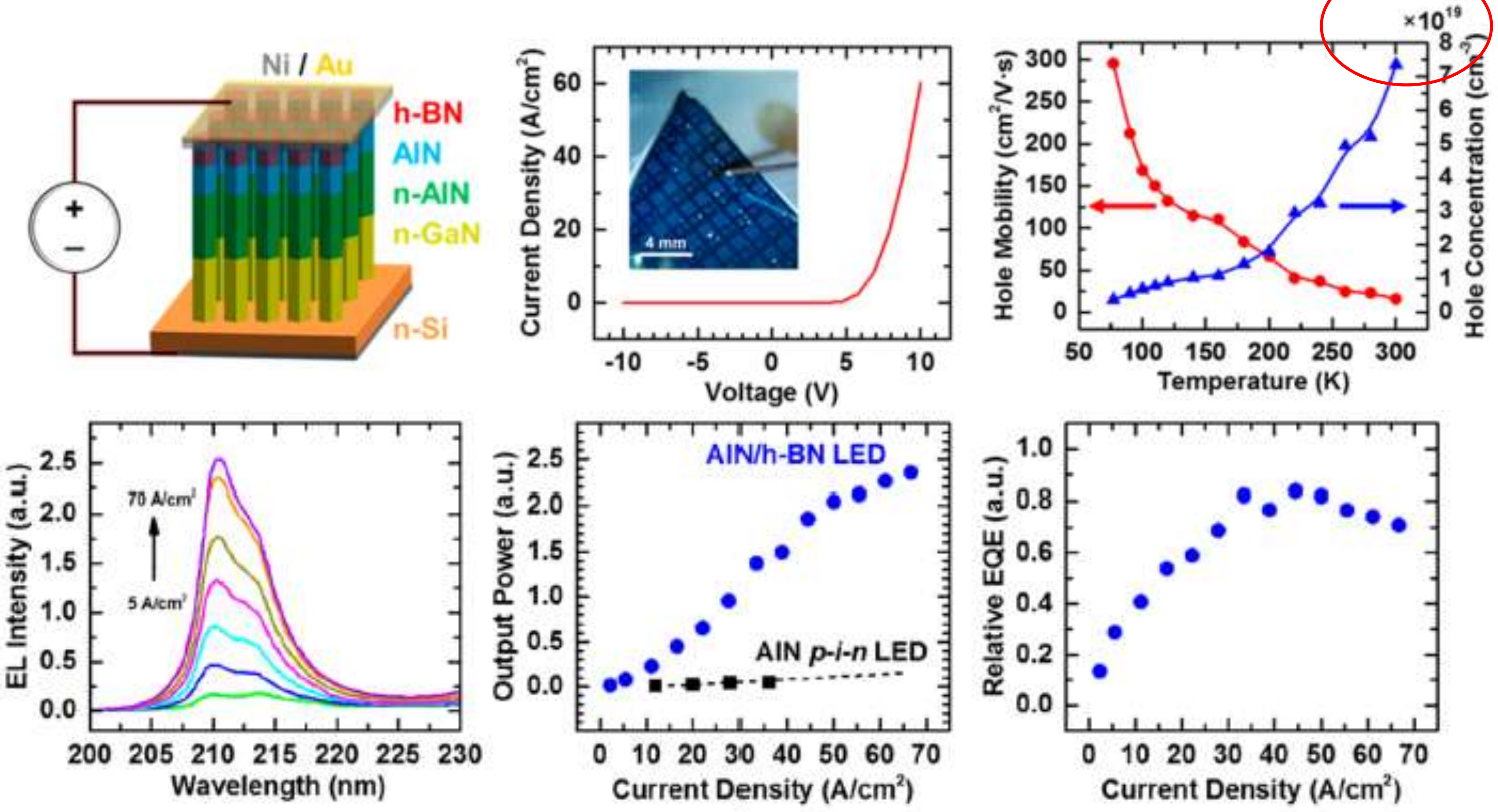


M. Koperski et al. ,Nanophotonics 6(6), 1289–1308 (2017)

R. Bourrellier et. al, Nano Lett. 2016, 16, 4317−4321

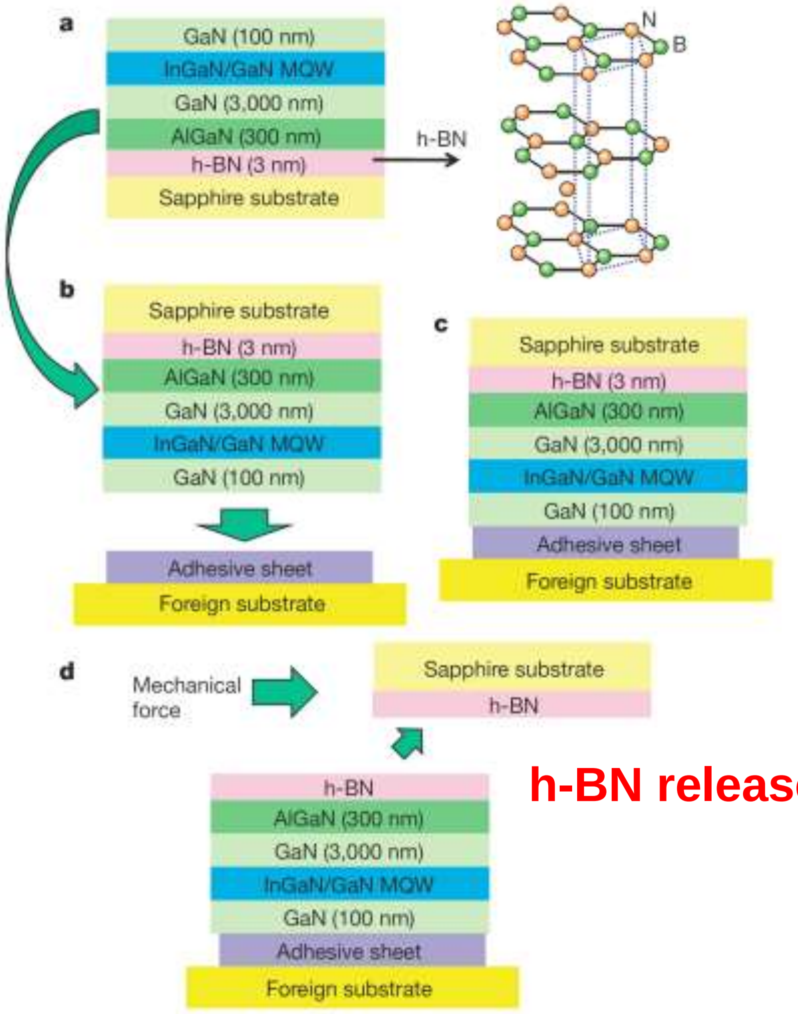
h-BN as p-type transparent material

P~10^{20} cm^{-3}

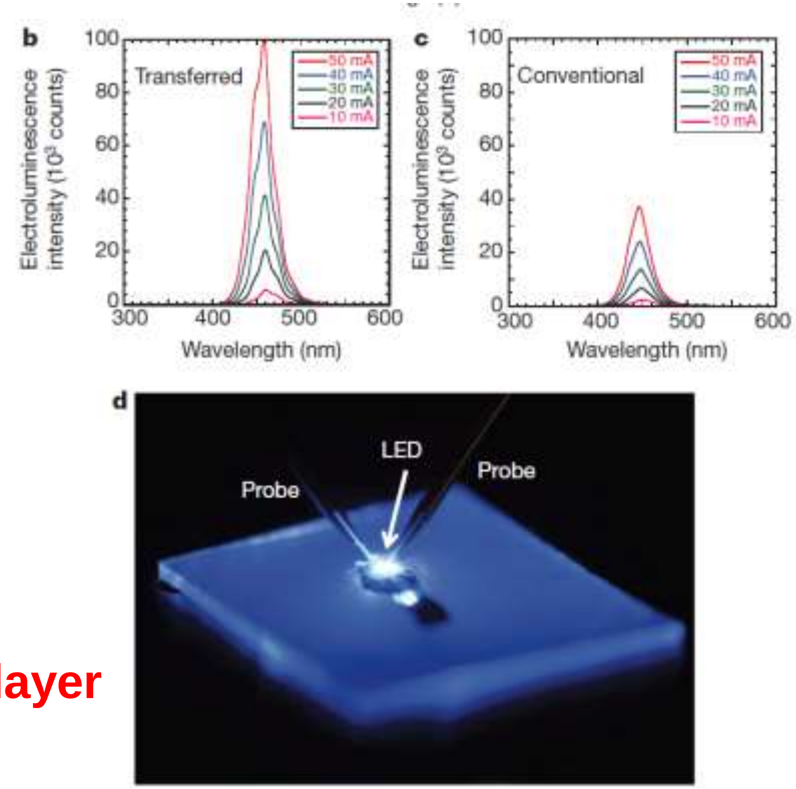


D. A. Laleyan et al. Nano Lett. 17, 3738 (2017)

Mechanical transfer of nitride-based devices

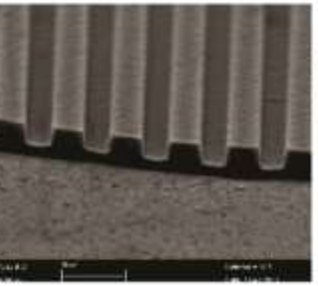


