Extraordinary properties of two-dimensional crystals – from graphene to transition metal dichalcogenides

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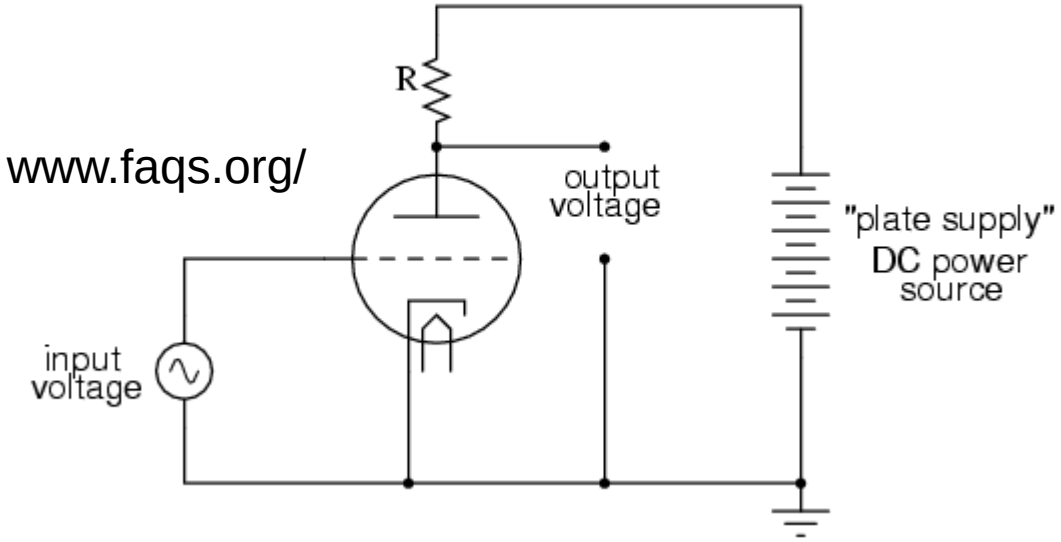
Vacuum electron tubes

Triode amplifier circuit

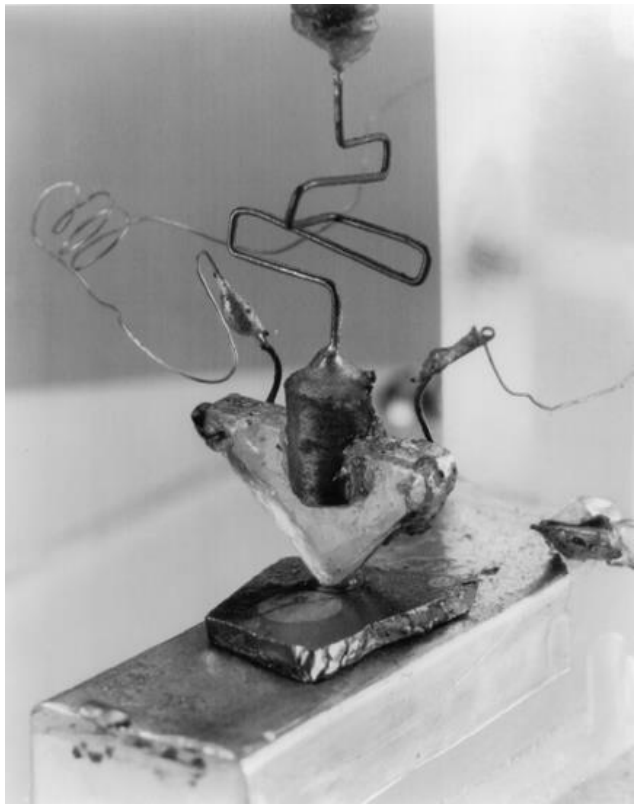


www.faqs.org/

First transistor…

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

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

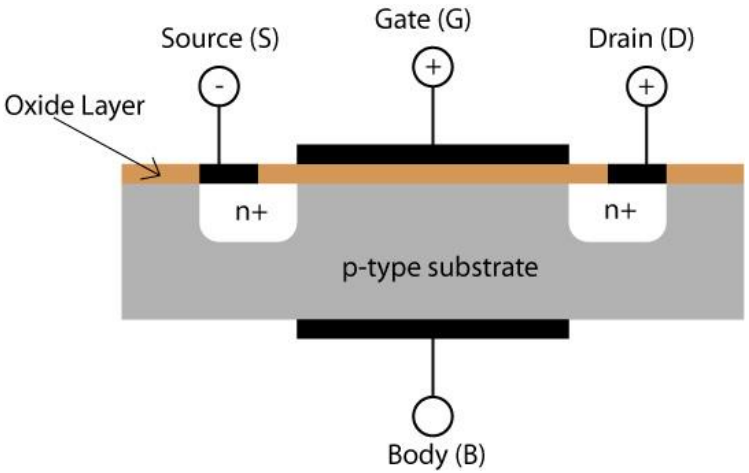


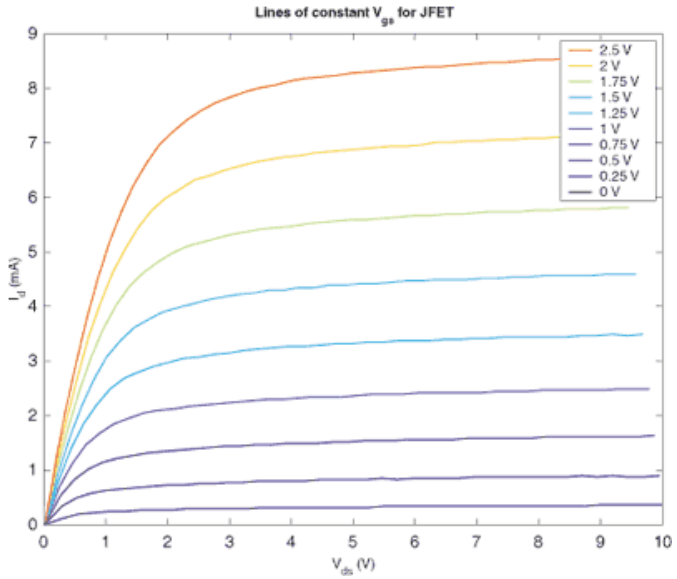
First point-contact transistor

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

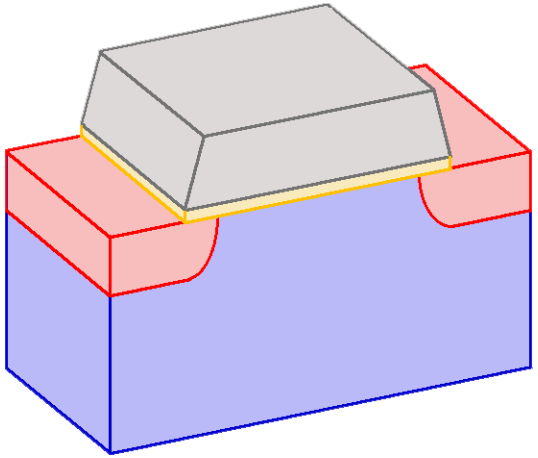
Field effect transistors

UNIVERSITY OF CAMBRIDGE

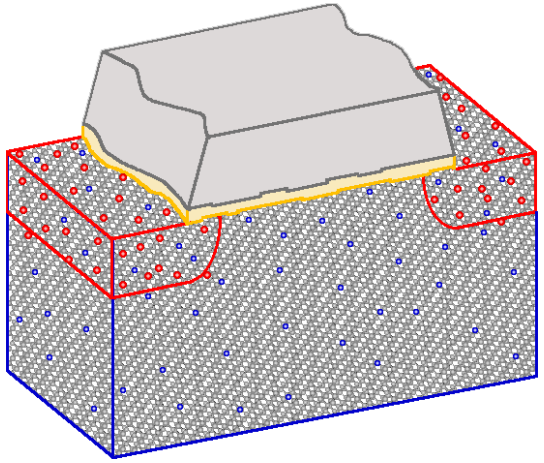




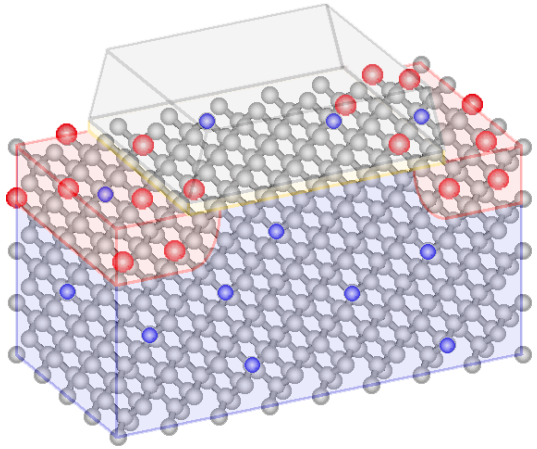
Miniaturization limits



we think that single
transistor looks like this



25 nm MOSFET
Production since 2008



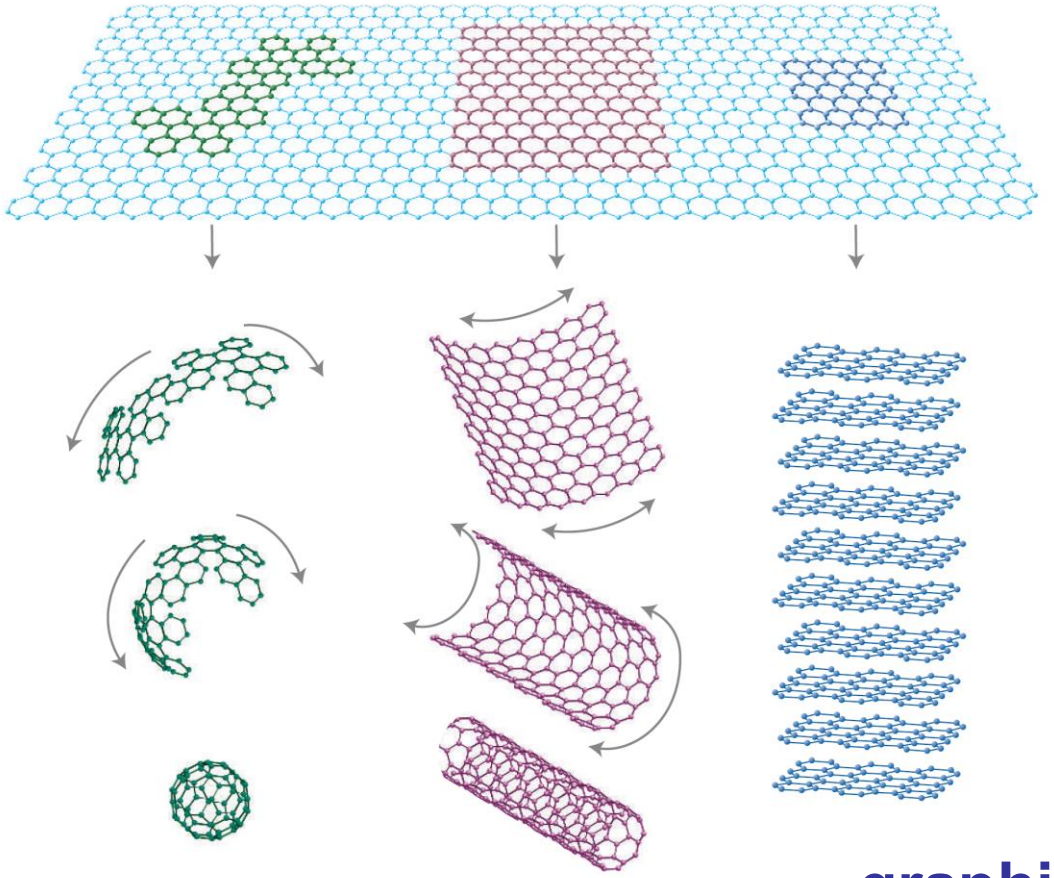
4,2 nm MOSFET ?

Asen Asenov, Glasgow

David Williams *Hitachi-Cambridge*

New ideas?

Graphene – a single layer of graphite…



fullerenes (0D)

nanotubes (1D)

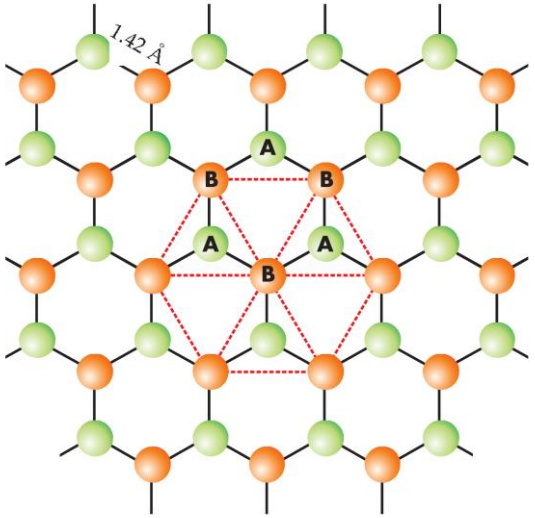
graphite (3D)

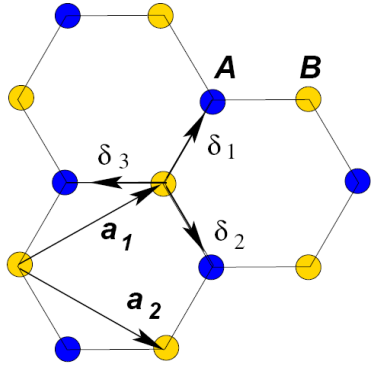
Basic block of different carbon allotropes….

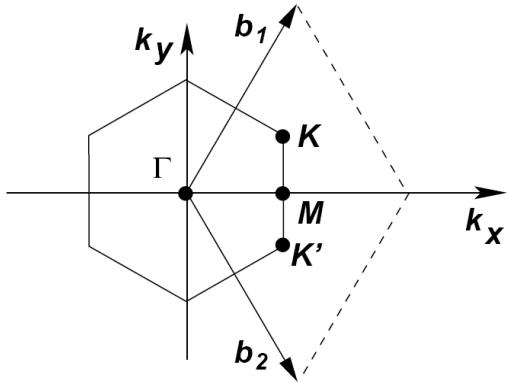
A.K. Geim and K.S. Novoselov,Nature 6, 183 (2007)

Band structure of graphene

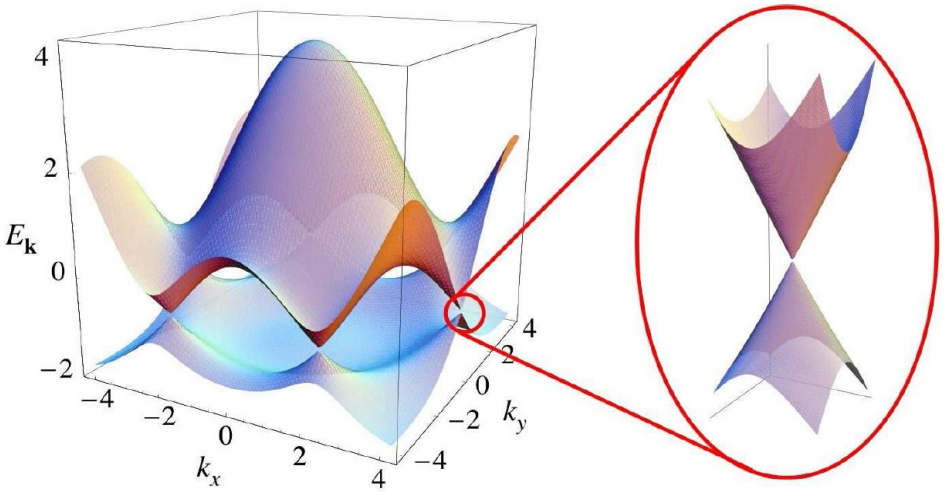
…known since years: (*P.R. Wallace, Phys. Rev. (1947)*)







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



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

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

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

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

The Nobel Prize in Physics 2010
Andre Geim, Konstantin Novoselov

The Nobel Prize in Physics 2010

Andre Geim

Konstantin Novoselov

Photo: Sergeom, Wikimedia Commons

Photo: University of Manchester, UK

Andre Geim

Konstantin Novoselov

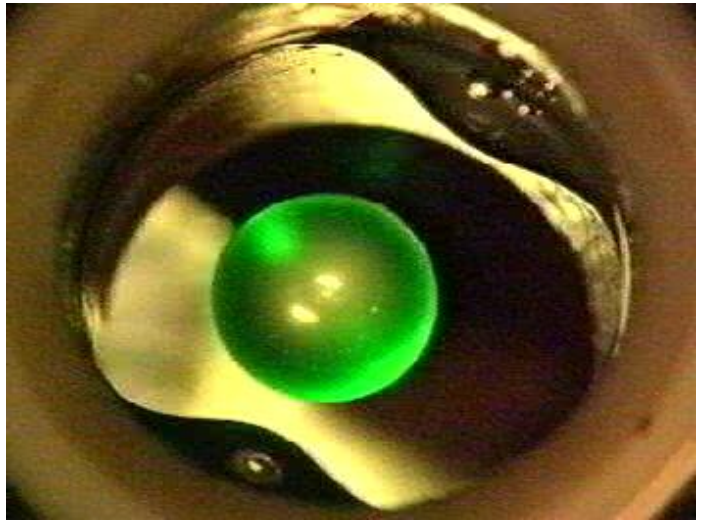
The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov *"for groundbreaking experiments regarding the two-dimensional material graphene"*

Ig Nobel Prize 2000

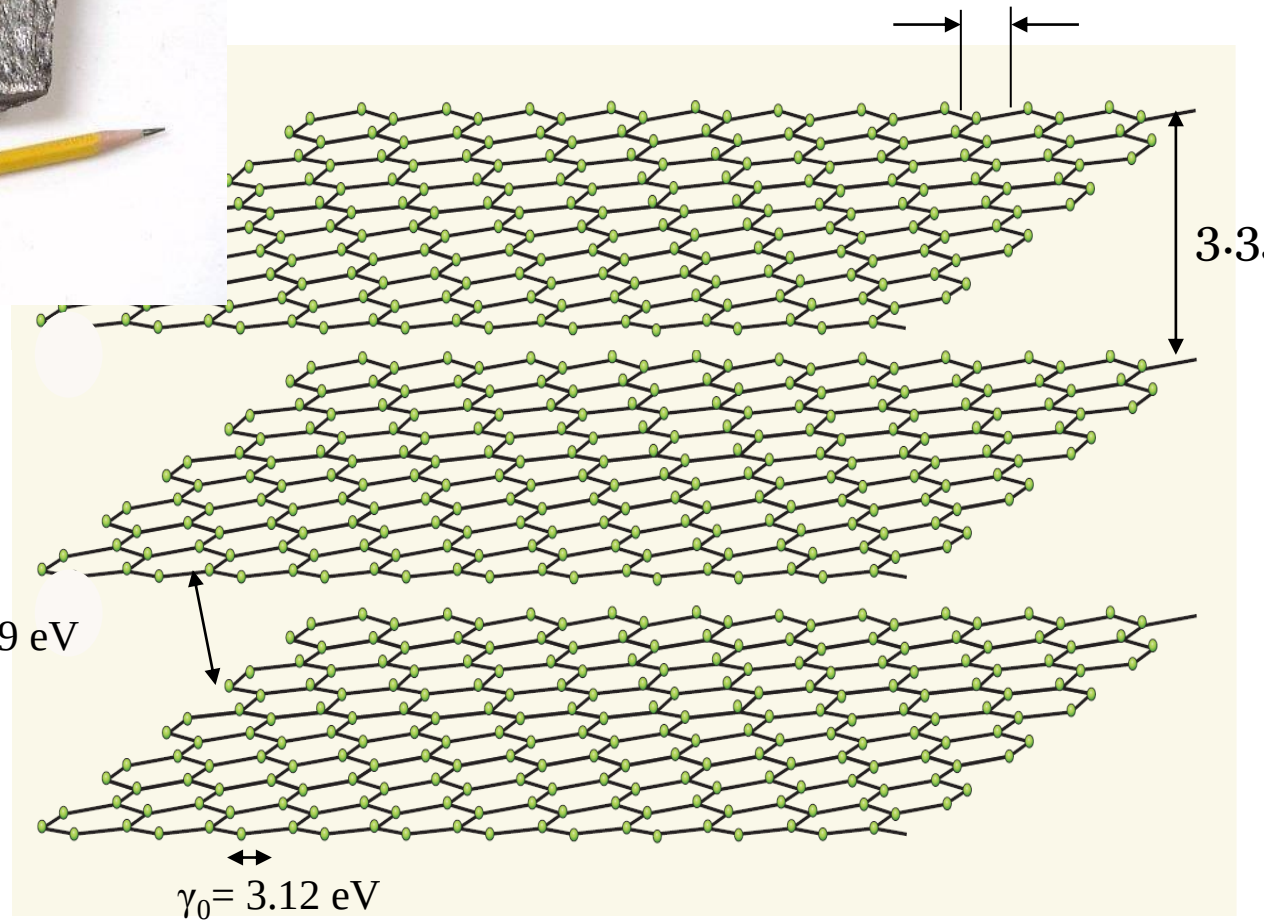
Andre Geim, University of Nijmegen (Netherlands)
Sir Michael Berry, Bristol University (UK),
„for using magnets to levitate a frog"

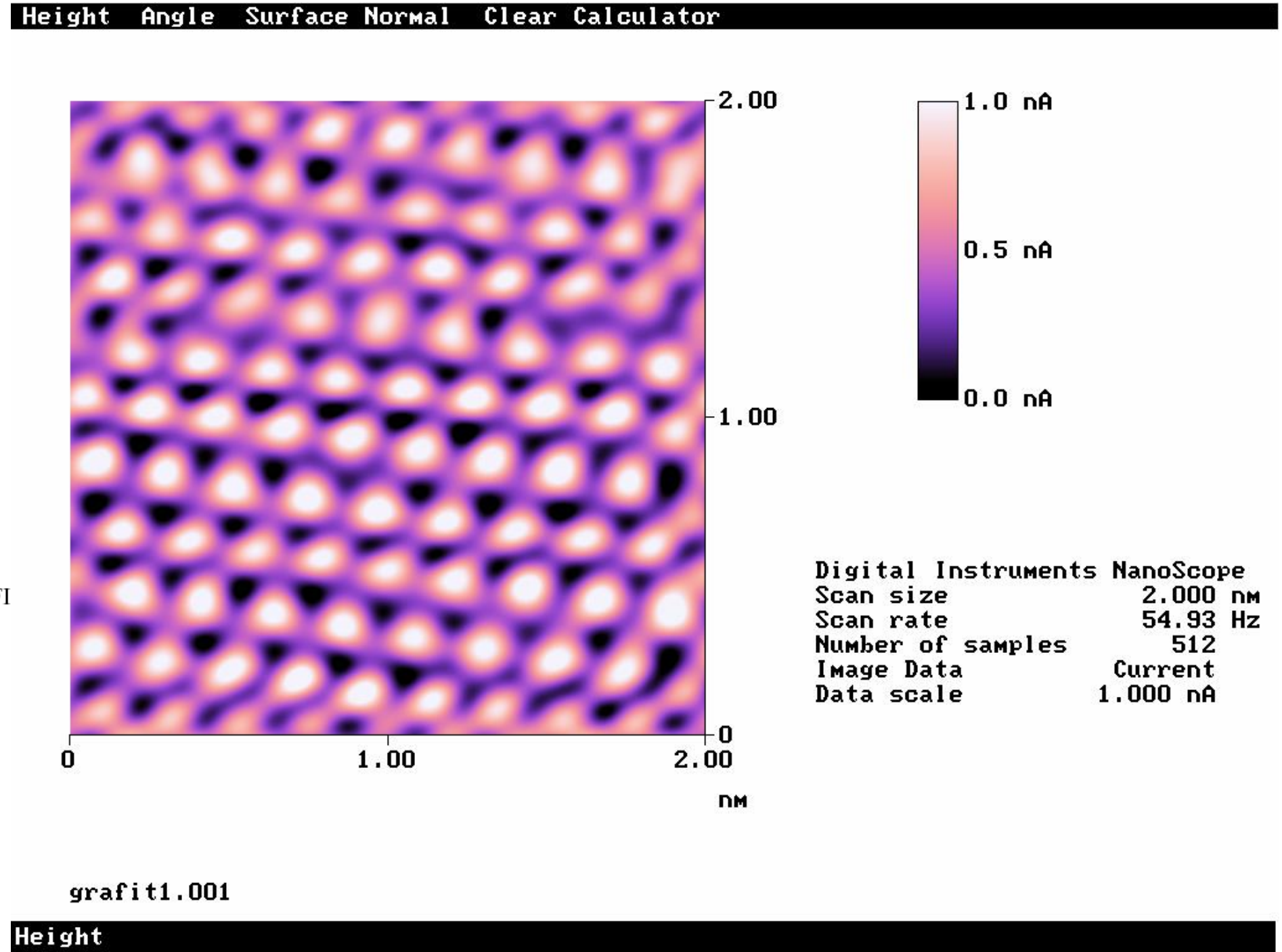
The motto of the Ig Nobel Prize is to „honour the achievements that first make people laugh, and then think…"

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



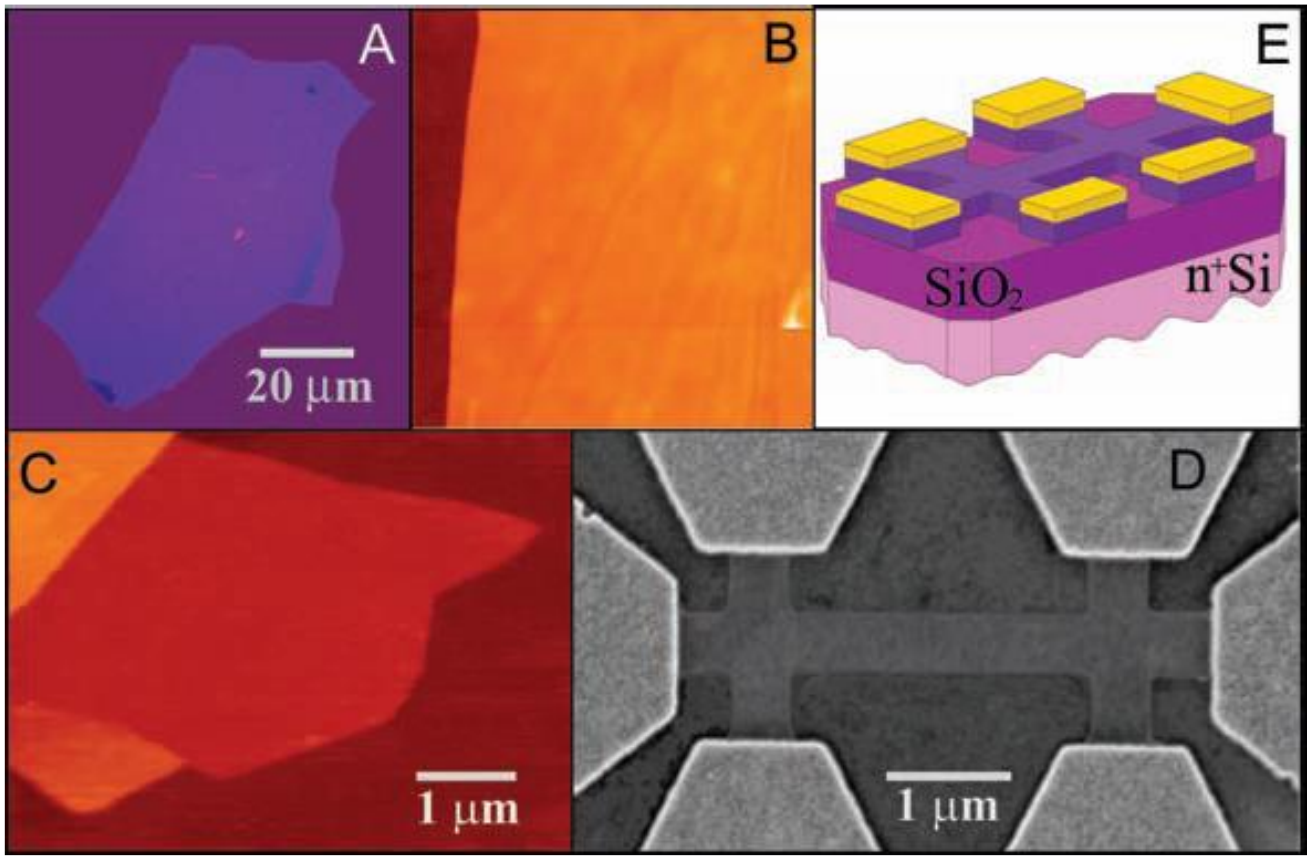
Graphite




Height Angle Surface Normal Clear Calculator
2.00
1.00
0
0
1.00
2.00
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

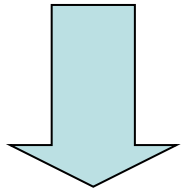


flake size ~10 μm

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

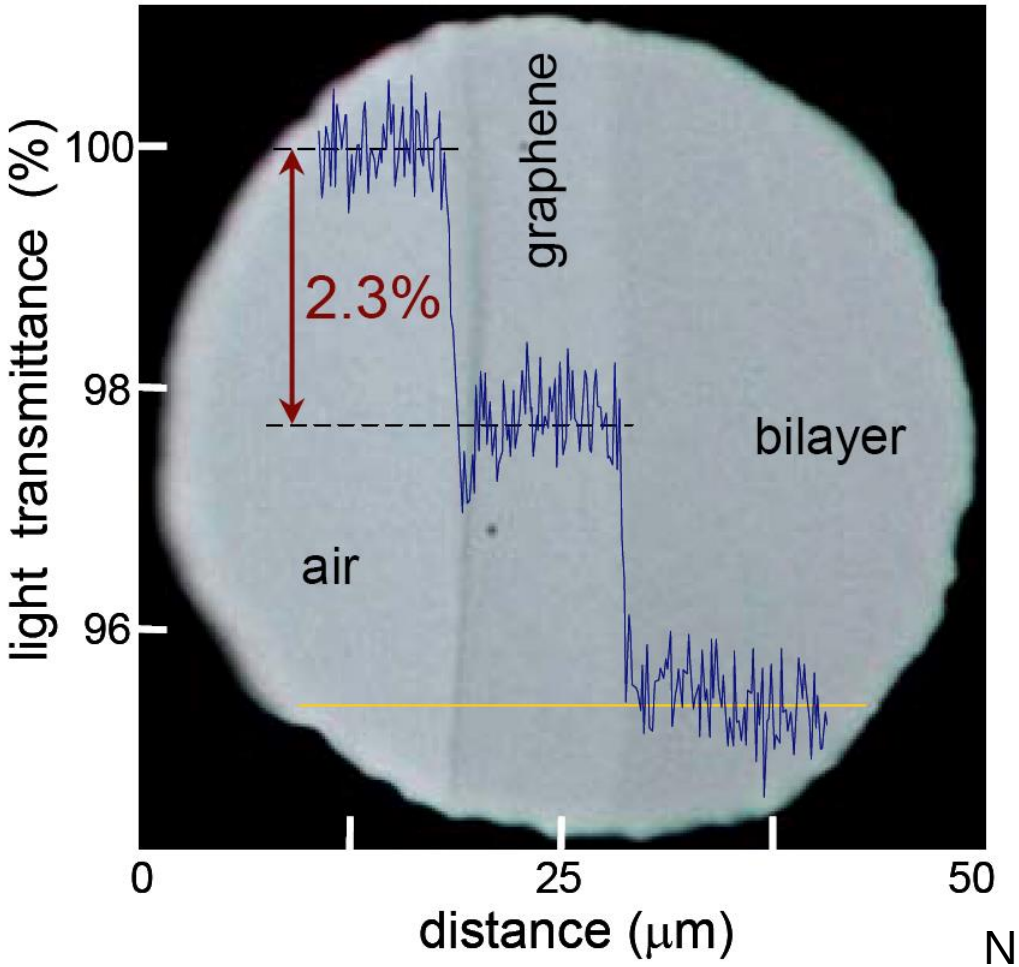
Graphene…

- 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…

Solar cells

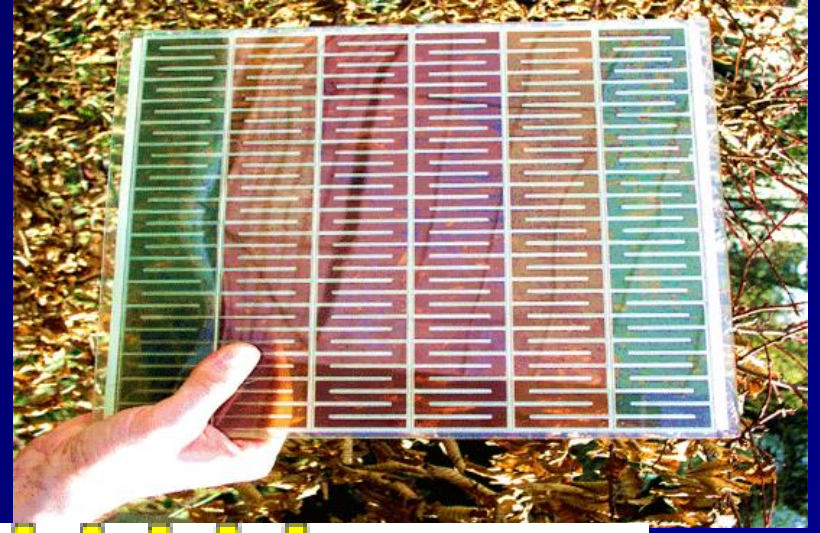

Kosuzume, Japan – 50 kW

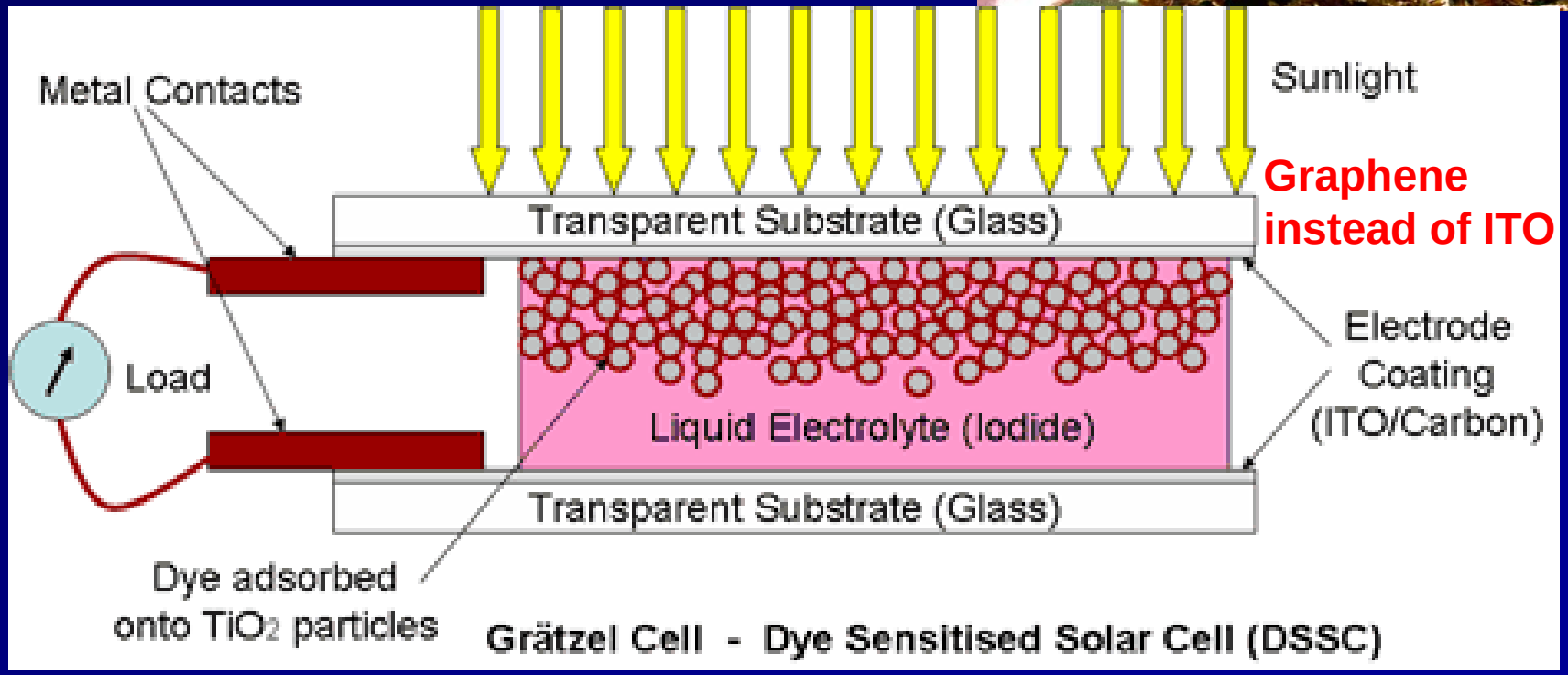

Geneva, Switzerland – 100 kW


Cudrefin, Switzerland -9.7 kW


Flotzheim, Germany – 8.4 kW

Improved Grätzel cells…

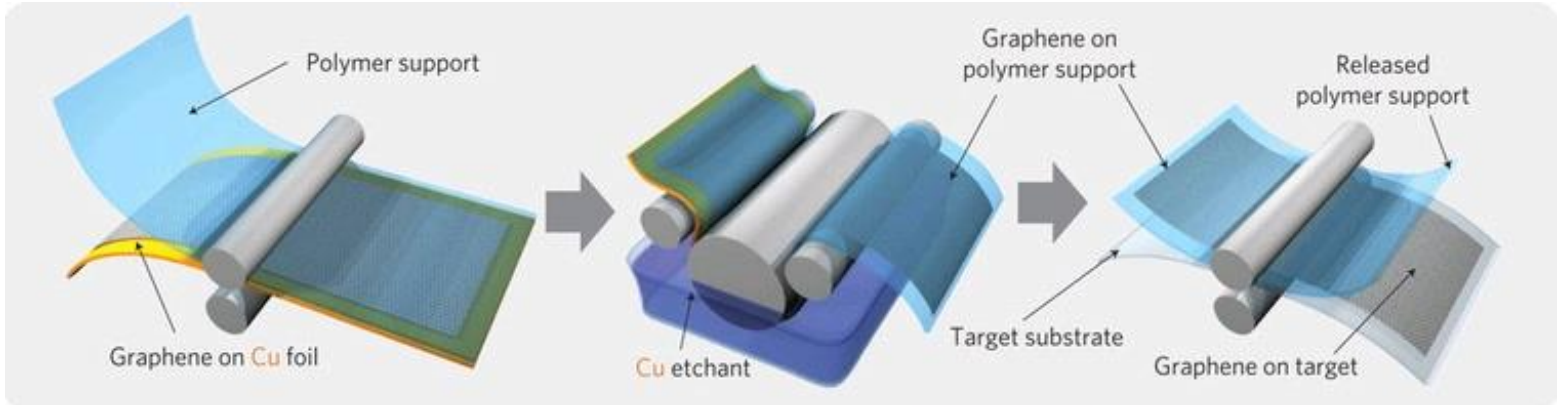


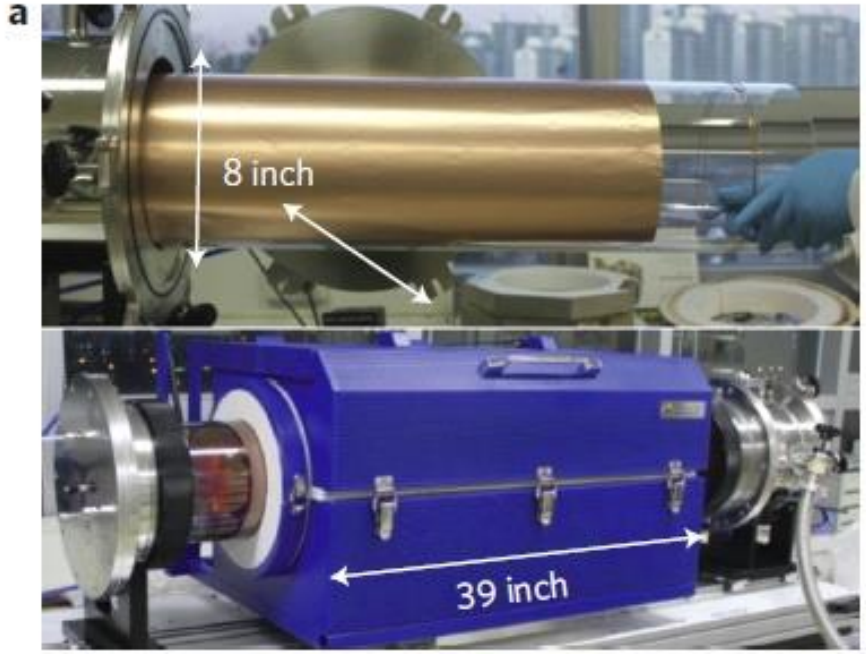


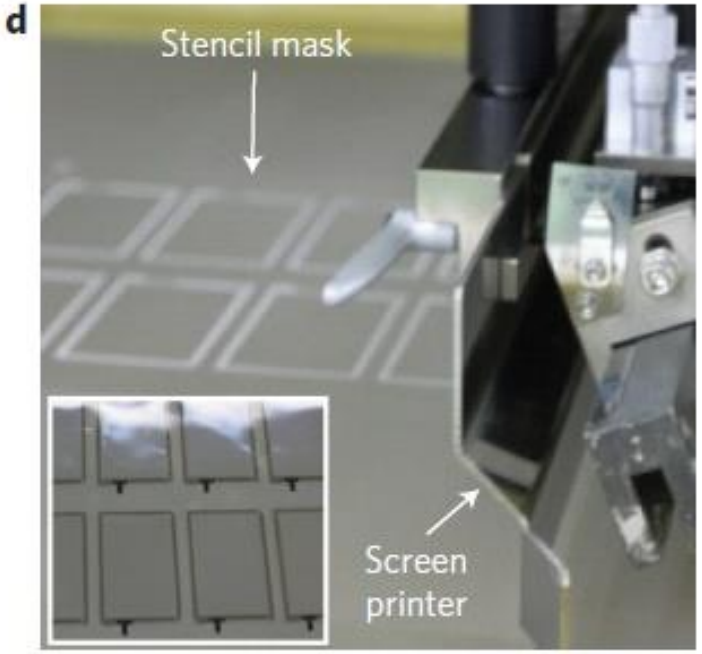
http://www.solarisnano.com/

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

Graphene „roll-to-roll”



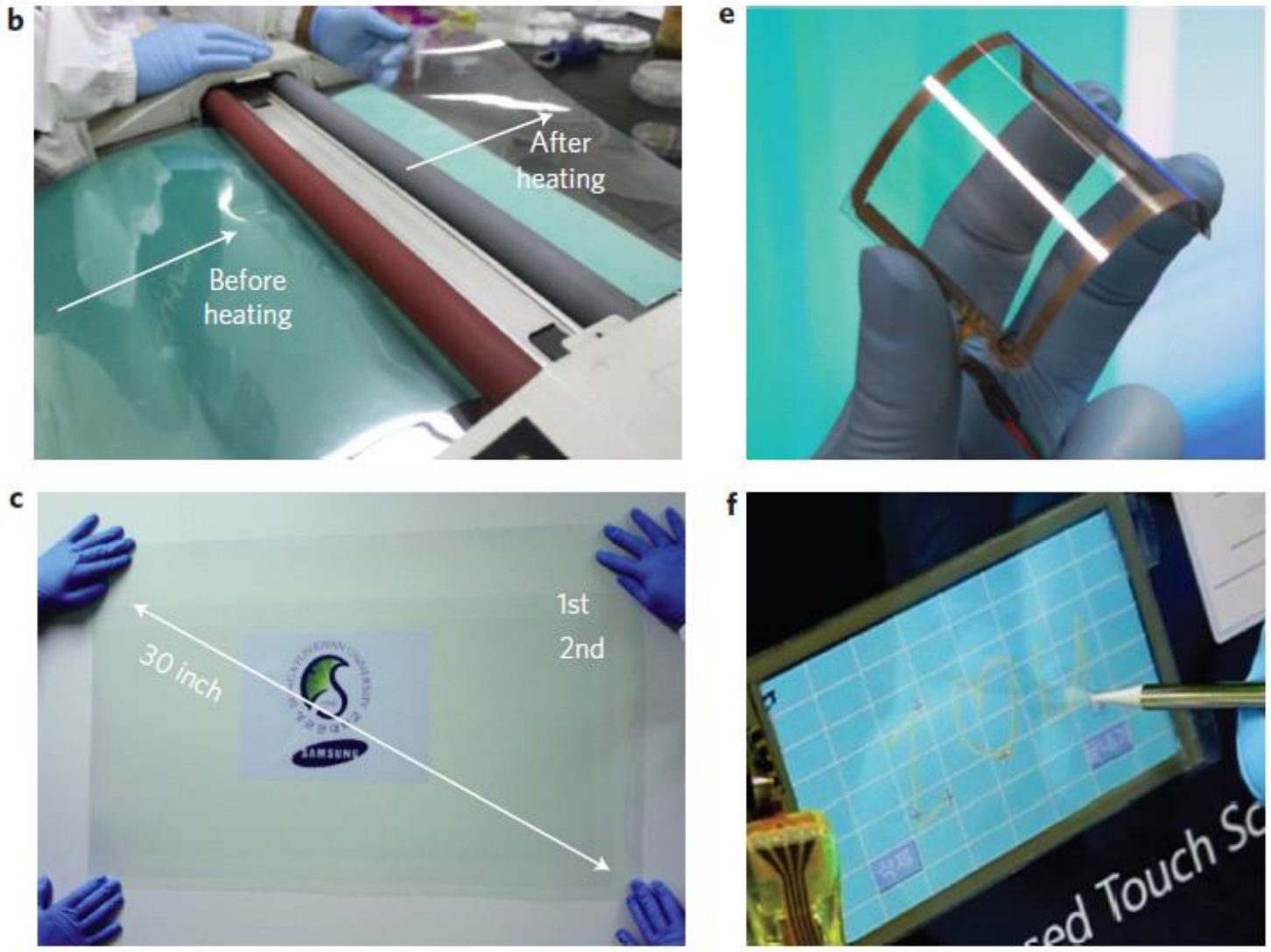




Bae et al. NATURE NANOTECHNOLOGY 5,574 (2010)

NATURE NANOTECHNOLOGY

Transparent and elastic touch screens



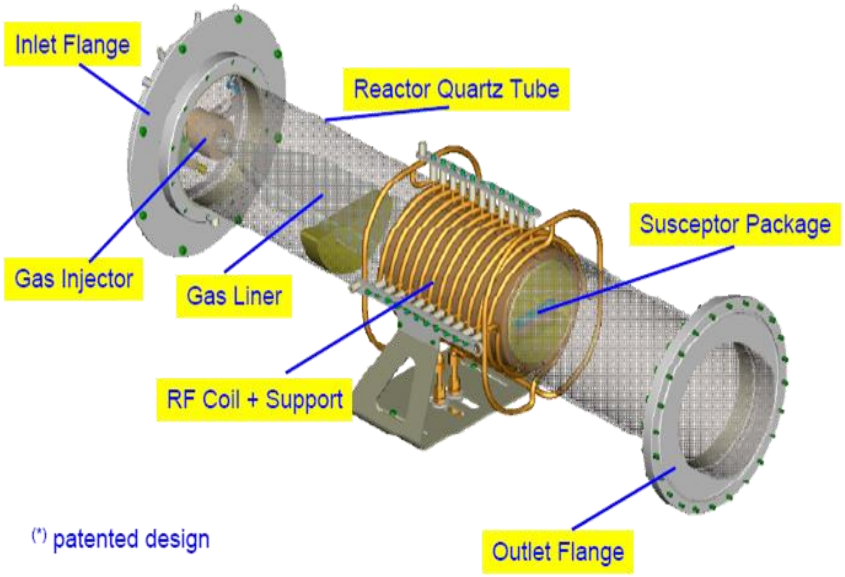
Bae et al. NATURE NANOTECHNOLOGY 5,574 (2010)