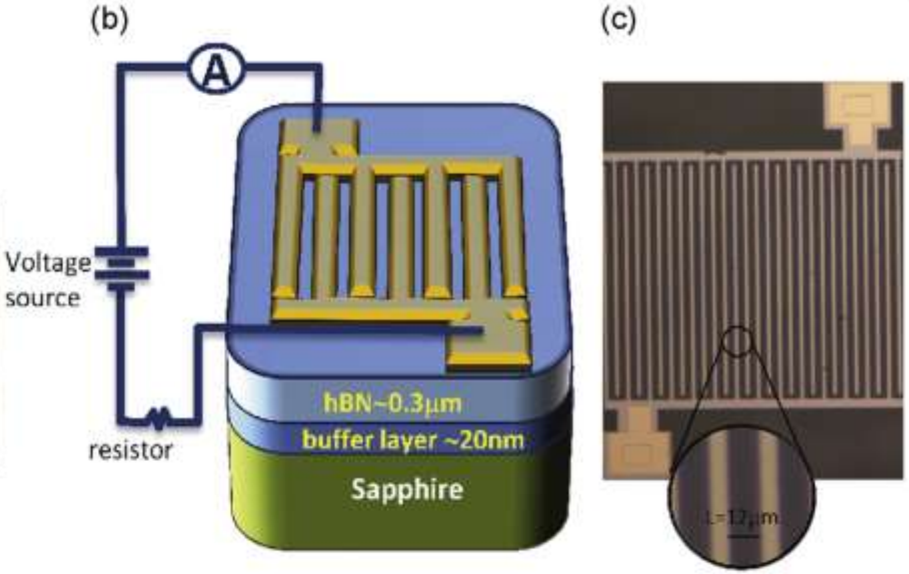
h-BN release layer



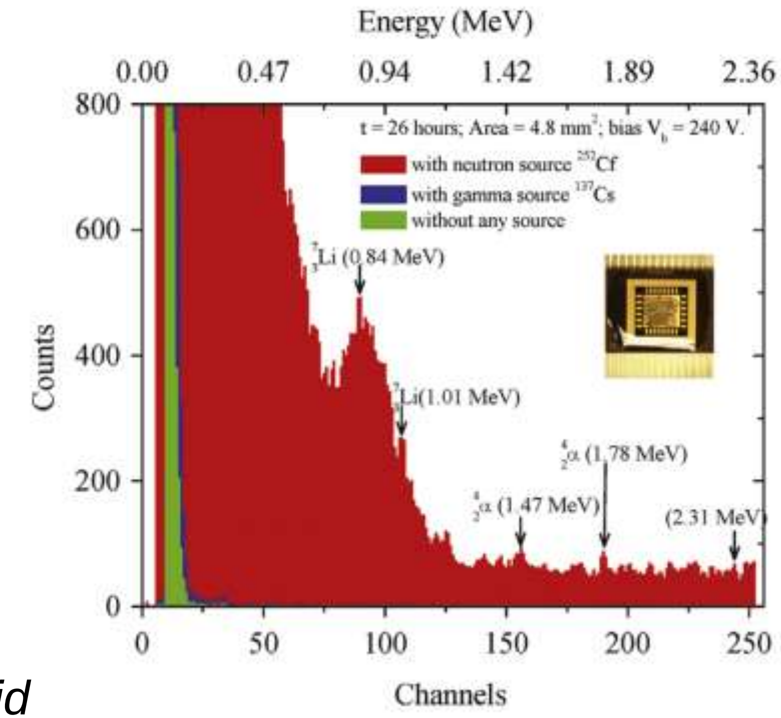
Y. Kobayashi et al. NATURE 484, 223 (2012)

BN- based neutron detectors





$$^{10}B + ^{1}_{0}n \rightarrow ^{7}Li^{*}(0.840MeV) + \alpha(1.470MeV)$$



H.X.Jiang and J.Y. LinECS Journal of Solid State Science and Technology, **6** (2) Q3012-Q3021 (2017)

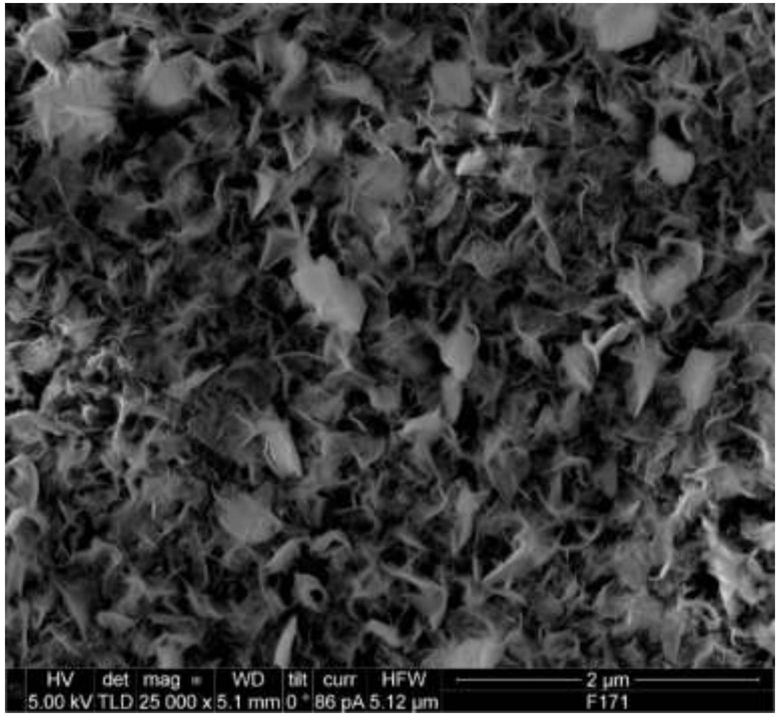
T.C. Doan et al. Nucl. Instr. Meth. Phys. Research A 748, 84 (2014)

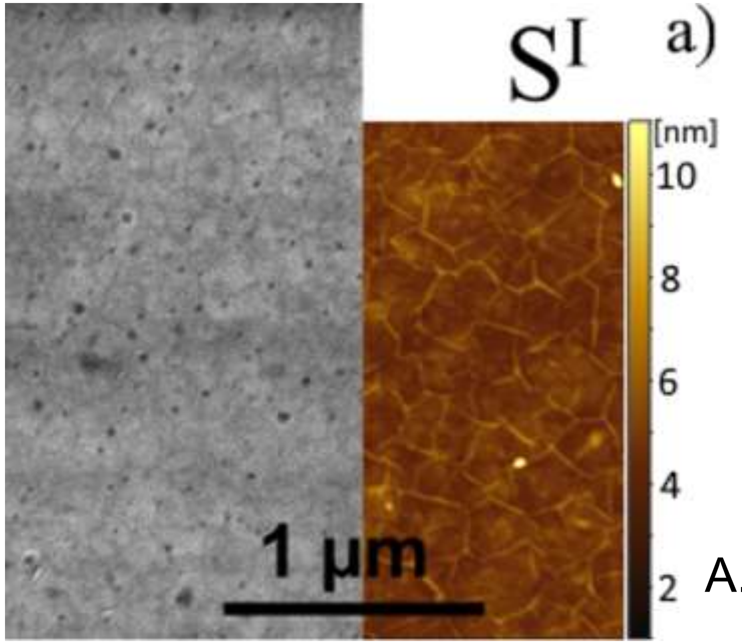
New MOVPE system

Established by Krzysztof Pakuła

Aleksandra Dąbrowska, Katarzyna Ludwiczak
fot. J.Iwański, J. Binder

From flakes to high quality hBN layers…

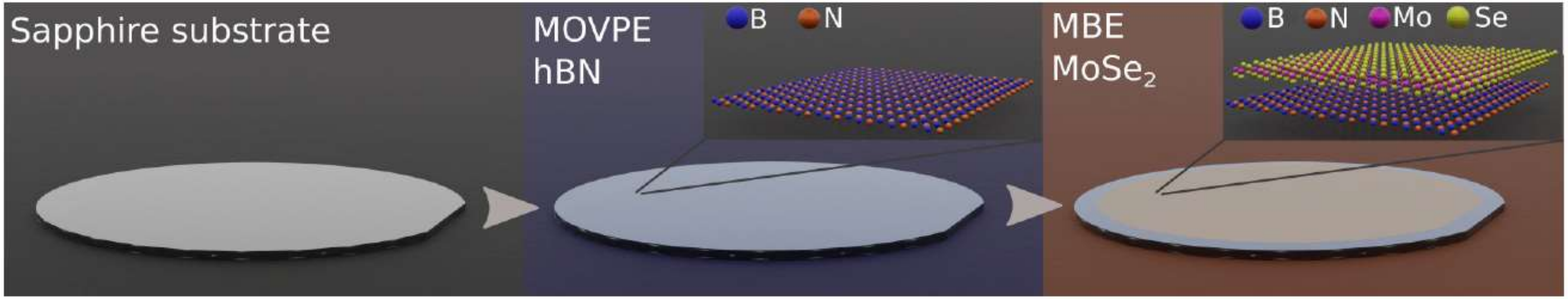




New possibilities!

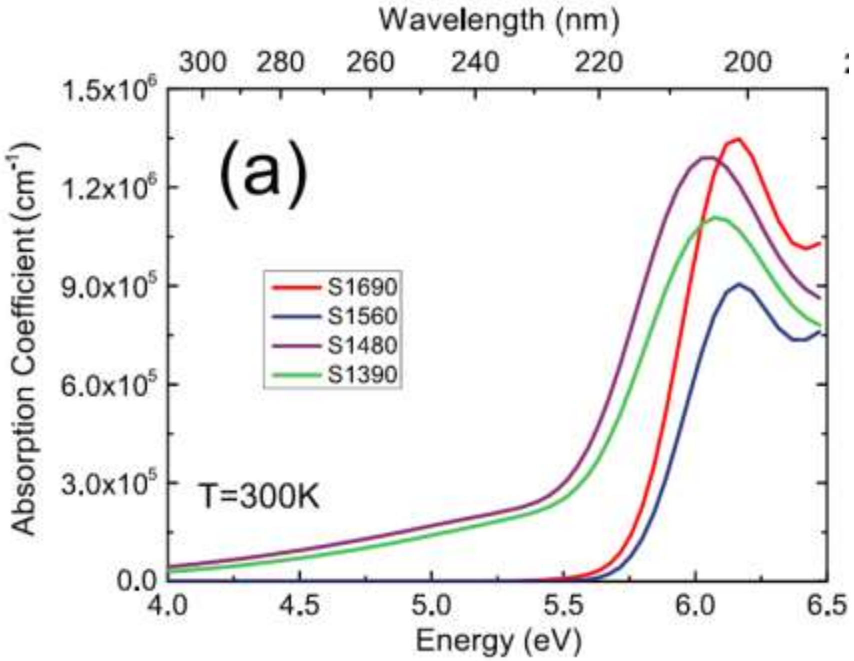
MBE $MoSe_2$ / BN MOCVD

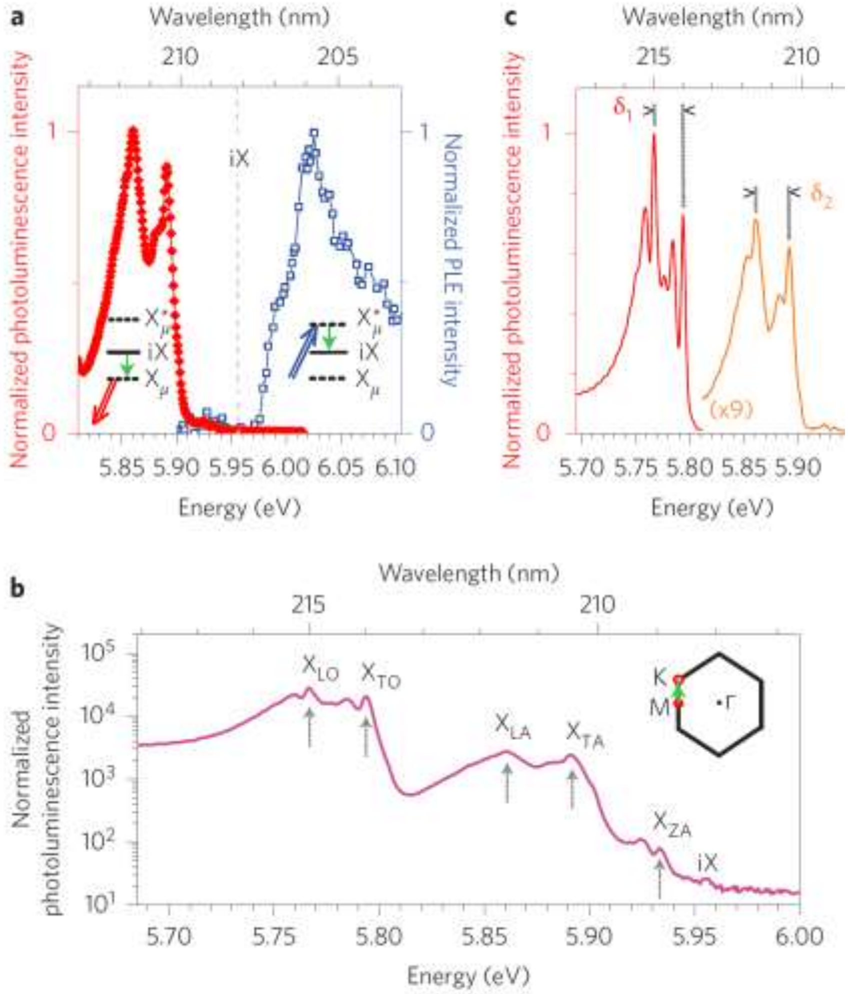
A. Dąbrowska et al. 2D Materials (2020)



K. Ludwiczak et al. ACS Appl. Mater. Interfaces 13, 47904 (2021).

Direct or indirect bangap?