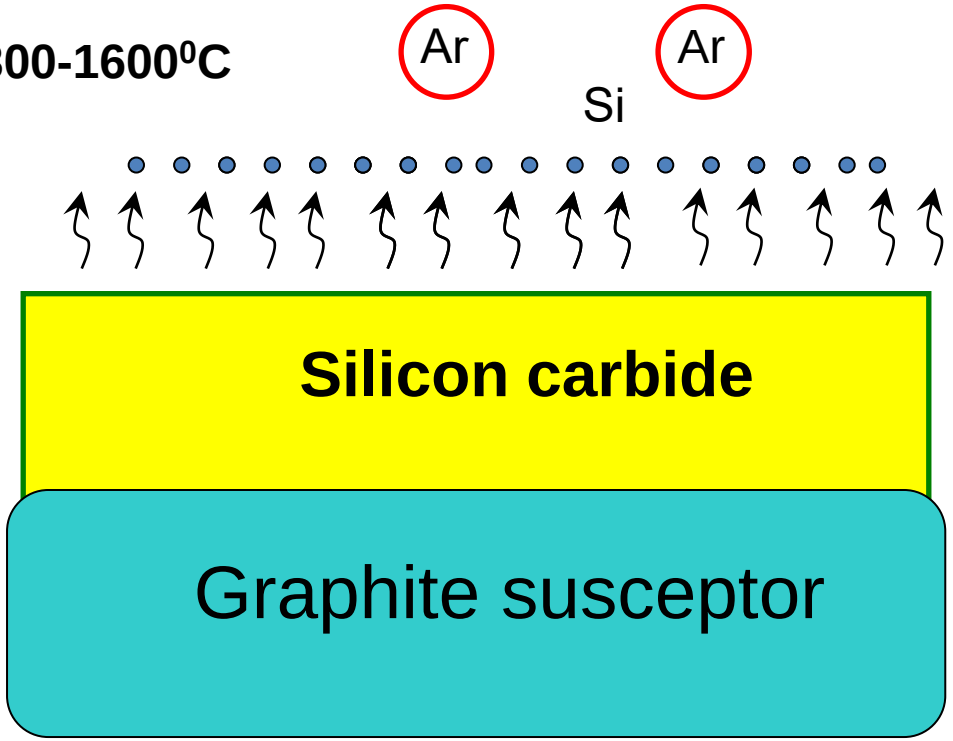
Sublimation method

(in Warsaw ~2006/2007)

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

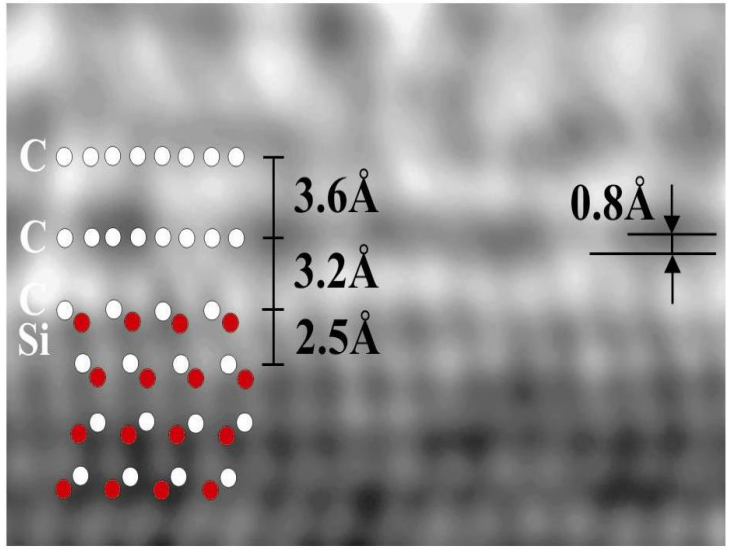
Graphitization at 1300-1600^{0}C





Aixtron VP508 CVD reactor (for SiC growth)

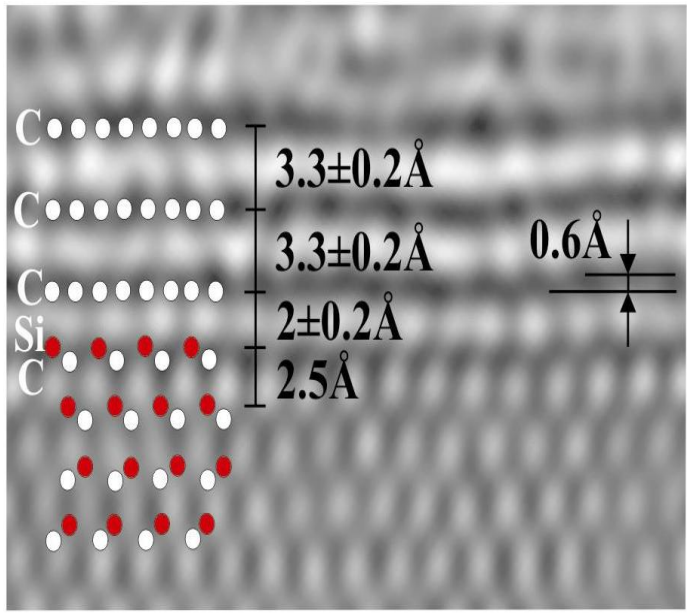
Graphene on SiC



[11$\bar{2}$0] HRTEM J. Borysiuk

Carbon face

(usually low p-type)



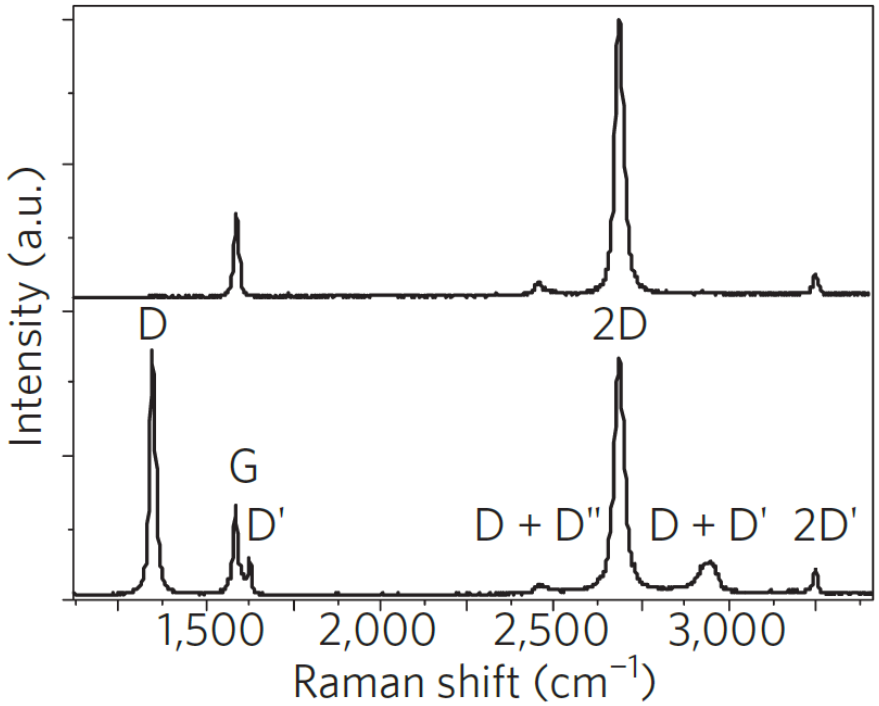
[11$\bar{2}$0] HRTEM J. Borysiuk

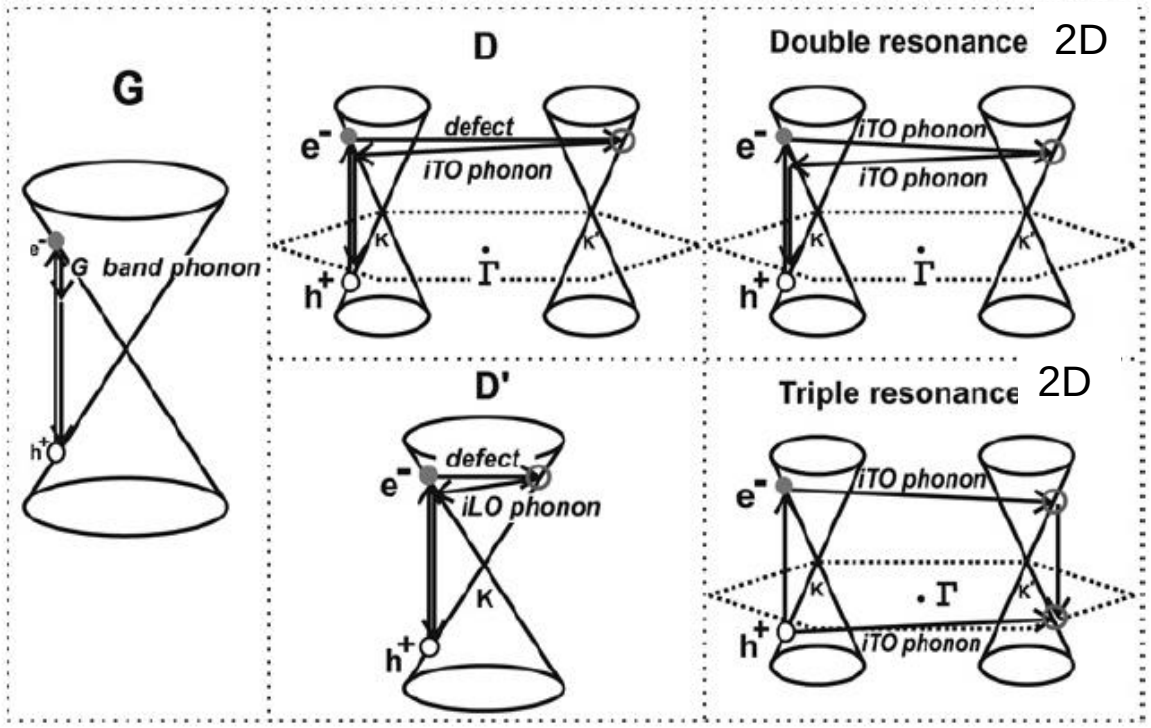
Silicon face

(usually highly n-type)

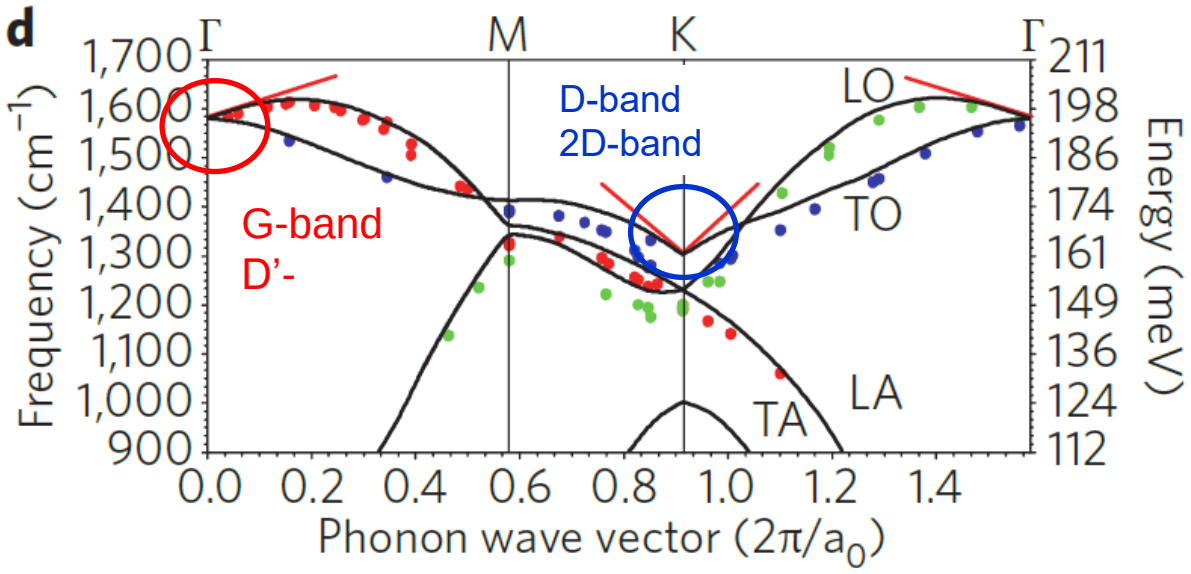
J. Borysiuk et al., J. Appl. Phys. **108,** 013518 (2010)

Raman spectra of graphene





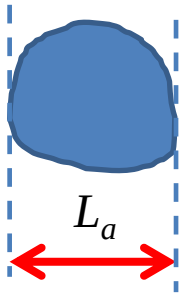
L. M. Malard et al. Phys. Rep. 473, 51 (2009)



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...



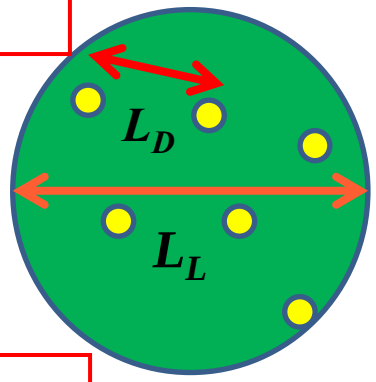
„Ideal" crystallites (flakes):

$$I(D) \propto L_a \qquad I(G) \propto L_a^2 \qquad \Rightarrow \qquad \frac{I(D)}{I(G)} \propto 1/L_a$$

L_a – flake size

Flakes with rare defects

$I(D)$ ∝ number of defects within the laser spot…



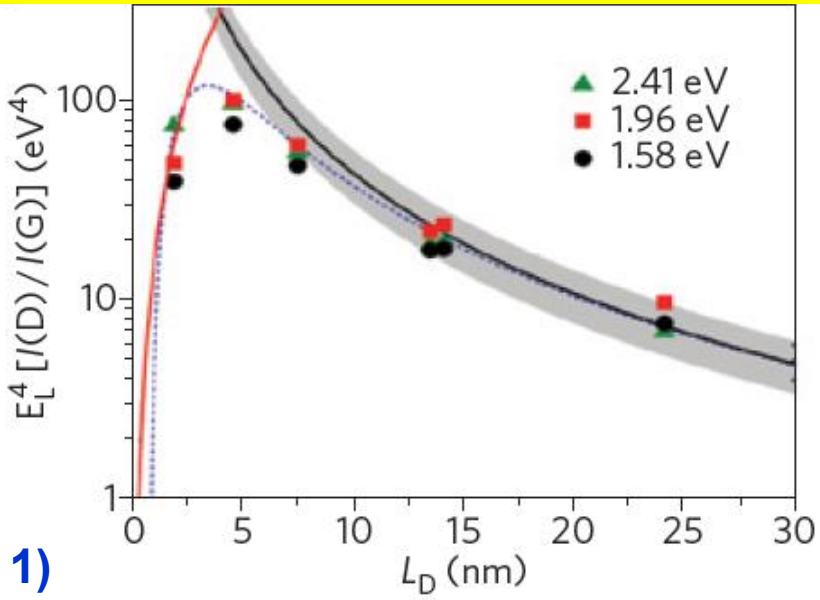
$$I(D) \propto (L_L/L_D)^2 \qquad I(G) \propto L_L^2 \qquad \Rightarrow \qquad \frac{I(D)}{I(G)} \propto 1/L_D^2$$

High disorder

$I(D)$ ∝ number of sp^2 rings

$I(G)$ ≅ constant (∝ relative motion of sp^2 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)

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

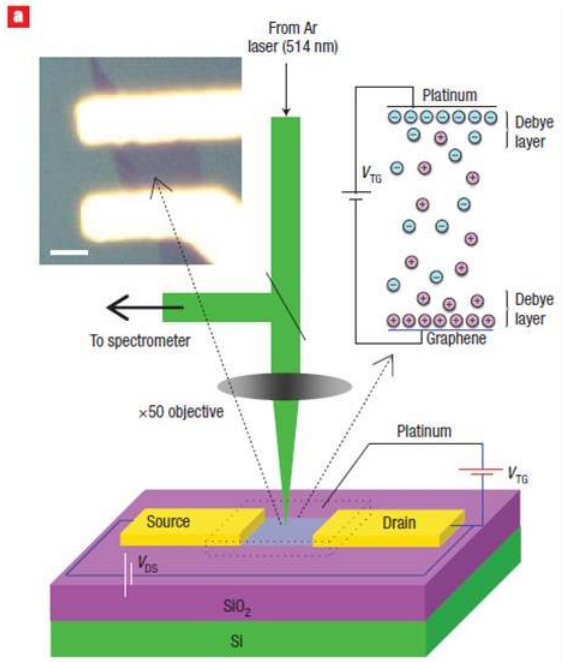
$$n_D(cm^{-2}) = \frac{5.9\times10^{14}}{E_L^4(eV^4)}\left(\frac{I(D)}{I(G)}\right)^{-1}$$

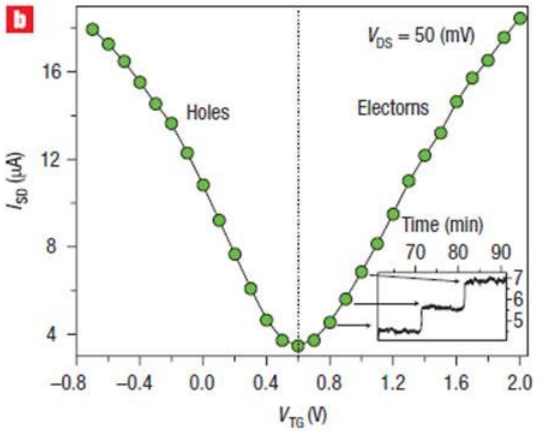
F. Tuinstra and J. L. Koenig, J. Chem. Phys. **53**, 1126 (1970)

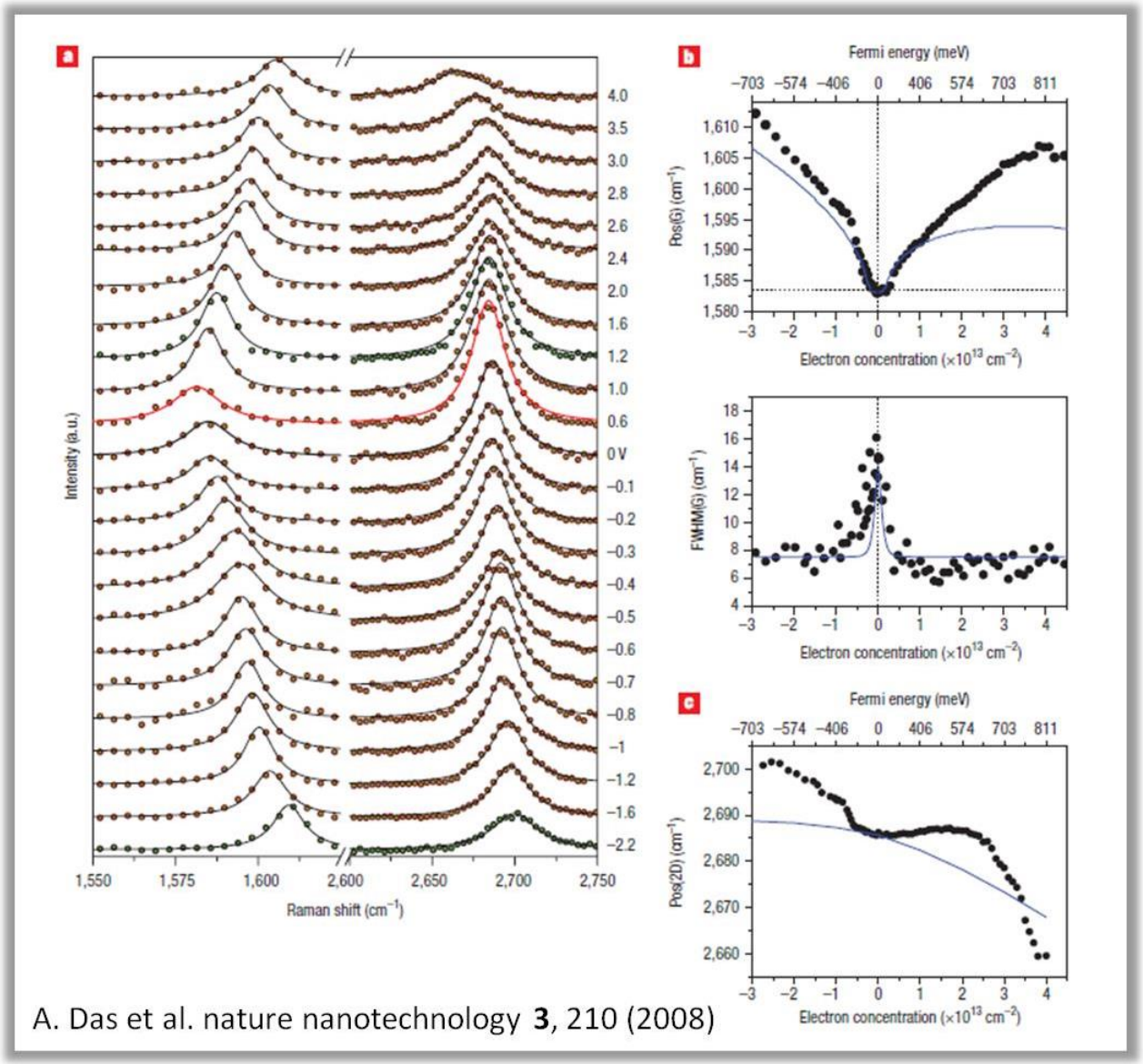
L. G. Cancado et al., Nano Lett. **11** 3190 (2011)

A. C. Ferrari and D. M. Basco,Nature Nanotechn. 8, 235 (2013)

Doping reference - solid electrolyte top gated exfoliated graphene

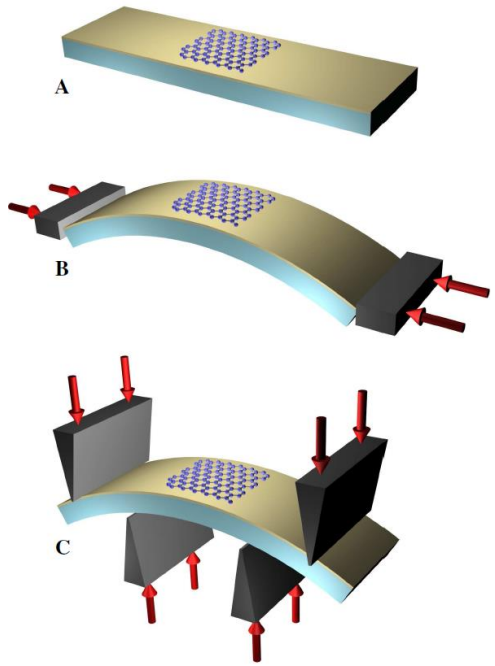


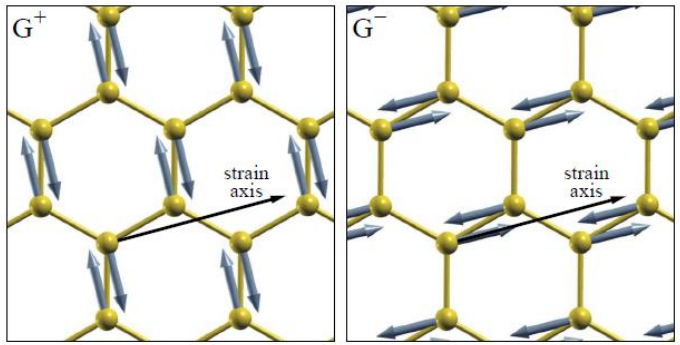


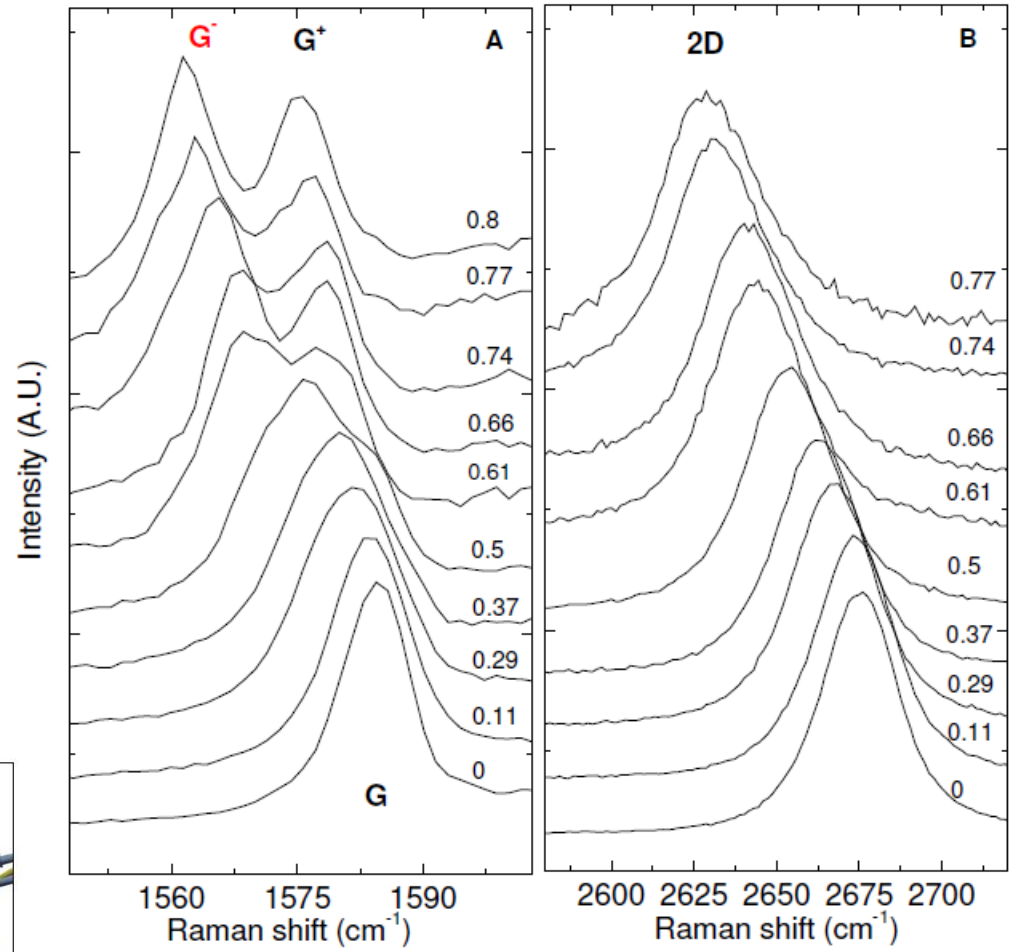


A. Das et al. nature nanotechnology **3**, 210 (2008)

Uniaxial strain influence on Raman spectra

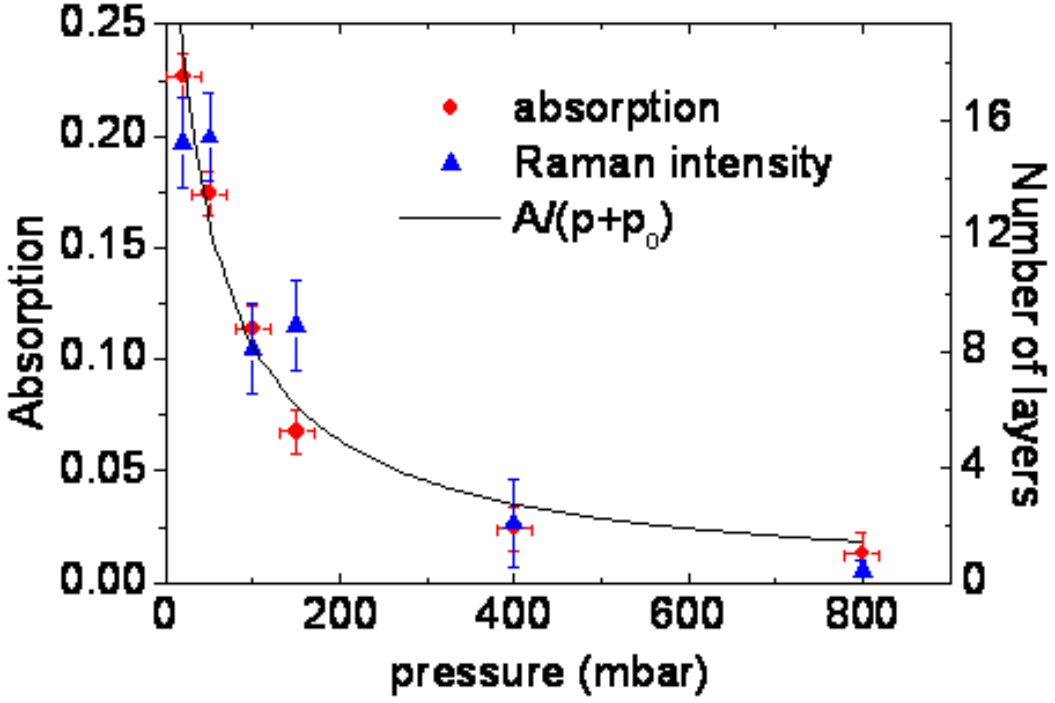


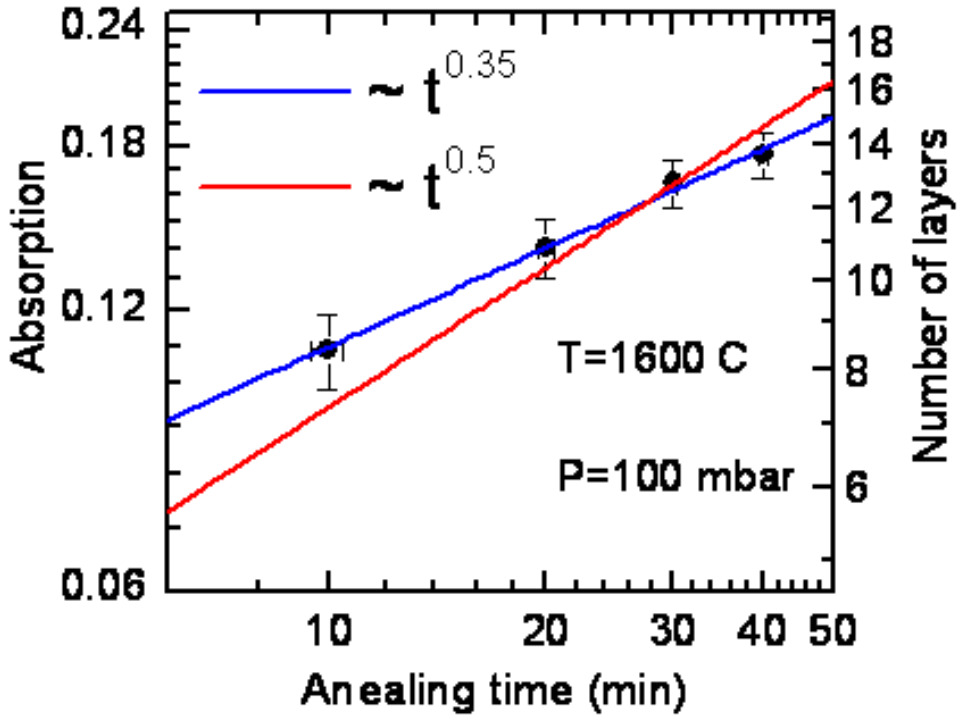




Mohiuddin et al. , Phys. Rev. B 79, 205433 (2009)

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

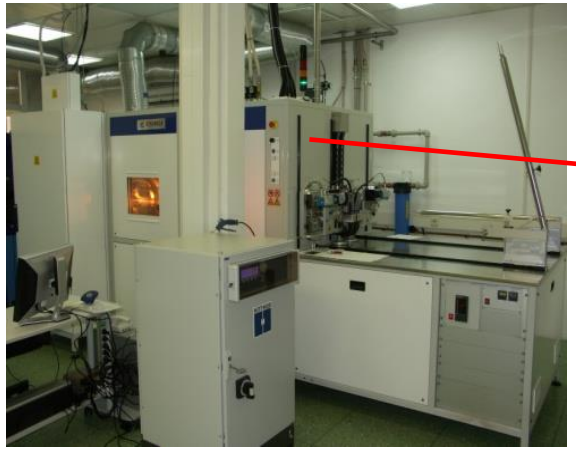


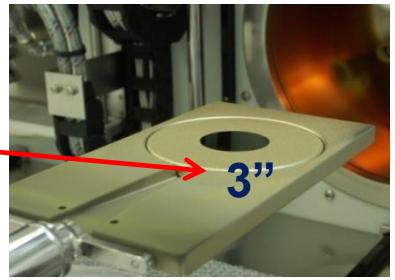


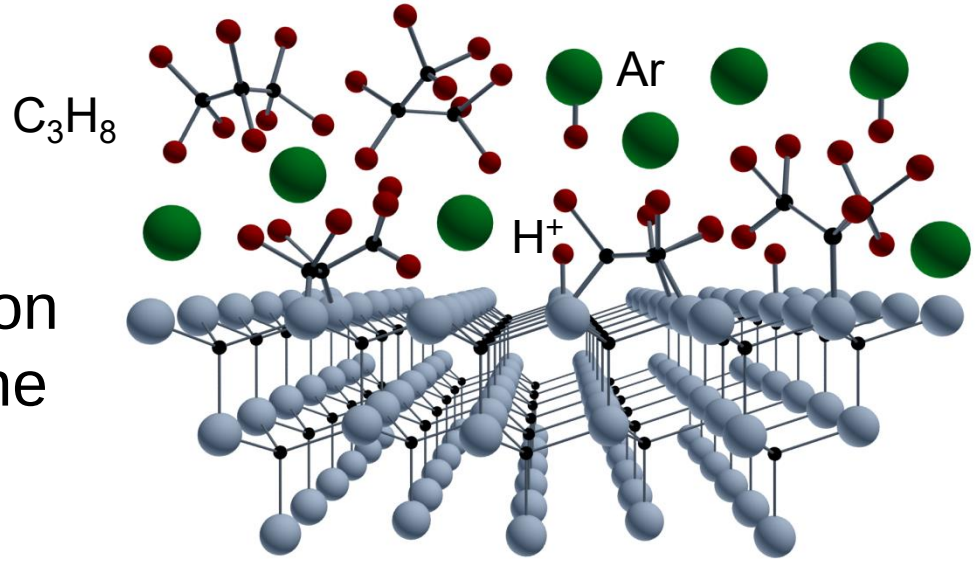
Growth kinetics driven by 2D – diffusion of Si!

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

Chemical Vapour Deposition







- suppression of sublimation
- decomposition of propane in Ar atmosphere

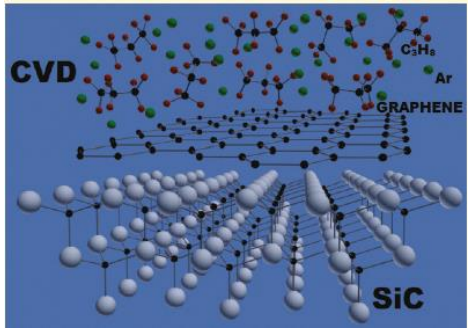
Standard CVD

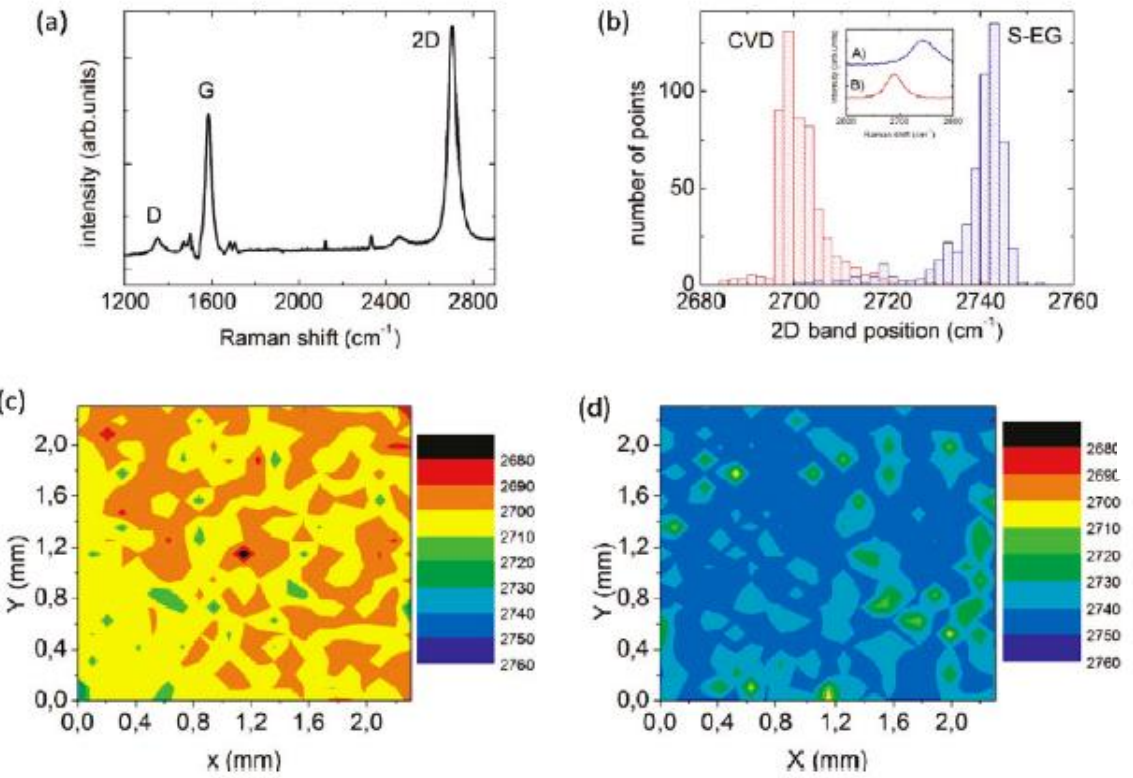
W. Strupinski et al. Nano Lett. 11, 1786 (2011)

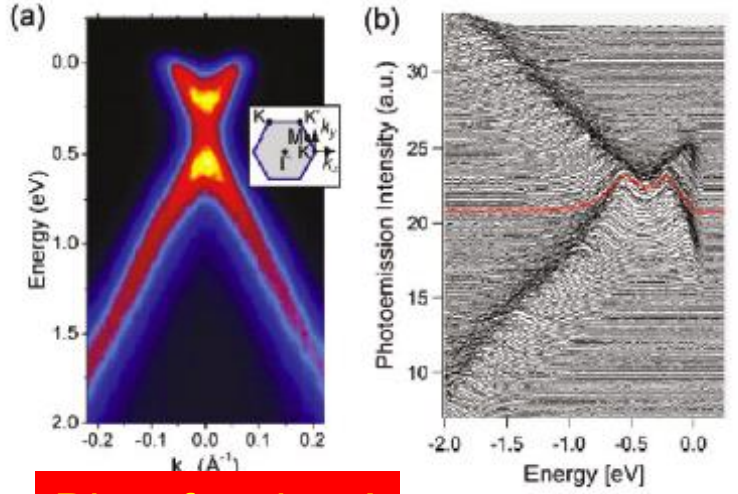
NANO LETTERS
LETTER
pubs.acs.org/NanoLett

Graphene Epitaxy by Chemical Vapor Deposition on SiC

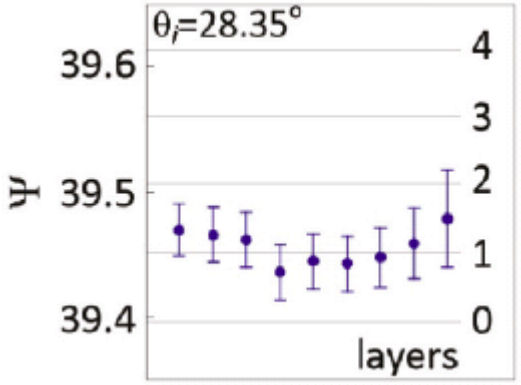
W. Strupinski,*[1] K. Grodecki,[1,2] A. Wysmolek,[2] R. Stepniewski,[2] T. Szkopek,[3] P. E. Gaskell,[3] A. Grüneis,[4,5] D. Haberer,[4] R. Bozek,[2] J. Krupka,[6] and J. M. Baranowski[1,2]





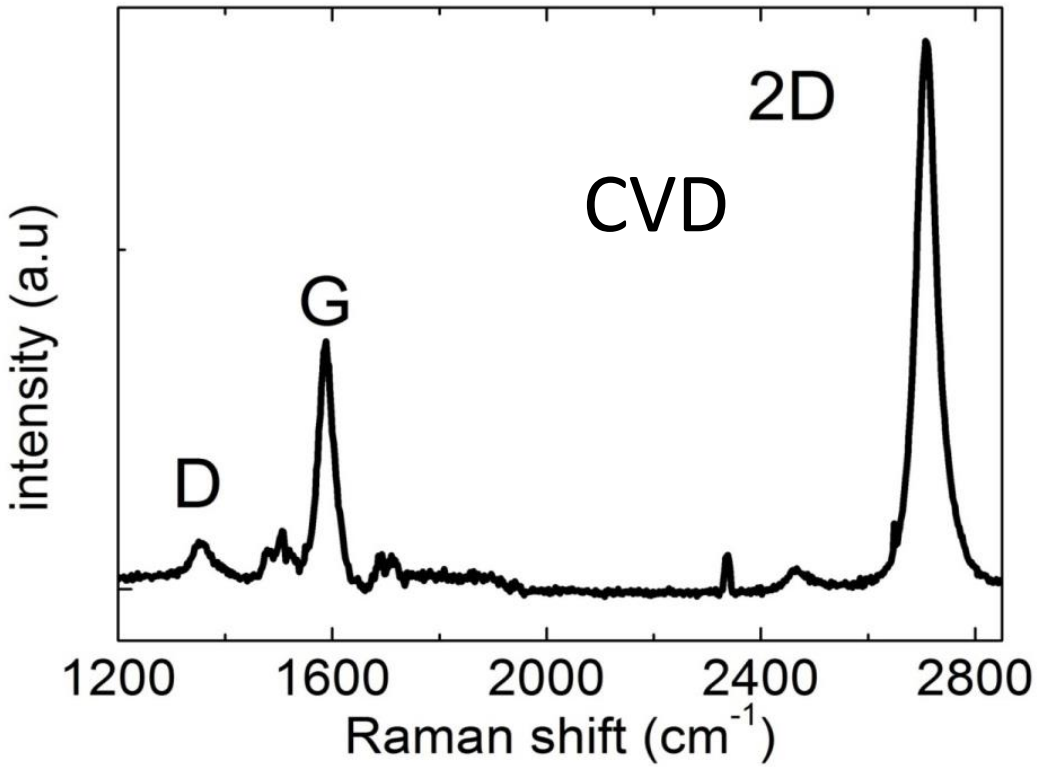


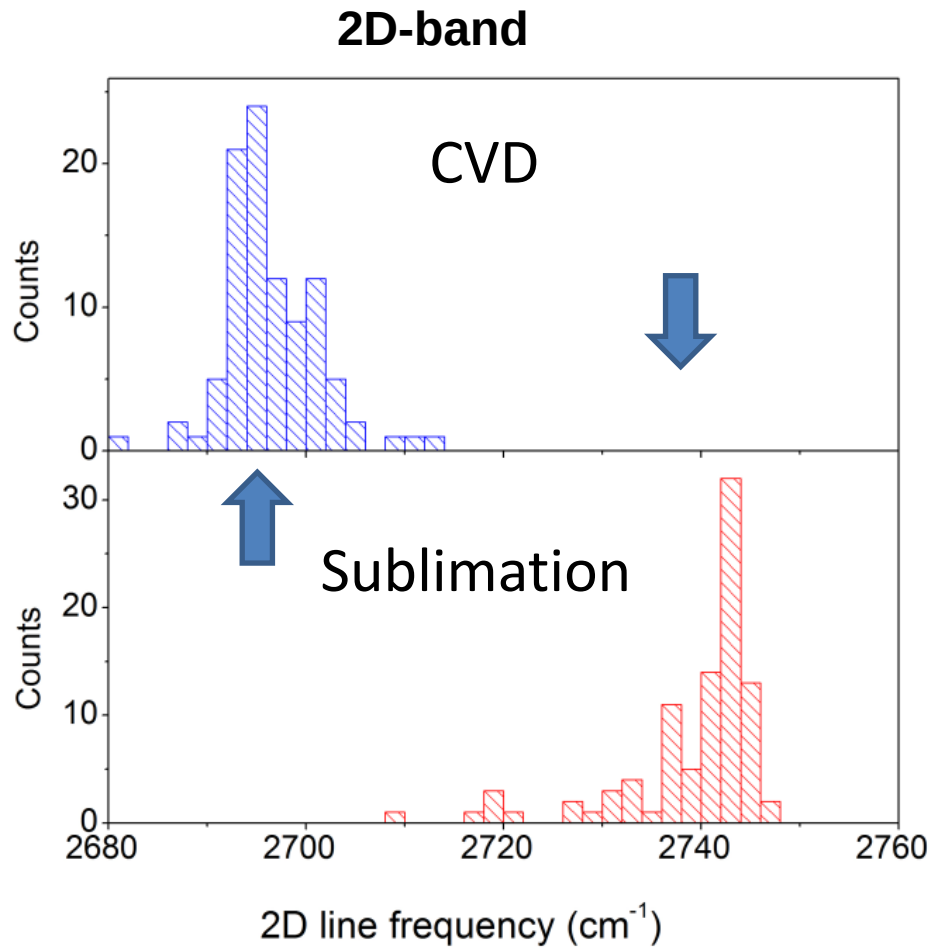
Dirac fermions!