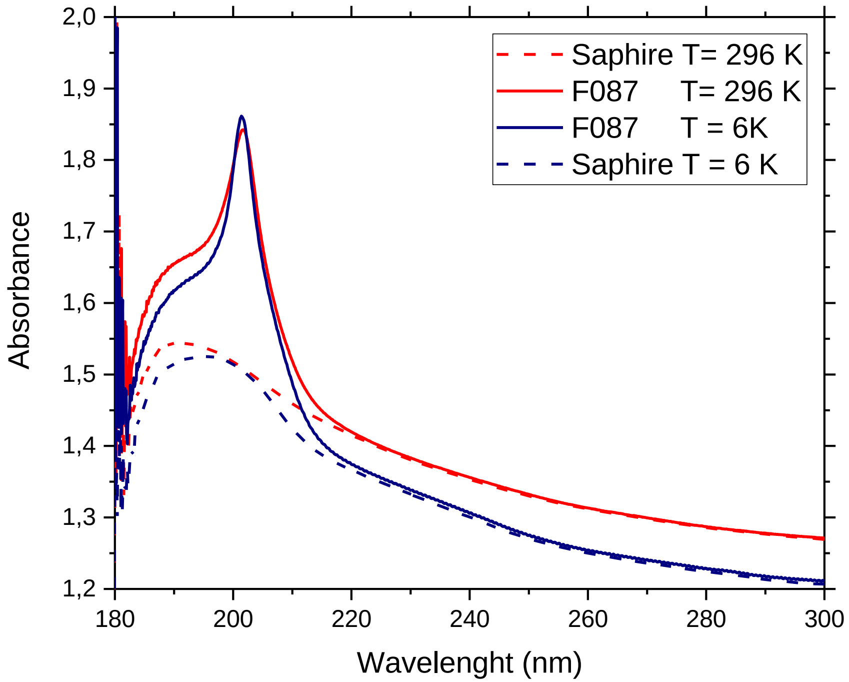


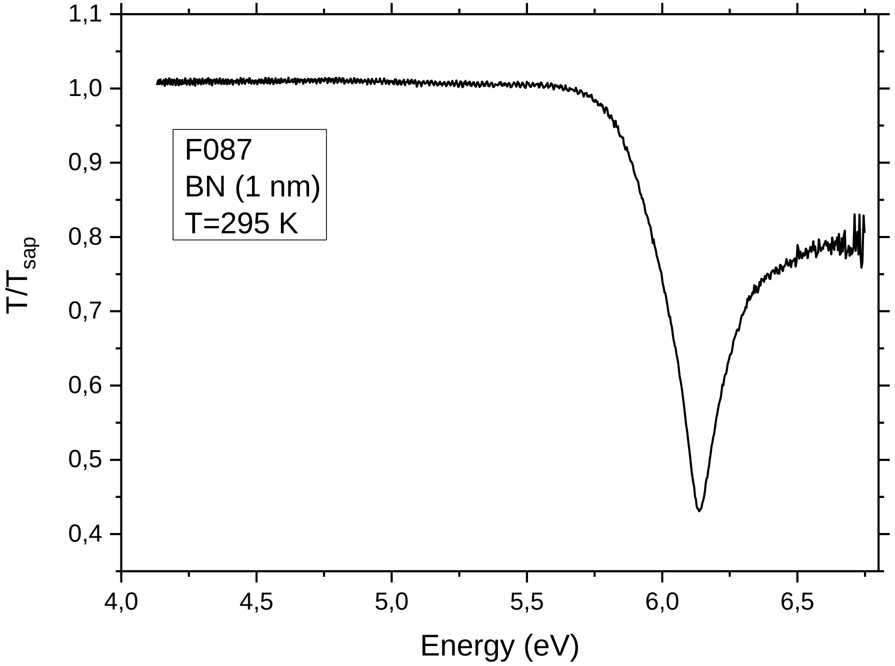
T. Q. P. Vuong et al. 2D Mater. **4** 021023 (2017)

G. Cassabois, P. Valvin and B. Gil, Nature Photonics 10, 262 (2016)

Optical absorption

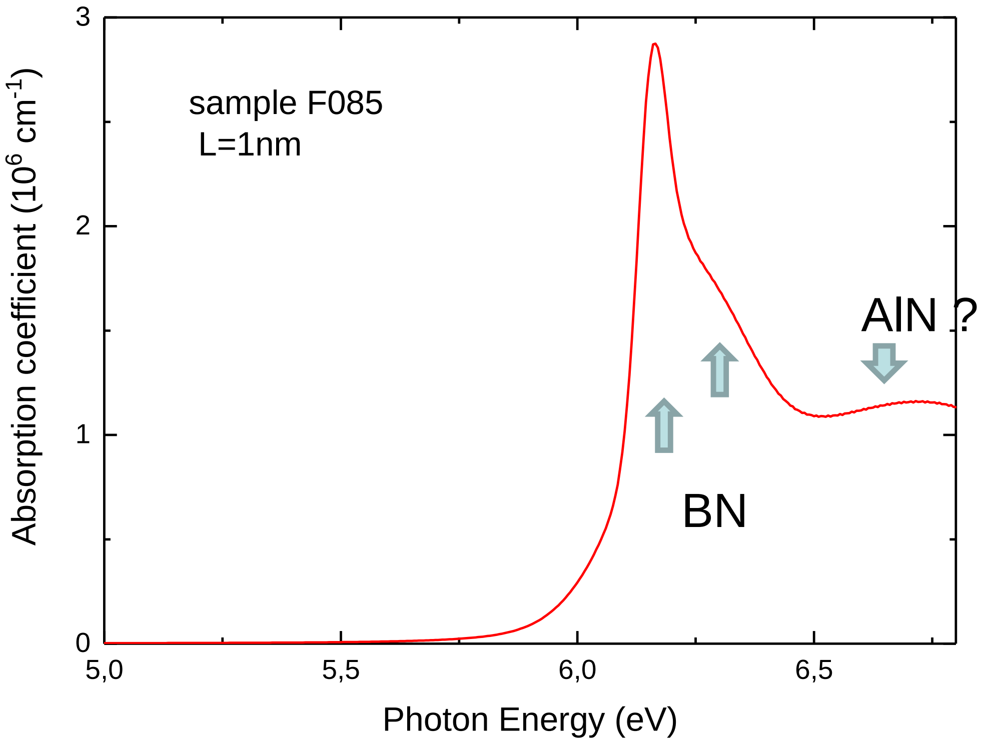
1nm thick BN layer (~4 ML)!!!

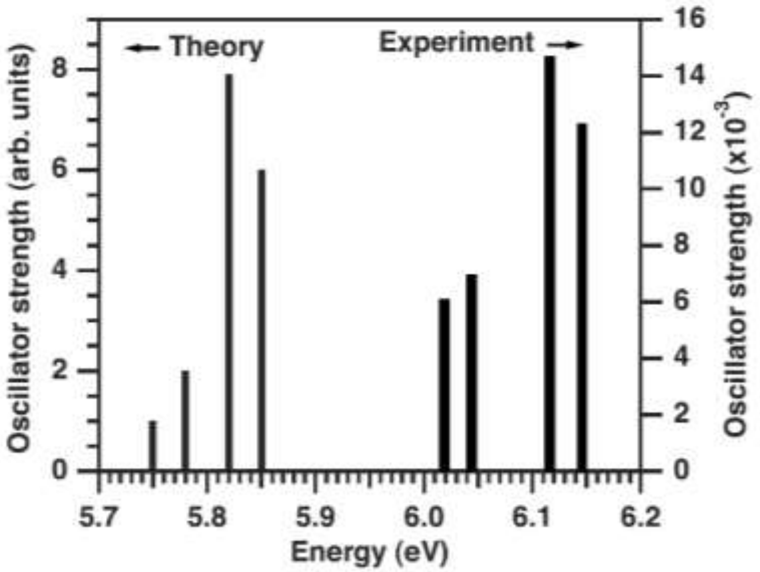




Cary 5000 UV-Vis-NIR

Excitonic structure of h-BN – experiment vs. theory





B. Arnauld et al. PRL **96,** 026402 (2006)

Direct-indirect transition in AlGaAs

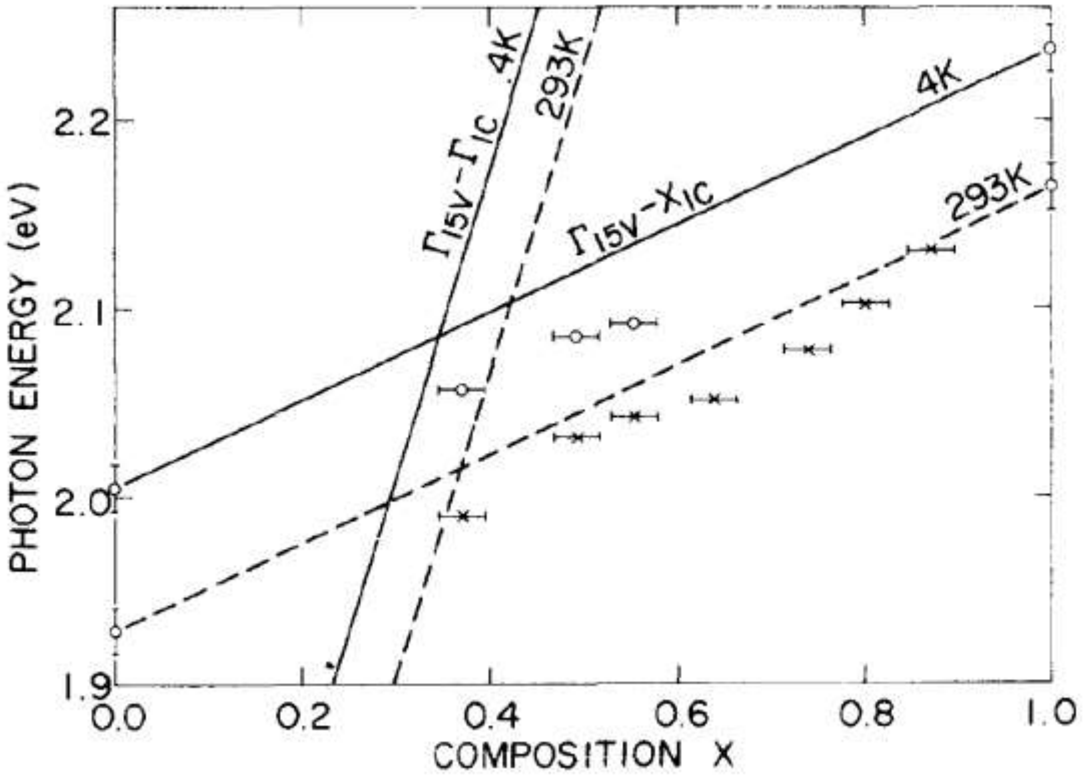
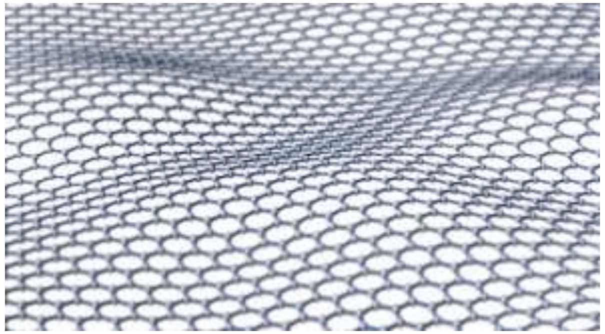


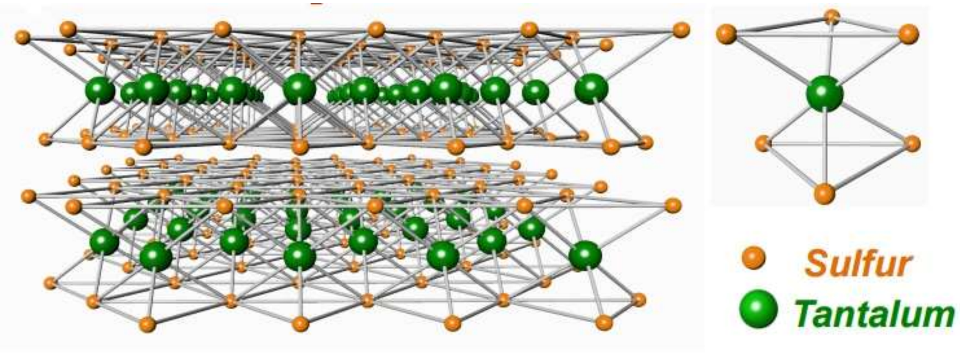
FIG. 9. Synopsis of luminescence peak positions for indirect-gap material at 4 K. (○) represents the bound-exciton peak and (×) the DA-pair peak position. The position of the DA-pair

B. Monemar et. al J. Appl. Phys. 47, 2604 (1976)

Graphene and other 2D materials – proximity effects ?