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

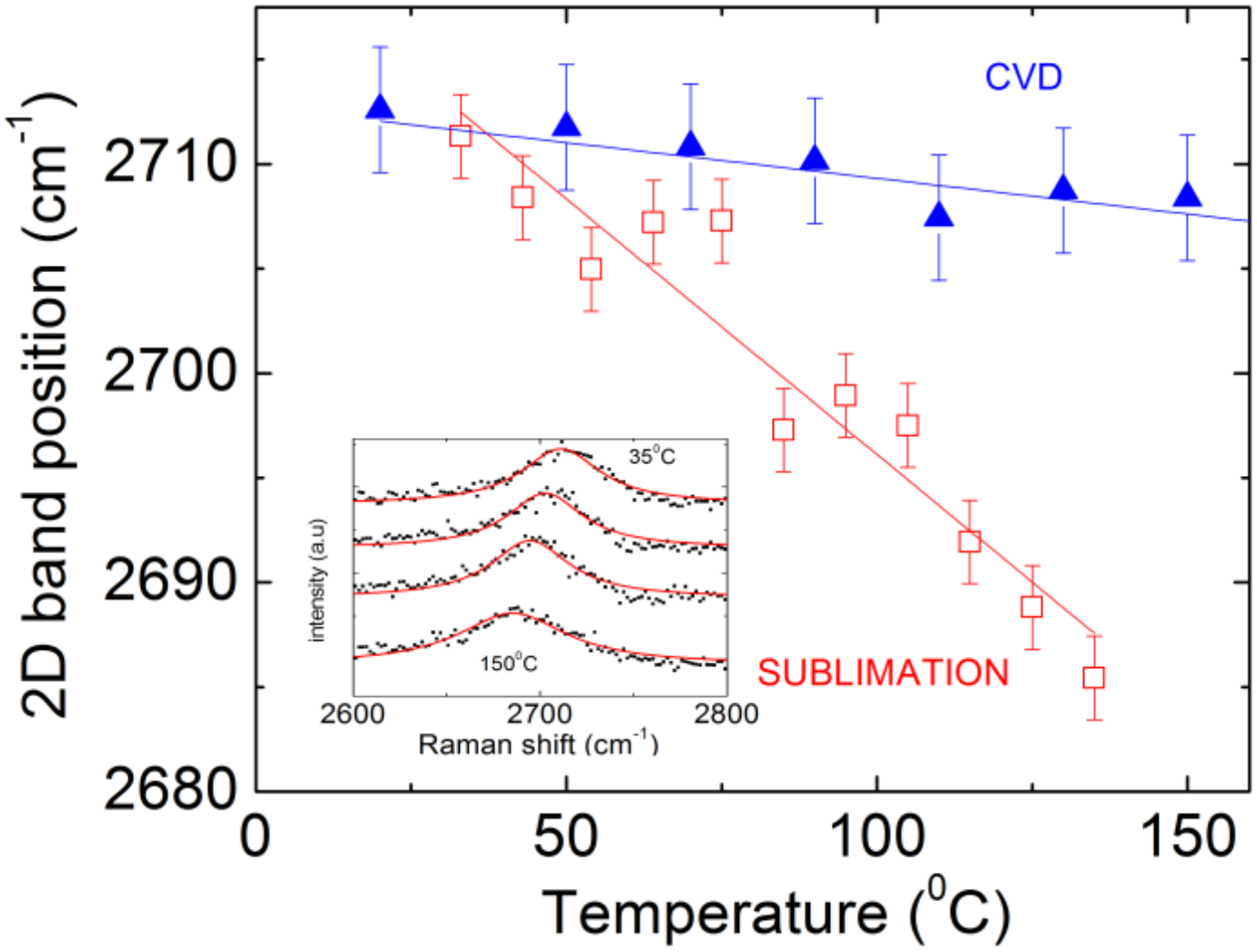
Interaction with the substrate





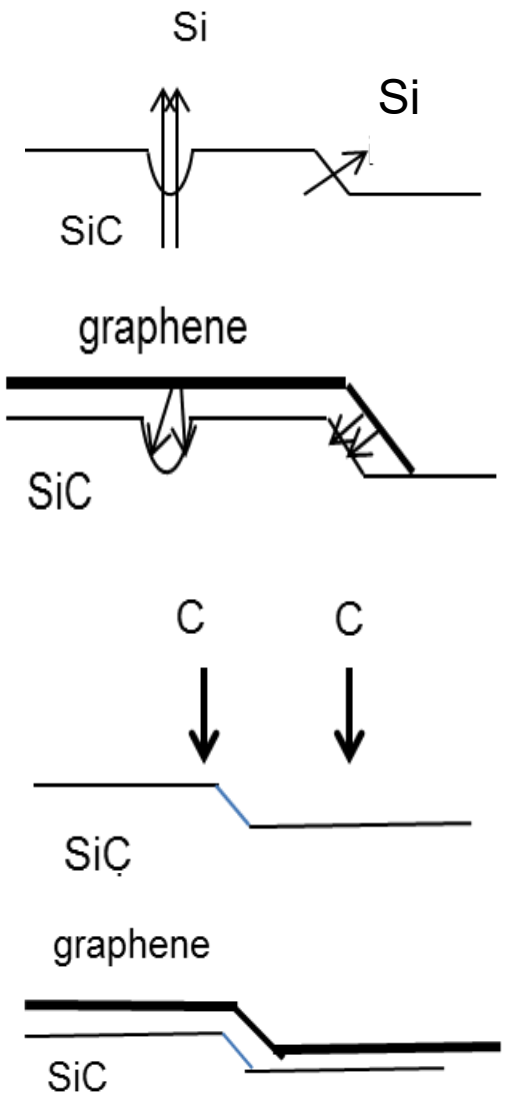
W. Strupinski et al. Nano Lett. 11, 1786 (2011)
K. Grodecki et al., J. Appl. Phys. 111, 114307 (2012)

Temperature dependence of 2D-band position

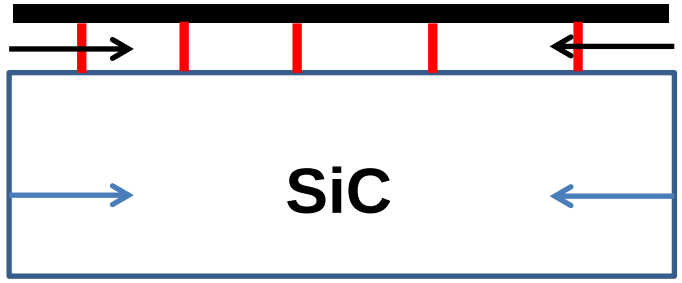


K. Grodecki et al., J. Appl. Phys. 111, 114307 (2012)

Interaction with the substrate



Sublimation

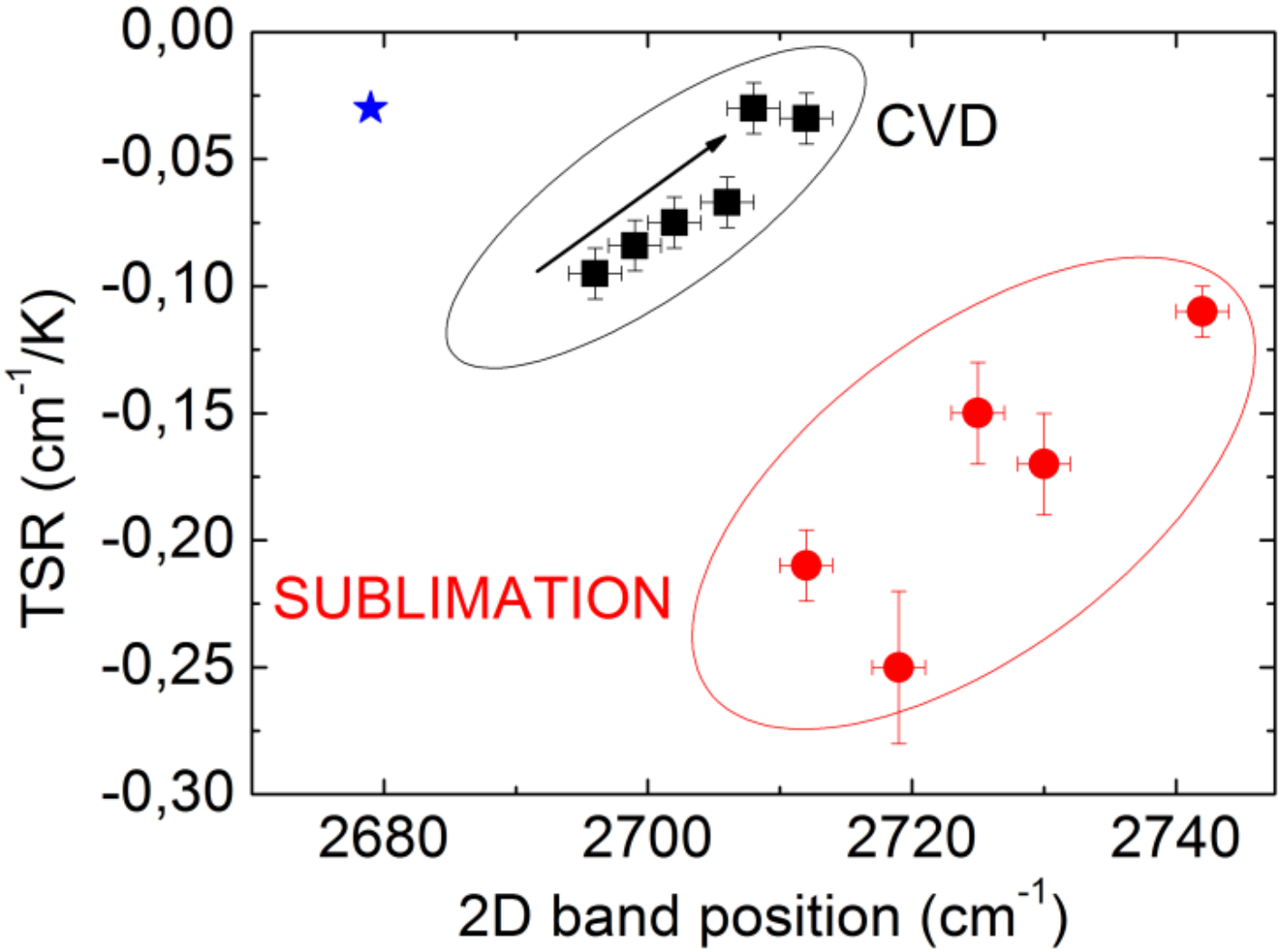


Graphene strongly **pinned** to the substrate (**defects**, step edges…)

CVD

Graphene can slide over the substrate…

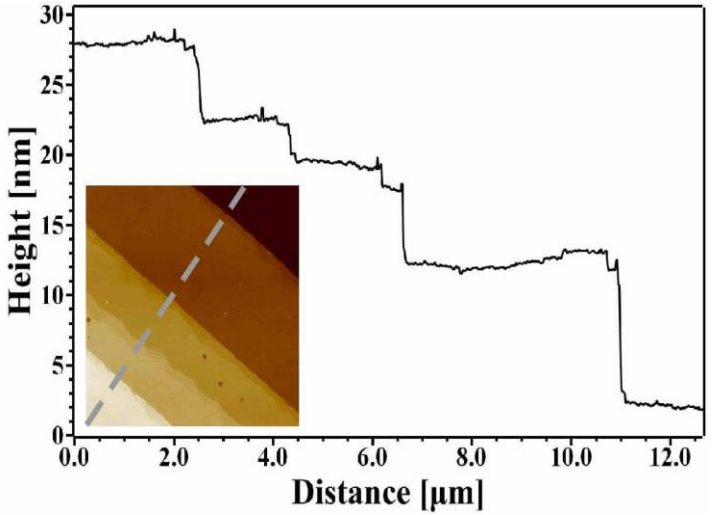
„Phase diagram”



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

Microscale Raman experiments

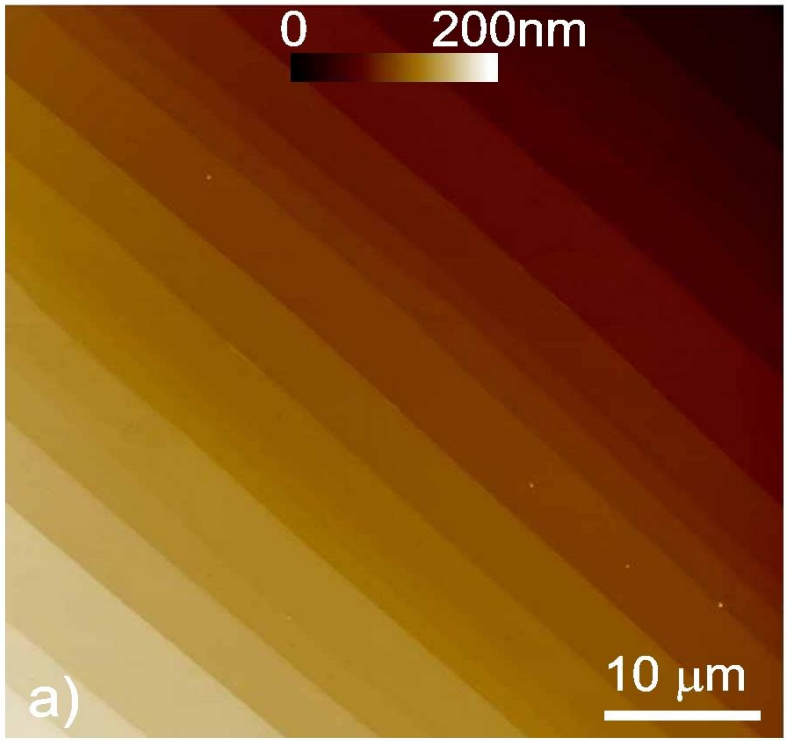
steps play a role…

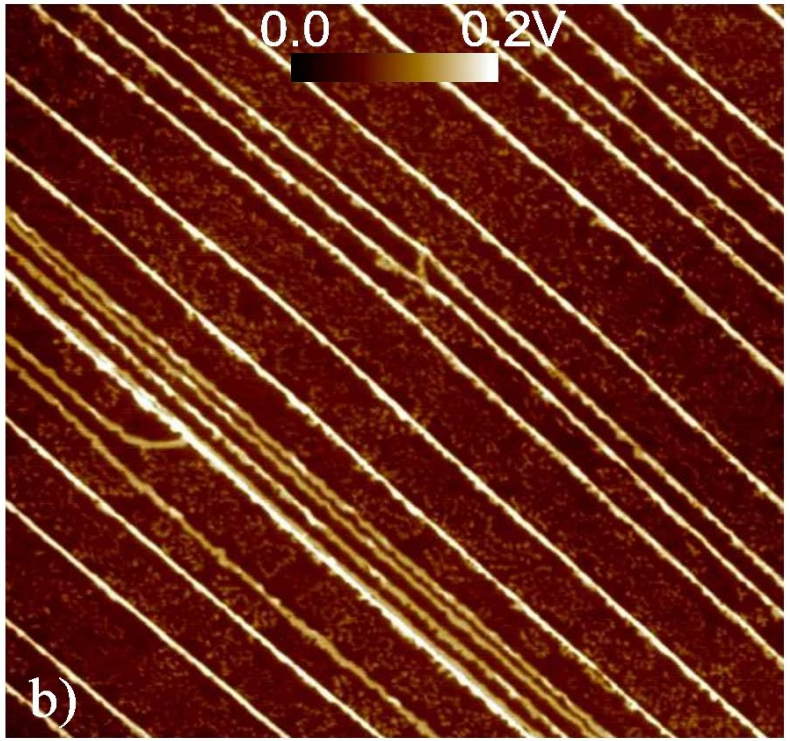


AFM & Kelvin Probe Microscopy

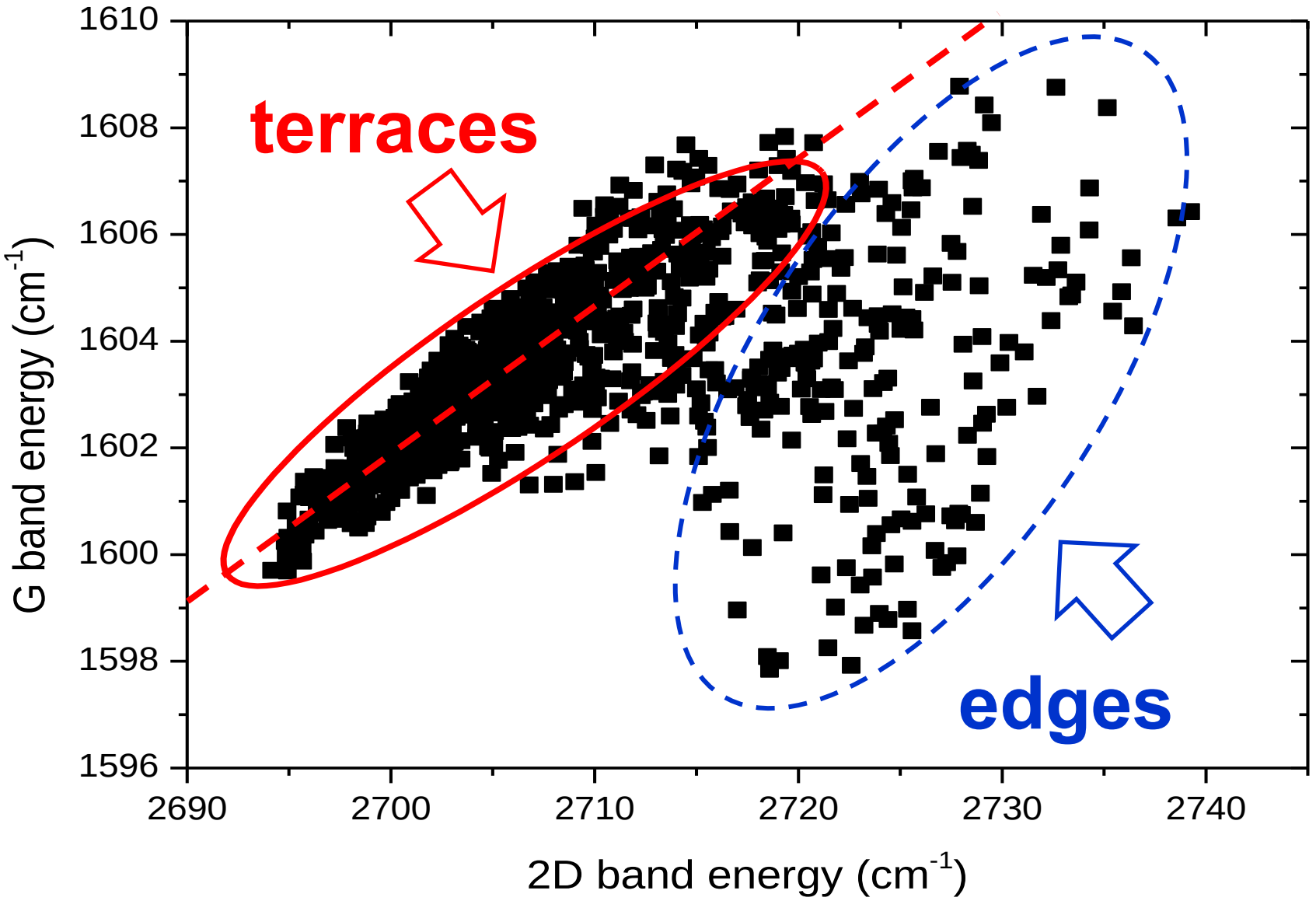
CVD graphene

4H-SiC Si-face





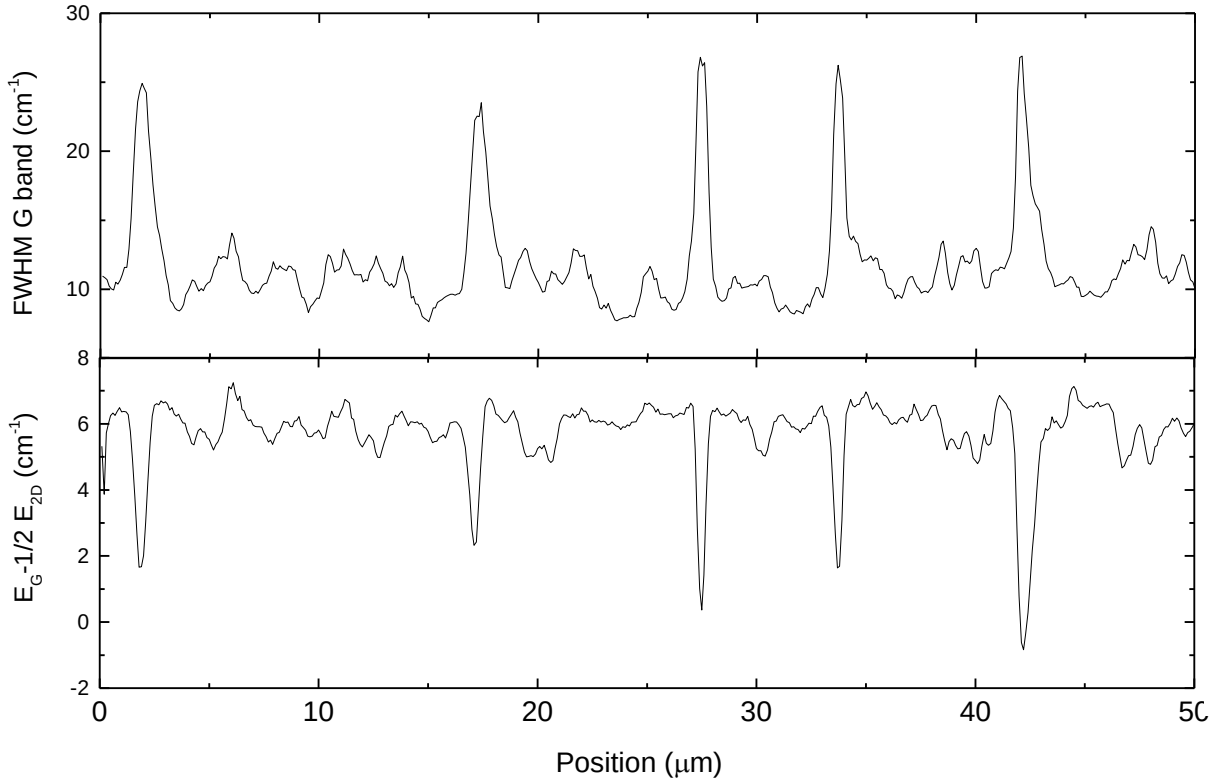
R. Bożek (2012)

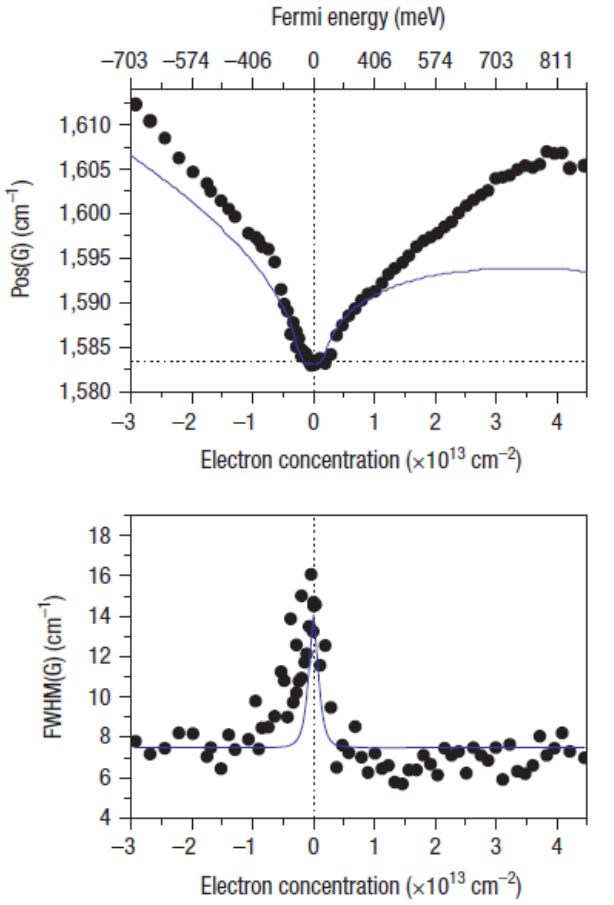


Grodecki et. al. APL , 100, 26 (2012)

FWHM vs. G-band position

CVD



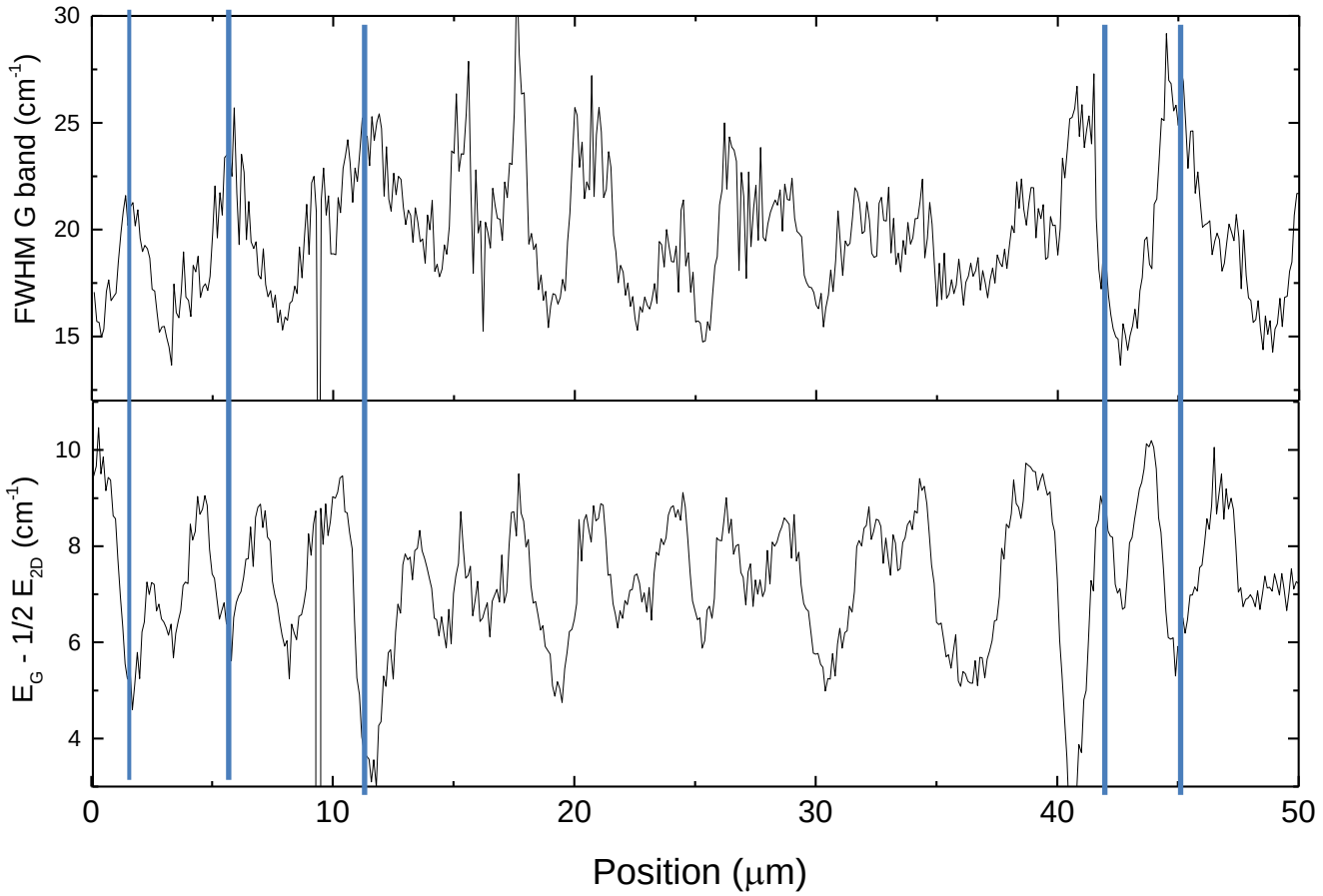


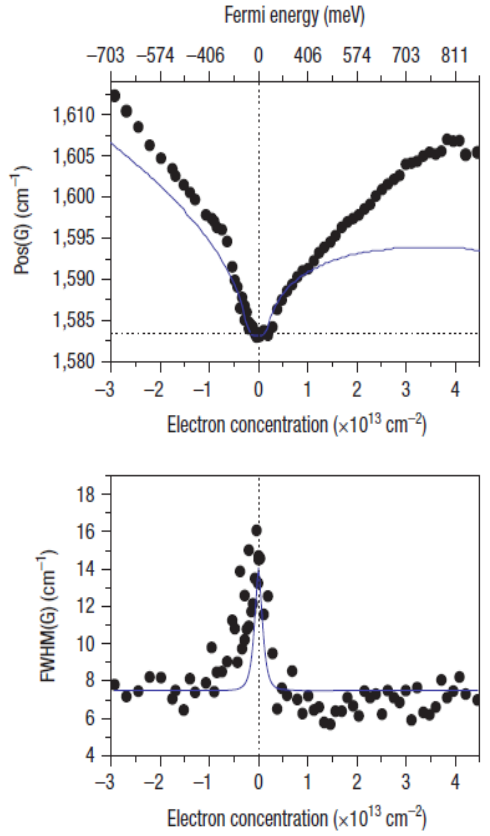
A. Das et al.
Nature Nan. 3, 210 (2008)

Well defined terraces!

G-band - FWHM vs. position

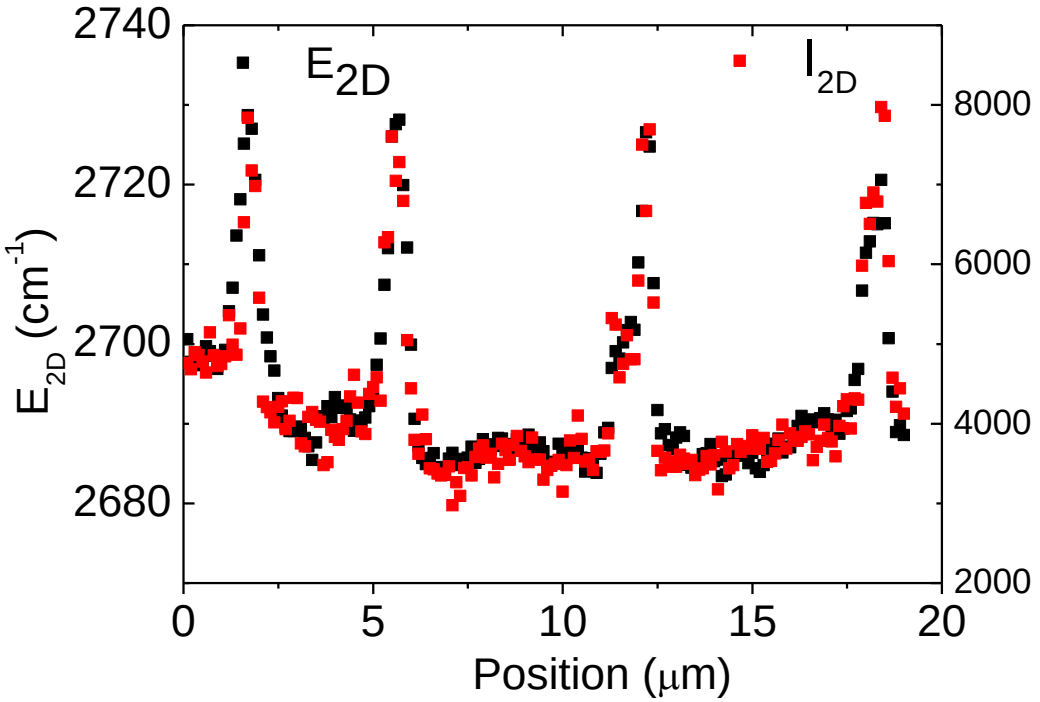
Sublimation





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

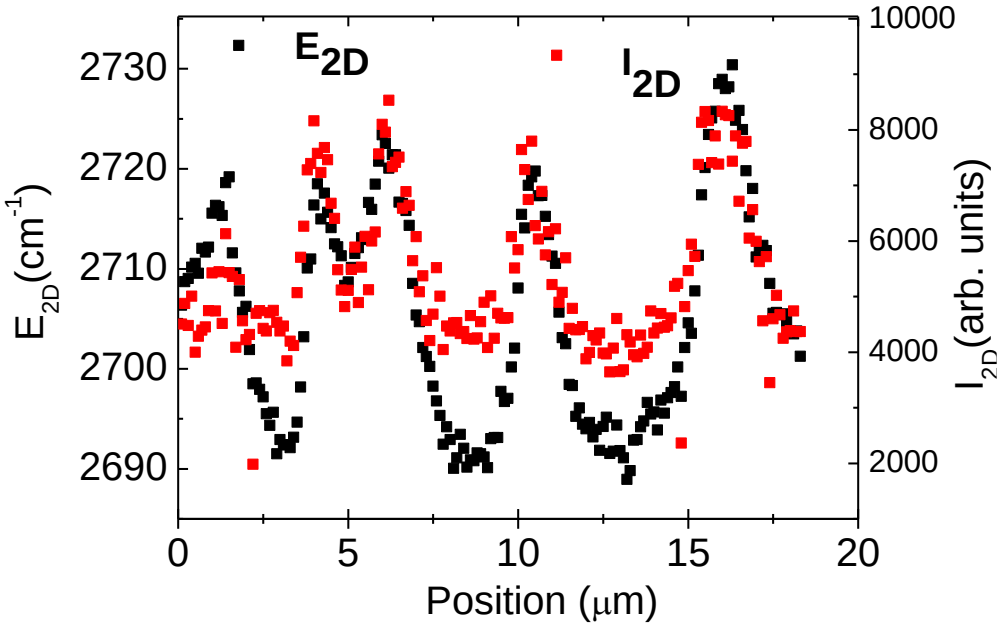
Erosion of steps…



CVD

Much better defined terraces and edges

Sublimation



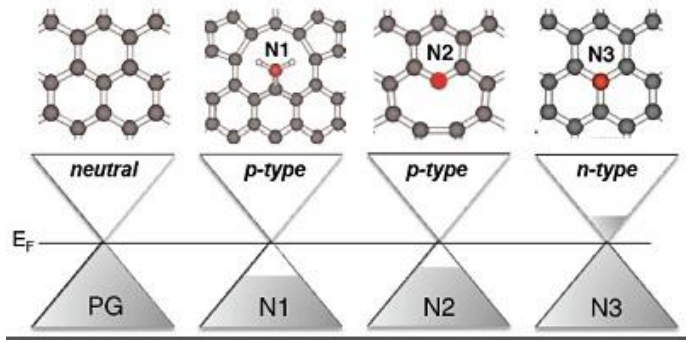
Nitrogen doping

Similar C-N and C-C bond lengths….

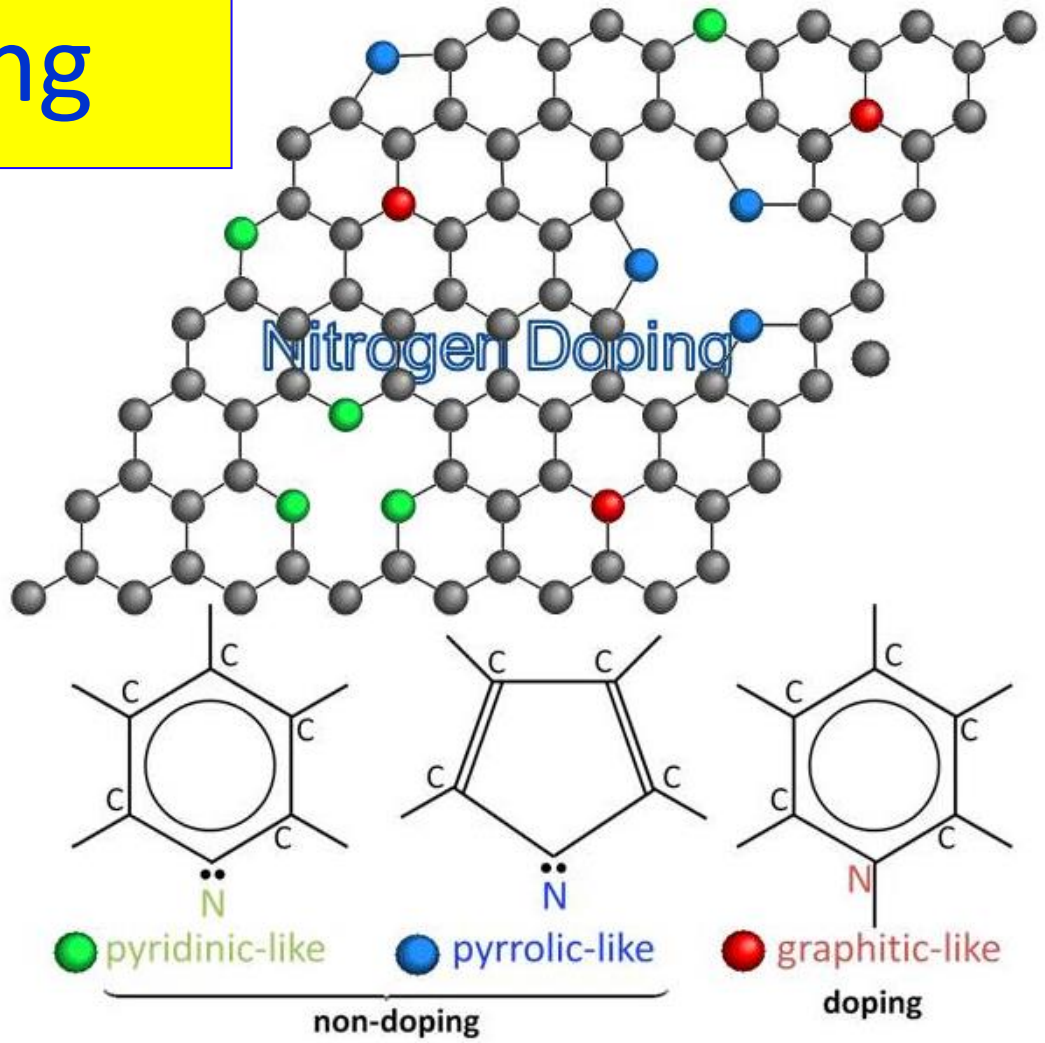
Motivation:

- control of carrier concentration
- enhanced biocompatibility
- controlled introduction of defects

Applications: nanoelectronics, energy storage, spintronics, biosensing...



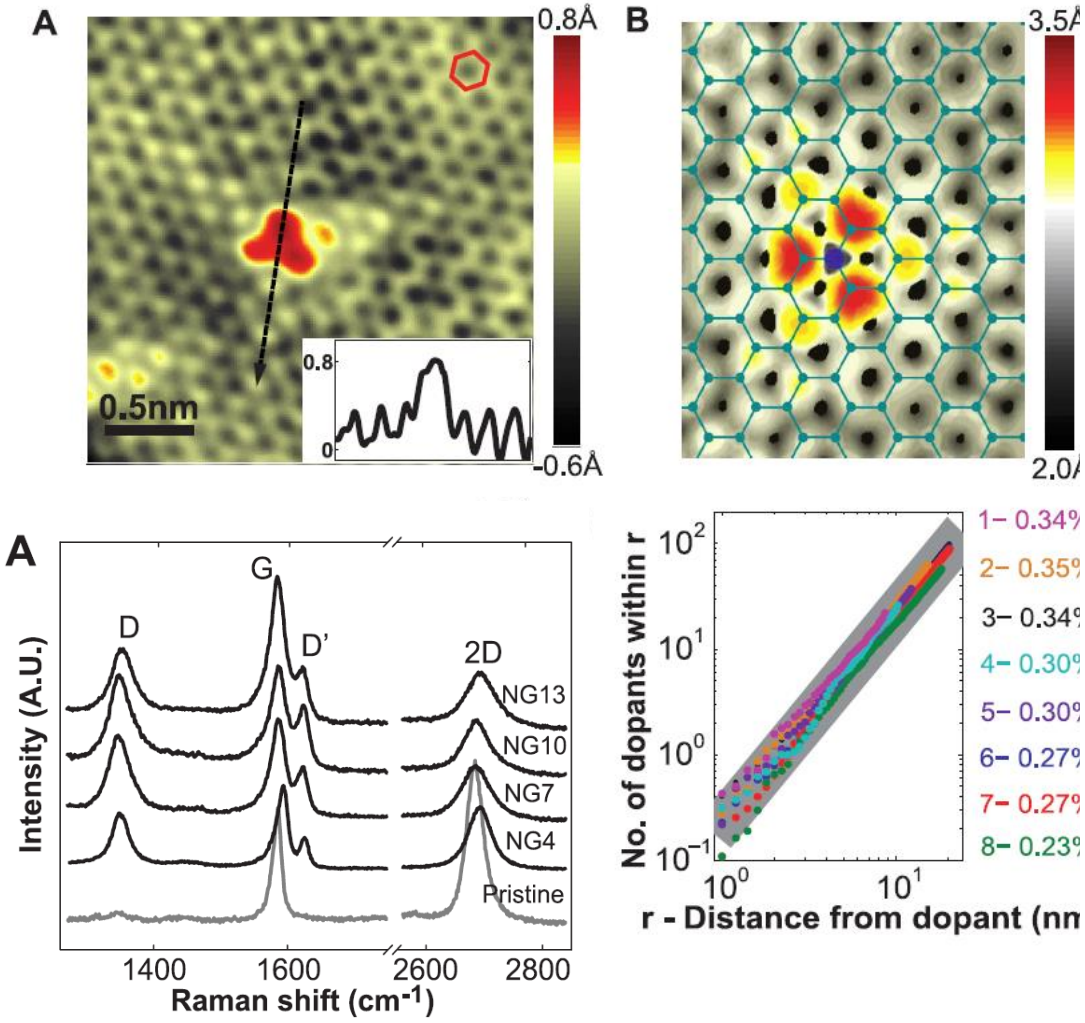
T. Schiros, et al. *Nano Lett.* **12**, 4025 (2012)

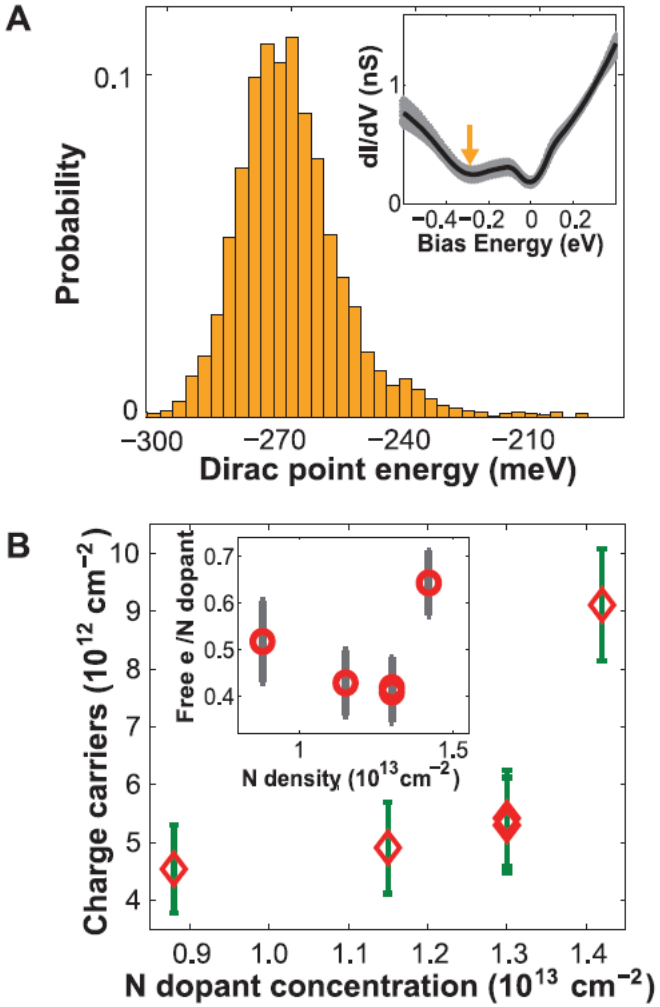


E. Velez-Fort et al. ACS Nano 6, 10893 (2012)

L. Zhao et al., Science 333 (6045), 999-1003 (2011)

Nitrogen doped graphene

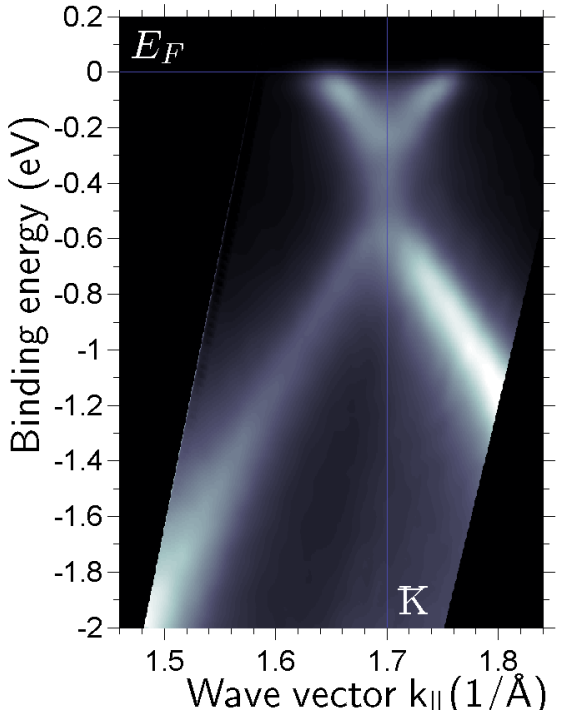




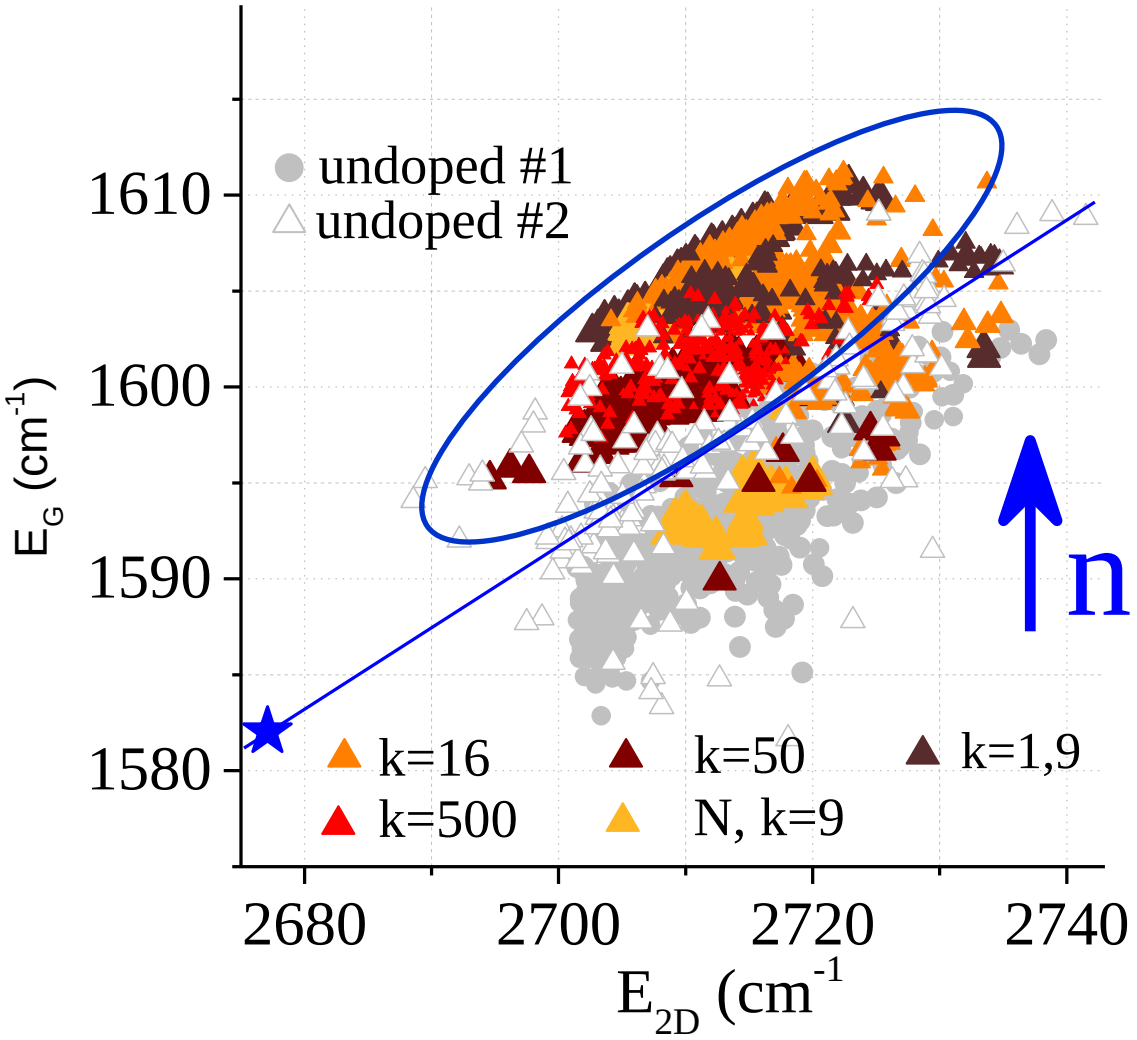
Zhao et al., *Science* **333**, 999 (2011)