Graphene **+** **TaS_2 = ?**



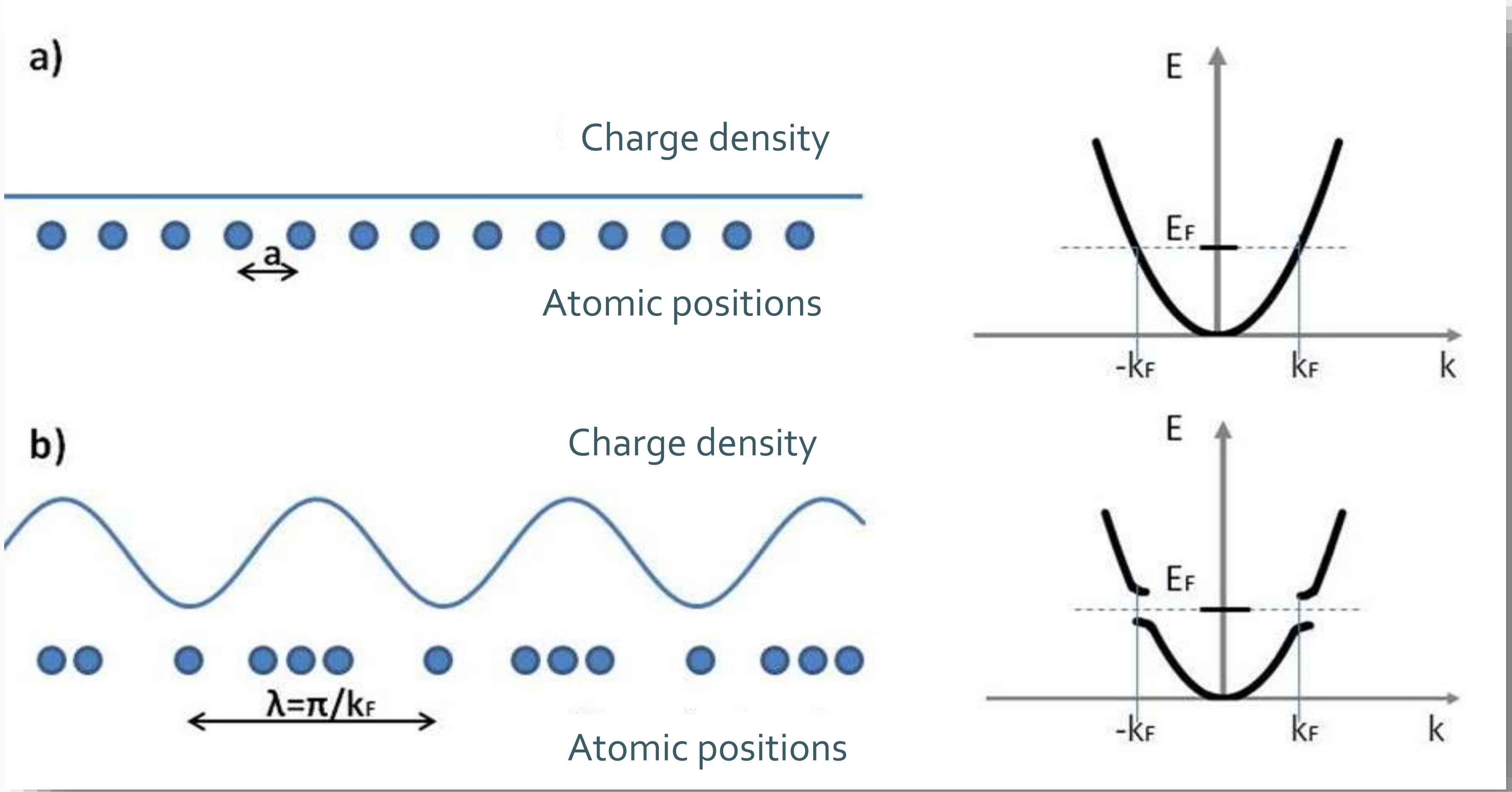


- High carriers mobility

- High spin-orbit coupling
(spin-orbit splitting 100 meV)

- 2D hybrid structures
- Is it possible to observe enhancement of spin-orbit coupling in graphene/1T-TaS2 hybrid structures?

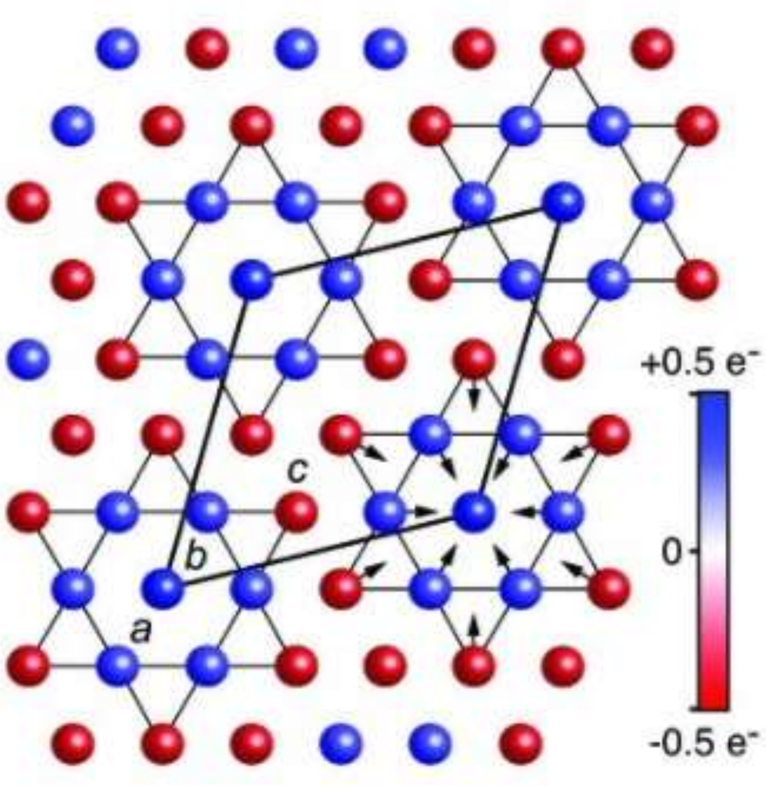
Charge density waves



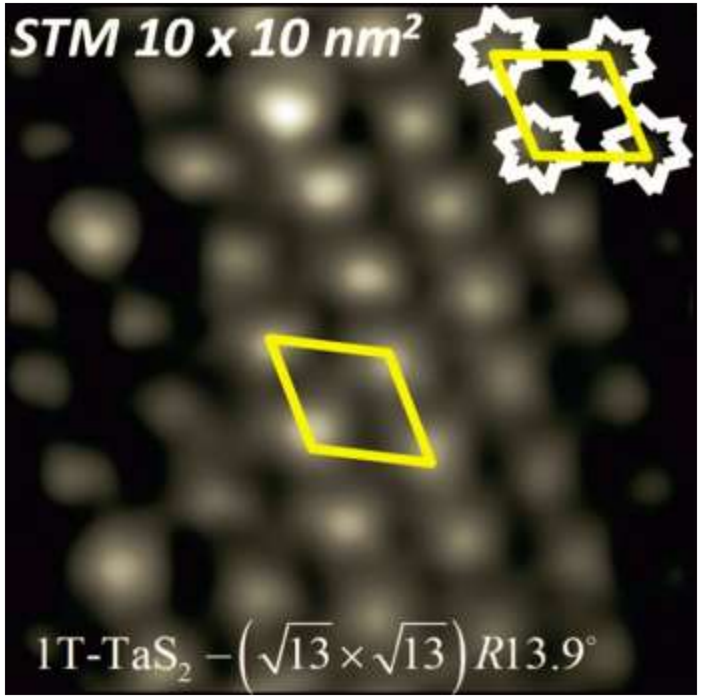
Thorne. Charge-density-wave conductors. *Physics Today, 49:42, May 1996.*

Charge density wave (CDW)

- Electron density standing wave due to strong coupling of charge carriers to atomic lattice
- Accompanied by periodic lattice distortion (PLD)
- Can be measured using scanning tunneling microscopy (STM)



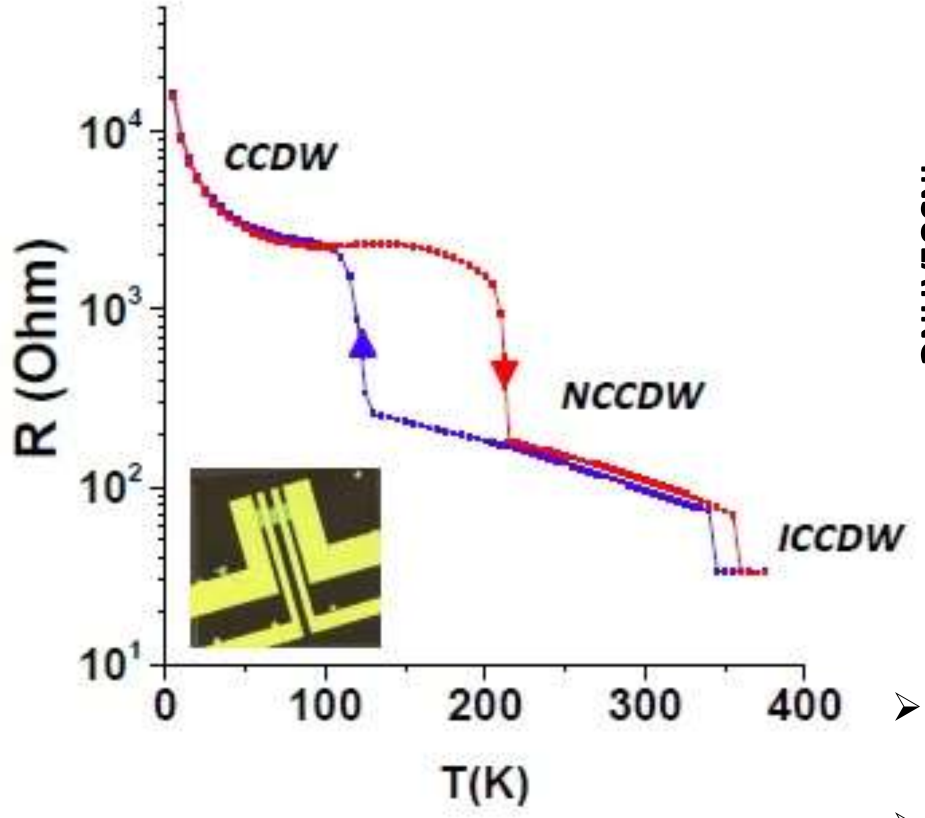
Phys. Rev. Lett. **105**, 187401 (2010)