N-doped graphene

ARPES:
n-doping
E_F =0.45 eV



Raman data

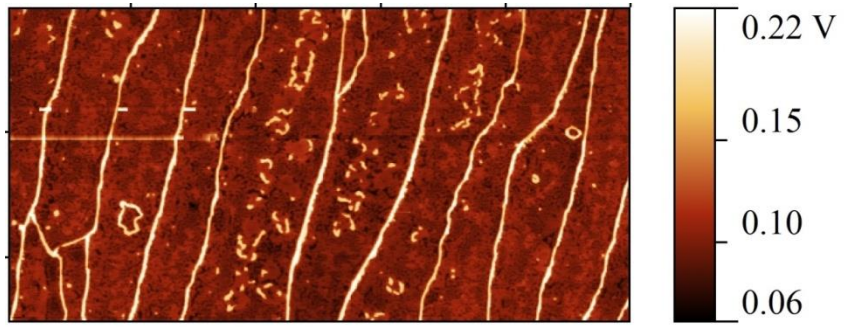


J. Urban et al. JAP (2014)

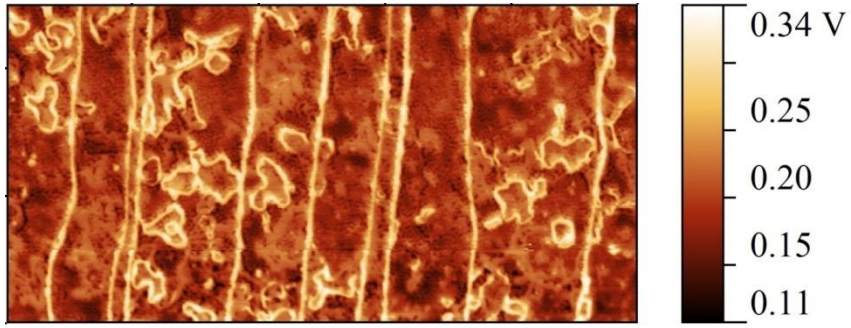
N - doped graphene

Defects generation…

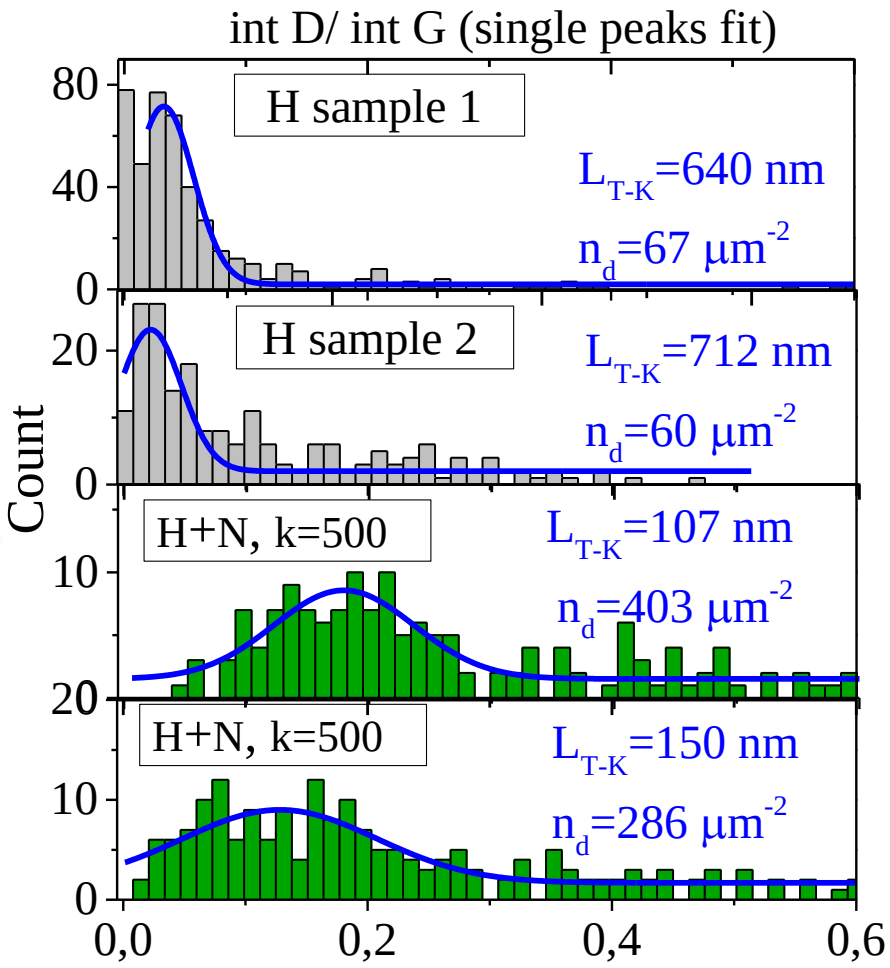
KPFM



Nominally undoped graphene



N-doped graphene



J. Urban et. al. JAP (2014)

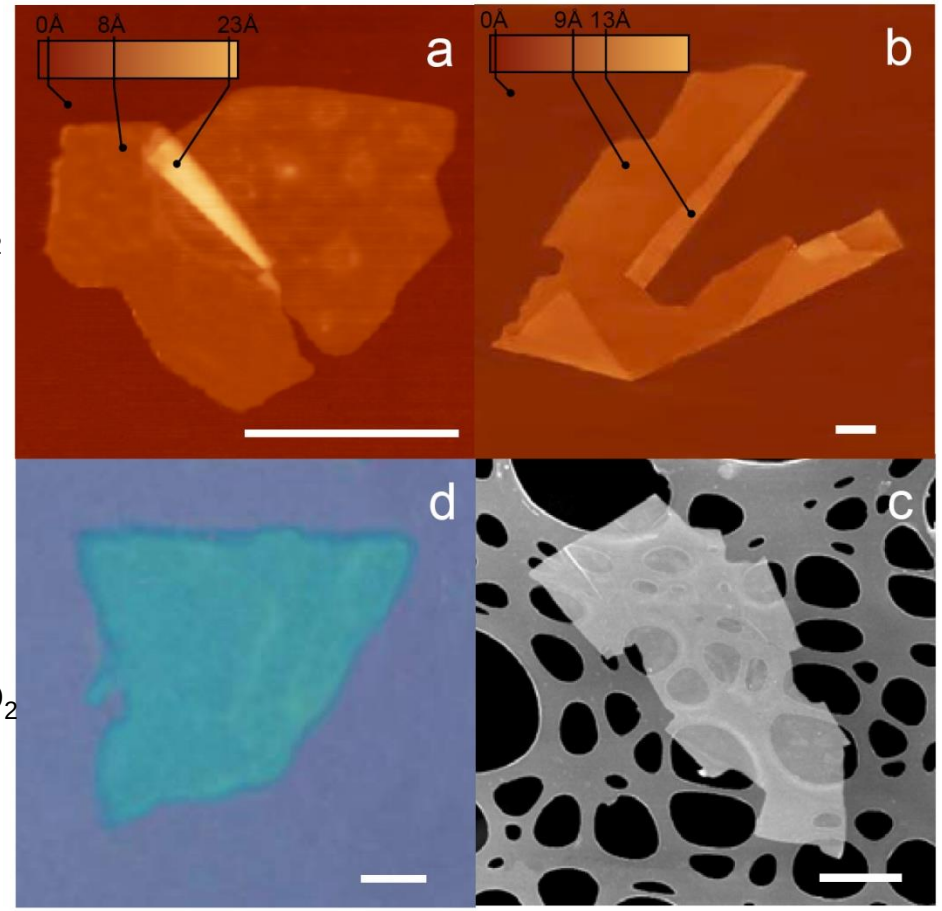
P. Dabrowski et. al, Carbon 94, 214 (2015)

Other 2D materials

Single layers

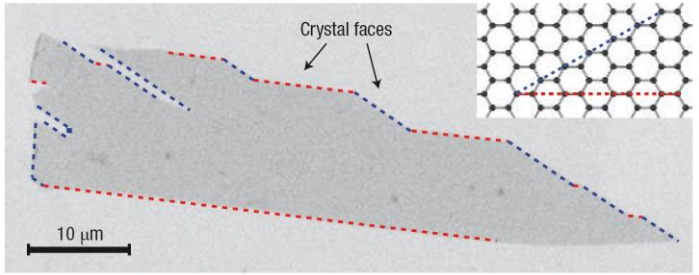
$NbSe_2$
on Si/SiO_2

MoS_2
on Si/SiO_2



graphite
on Si/SiO_2

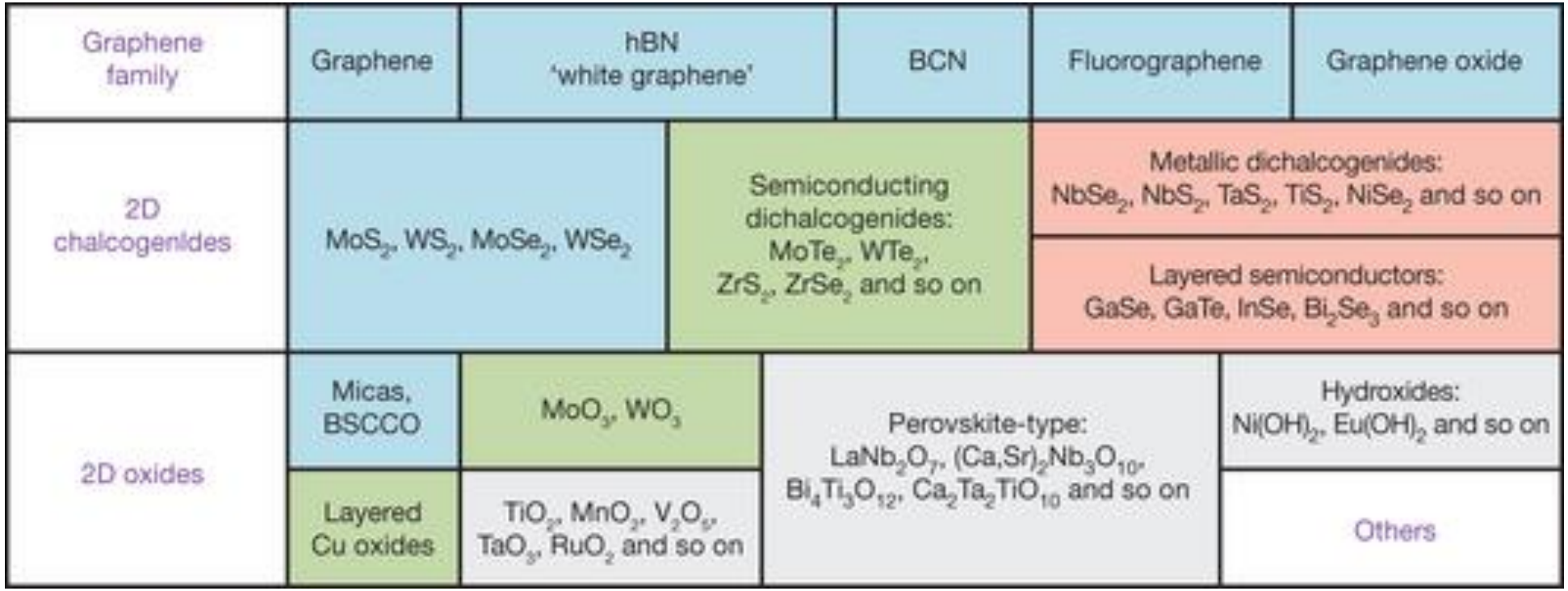
graphene "big flake"



$Bi_2Sr_2CaCu_2O_x$
on carbon

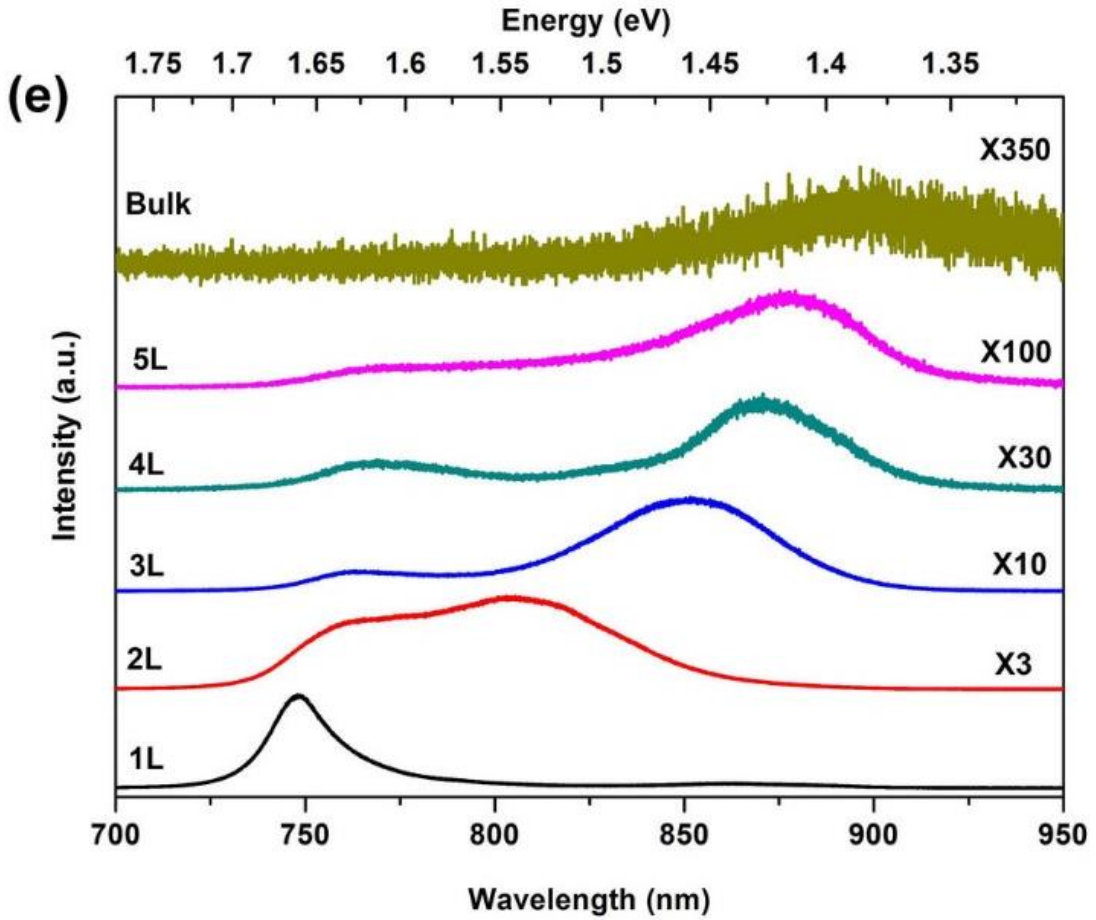
K.S. Novoselov, *et al.*, *Two-dimensional atomic crystals*, *Proc. Natl Acad. Sci. USA,* **102,** 10451–10453 (2005)
K.S. Novoselov and A.K. Geim,
The rise of graphene, Nature Materials, **6**, 183, (2007)

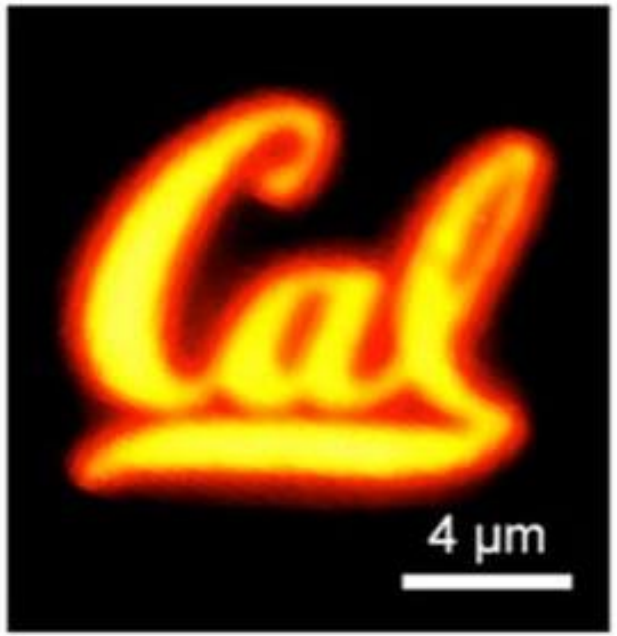
Van der Waals heterostructures – new possibilities



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

Unexpected behavior of the emission



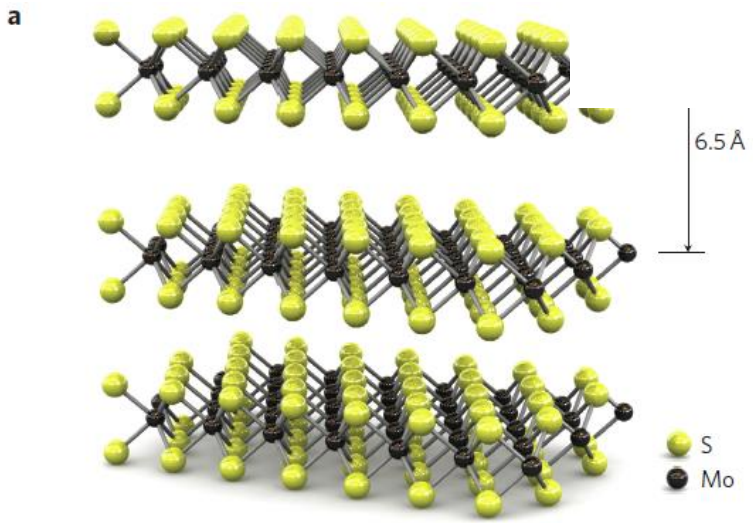


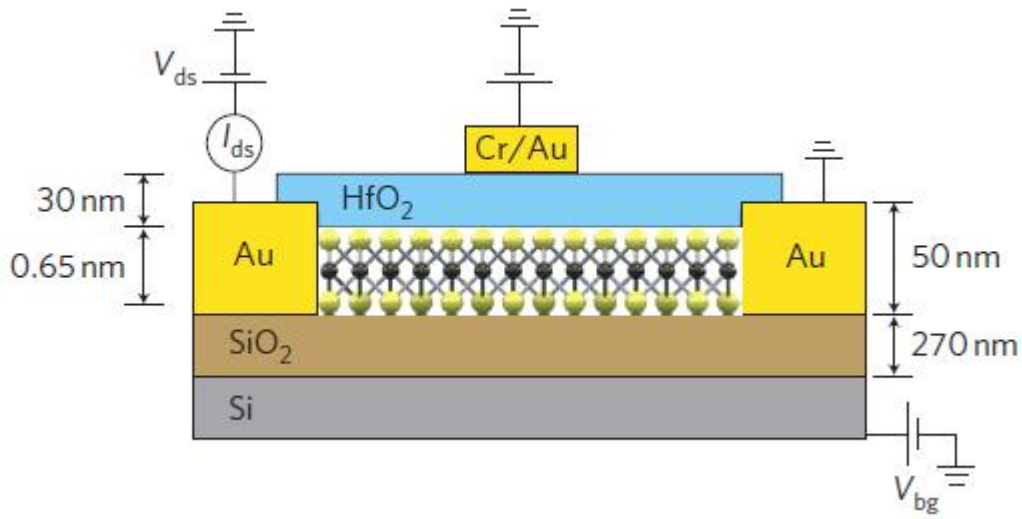
H. Terrones et al. Scientific Reports 4, 4215 (2014)

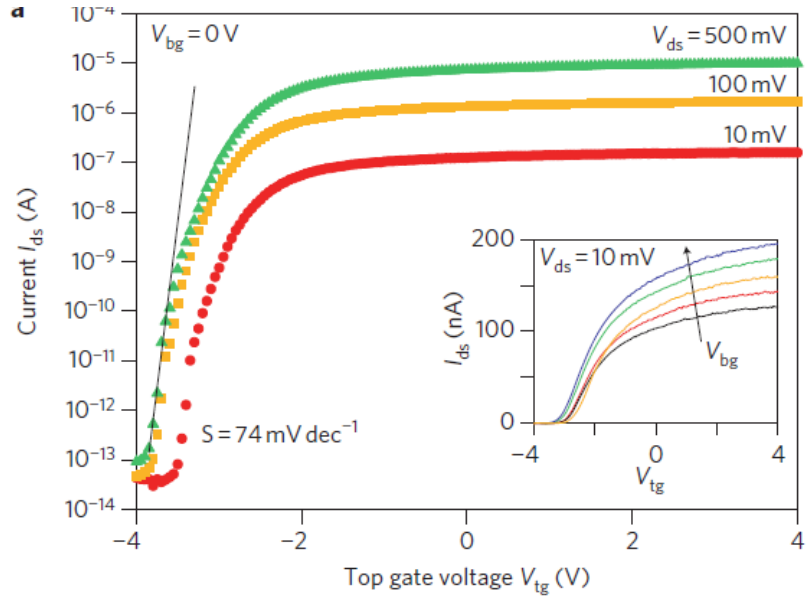
M. Amani et al. SCIENCE 350, 1065 (2015)

MoS_2 – silicon competitor?

Scotch tape method works!

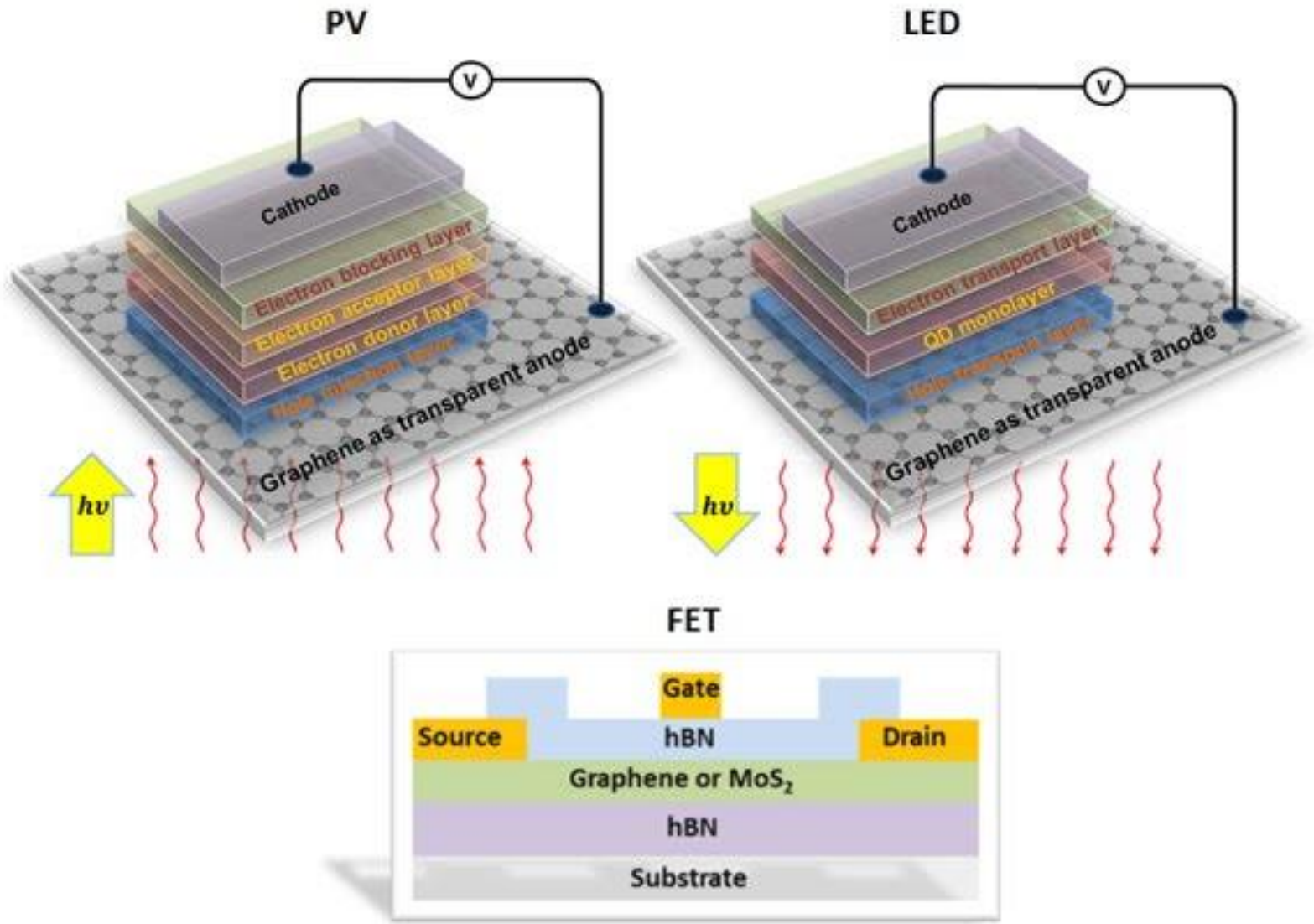






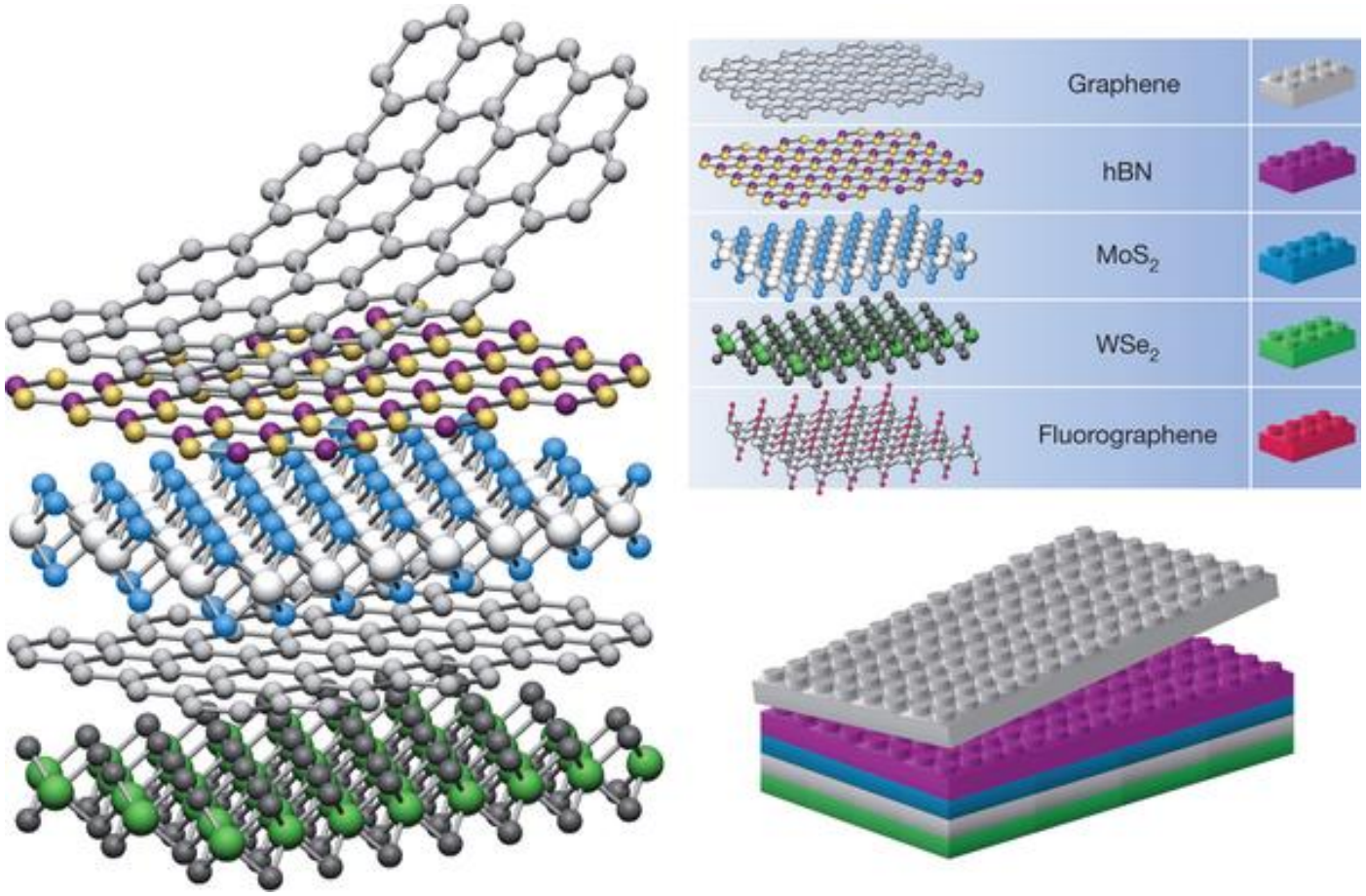
B. Radisavljevic et al., Nature naotechnology (2011)

Optoelectronics



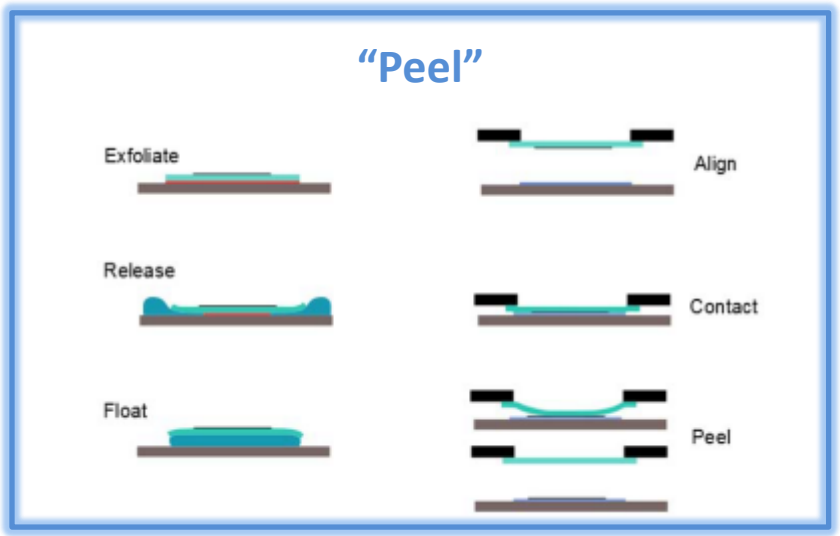
http://hspark.unist.ac.kr/research/

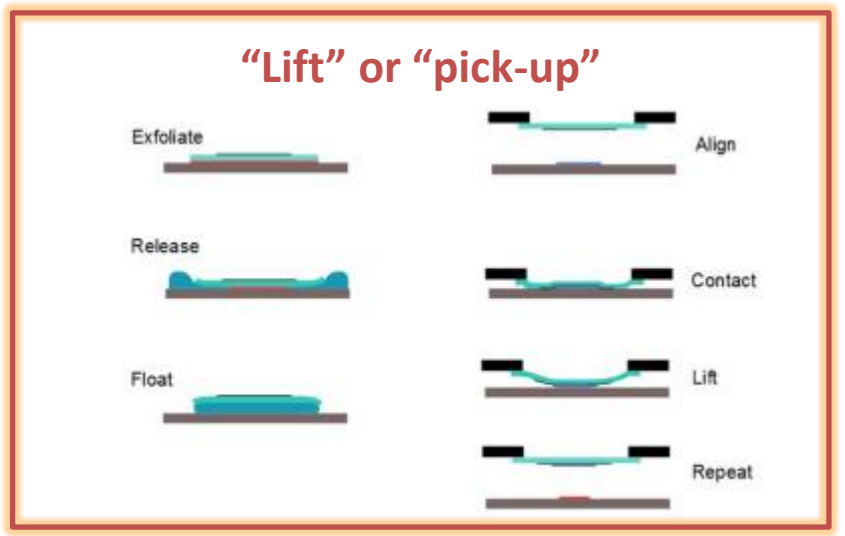
Nano-LEGO system

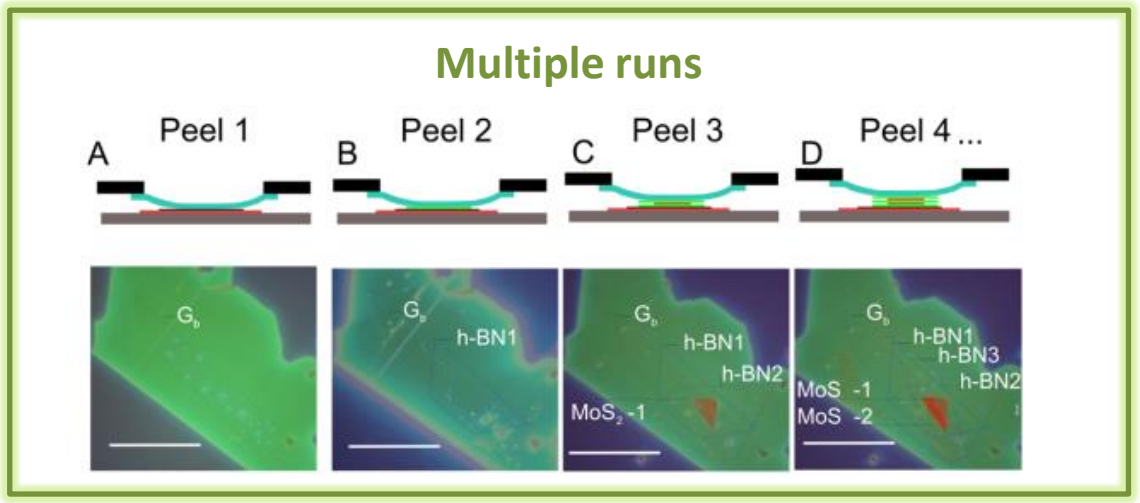


A. K. Geim & I. V. Grigorieva, Nature 499, 419 (2013)

Fabrication







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

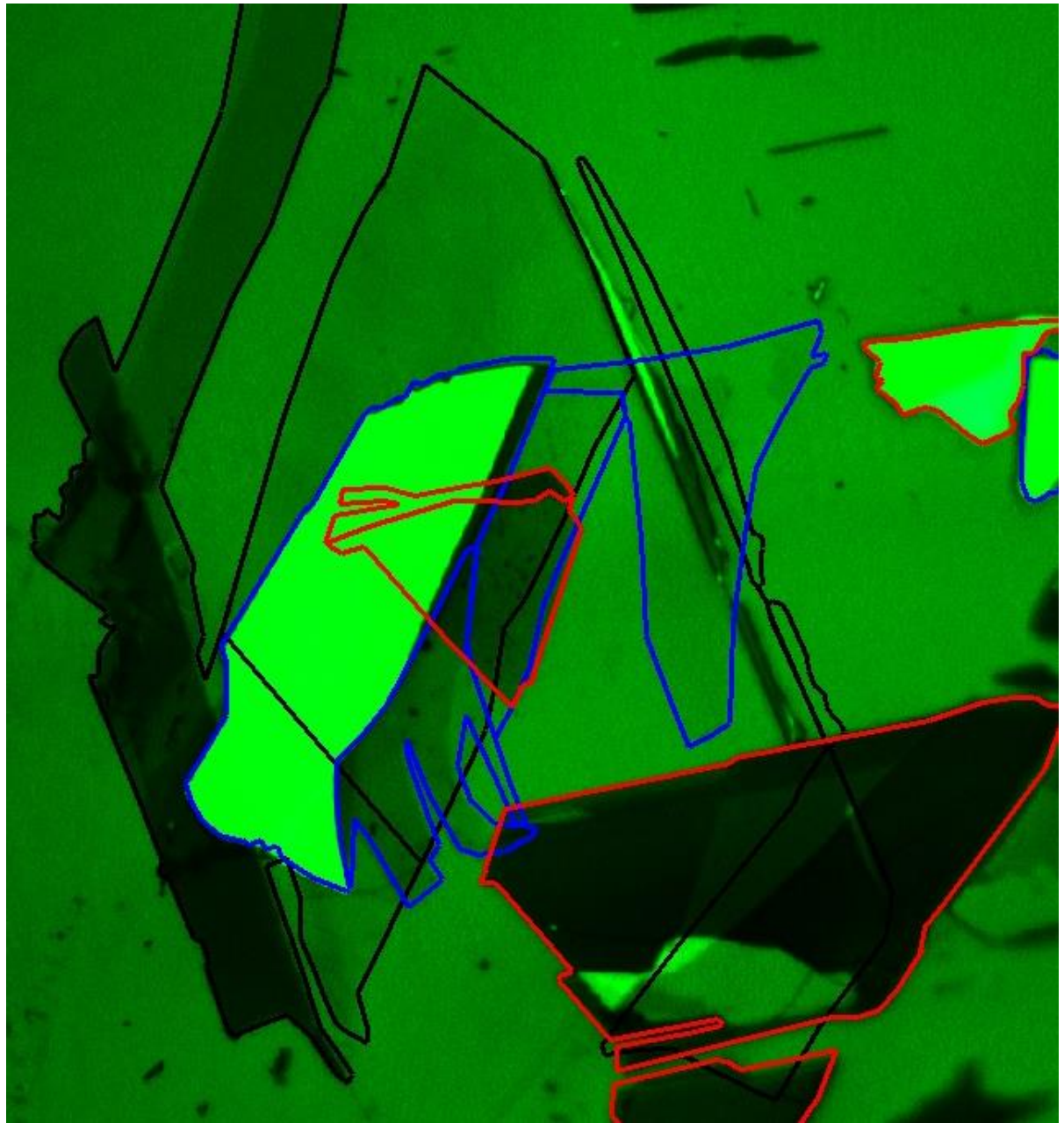
Transfer

Gr

BN

A. Kozikov
University of Manchester

Transfer



Gr

BN

MoS_2

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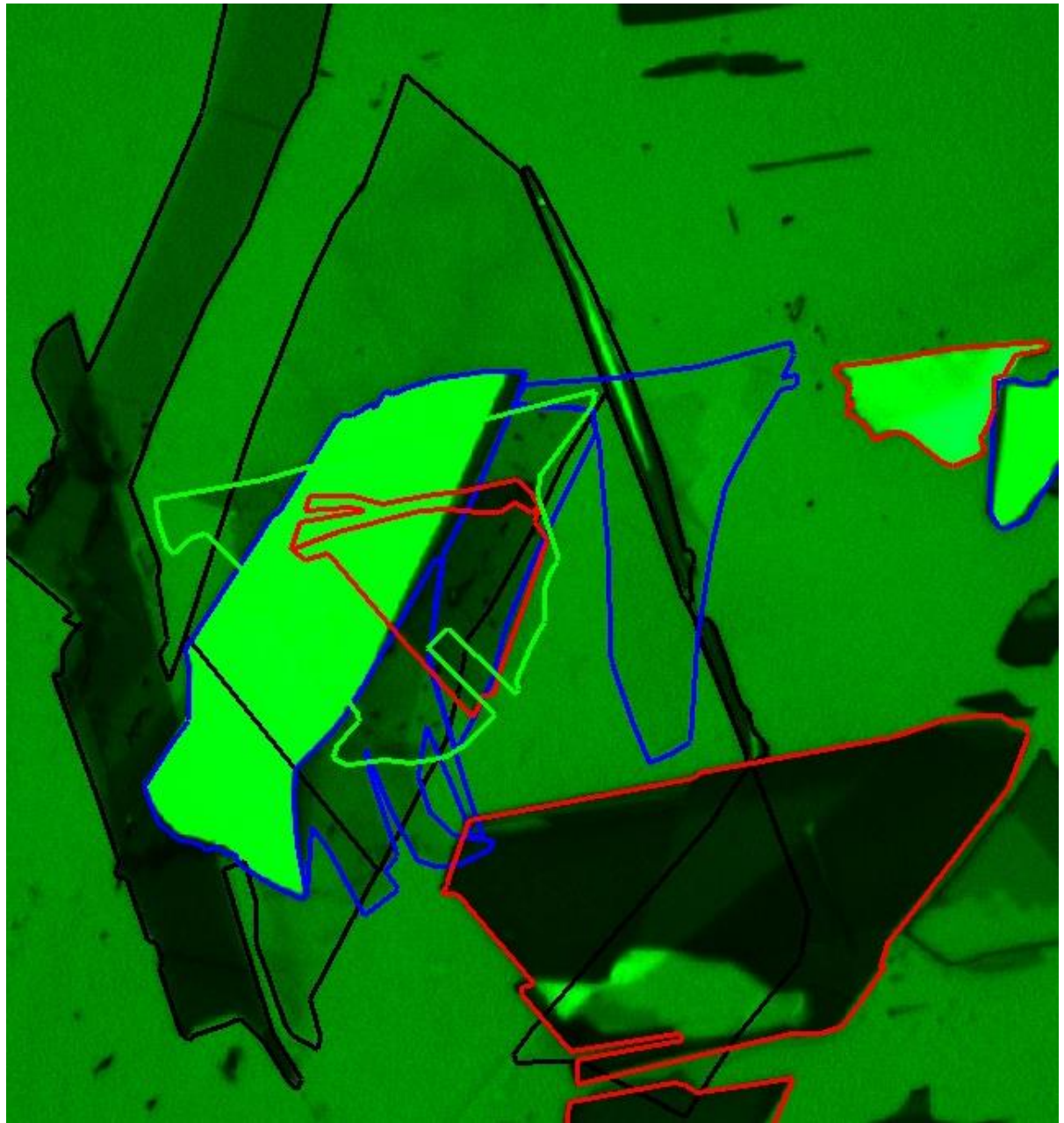
Transfer



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BN

MoS_2

BN

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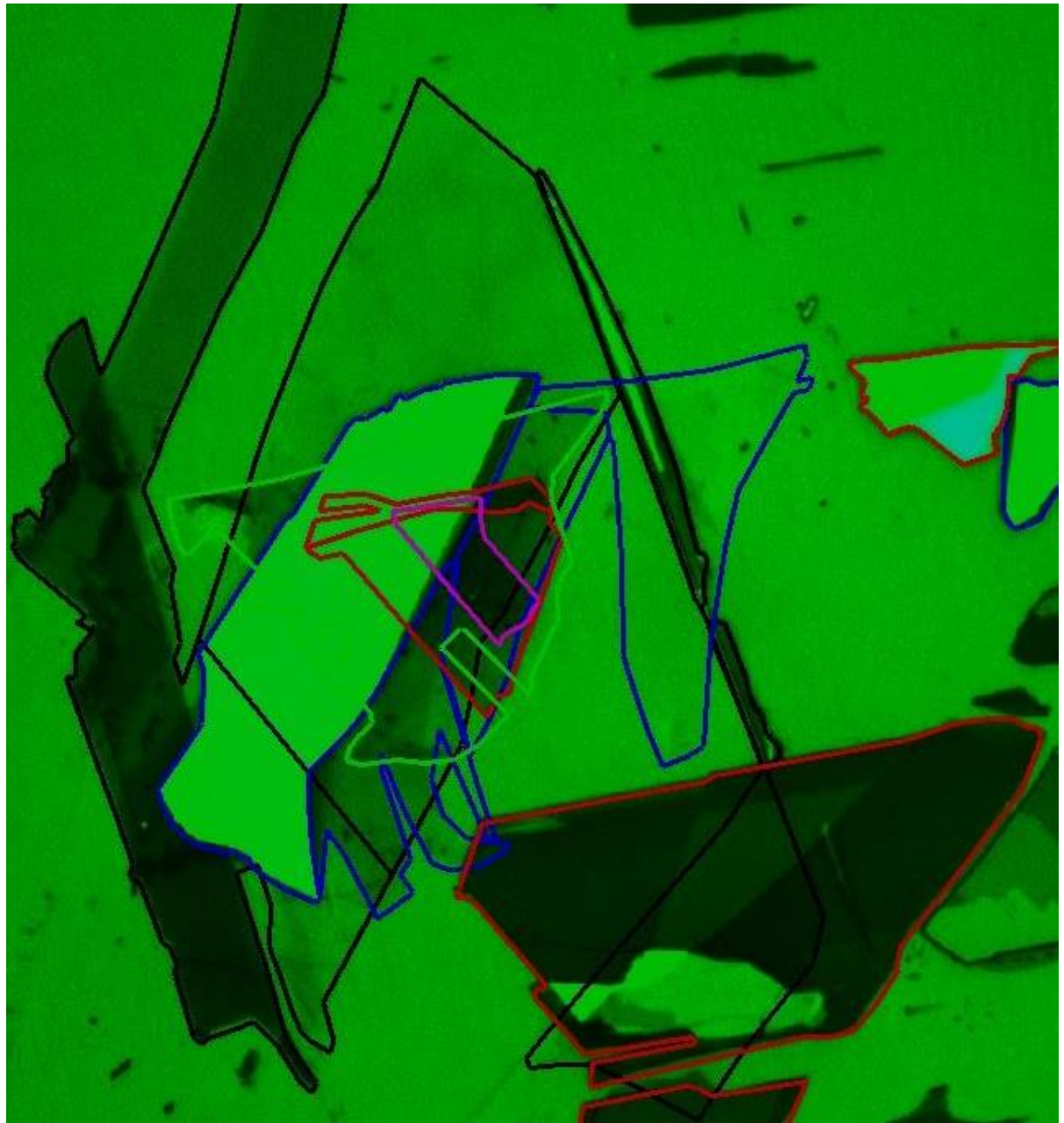

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BN

MoS_2

BN

WSe_2

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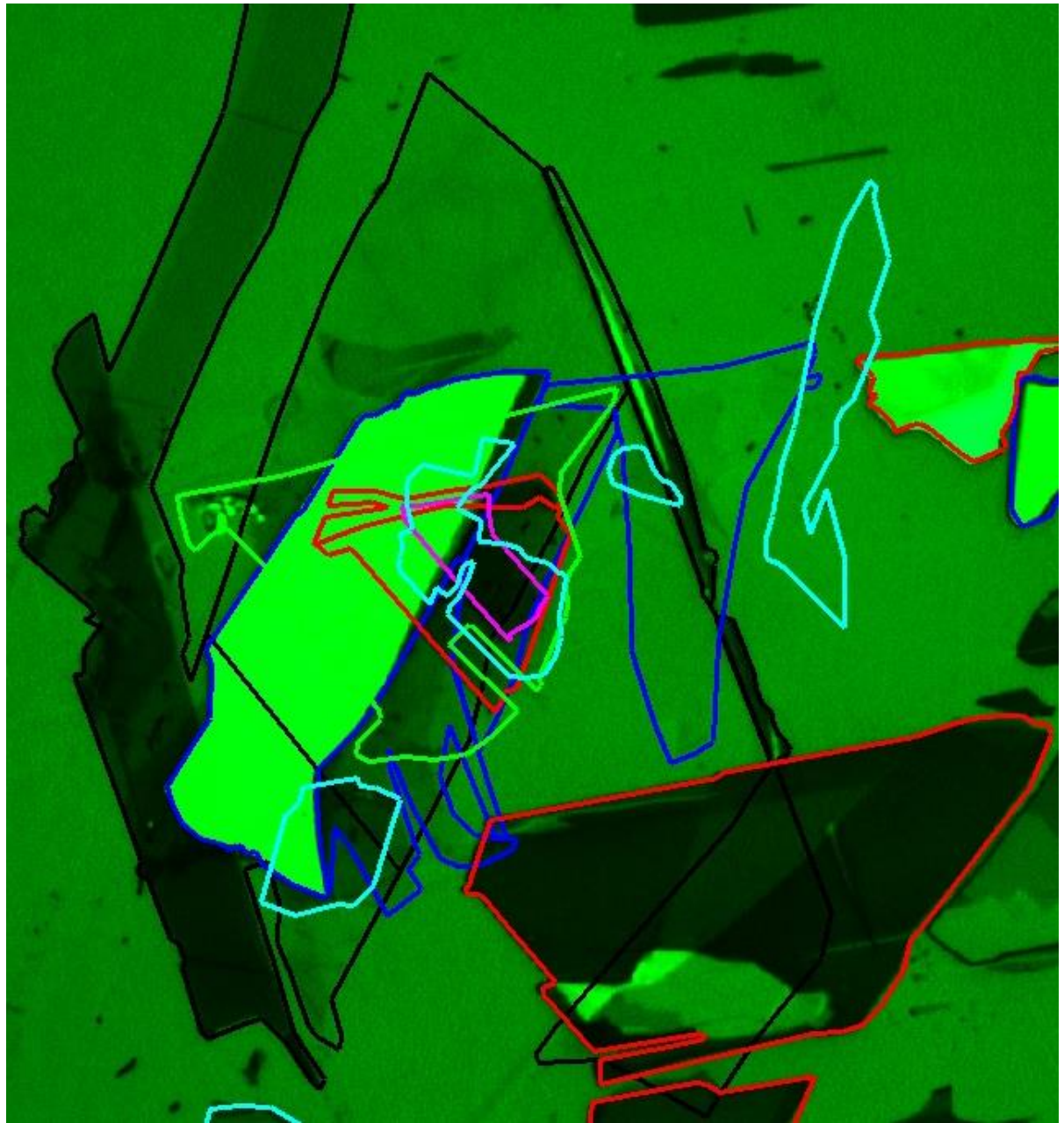
Transfer



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MoS_2

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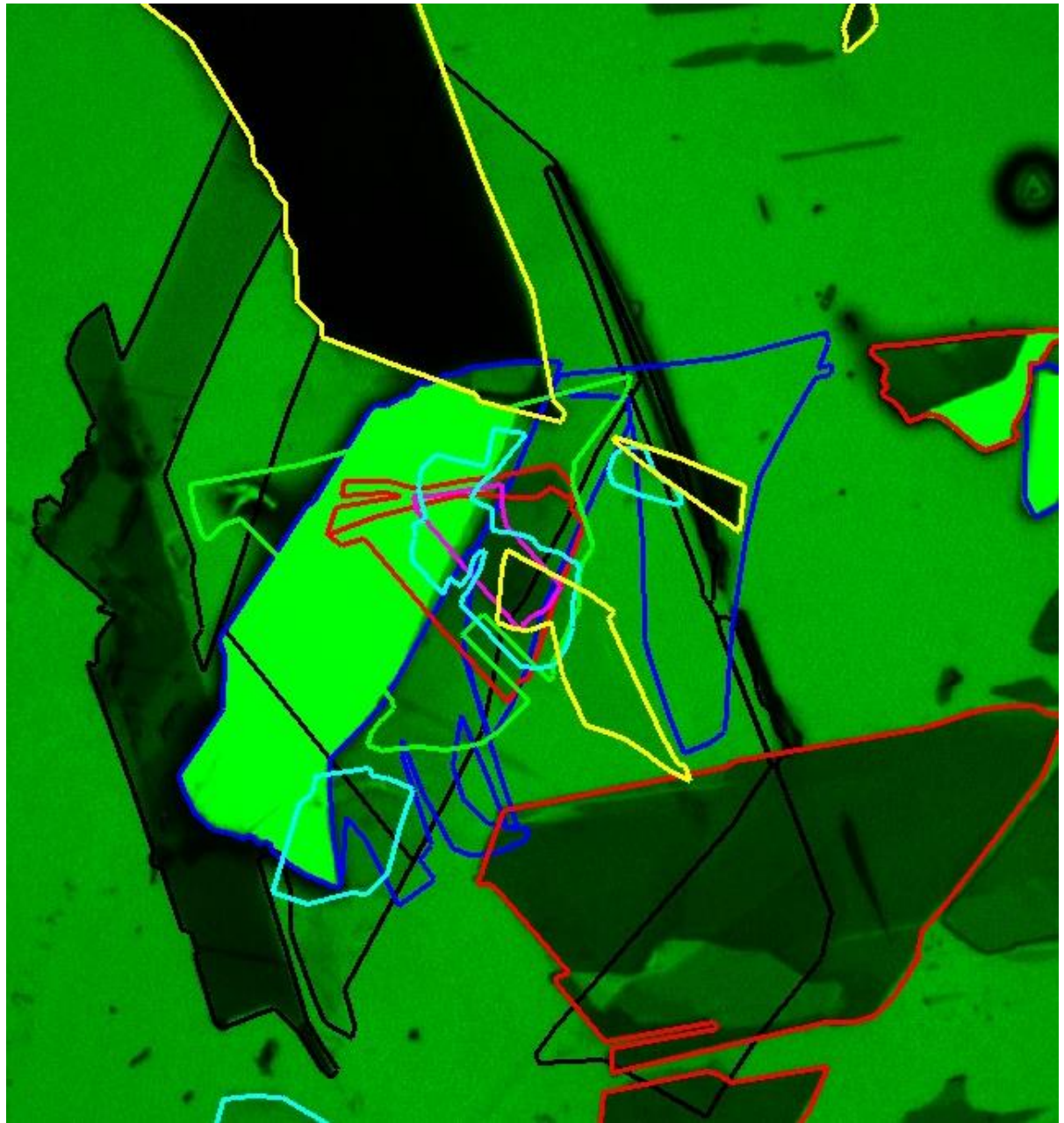

Gr

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MoS_2

BN

WSe_2

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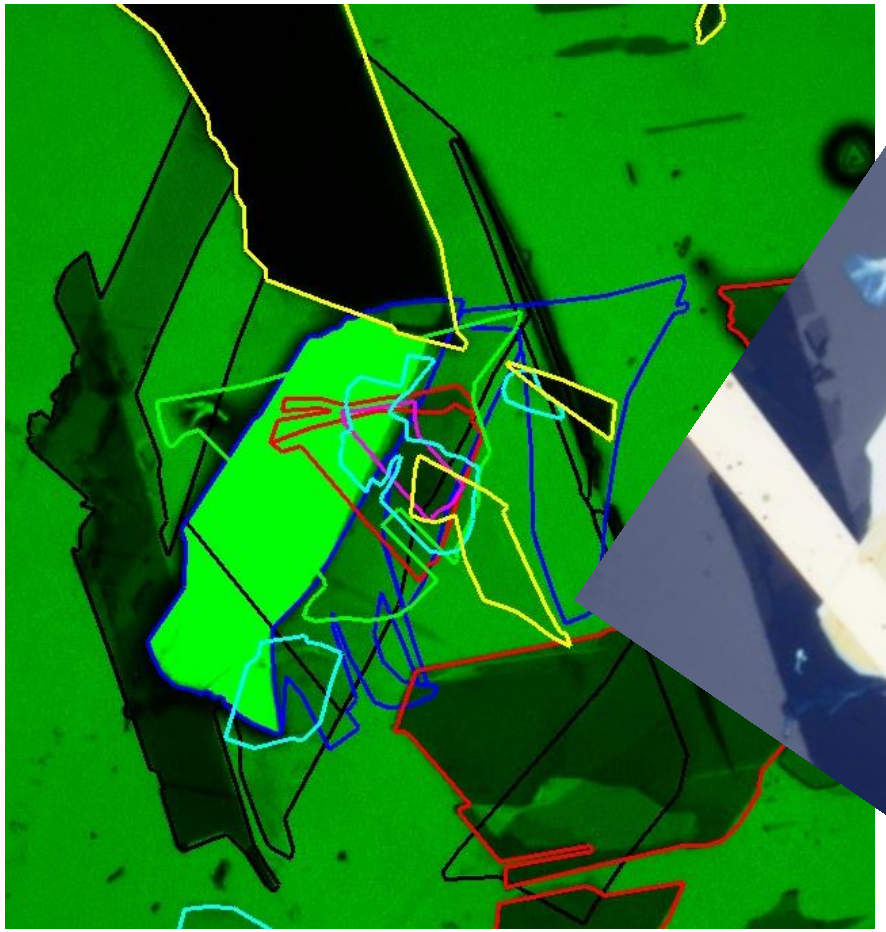
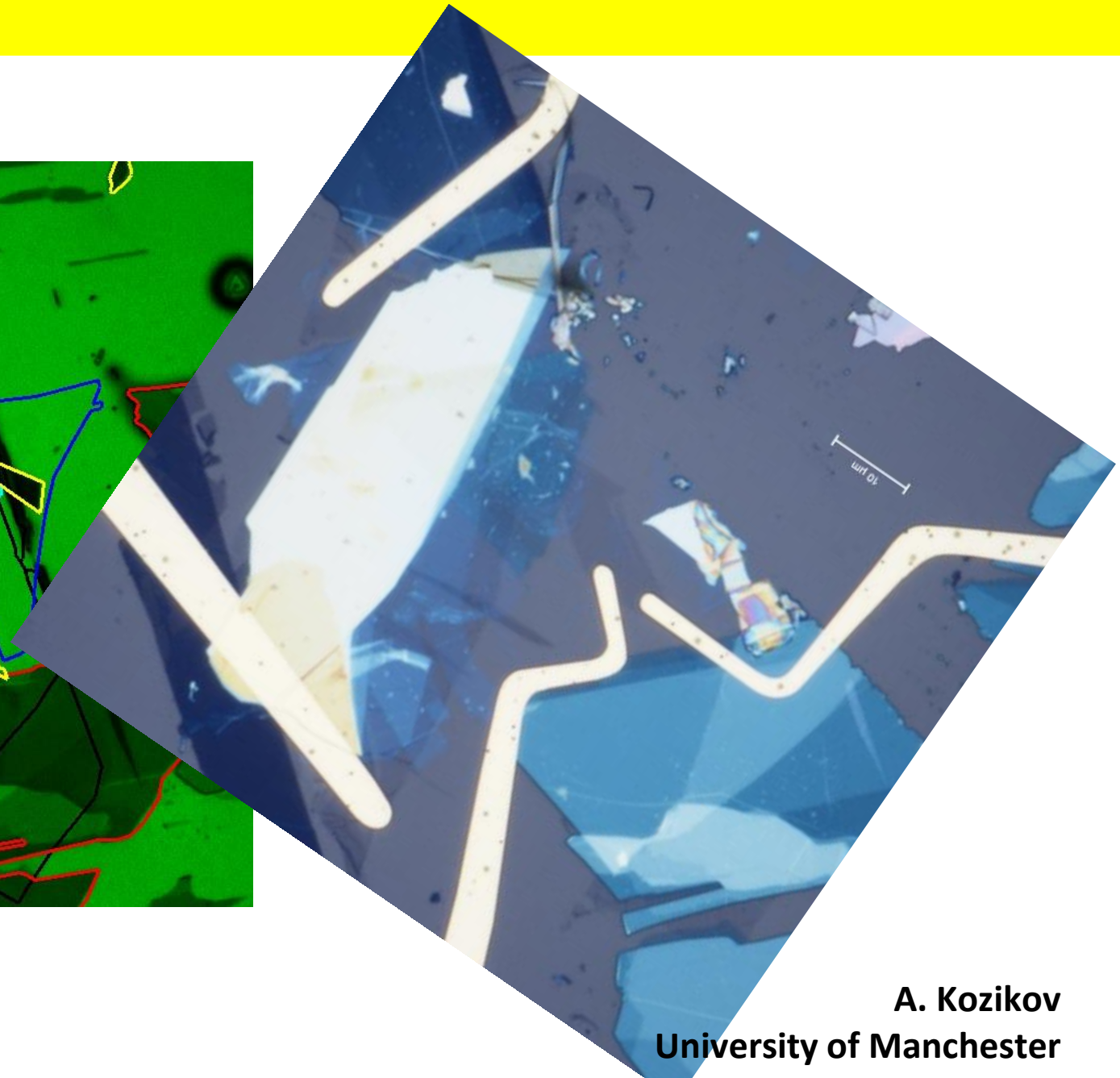
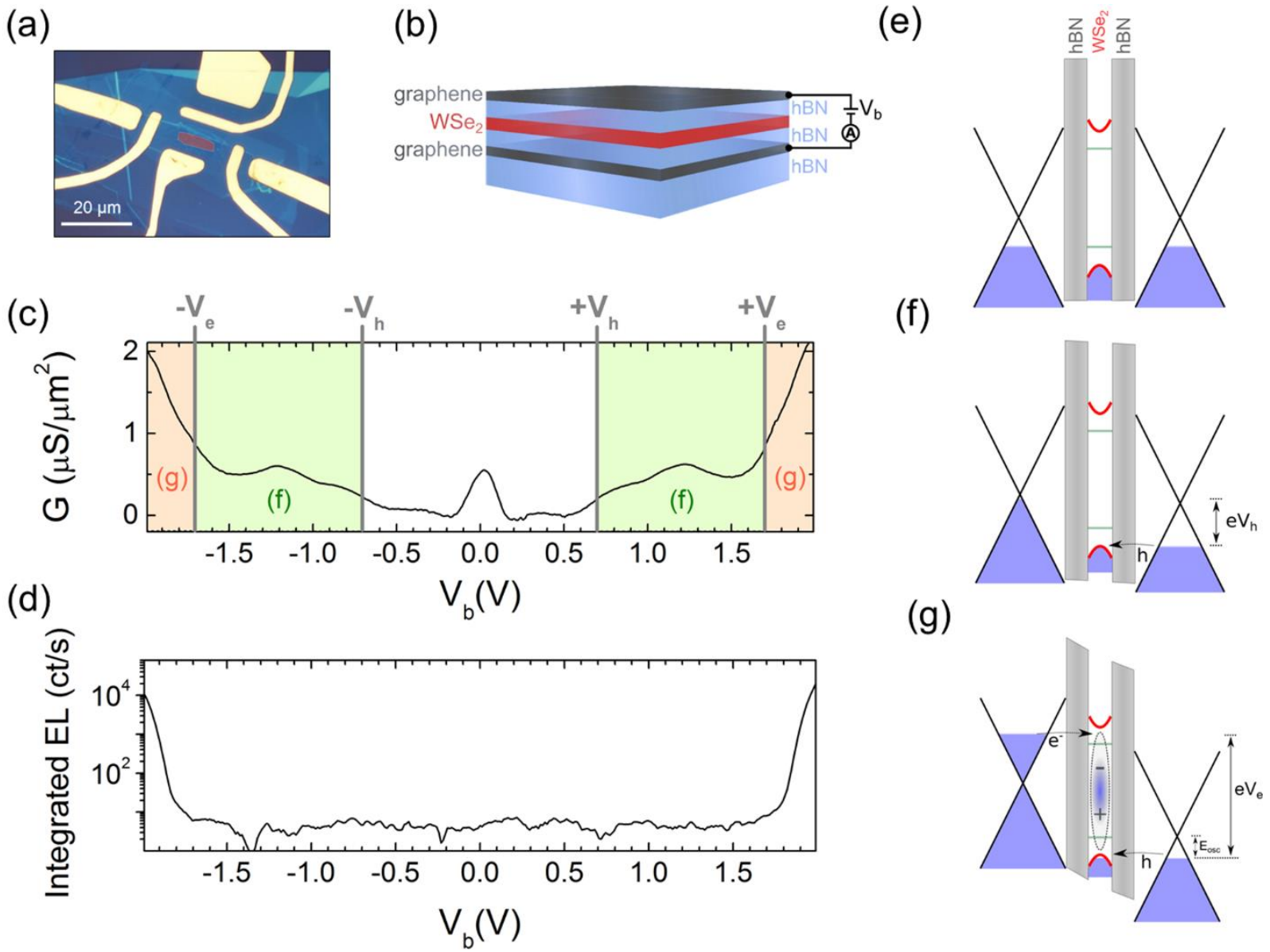




A. Kozikov
University of Manchester

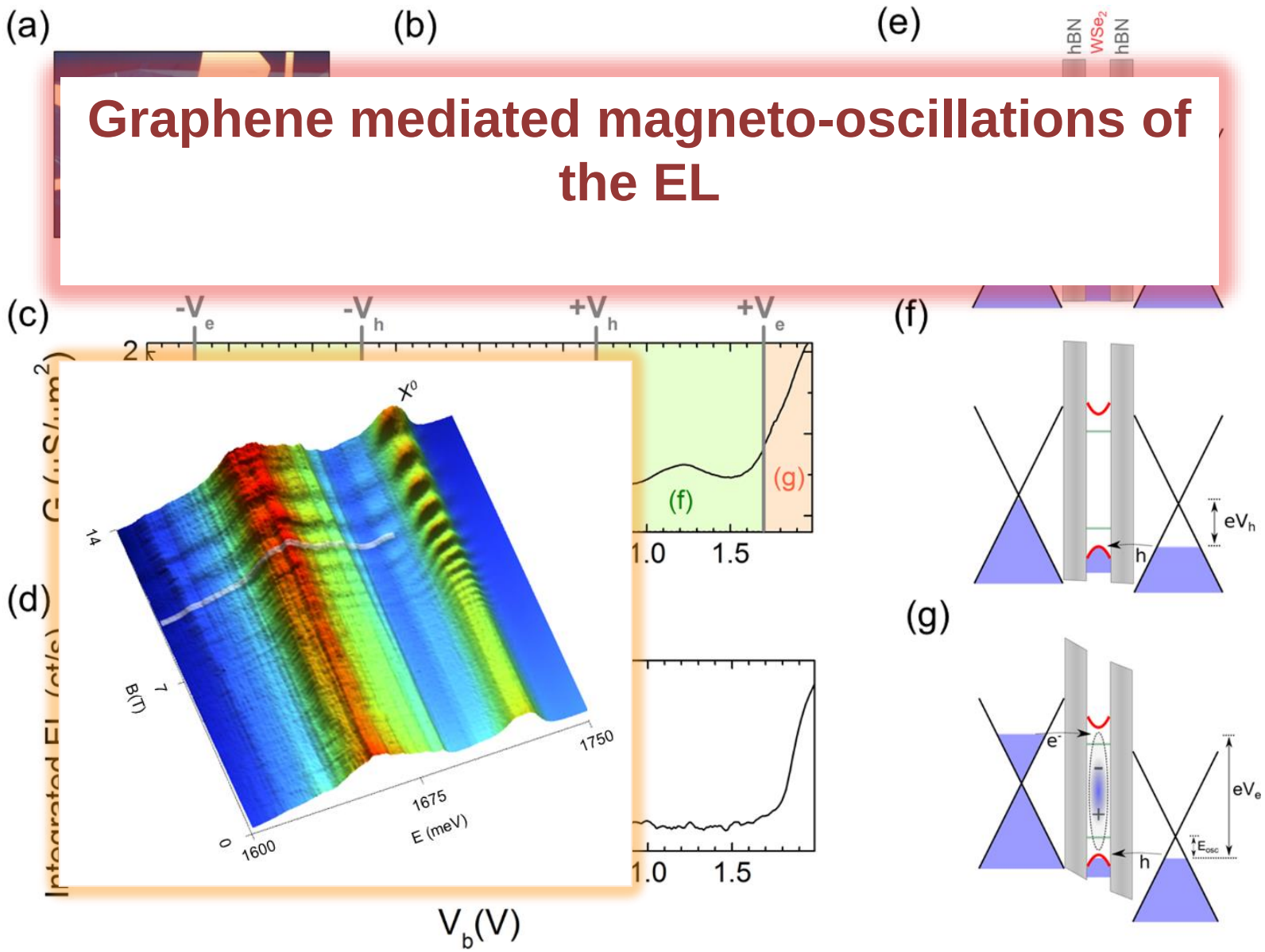
Structures with a single TMDC



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

Structures with a single TMDC

Graphene mediated magneto-oscillations of the EL



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

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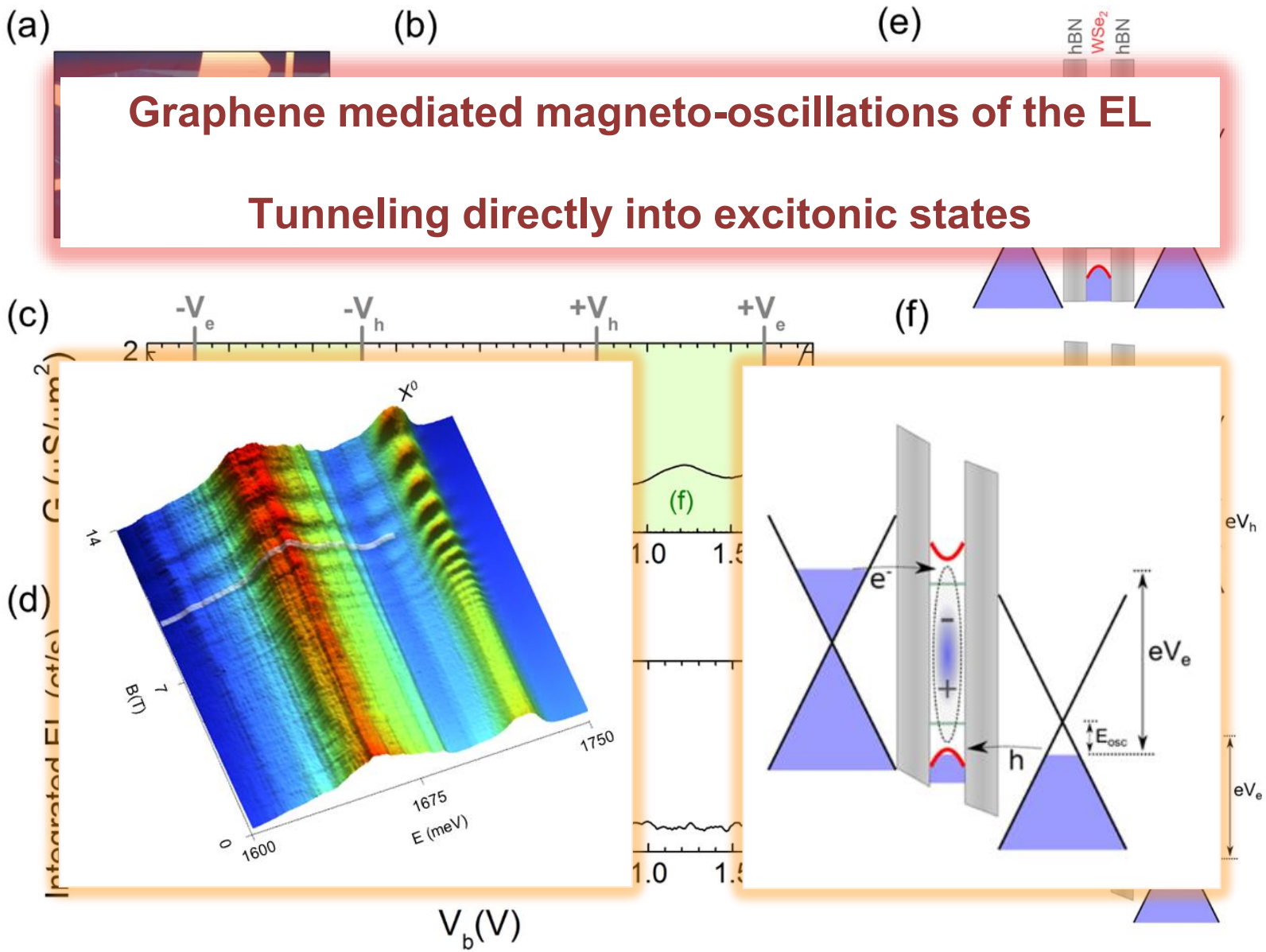
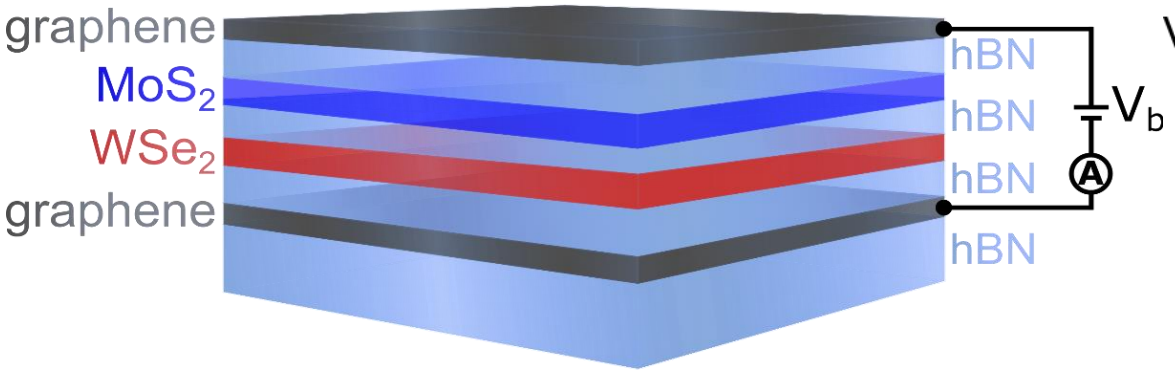


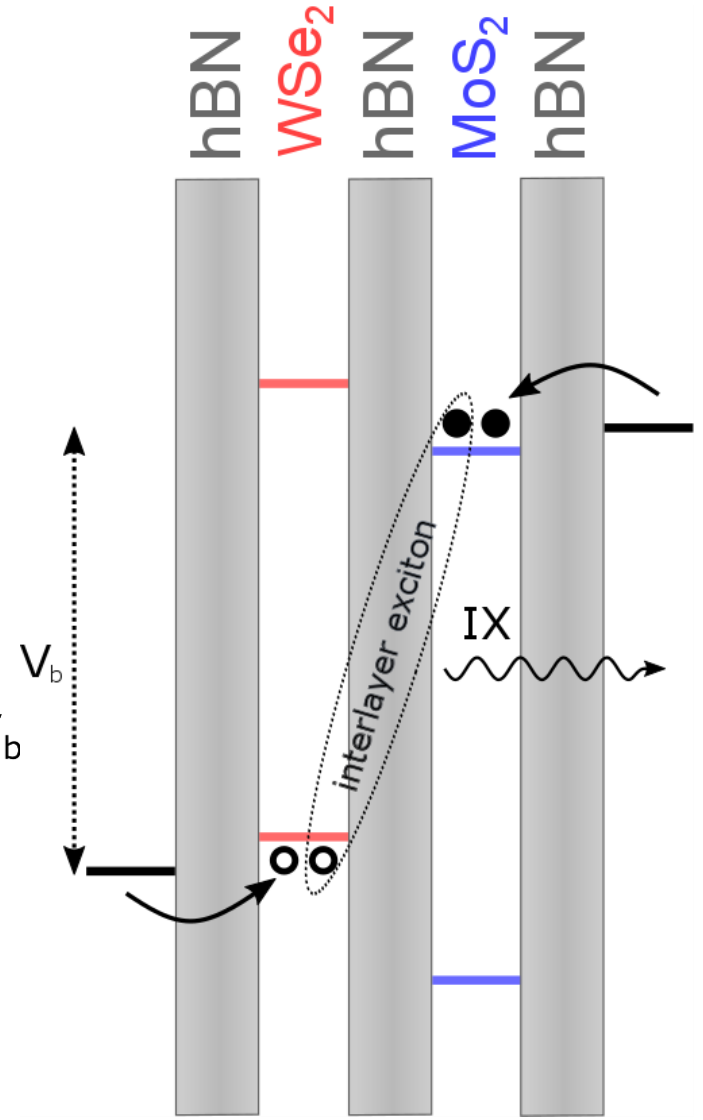
J. Binder et al. *Nano Letters* 17, 1425 (2017)

Two TMDCs in a vdW heterostructre

Increase in complexity:

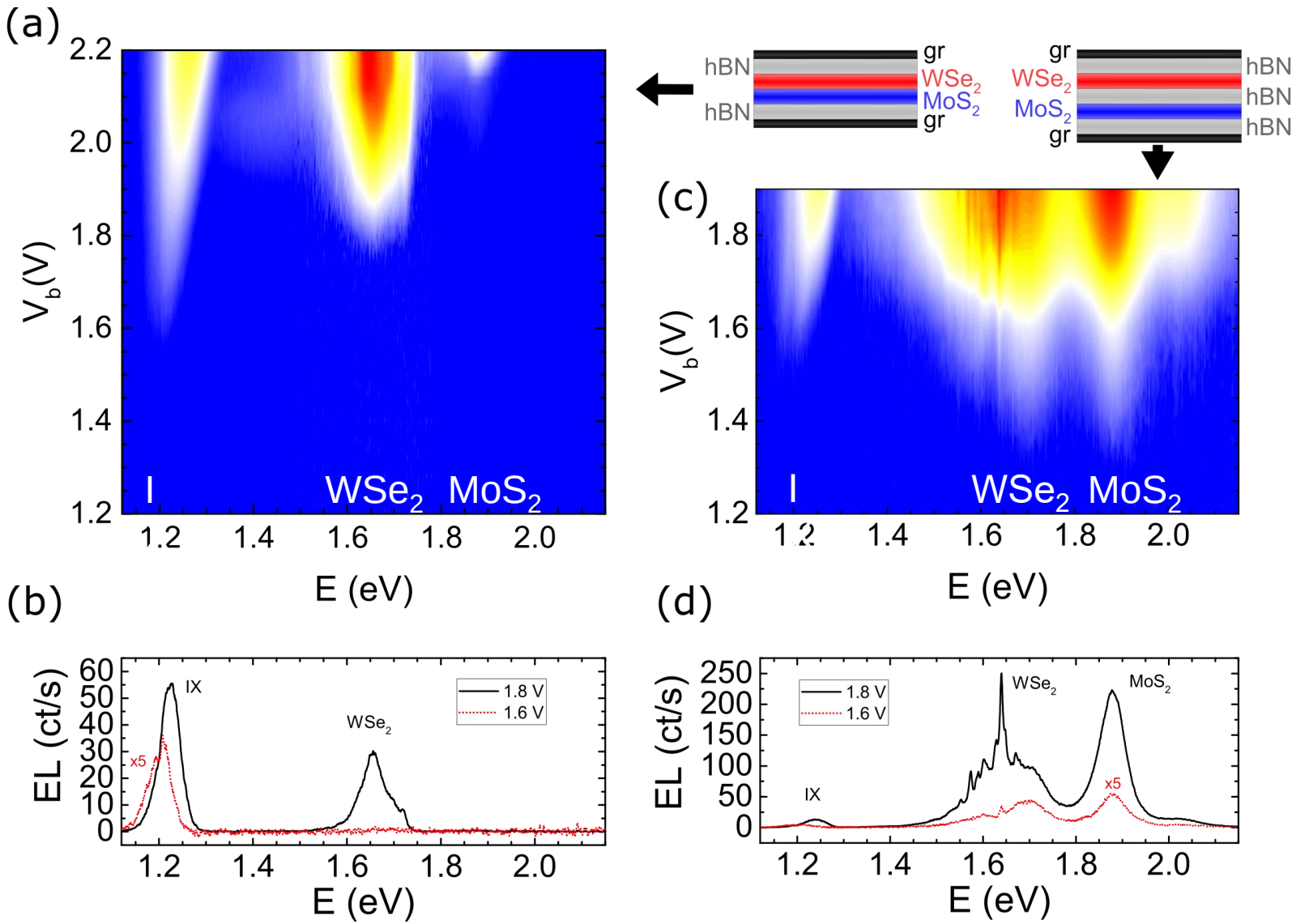
- Adding a 2nd TMDC monolayer
- Indirect (interlayer) excitons!



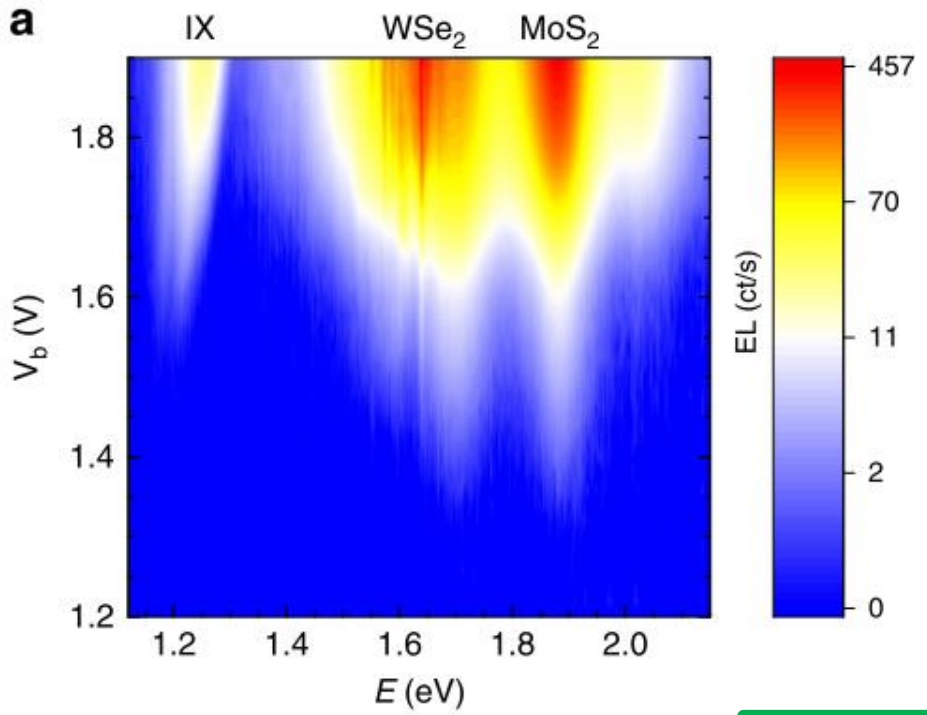


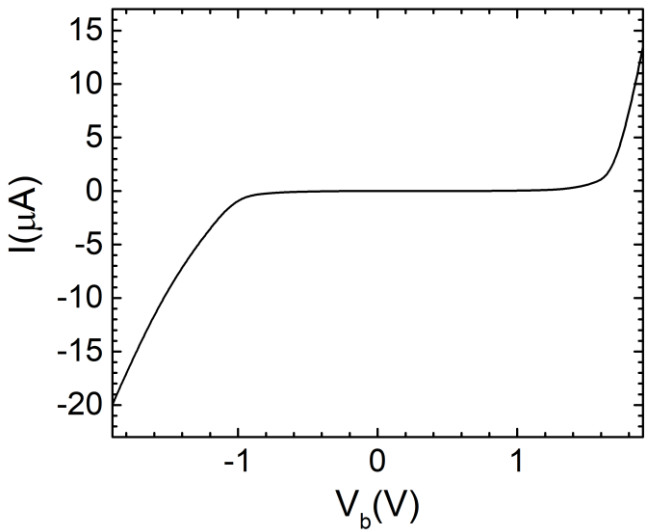
J. Binder et al. *Nature Communications* 10:2335 (2019)

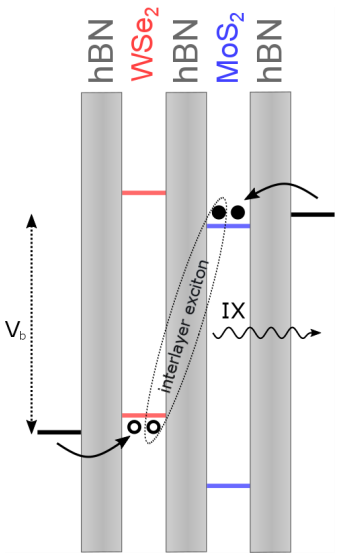
Electroluminescence

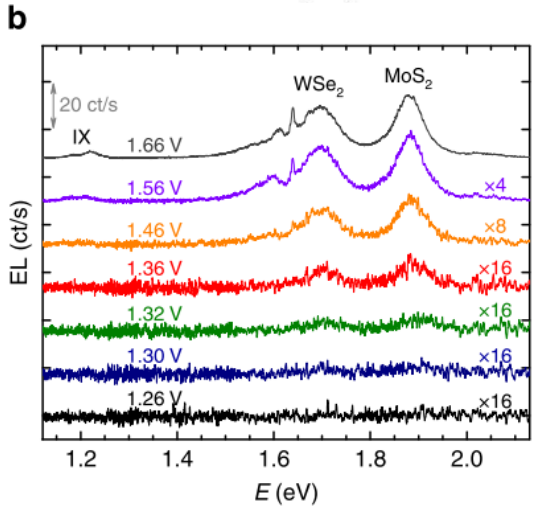


Electroluminescence







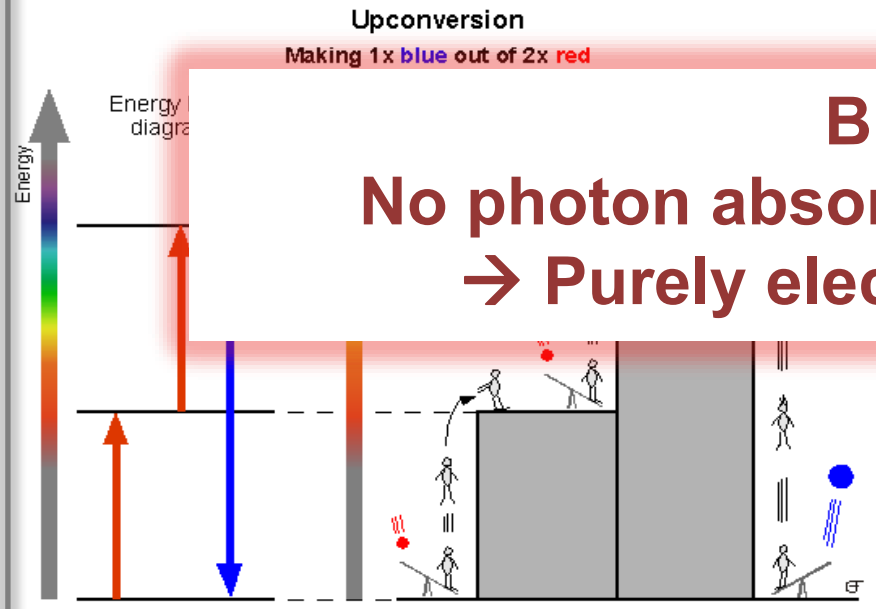


- EL of WSe_2 and MoS_2 appear at lower voltages than IX
- At a voltage of about 1.3 V we observe emission of WSe_2 and MoS_2 with an energy of ≈ 1.7 and 1.9 eV

UPCONVERSION of ≈ 0.6 eV

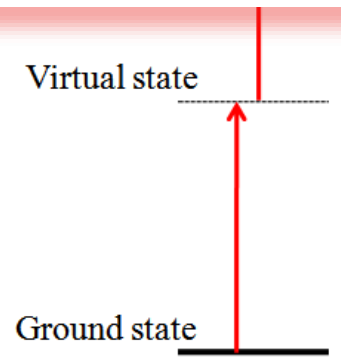
Upconversion (optical excitation)

Photon upconversion (e.g. ions)



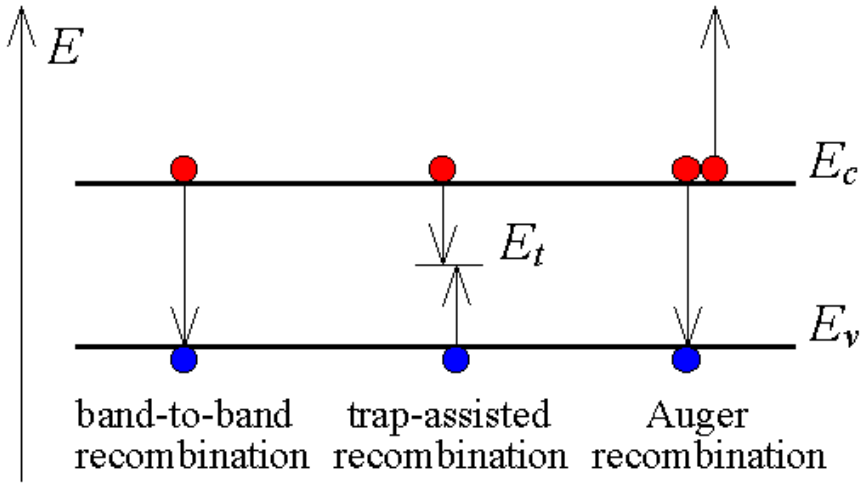
https://guedel.dcb.unibe.ch/research/hug_upc.htm

Nonlinear optical processes (second harmonic generation, two photon absorption

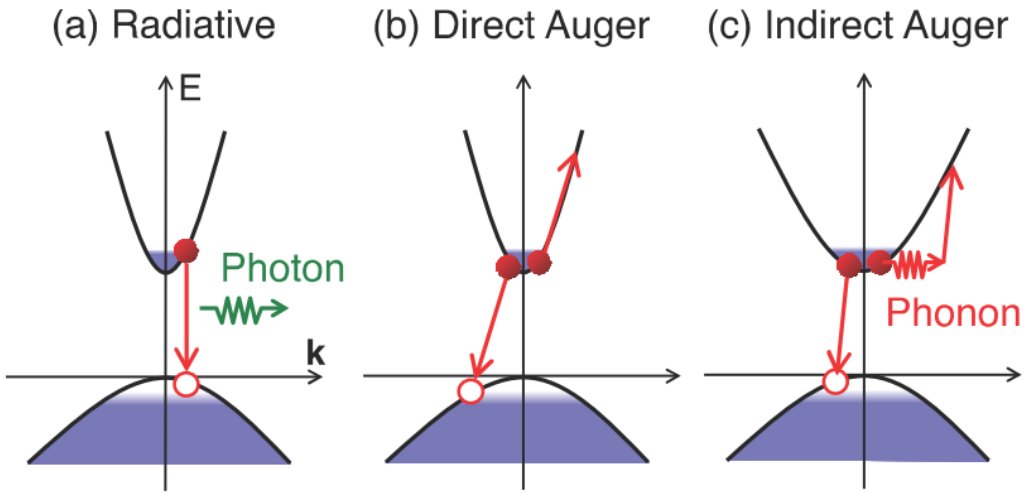


BUT:
No photon absorption in our case!
→ Purely electrical injection

Auger effect

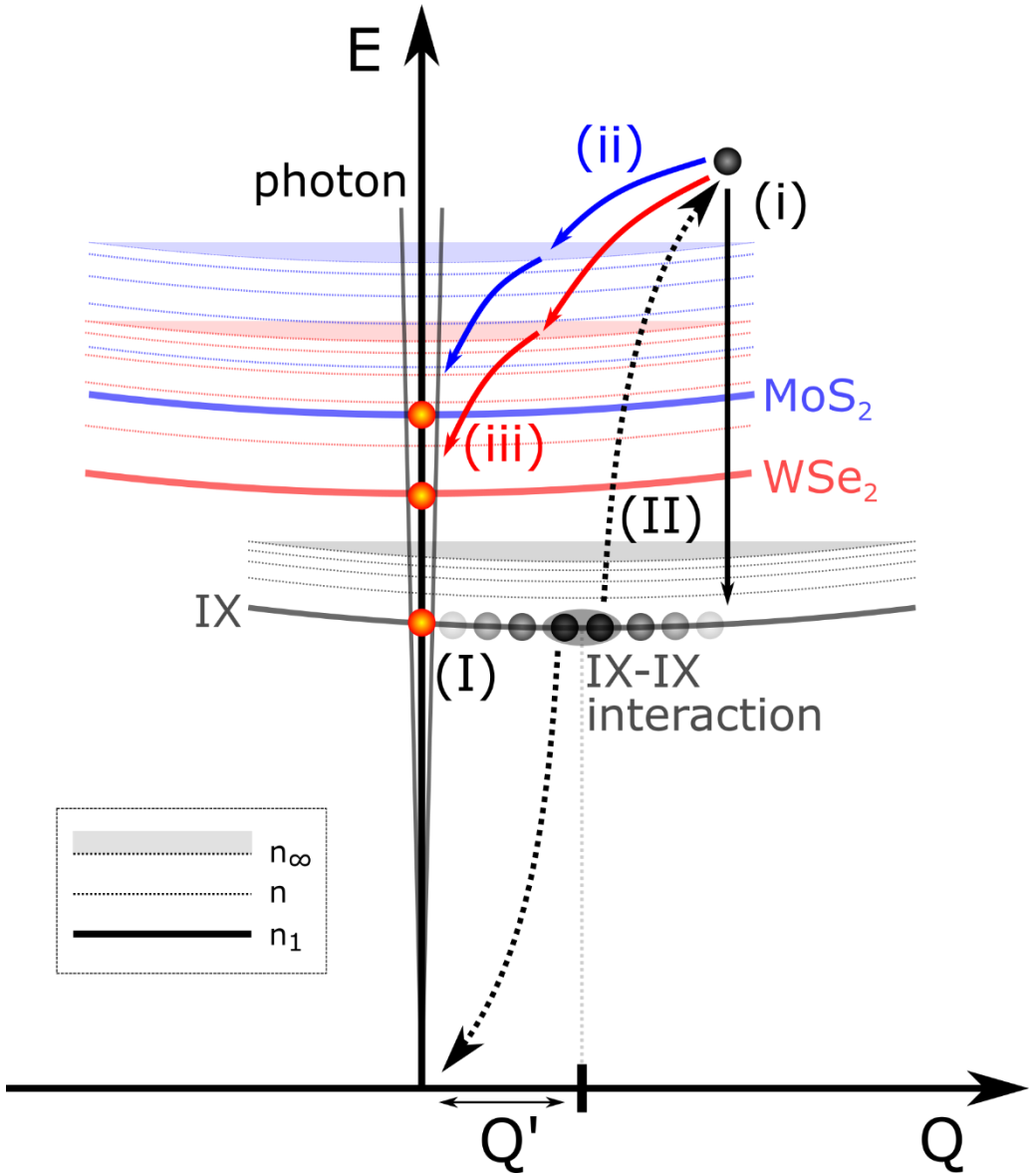


https://ecee.colorado.edu/~bart/book/book/chapter2/ch2_8.htm



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

Excitonic Auger Upconversion?