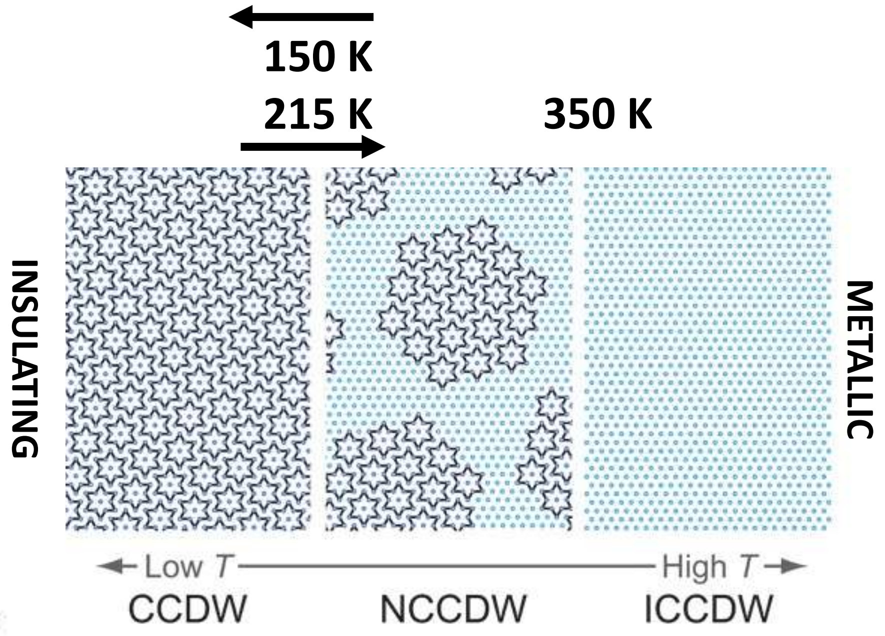
I. Lutsyk et. al, Phys. Rev. B **98**, 195425 (2018)

- PLD: superlattice of „stars" (13 Ta atoms + 26 S atoms)
- Charge carriers localised at stars centre -> system is insulating in CCDW phase

1T-TaS2: phase diagram



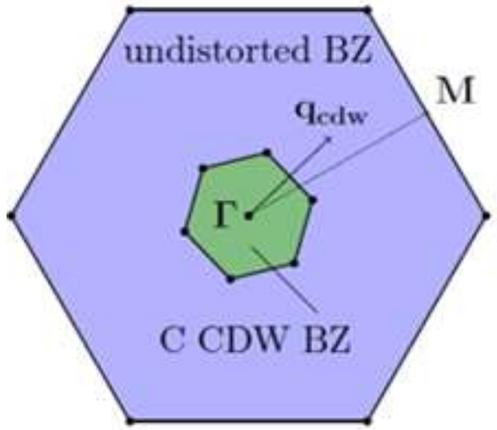
Adina Luican-Mayer, Jeffrey R. Guest, and Saw Wai Hla,
arXiv:1506.04102v1



M. Yoshida et al. **Sci. Adv**. (**2015**)

- **ICCDW** = incommensurate charge density wave, no PLD, metallic
- **NCCDW** = nearly commensurate CDW, domains of PLD stars
- **CCDW** = commensurate CDW, PLD, insulating

Raman scattering from TaS_2



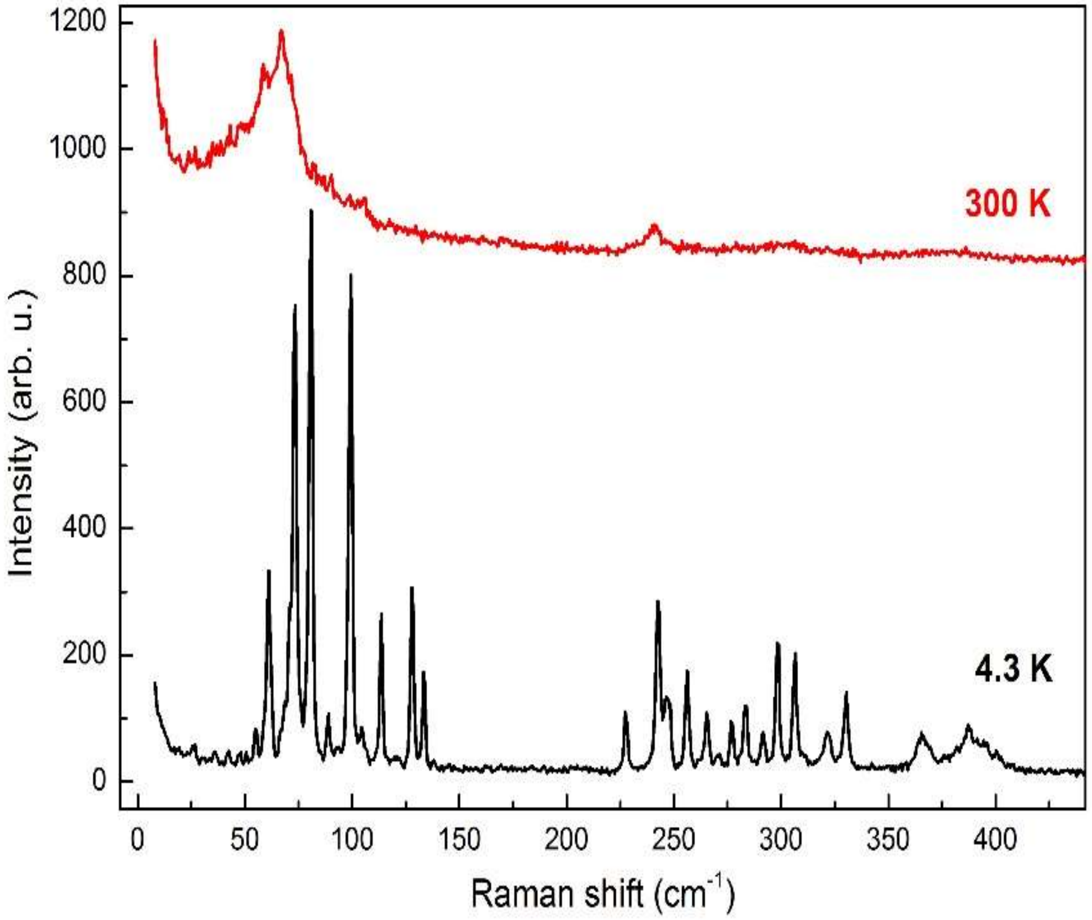
PHYSICAL REVIEW B **93**, 214109 (2016)