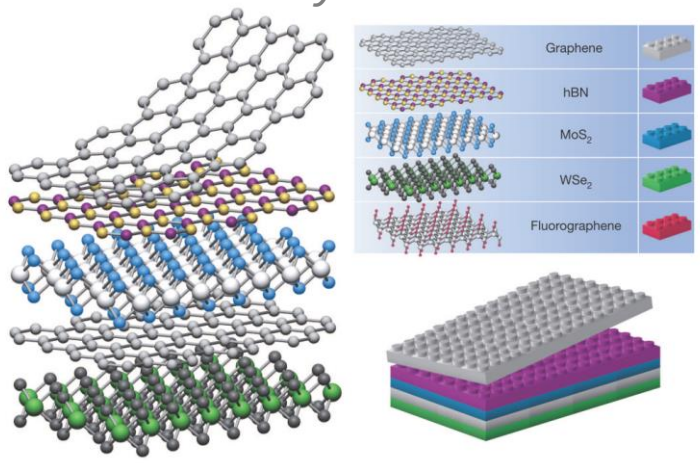


J. Binder et al. *Nature Communications* 10:2335 (2019)

h-BN – basic element of van der Waals heterostrucutres

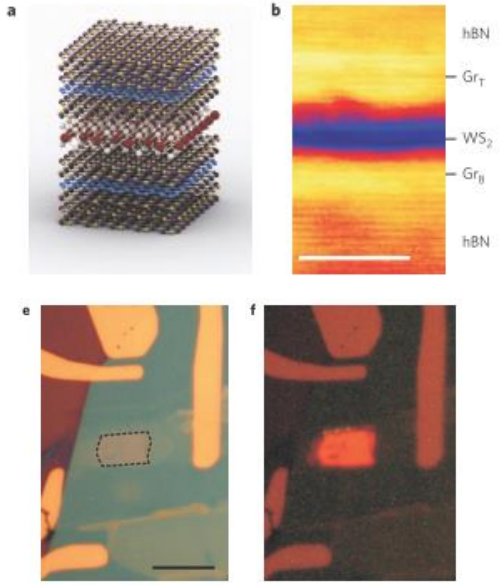
Basic idea

"atomic-scale Lego" with 2D crystals



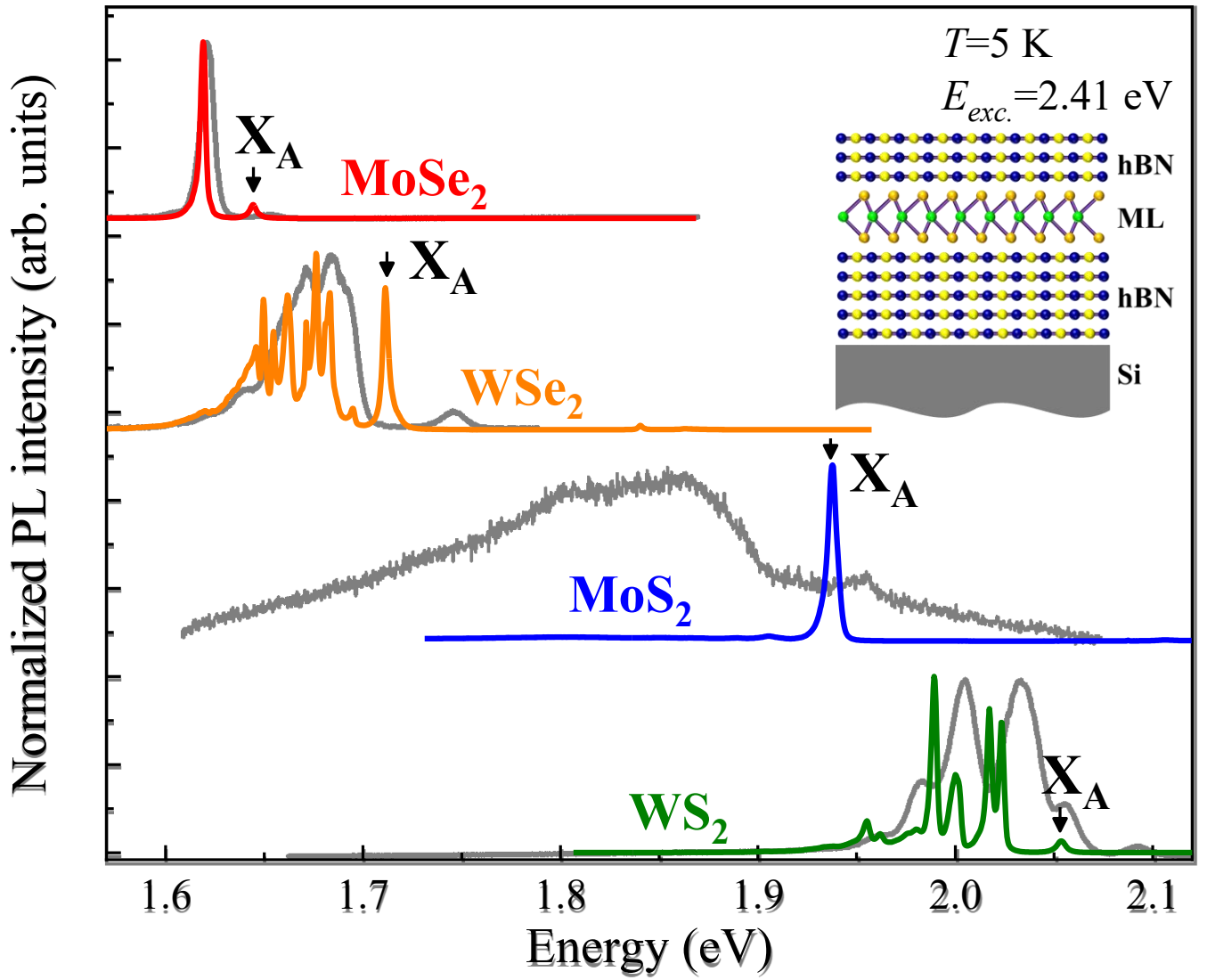
A. K. Geim, I. V. Grigorieva, Nature **499**, 420 (2013)

Light-emitting diodes



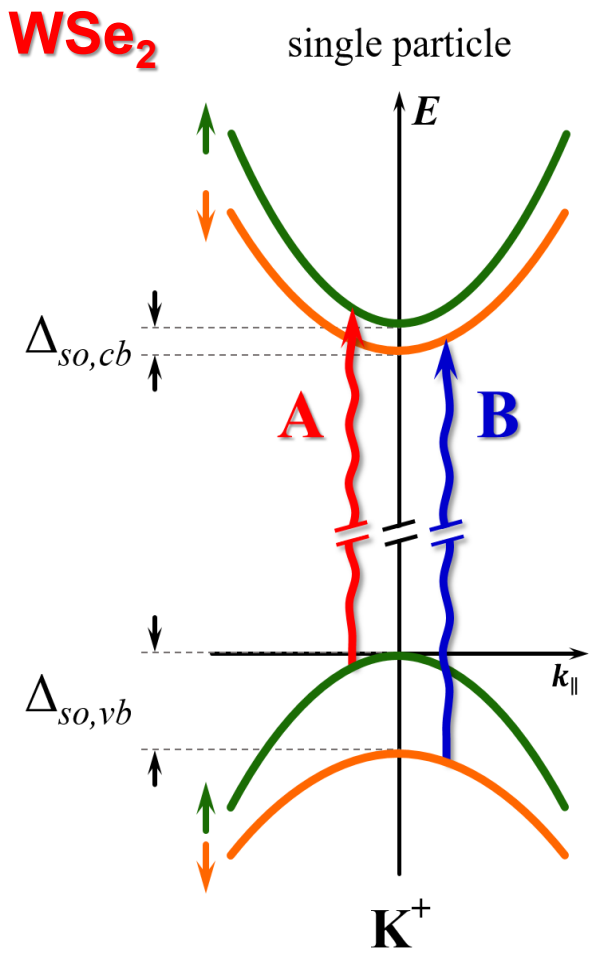
F. Withers et al. Nature materials **14**, 302 (2015)

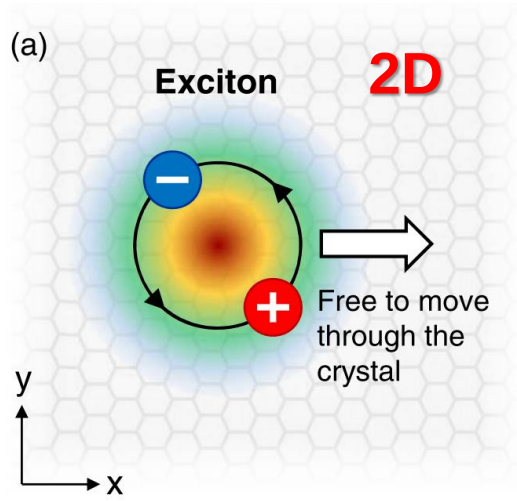
h-BN protective layers



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

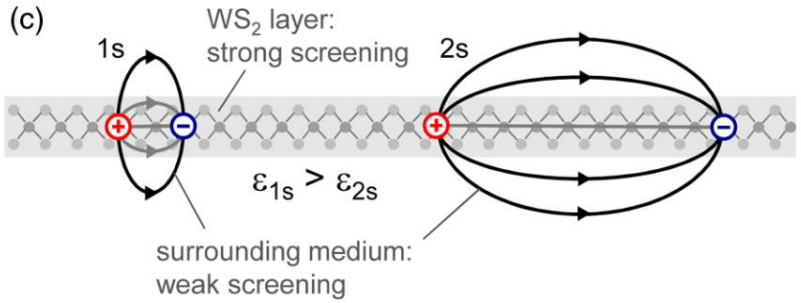
Excitonic ladder in S-TMD monolayers





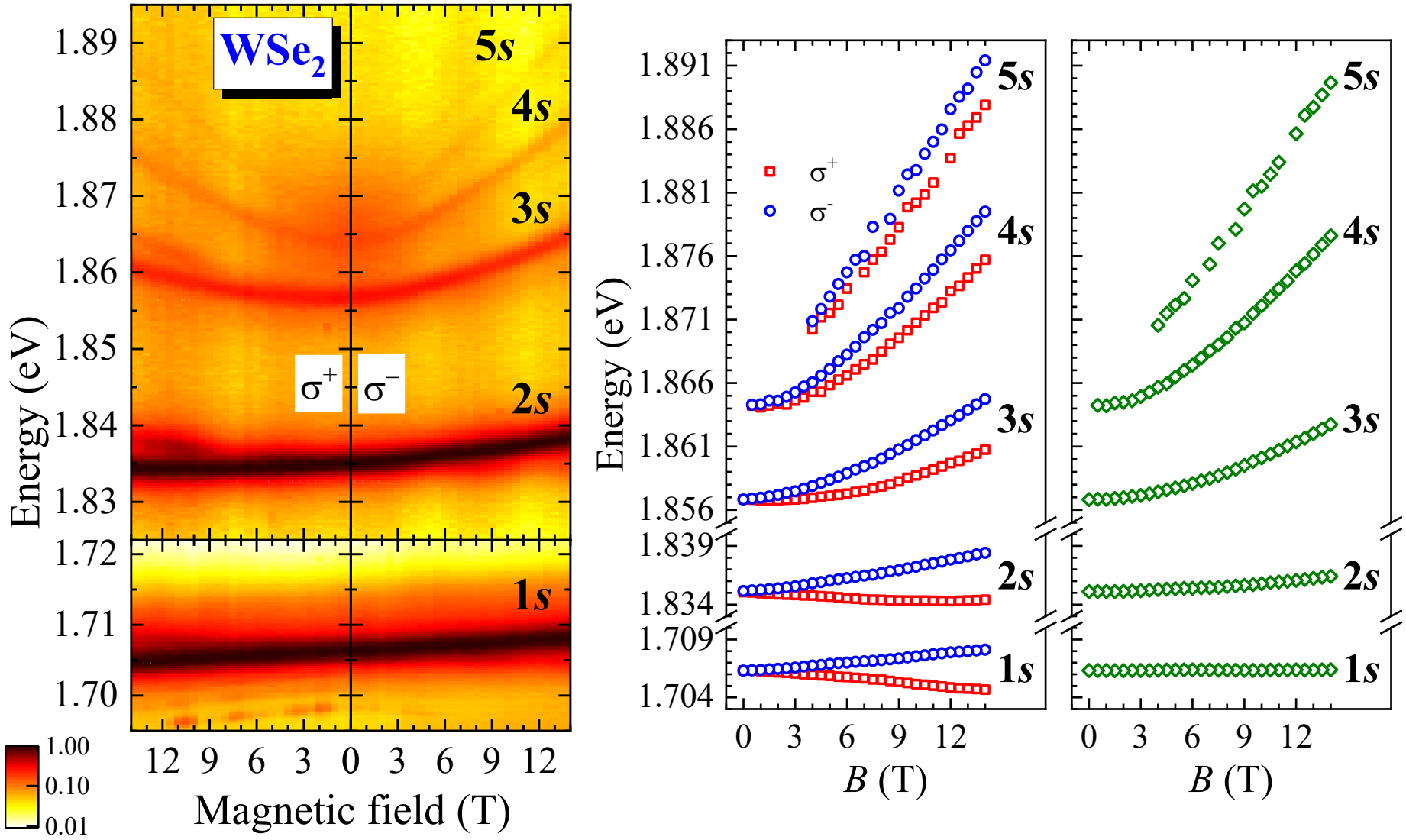
G. Wang et al., *Rev. Mod. Phys.* 90, 021001 (2018)

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



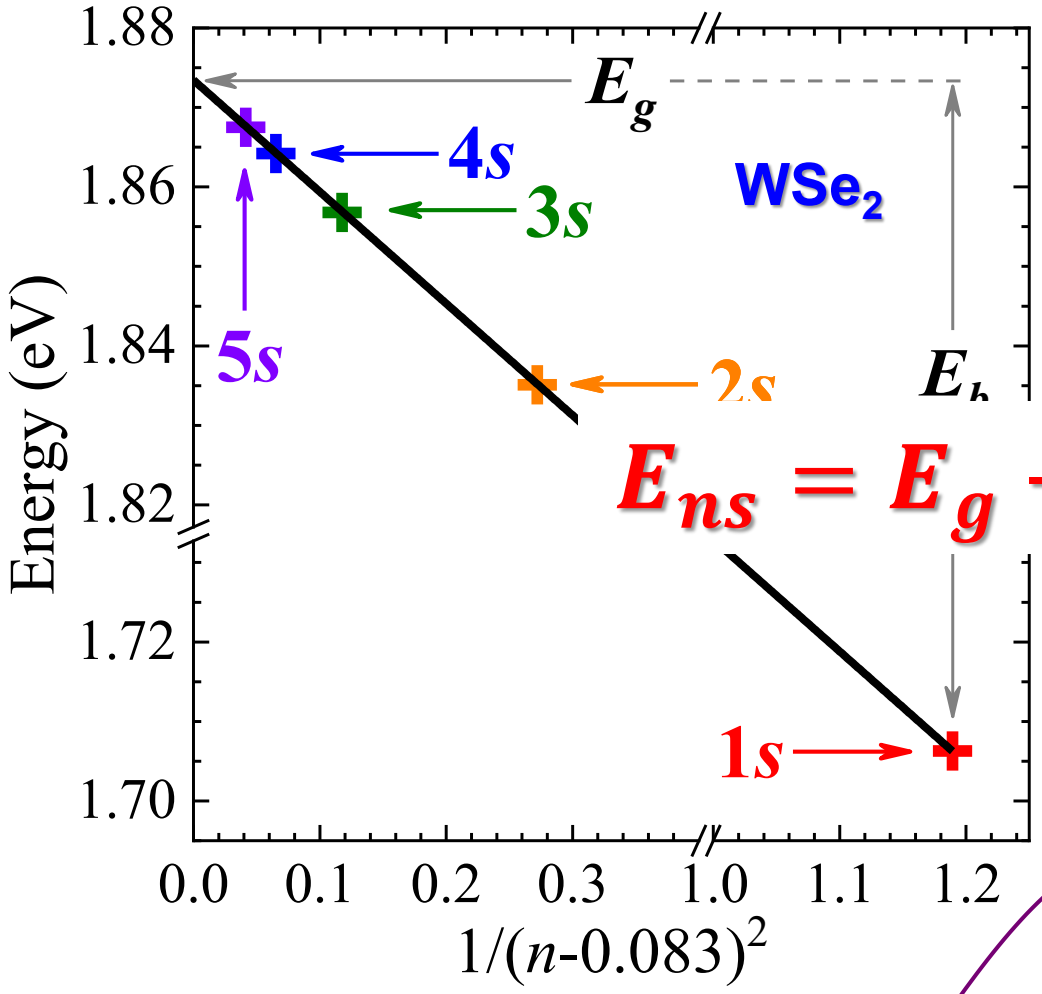
A. Chernikov et al., Phys. Rev. Lett. 113, 076802 (2014)

Examlpe - 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



Keldysh potential

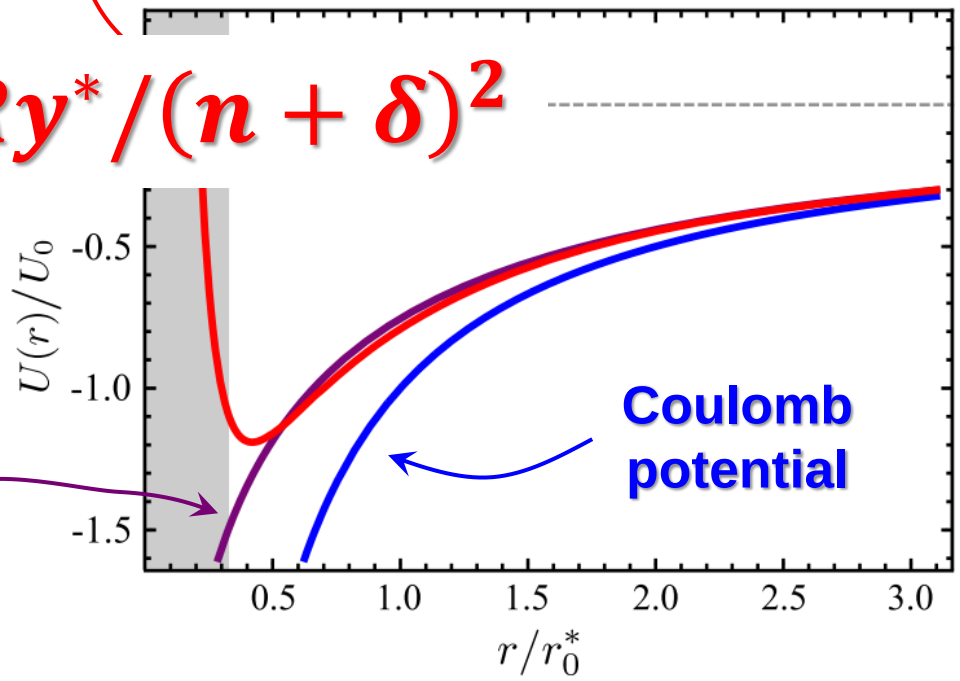
solvable numerically ☹

Kratzer potential

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

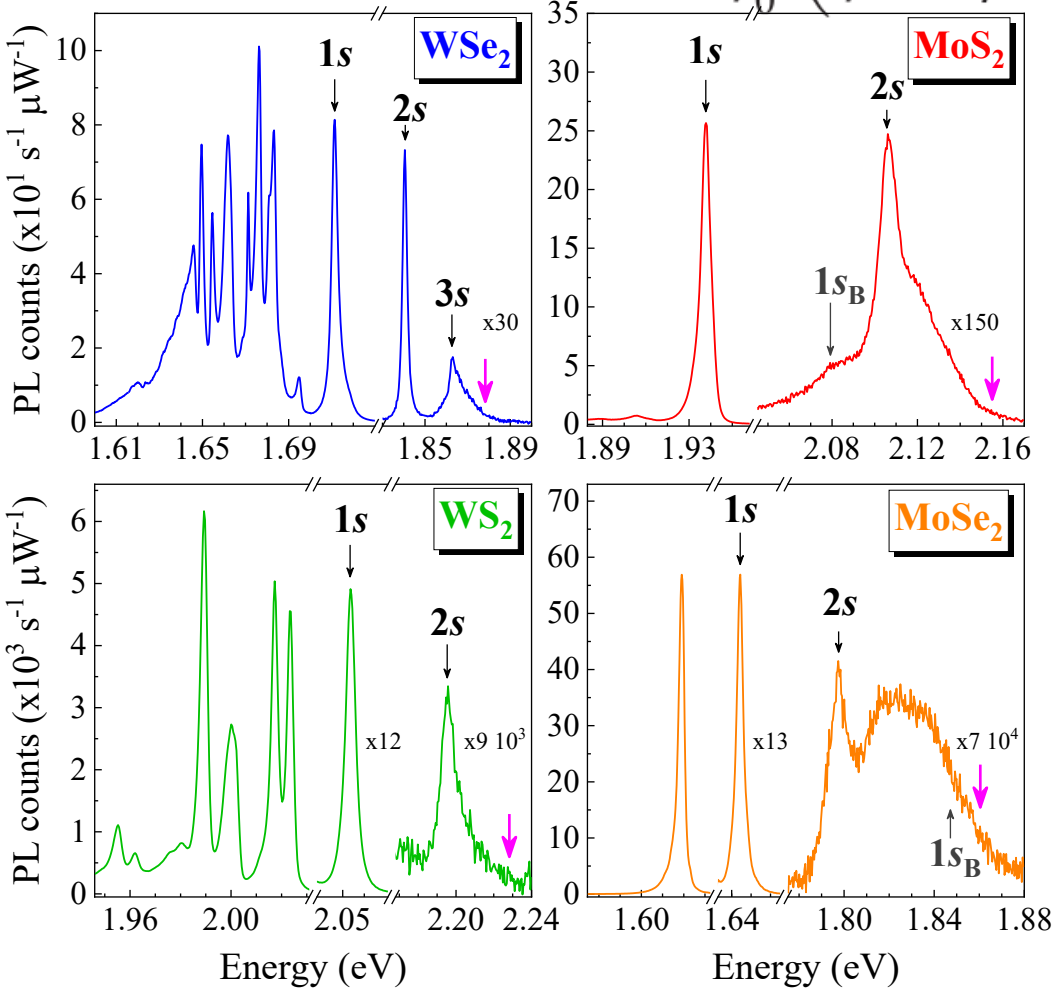
solvable analytically ☺

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



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

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



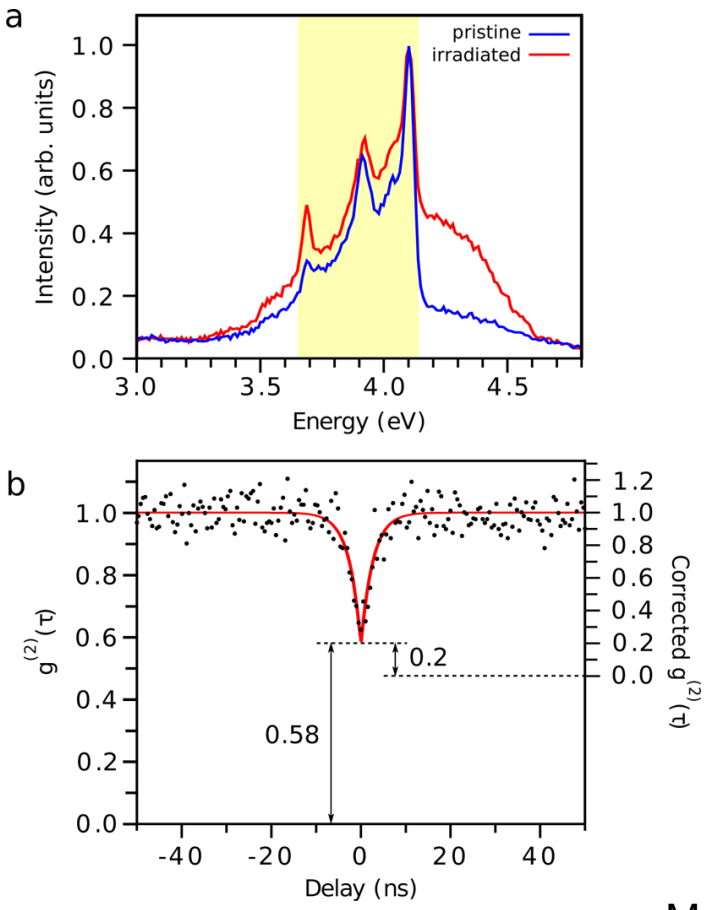
$$E_{ns} = E_g - Ry^*/(n+\delta)^2$$

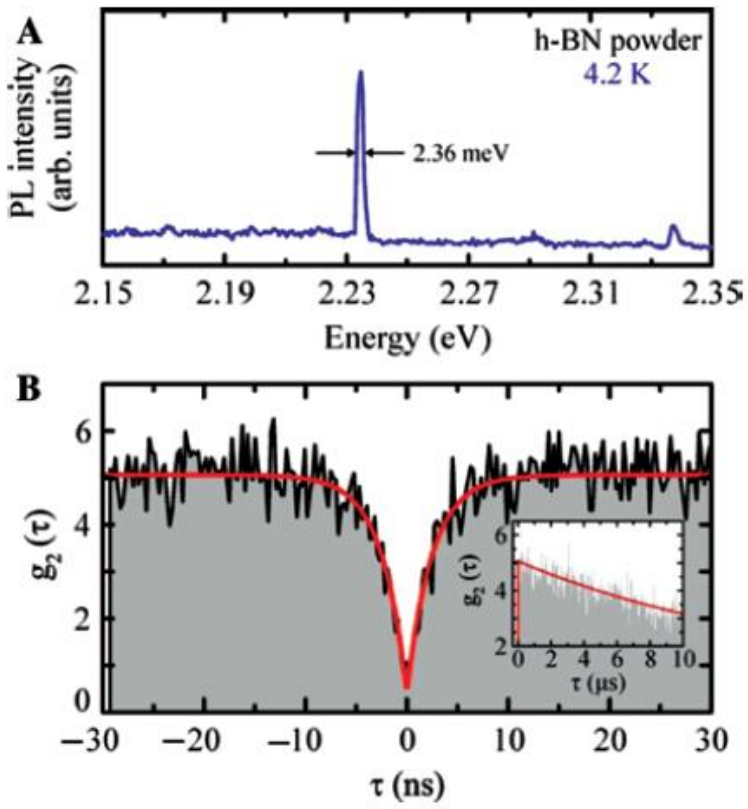
ML	E_b [1]
MoS_2	217 meV
$MoSe_2$	216 meV
WS_2	174 meV
WSe_2	167 meV

[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



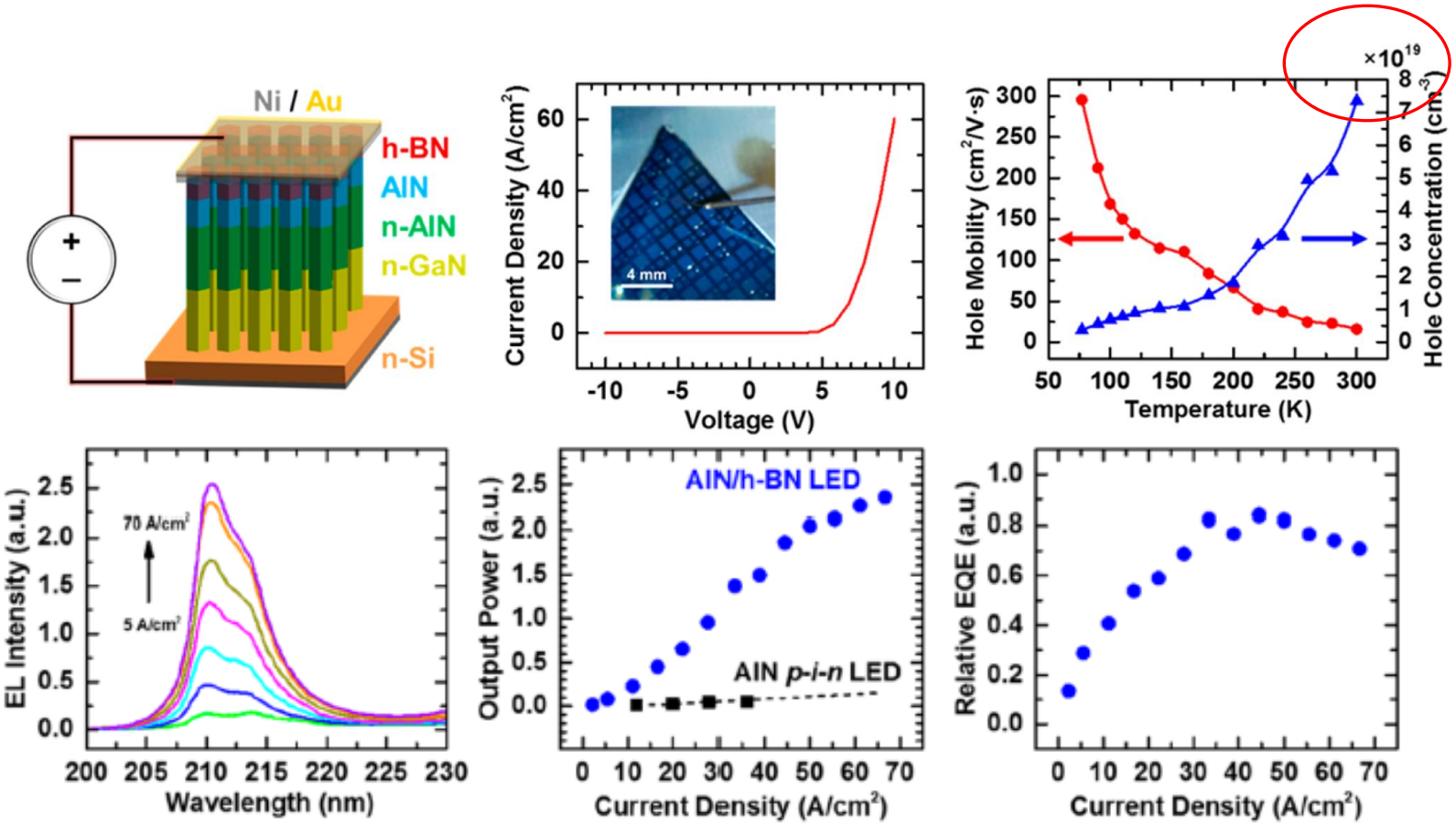


M. Koperski et al. ,Nanophotonics 6(6), 1289–1308 (2017)

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

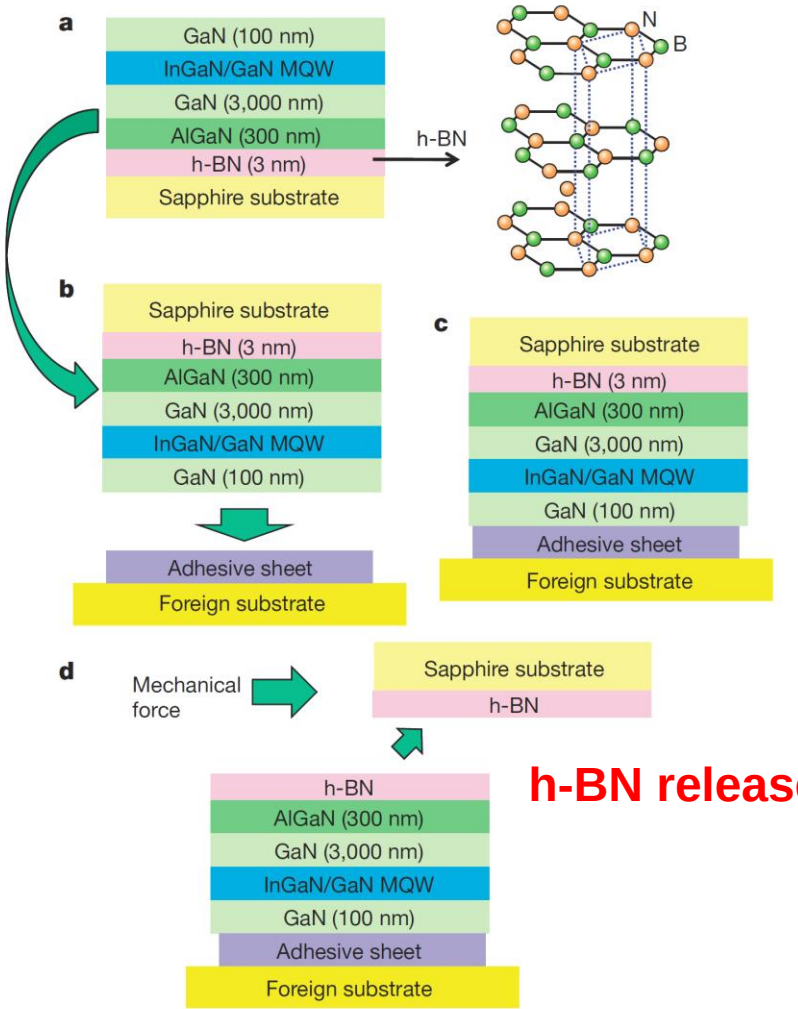
h-BN as p-type transparent material

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

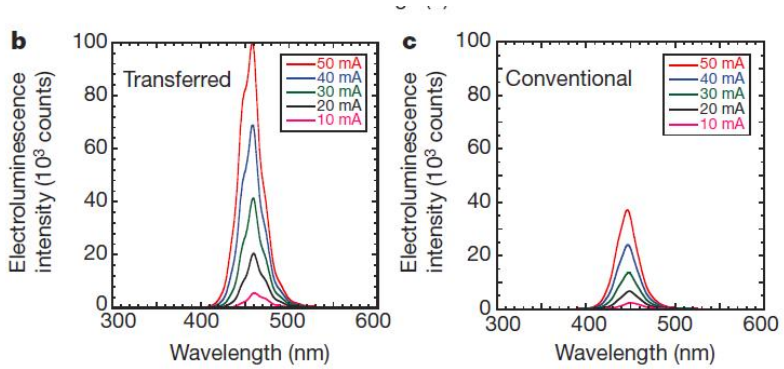


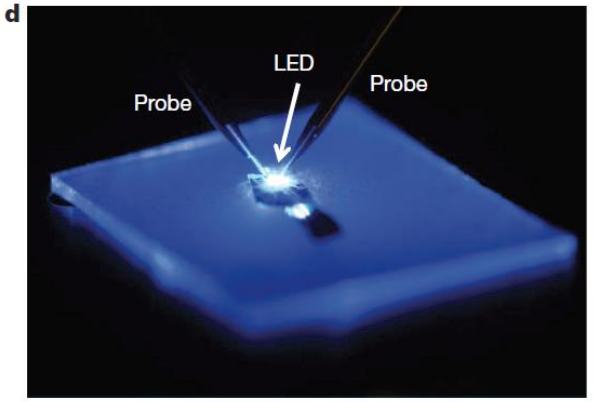
D. A. Laleyan et al. Nano Lett. 17, 3738 (2017)

Mechanical transfer of nitride-based devices



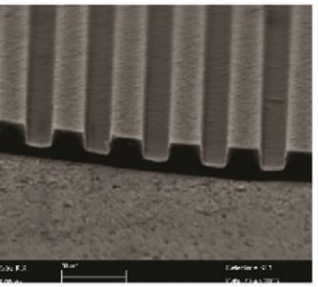
h-BN release layer

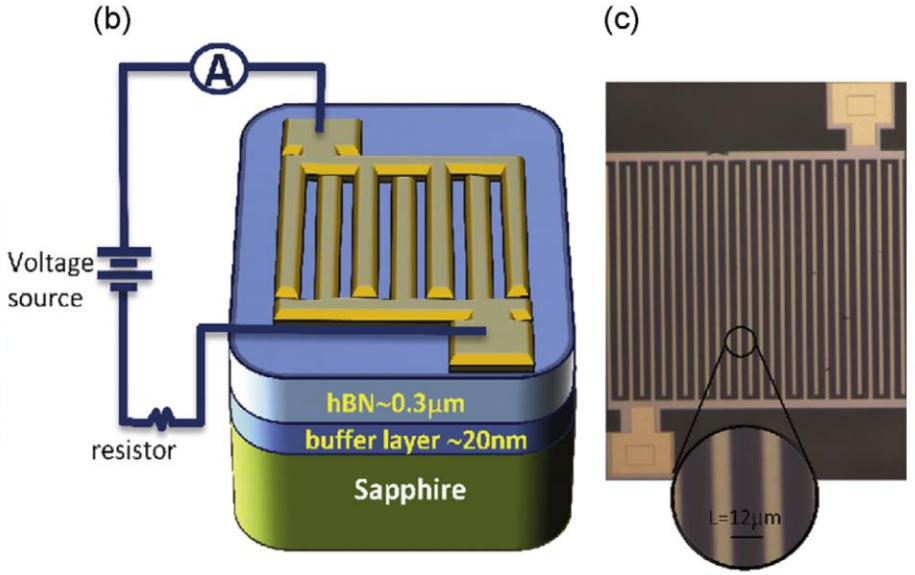




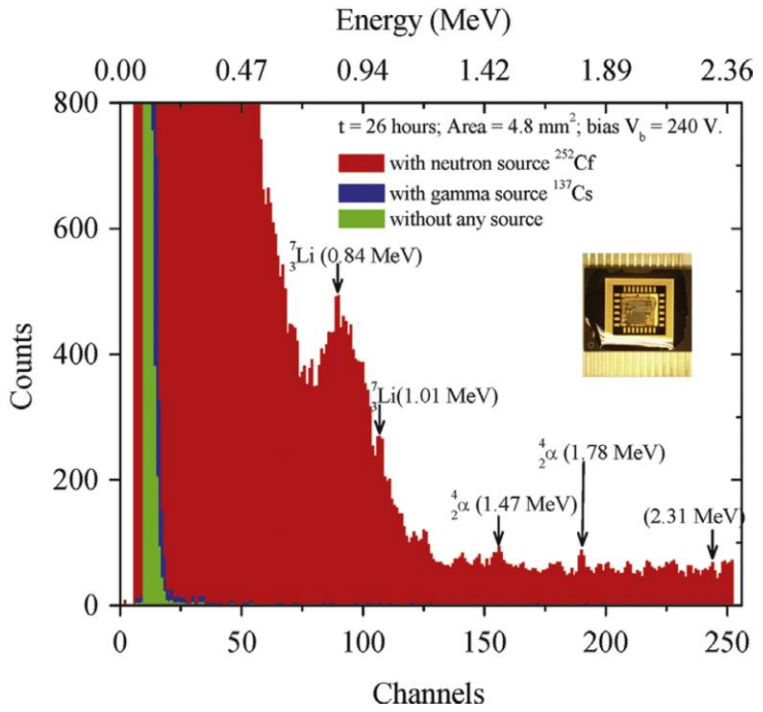
Y. Kobayashi et al. NATURE 484, 223 (2012)

BN- based neutron detectors





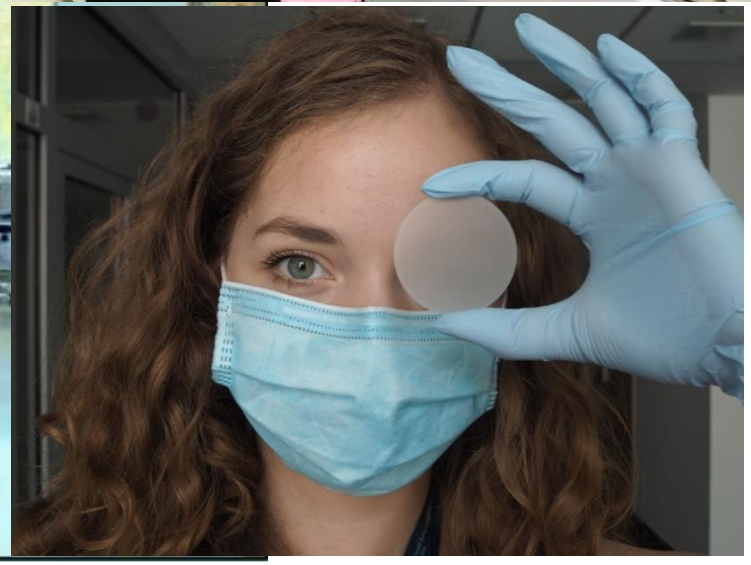
$$^{10}B + {}^{1}_{0}n \rightarrow {}^{7}Li^{*}(0.840MeV) + \alpha(1.470MeV)$$



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)

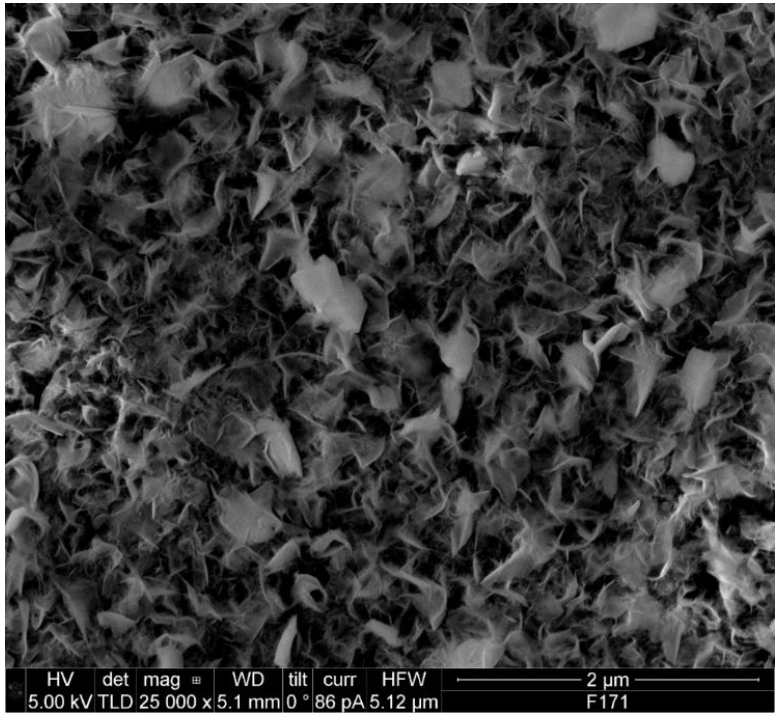
New MOVPE system

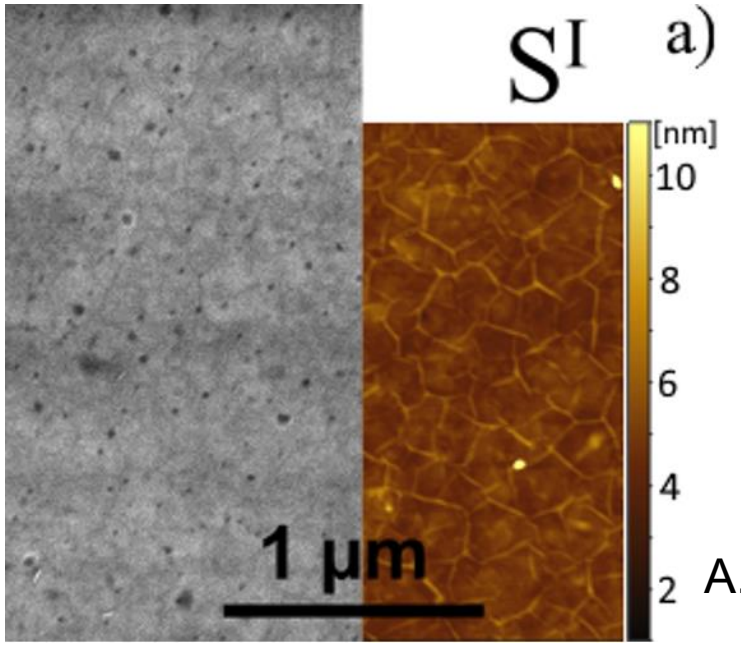


Established by Krzysztof Pakuła

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

From flakes to high quality hBN layers…

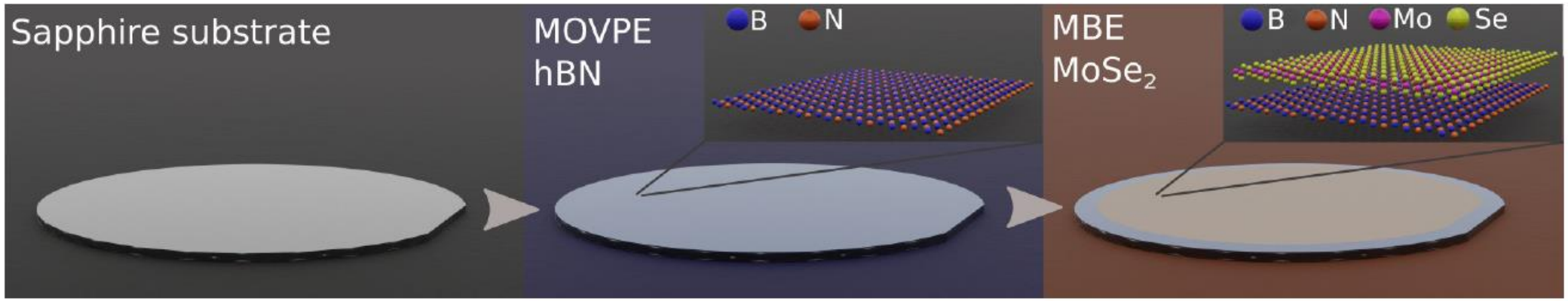




New possibilities!

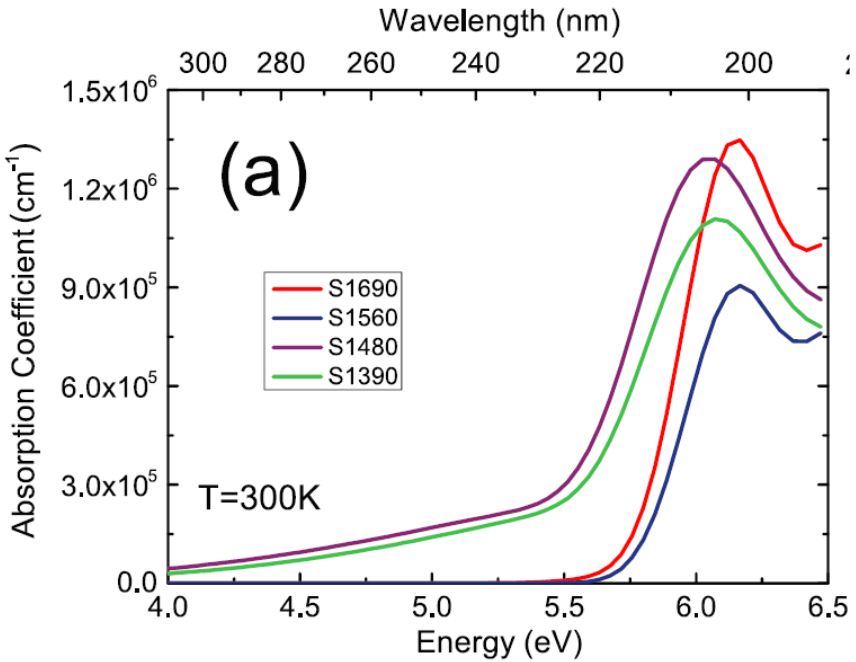
MBE $MoSe_2$ / BN MOCVD

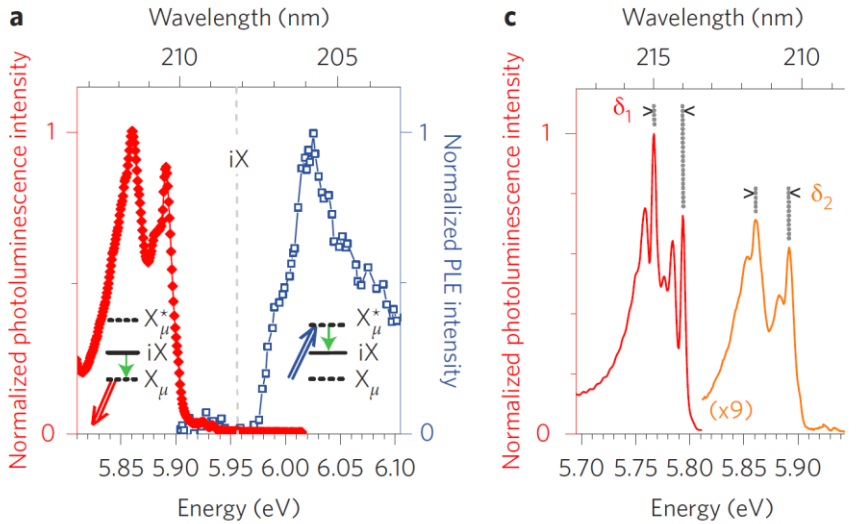
A. Dąbrowska et al. 2D Materials (2020)

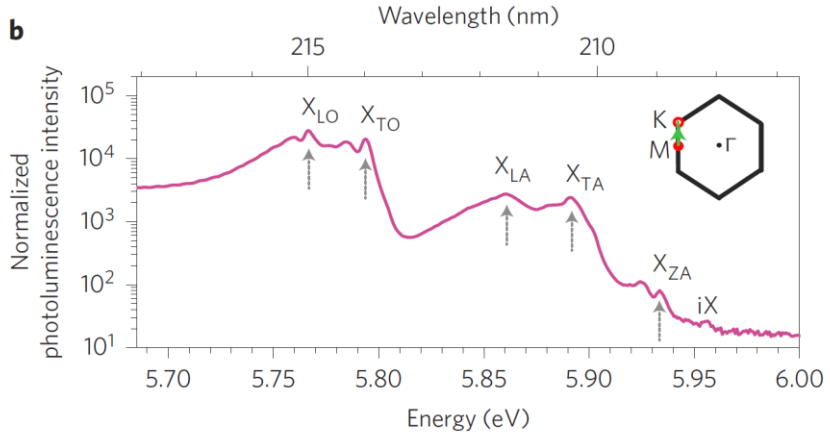


K. Ludwiczak et al. ACS Appl. Mater. Interfaces 13, 47904 (2021).

Direct or indirect bangap?





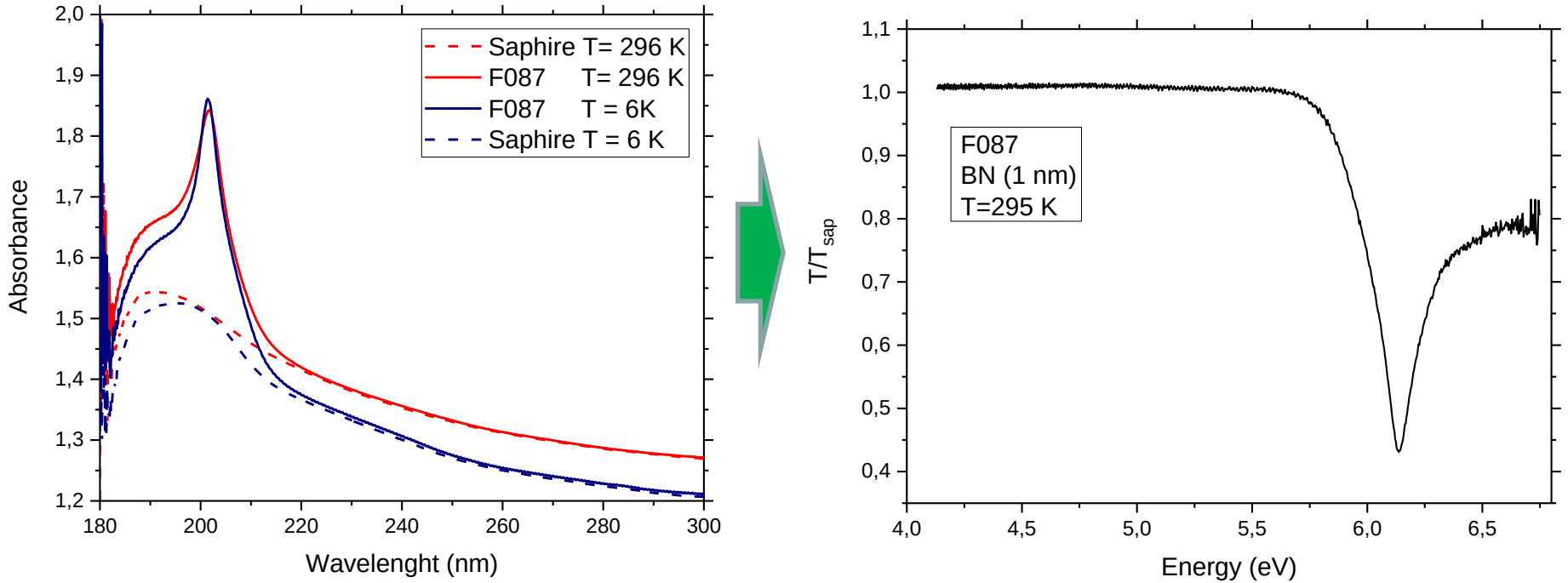


T. Q. P. Vuong et al. 2D Mater. **4** 021023 (2017)

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

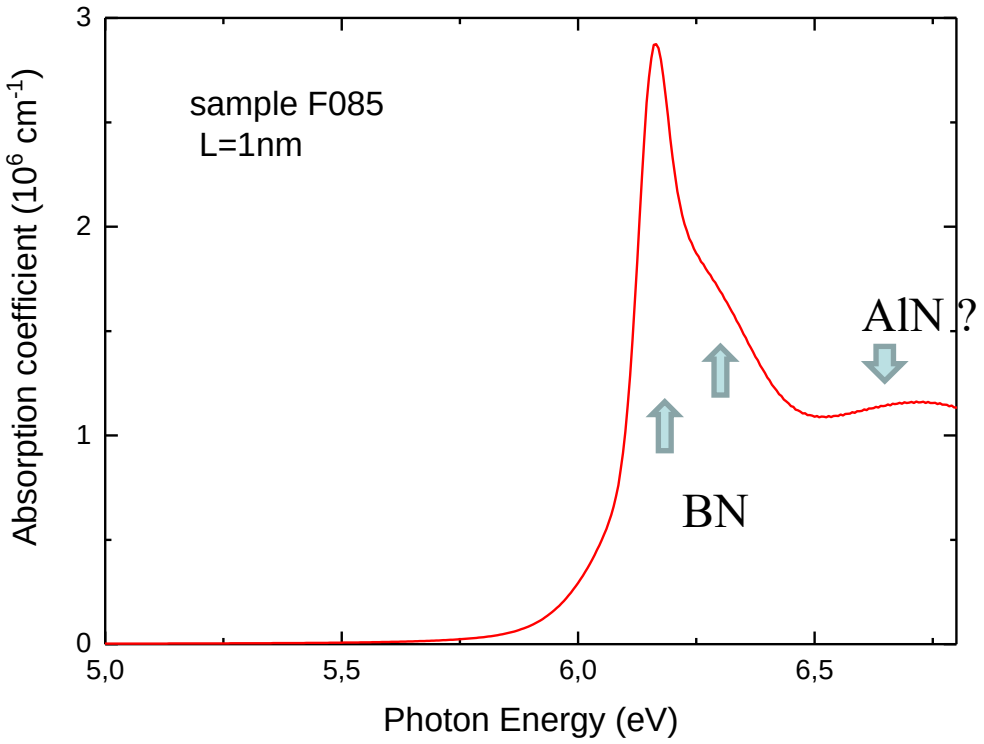
Optical absorption

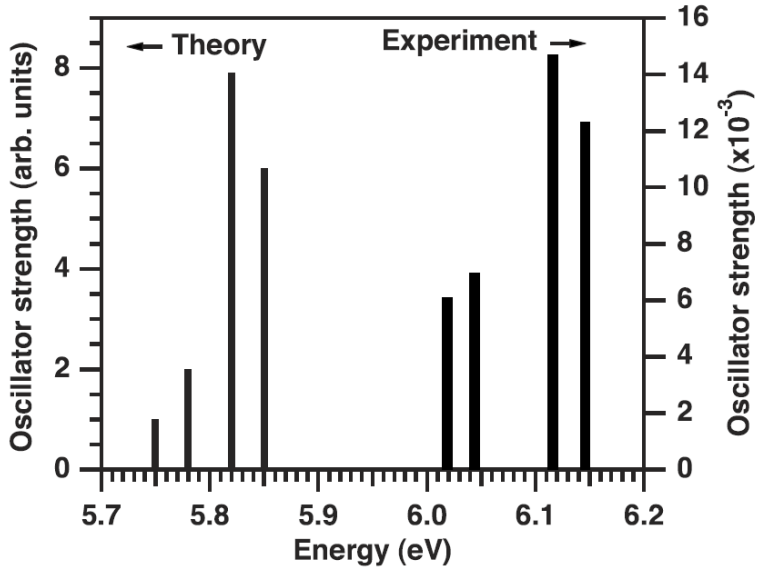
1nm thick BN layer (~4 ML)!!!



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

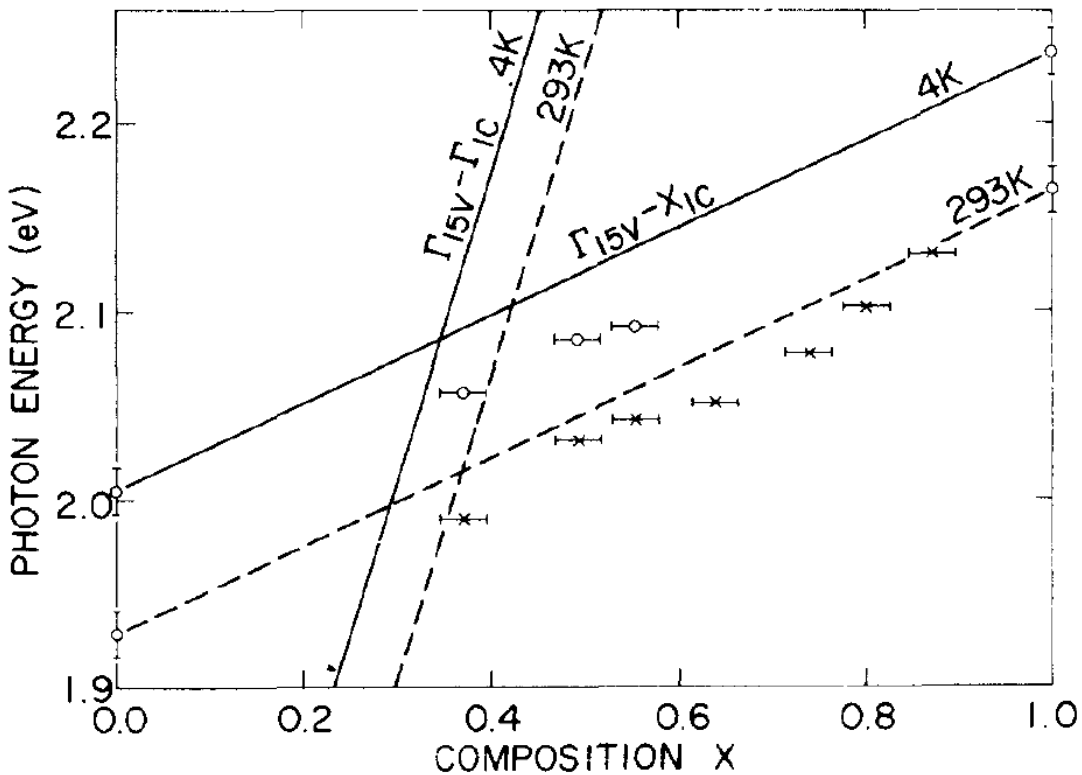
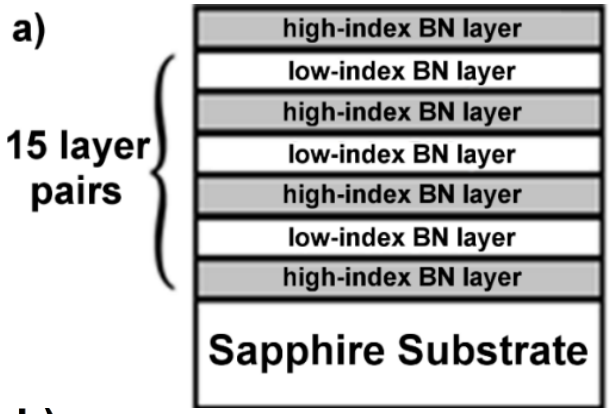


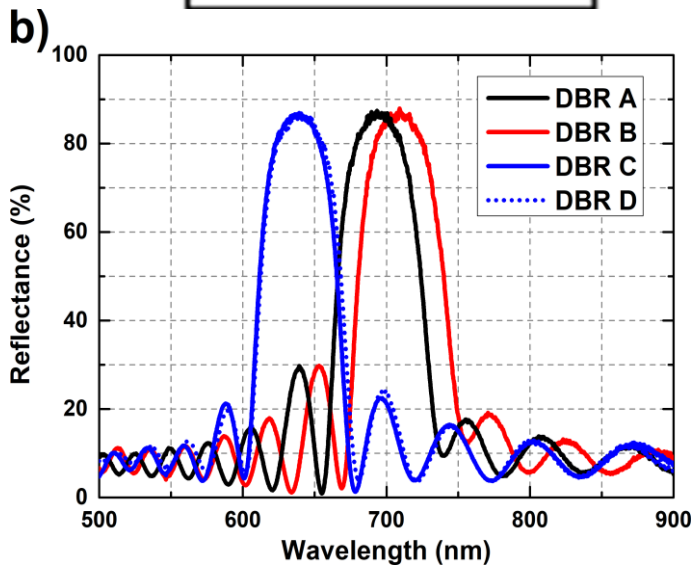
FIG. 9. Synopsis of luminescence peak positions for indirect-gap material at 4 K. (○) represents the bound-exciton peak and (×) the DA-pair peak position. The position of the DA-pair

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

MOVPE-grown BN@UW

Bragg reflectors…

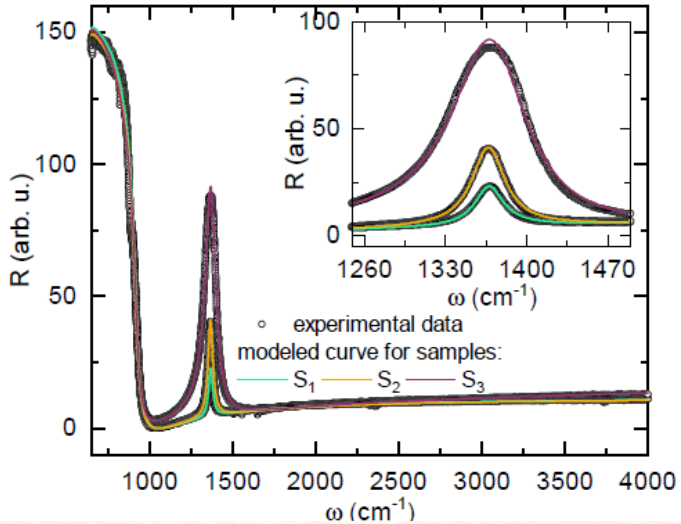




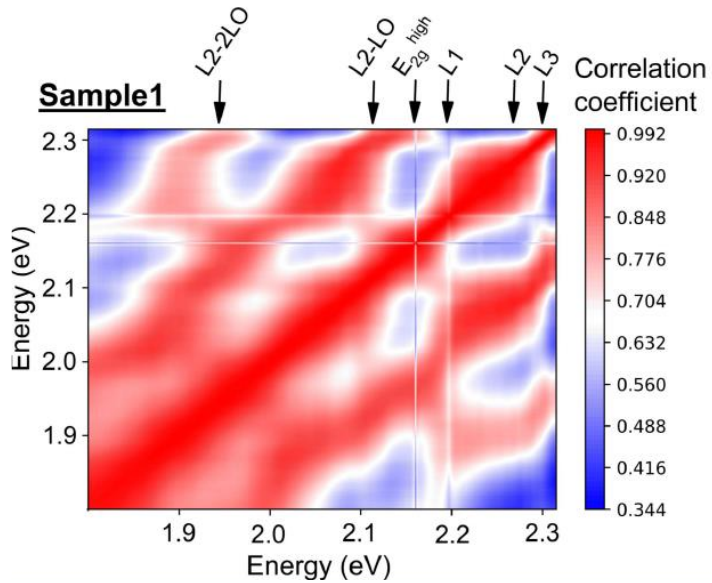
A. Ciesielski

Giant phonon anomaly in BN epitaxial layers

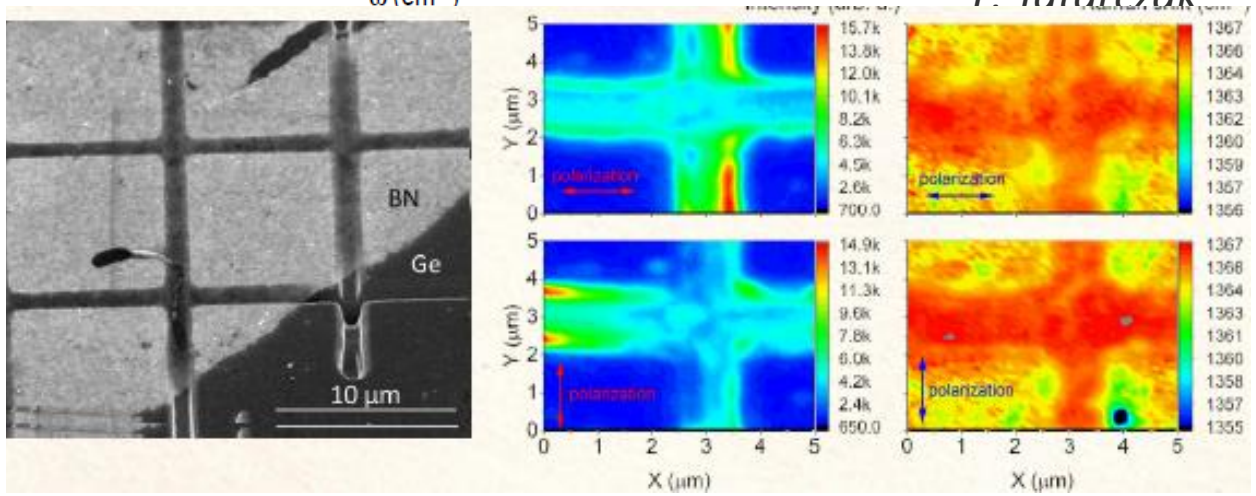
J. Iwański



SPE in epitaxial BN layers



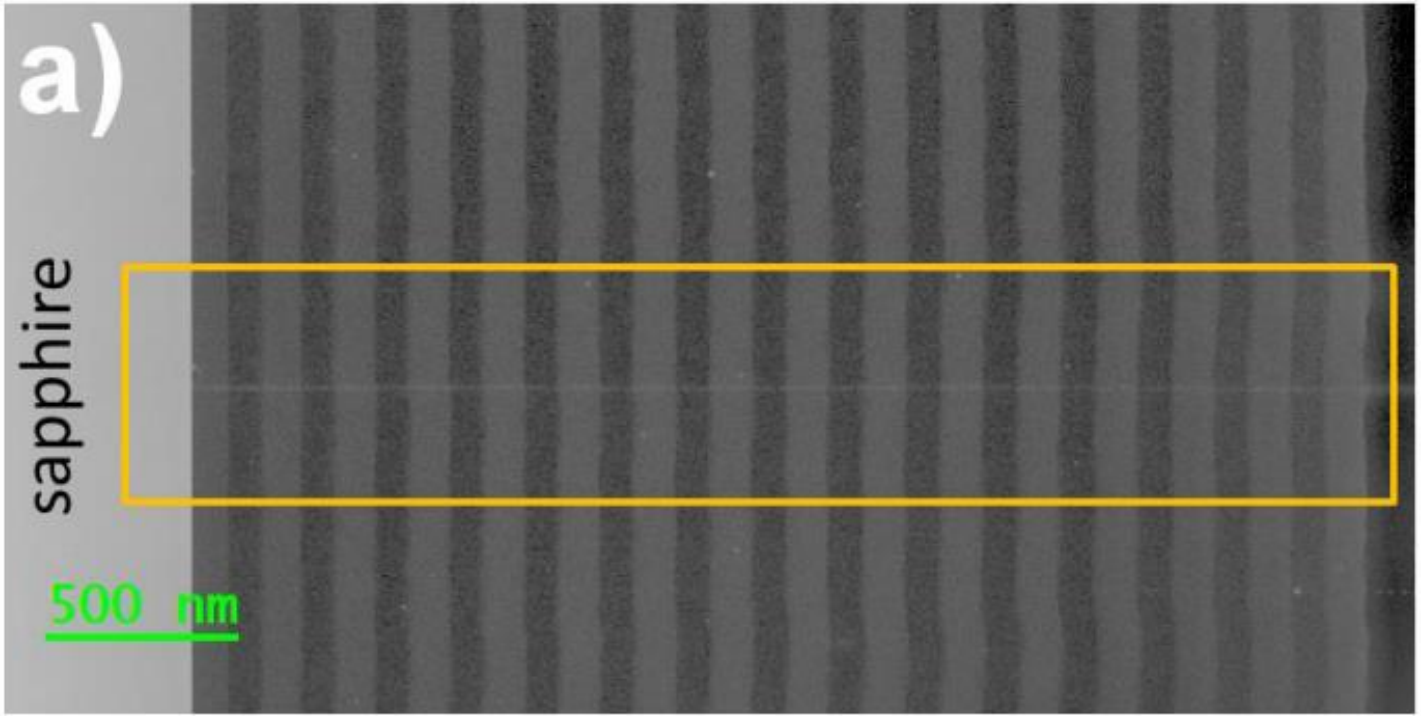
P. Tatarczak



Fabrication of hexagonal boron nitride membranes on germanium

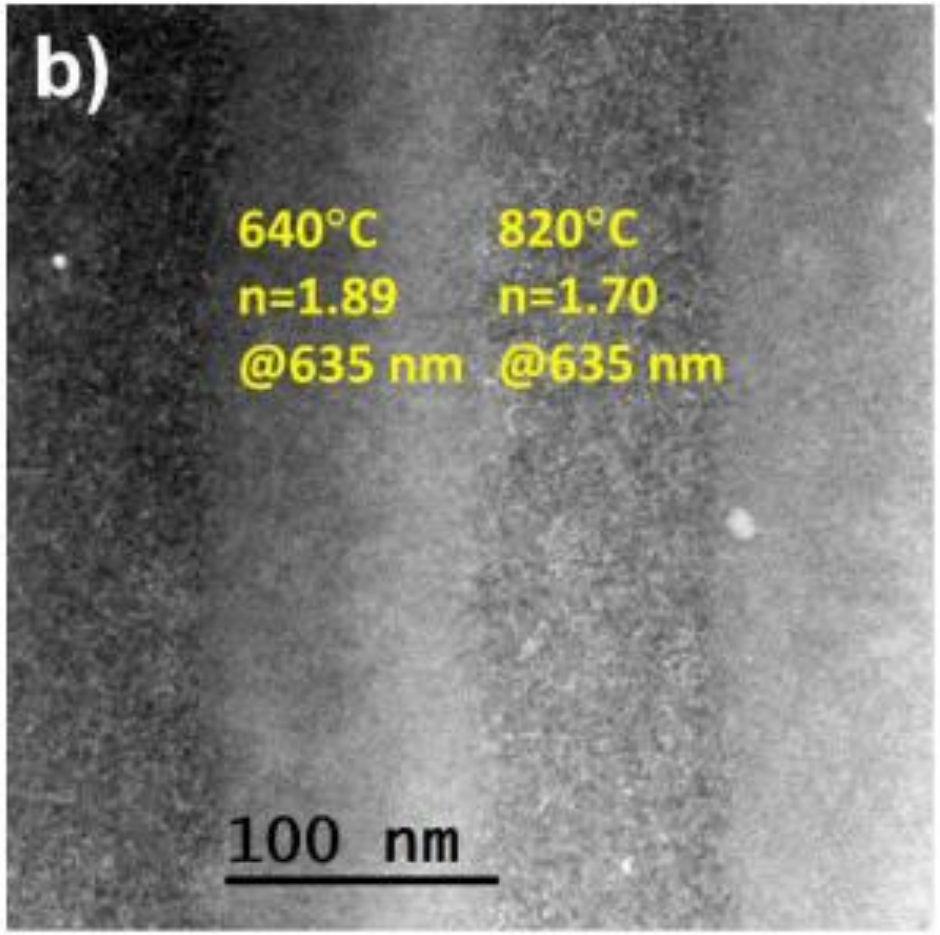
J. Rogoża

Distributed Bragg Reflector (DBR)



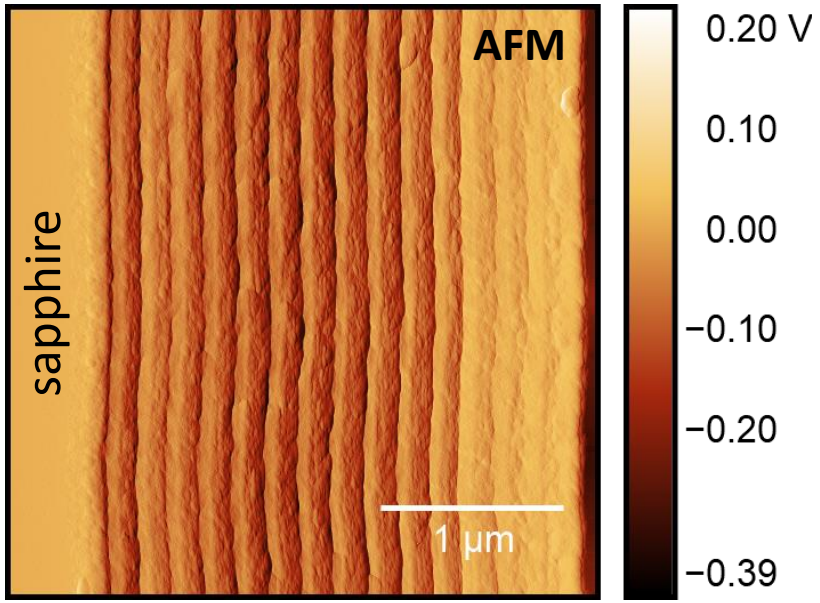
Cross-sectional STEM

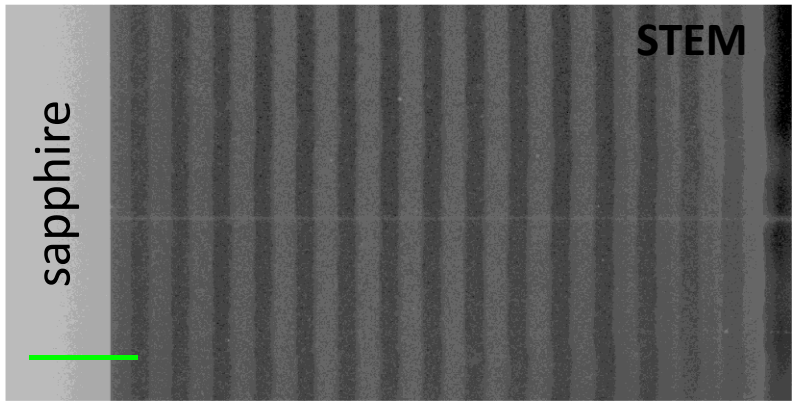
J. Turczyński, S. Kret IFPAN

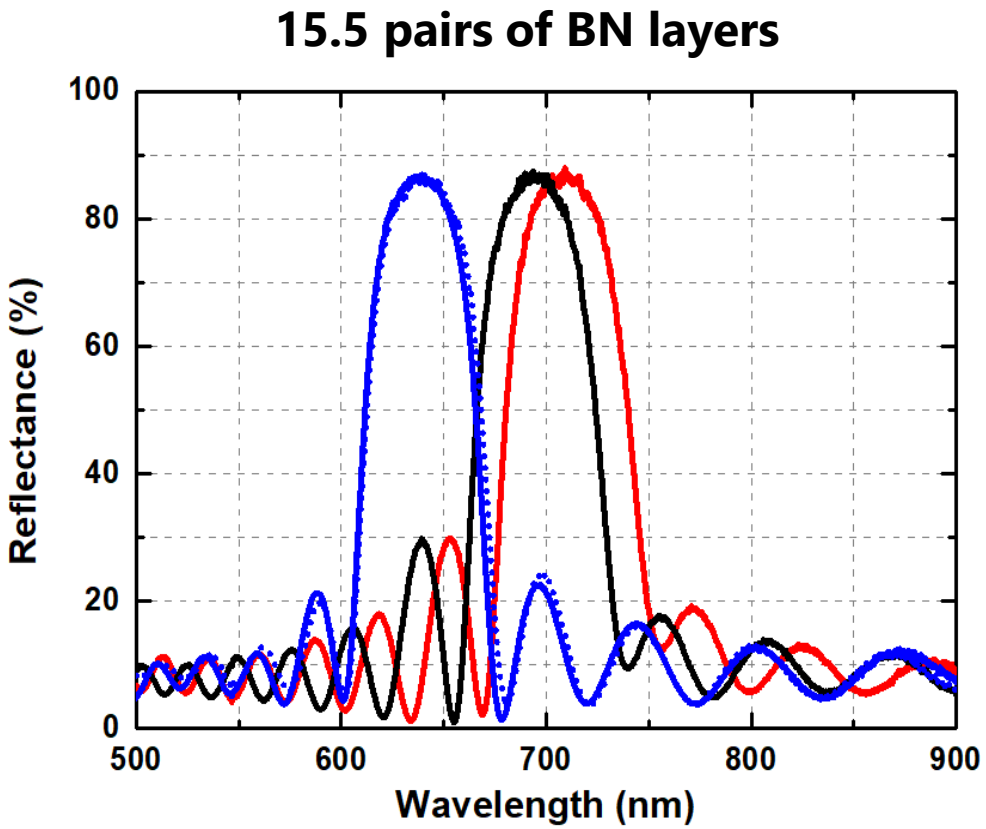


A. Ciesielski et al. arXiv:2206.02168 (2022)

All-BN Distributed Bragg Reflectors Fabricated in a Single MOCVD Process

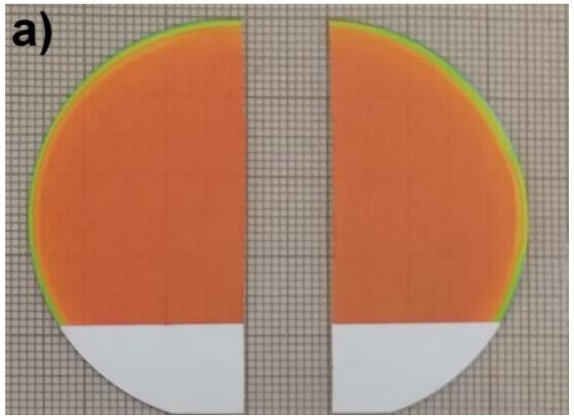


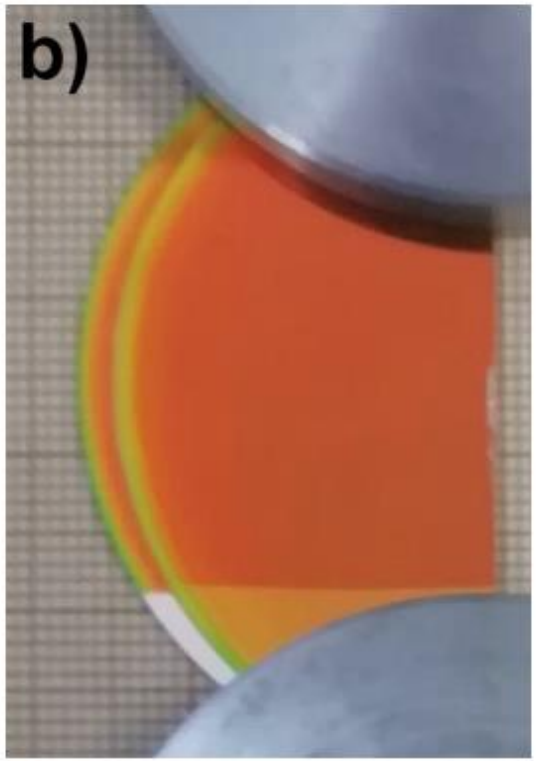


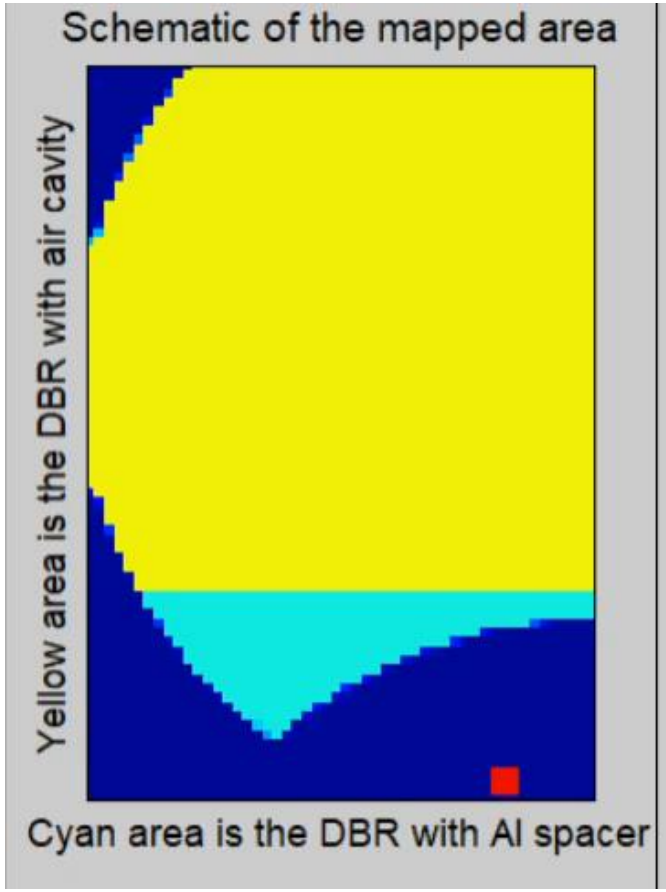


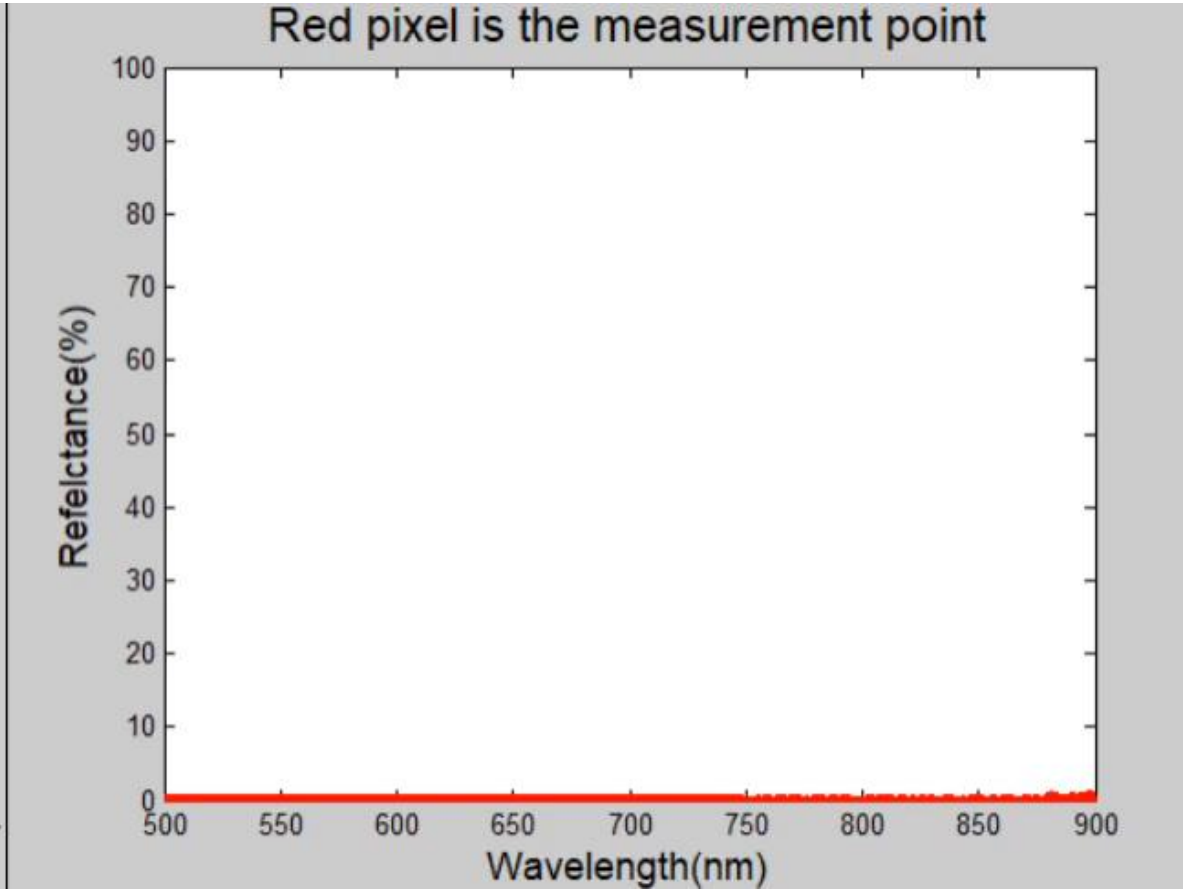
A. Ciesielski et al. arXiv:2206.02168 (2022)

Air-filled cavity



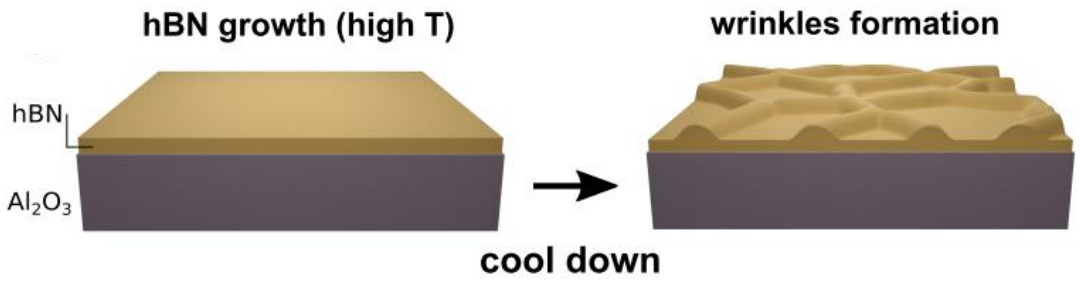






hBN nanostructures

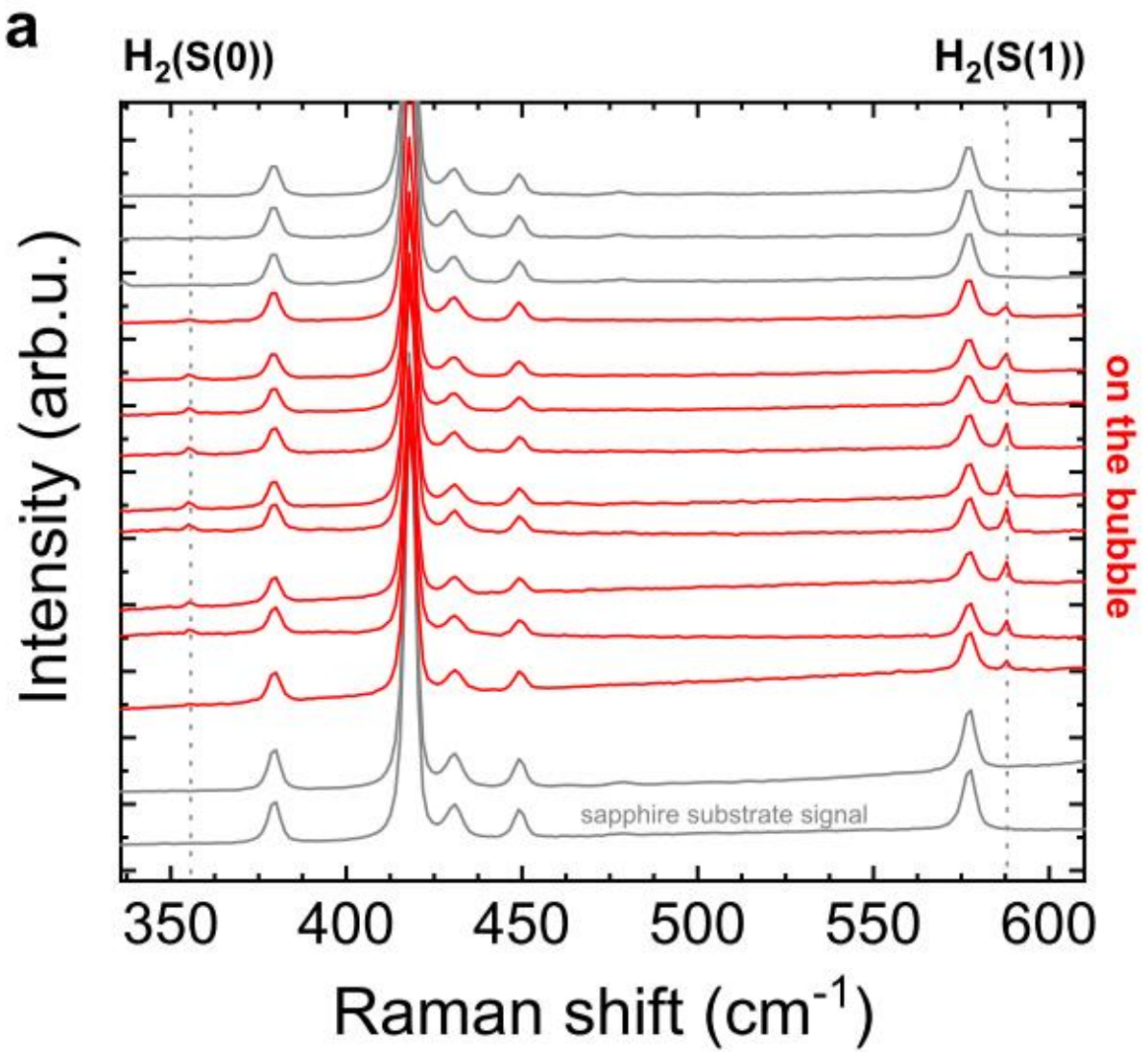
Bubble formation / Bubble deformation

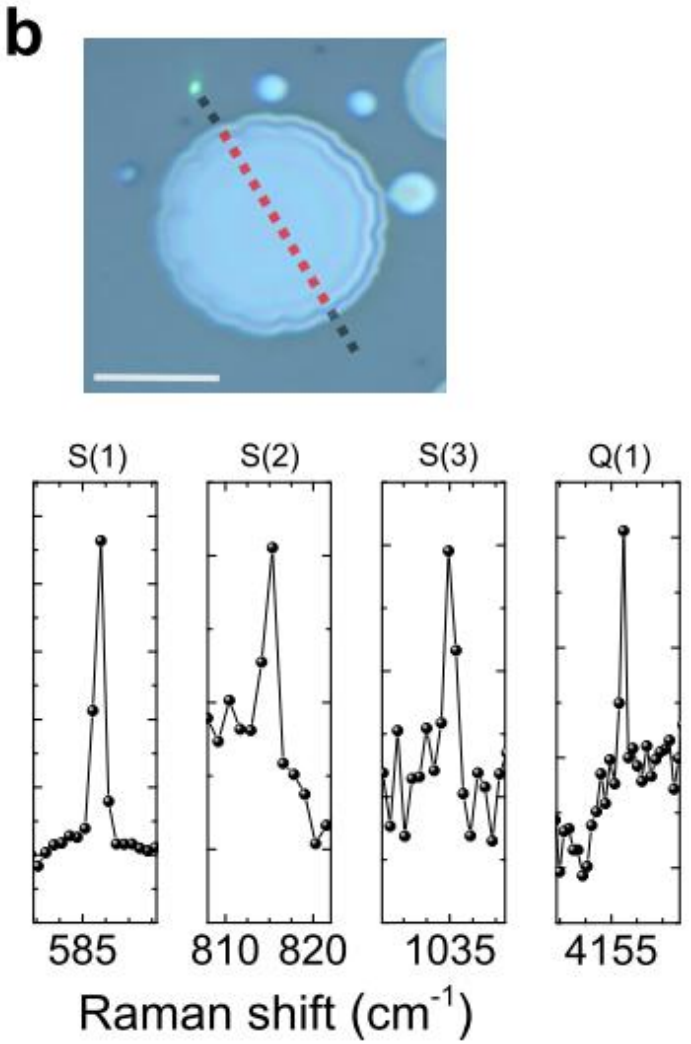


Scanning electron microscope video:

J. Binder et al. *Nano Letters* 23, 1267–1272 (2023)

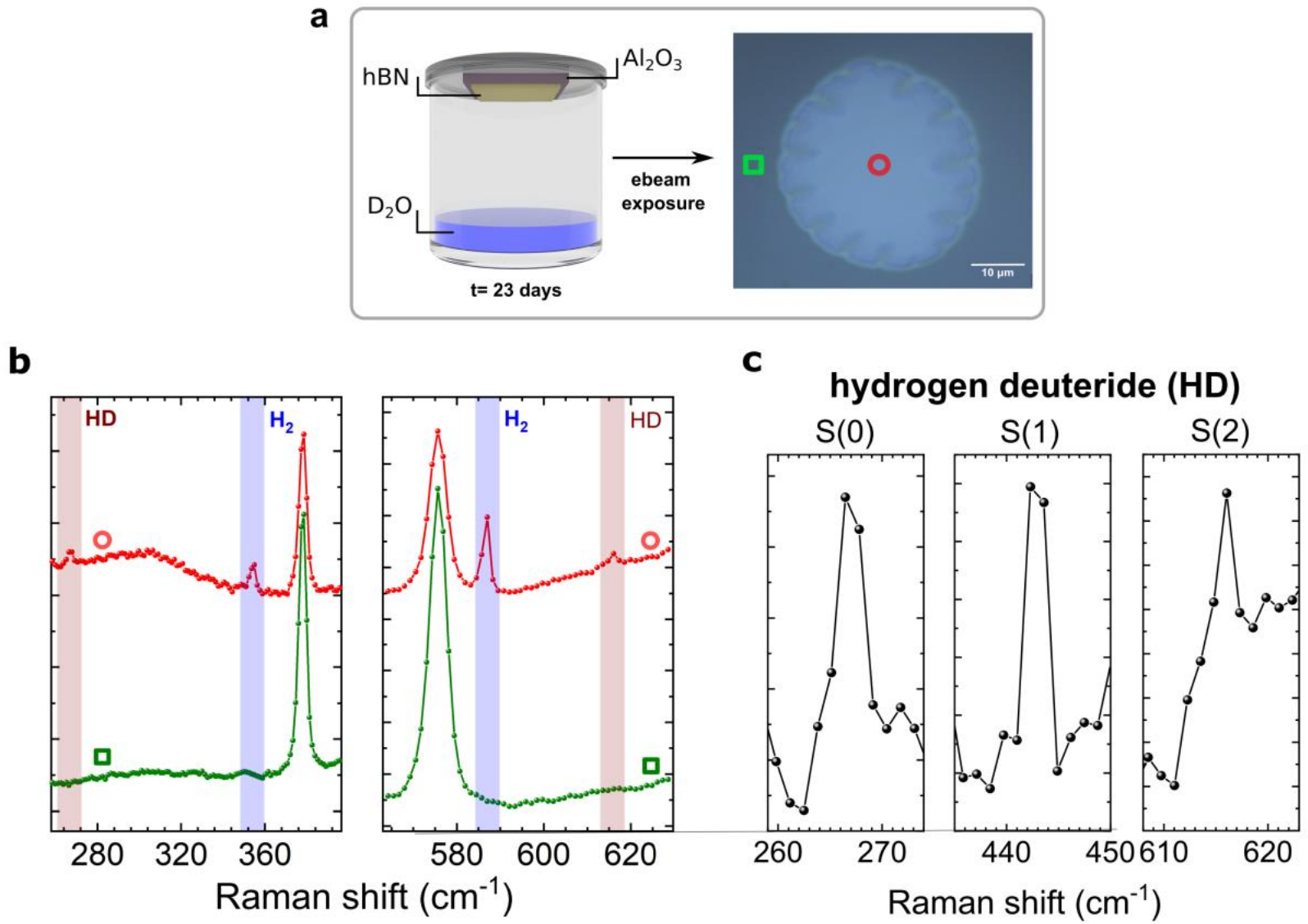
Hydrogen-filled bubbles (Raman of H_2)



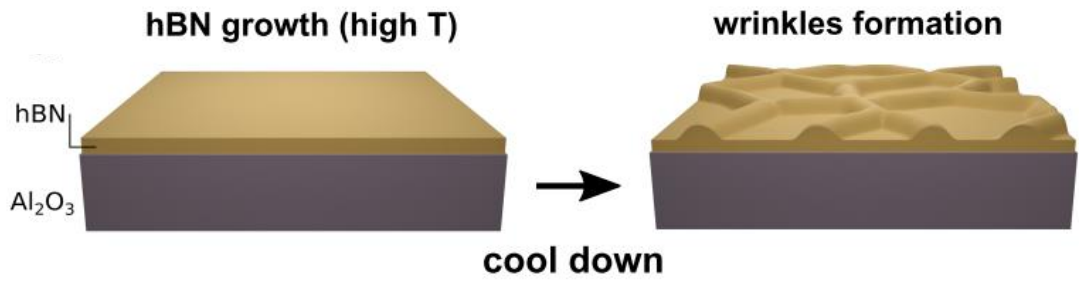


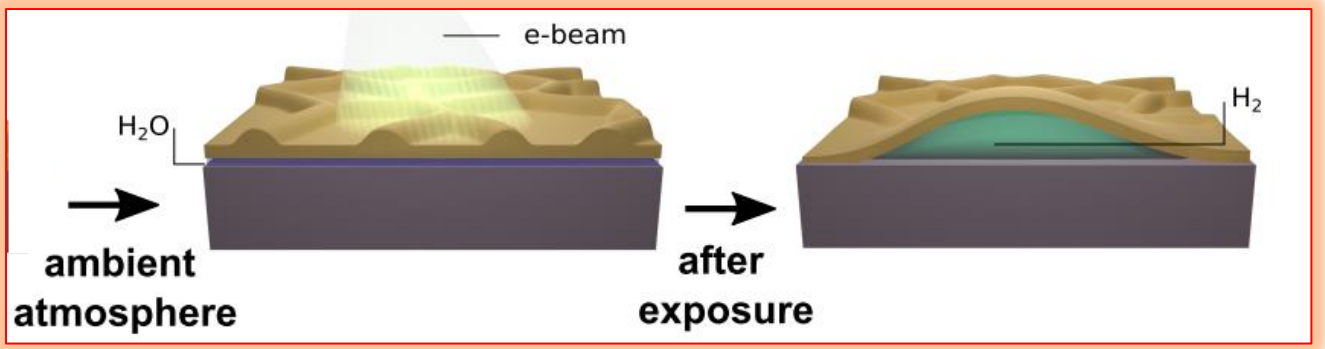
J. Binder et al. *Nano Letters* 23, 1267–1272 (2023)