UNIT CELL

3 atoms	→	**39 atoms**
9 phonon modes		**117 phonon modes**

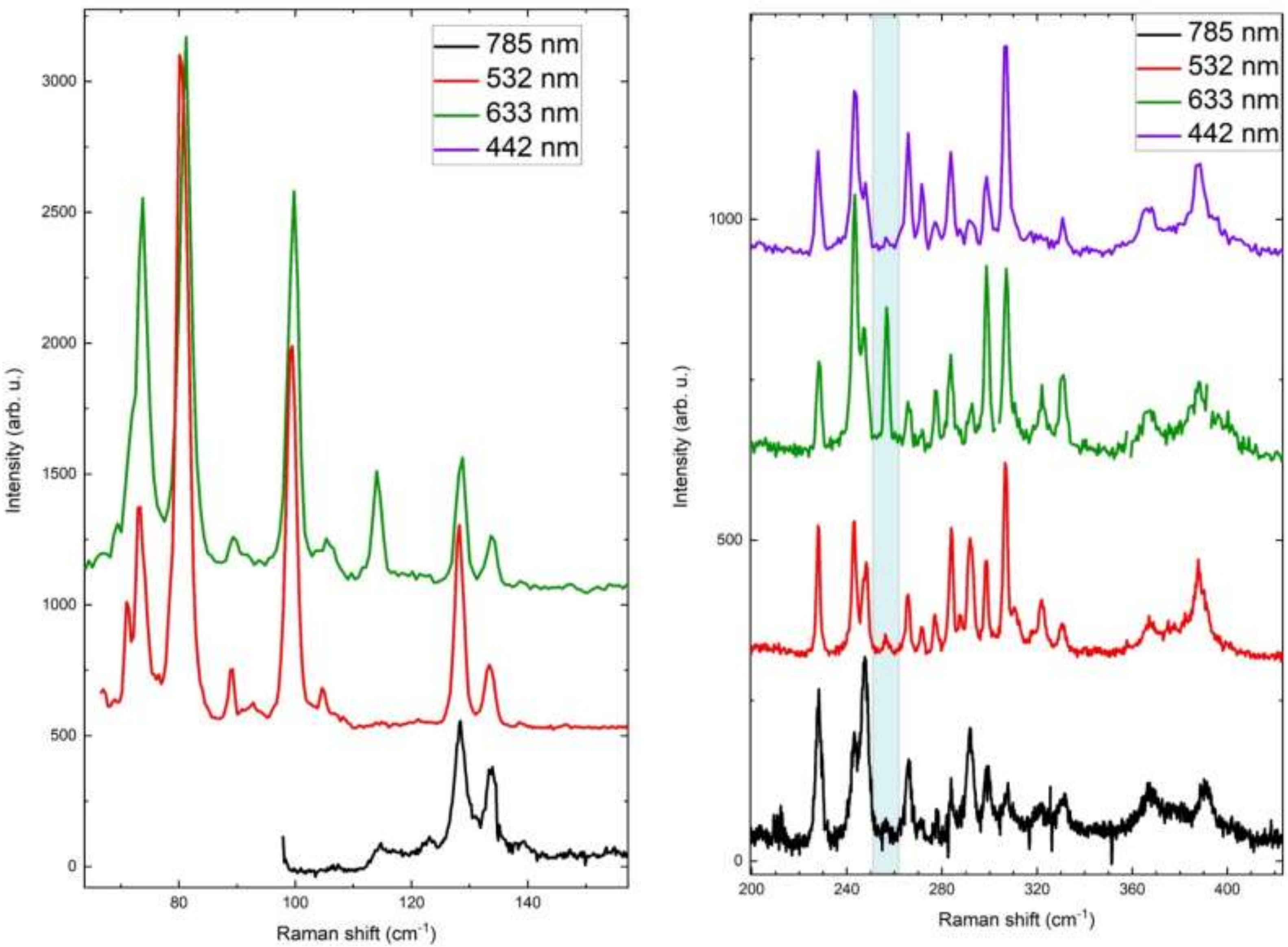
The first undistorted Brillouin zone 1T-TaS_2 (blue) and the first Brillouin zone in the CCDW phase (green).

Raman scattering from TaS_2



exc. 532 nm

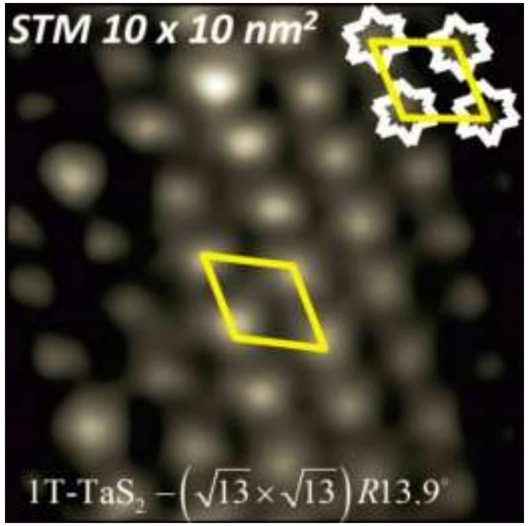
Resonant effect



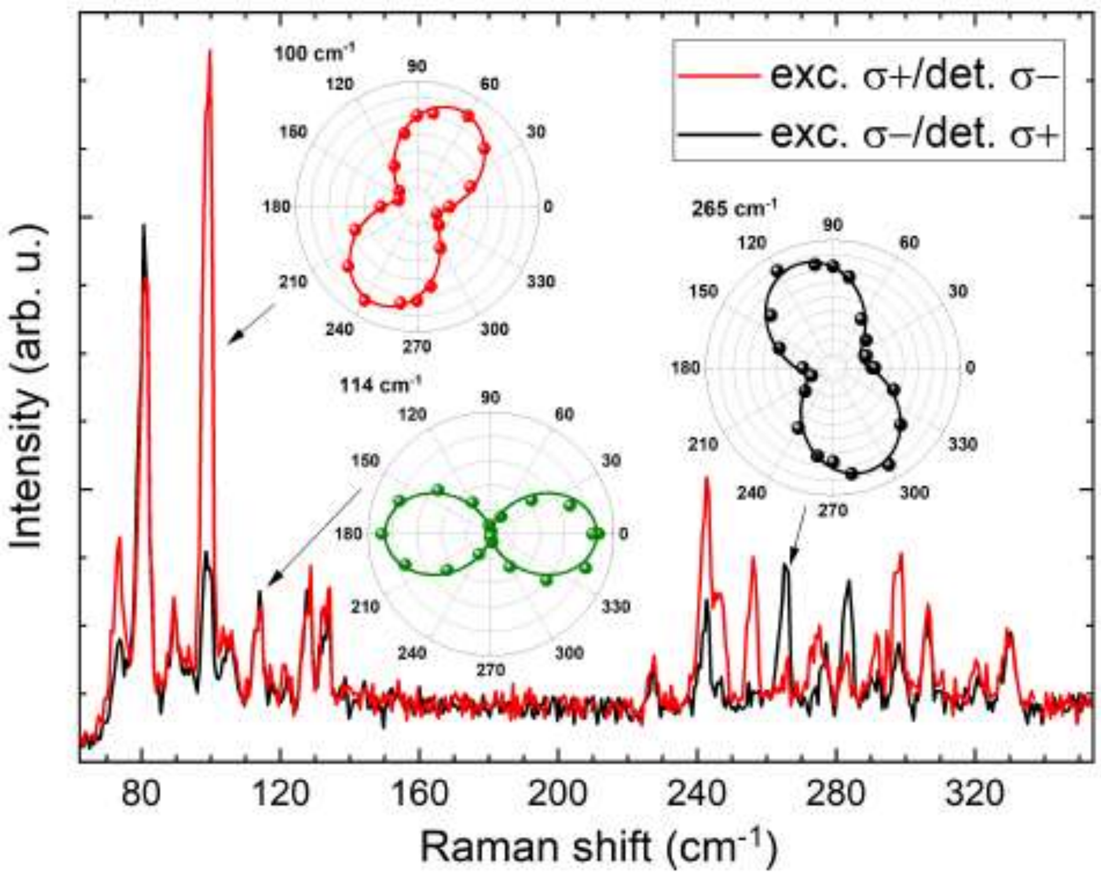
M. Furman et. al (2019)

Raman Optical Activity of 1T-TaS_2

Charge density wave (CDW)



I. Lutsyk et. al, Phys. Rev. B **98**, 195425 (2018)



E. M. Lacinska, M. Furman, J. Binder, I. Lutsyk, P. J. Kowalczyk, R. Stepniewski, and A. Wysmolek, Nano Letters 2022, 22, 7, 2835-2842 (2022)

Thank you for your attention!