Heavy water / intercalation / radiolysis

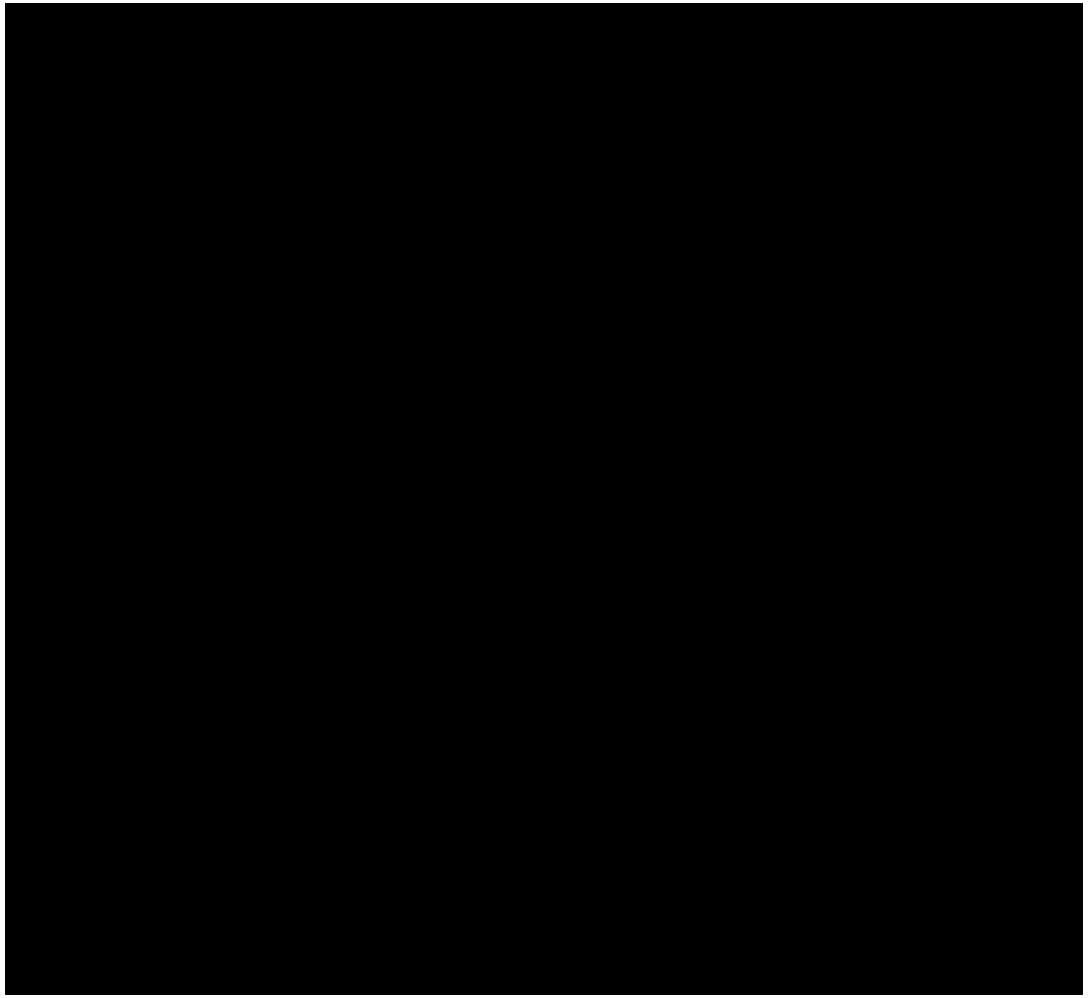


Bubble formation / Bubble deformation



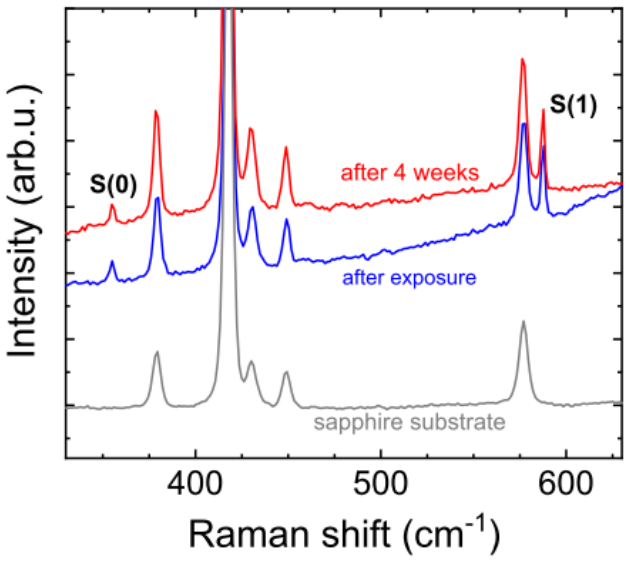


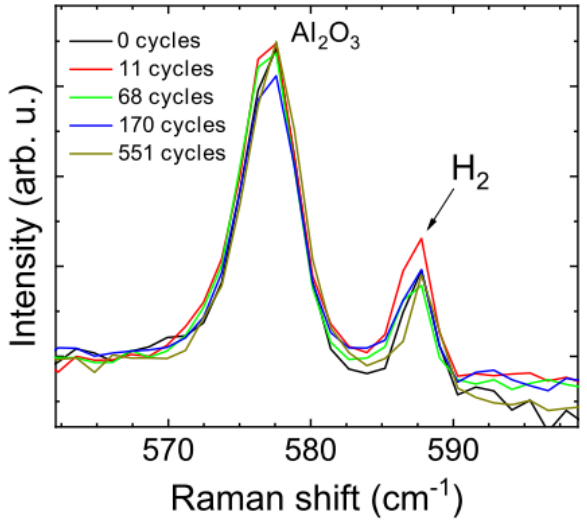
Scanning electron microscope video:

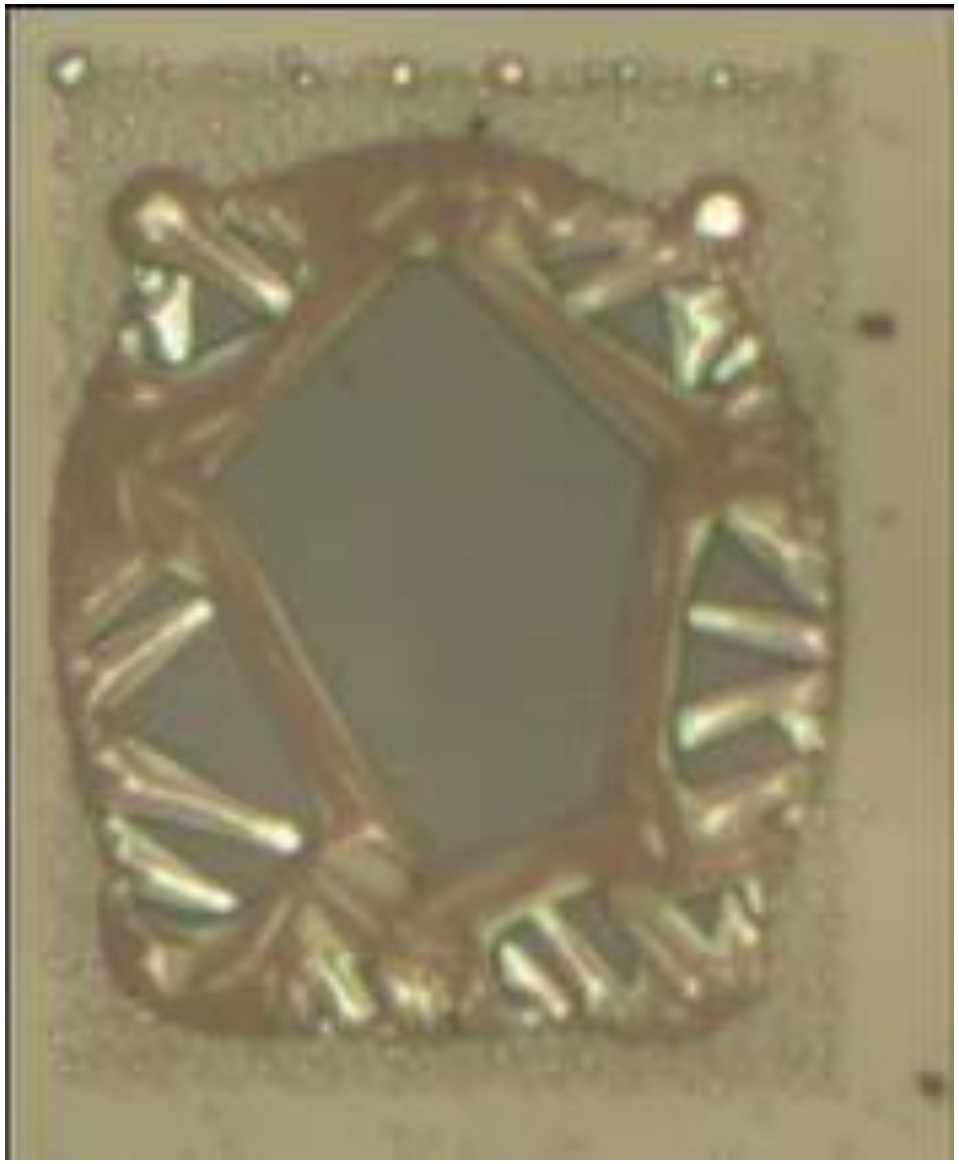


J. Binder et al. *Nano Letters* 23, 1267–1272 (2023)

H2 – long term stability







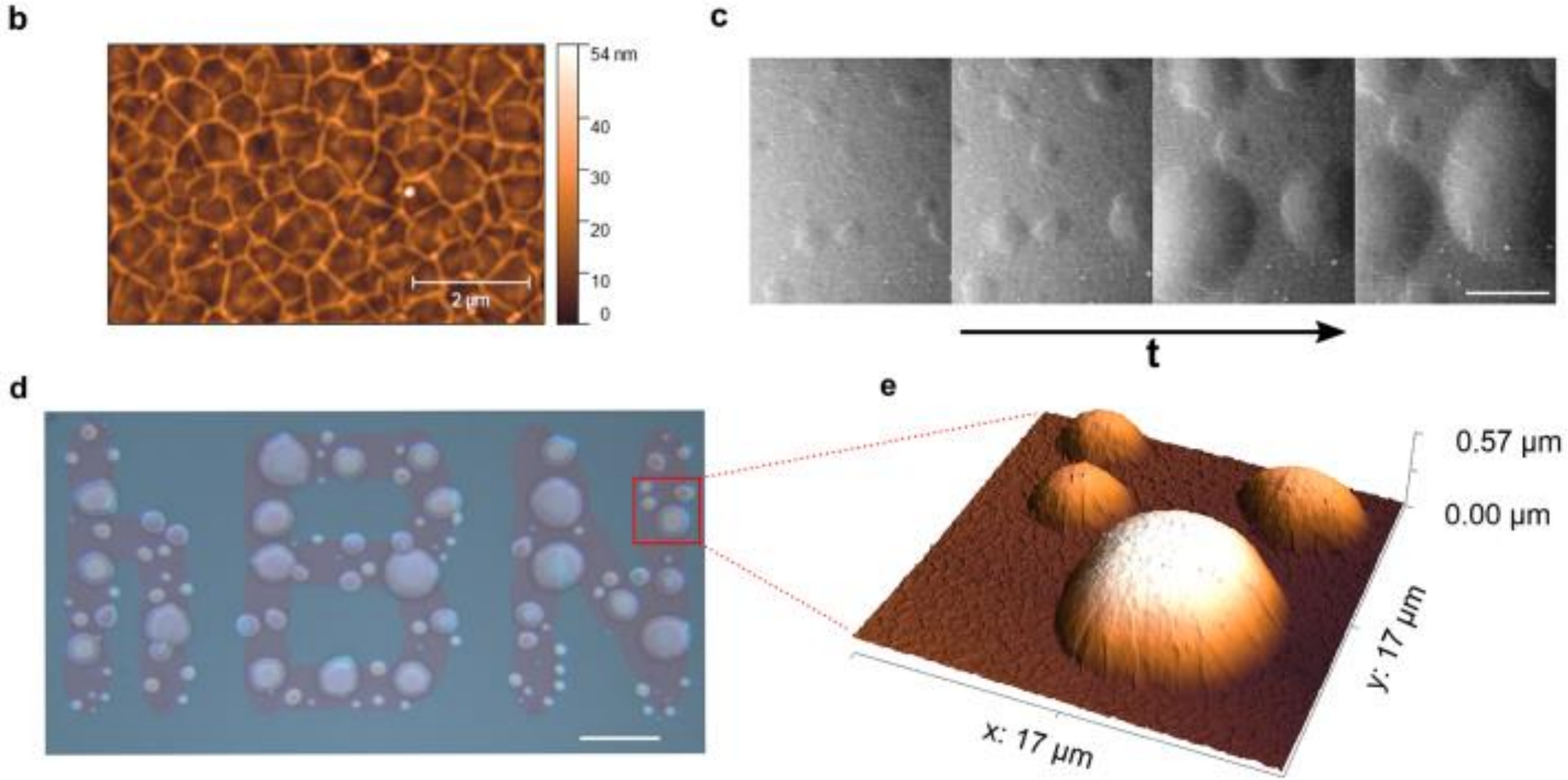
Optical microscope video:

Pressure cycle (0.1 -0.4 bar)

Bubble size: 150 µm x 200 µm

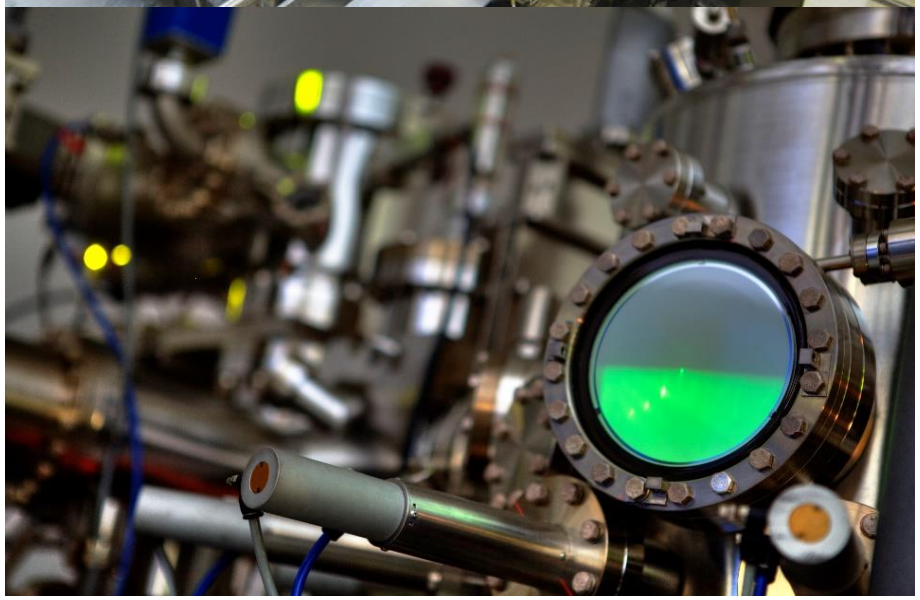
hBN thickness: ~40 nm

AFM / ebeam lithography bubbles



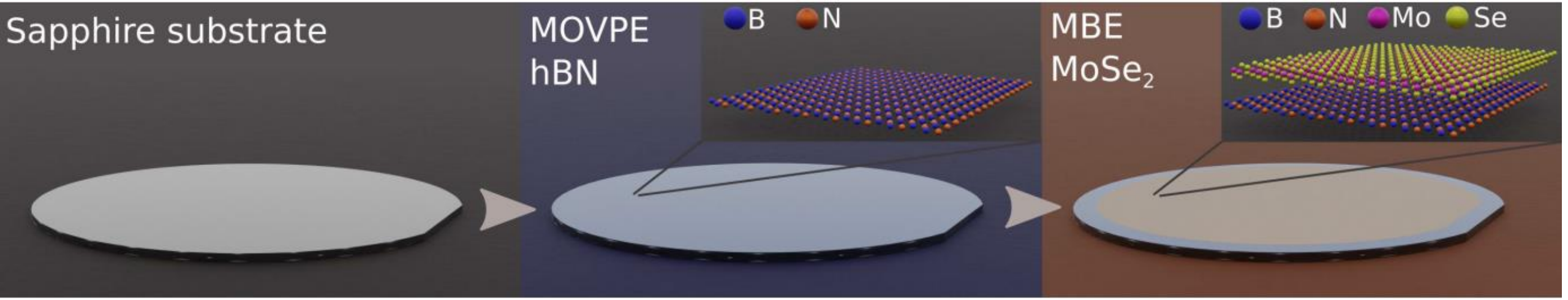
J. Binder et al. *Nano Letters* 23, 1267–1272 (2023)

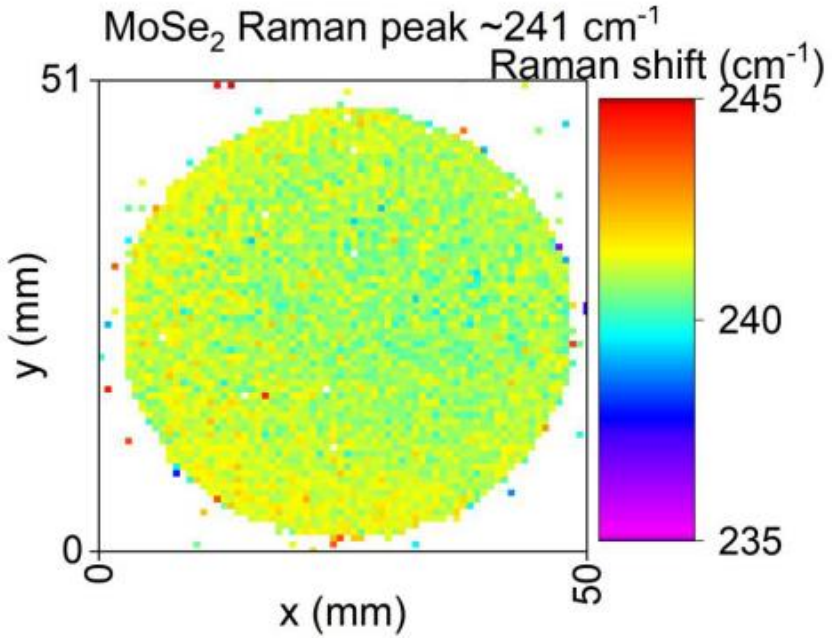
Collaboration with MBE group

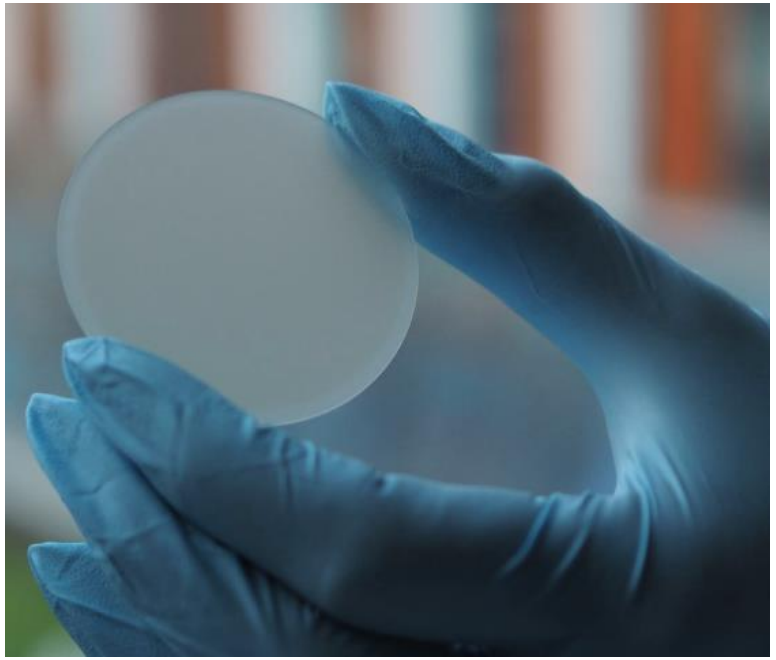


Prof. Wojciech Pacuski and students ☺
Faculty of Physics University of Warsaw

MOVPE BN as substrate for TMD growth

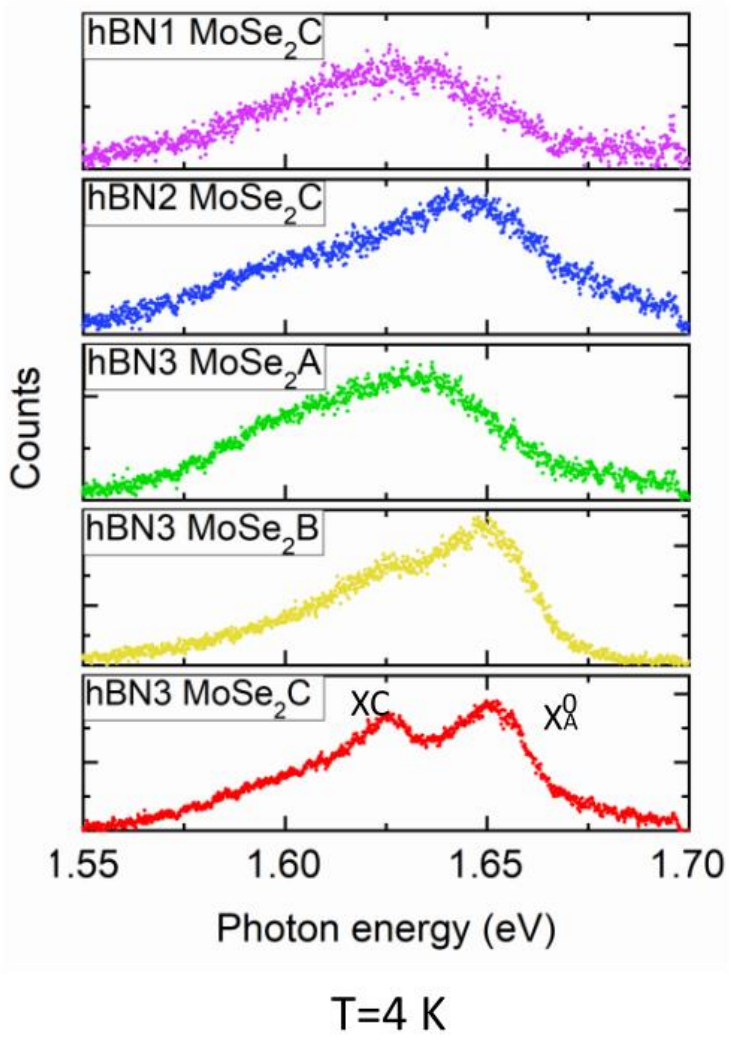


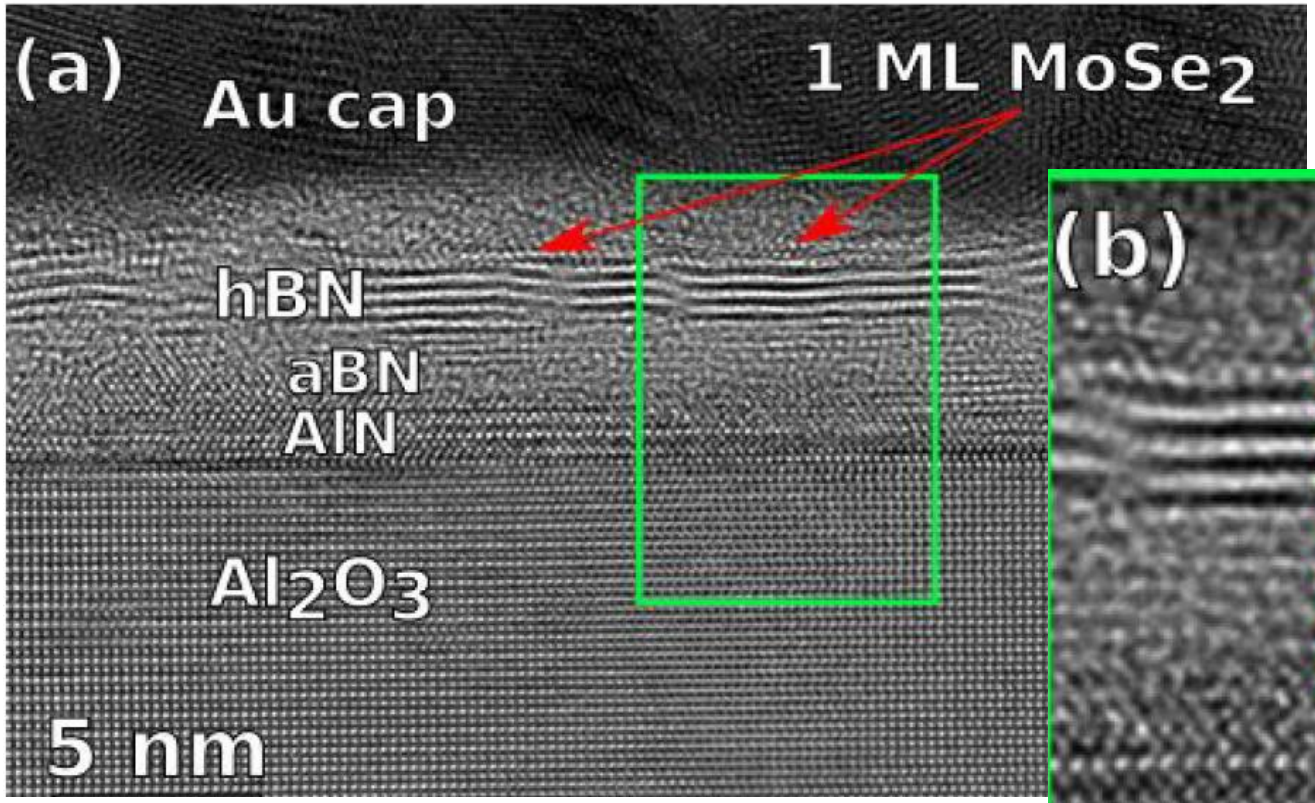


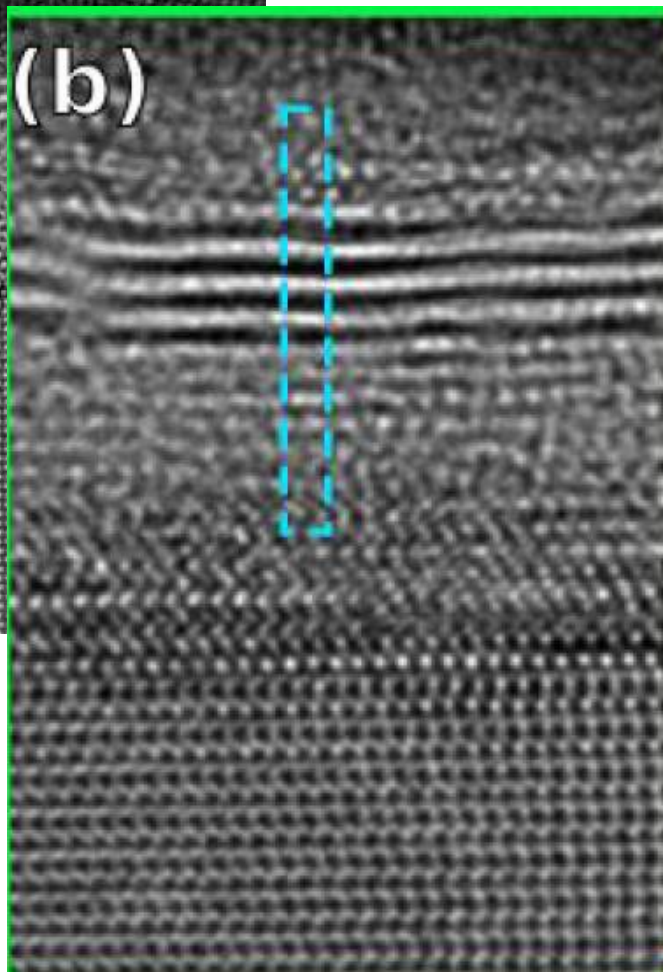


K. Ludwiczak et al. ACS Applied Materials & Interfaces 13, 47904 (2021)

MOVPE BN as substrate for TMD growth





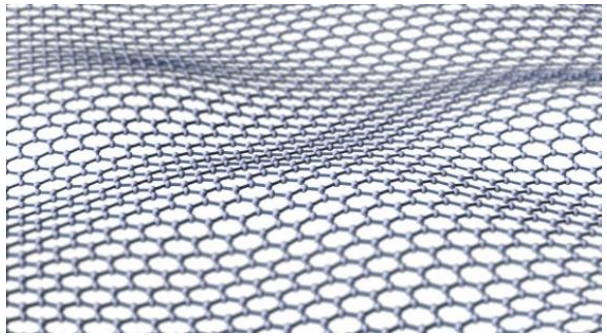


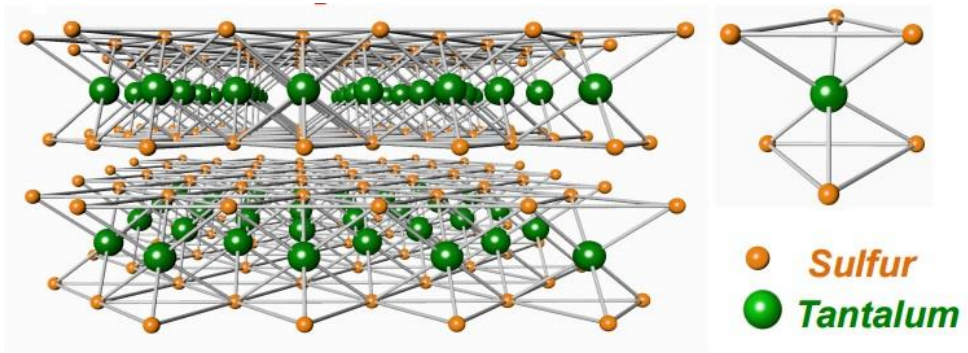
TEM:
B. Kurowska, J. Turczyński, S. Kret IFPAN

K. Ludwiczak et al. ACS Applied Materials & Interfaces 13, 47904 (2021)

Graphene and other 2D materials?

Graphene + **TaS_2 = ?**



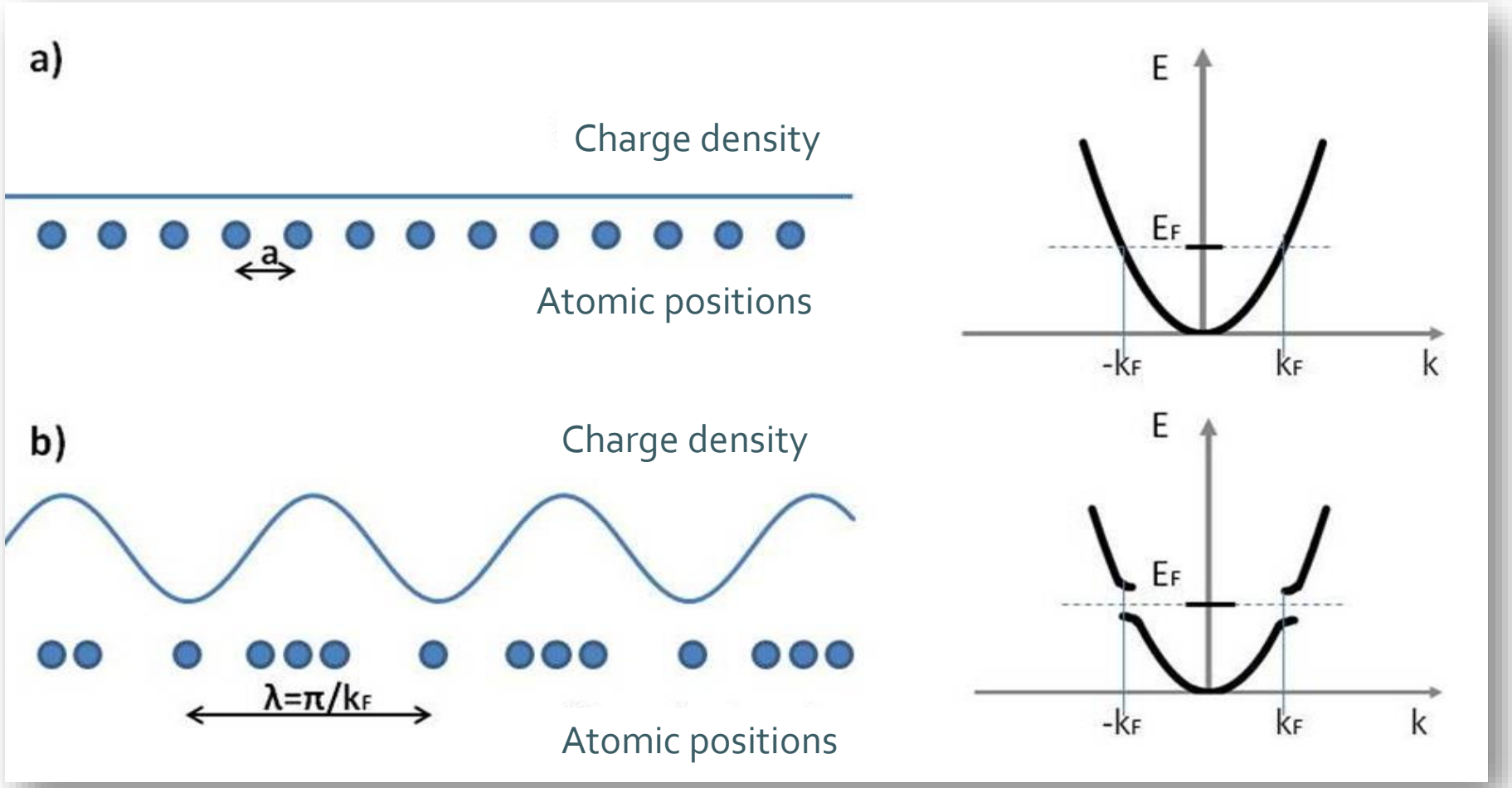


- High carriers mobility
- High spin-orbit coupling (spin-orbit splitting 100 meV)

➢2D hybrid structures

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

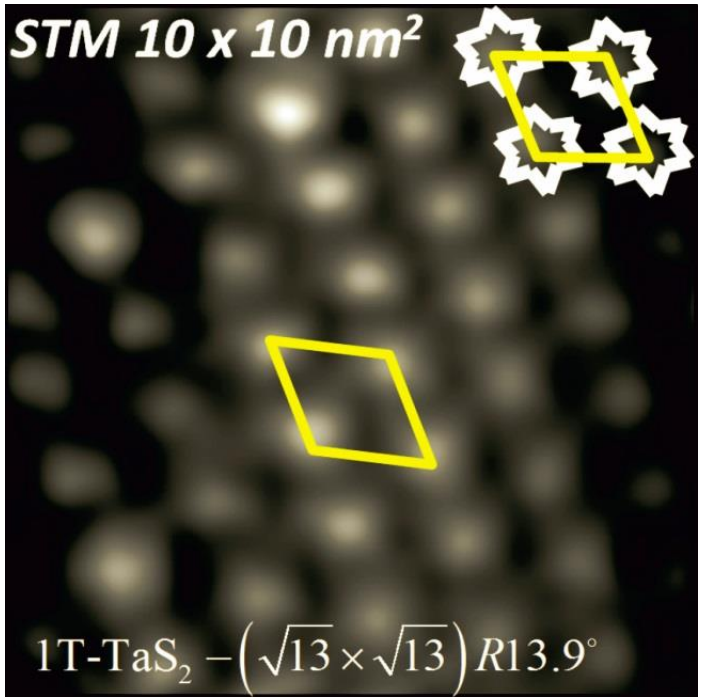
Charge density waves

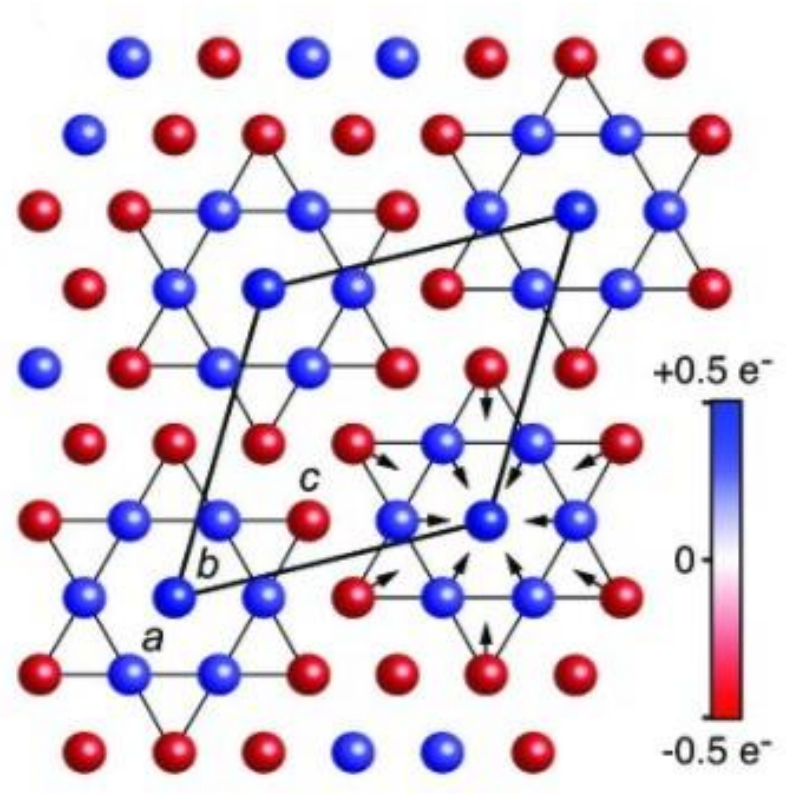


Thorne. Charge-density-wave conductors. *Physics Today, 49:42, May 1996.*

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)



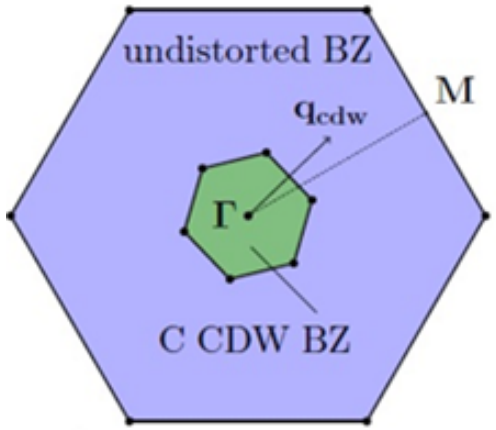


Phys. Rev. Lett. **105**, 187401 (2010)

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

Raman scattering from TaS_2



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

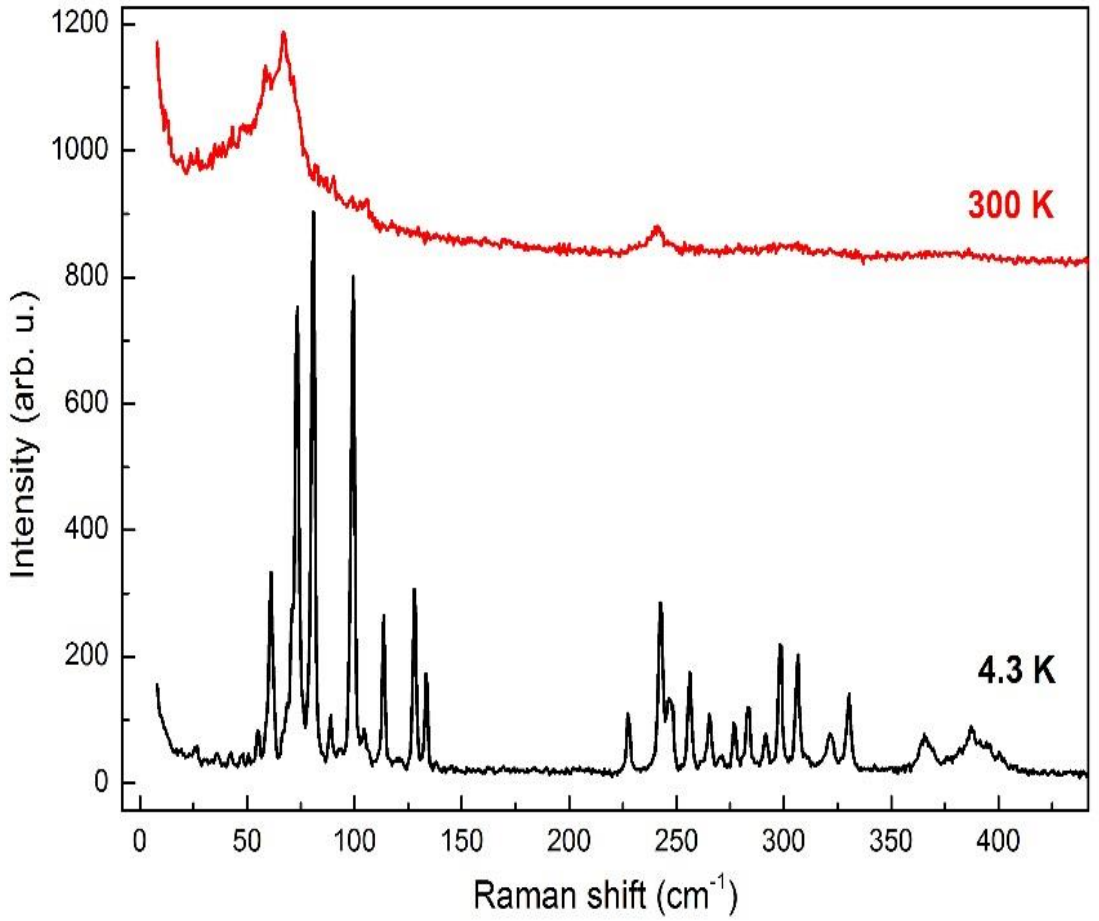
UNIT CELL

3 atoms → **39 atoms**

9 phonon modes → **117 phonon modes**

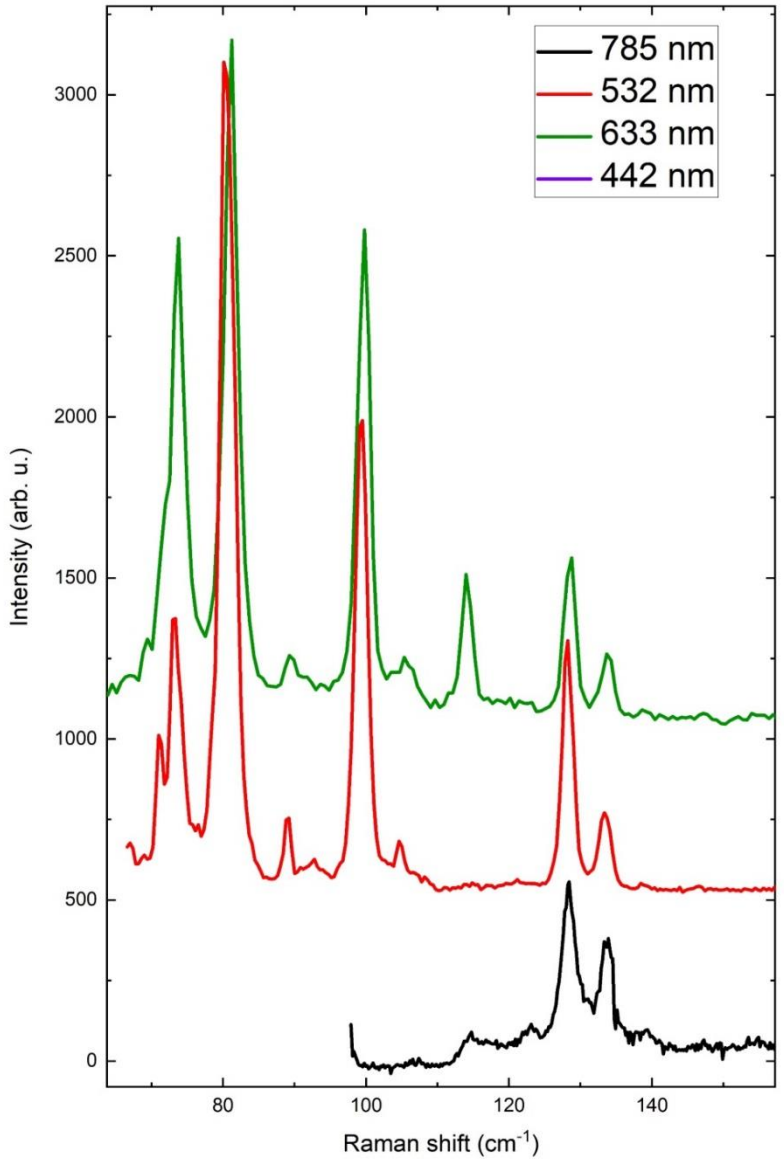
The first undistorted Brillouin zone 1T-TaS_2 (blue) and the first Brillouin zone in the CCDW phase (green).

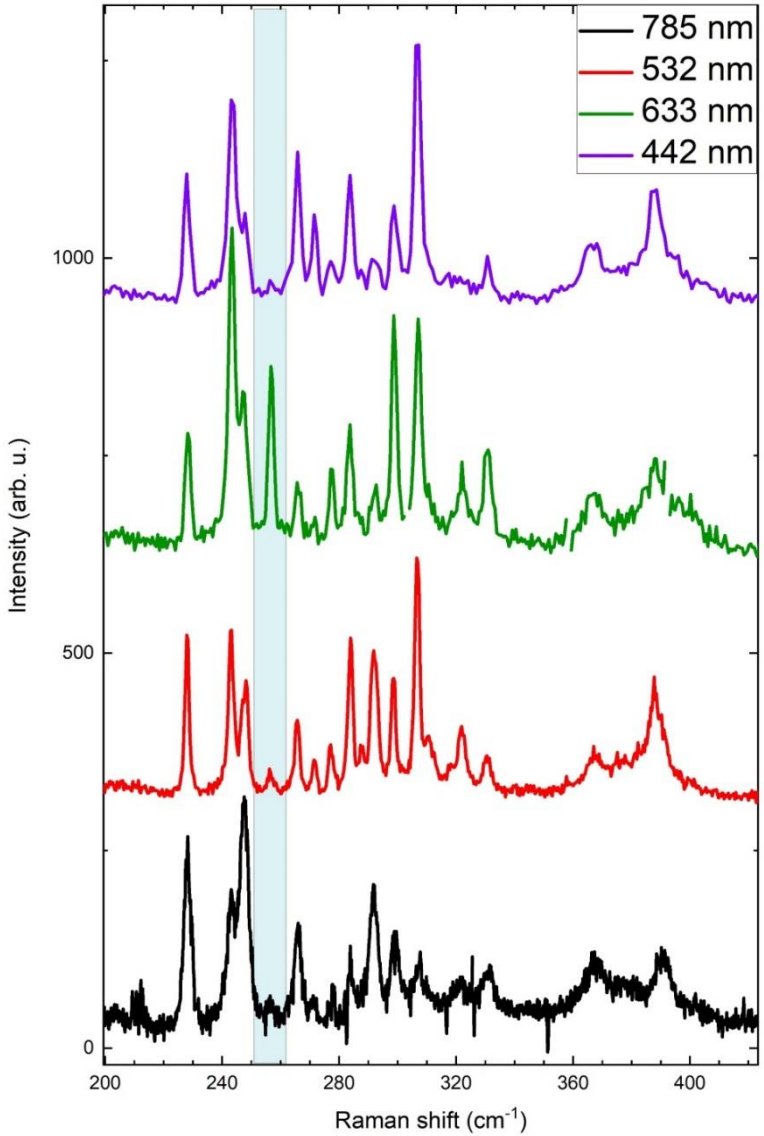
Raman scattering from TaS_2



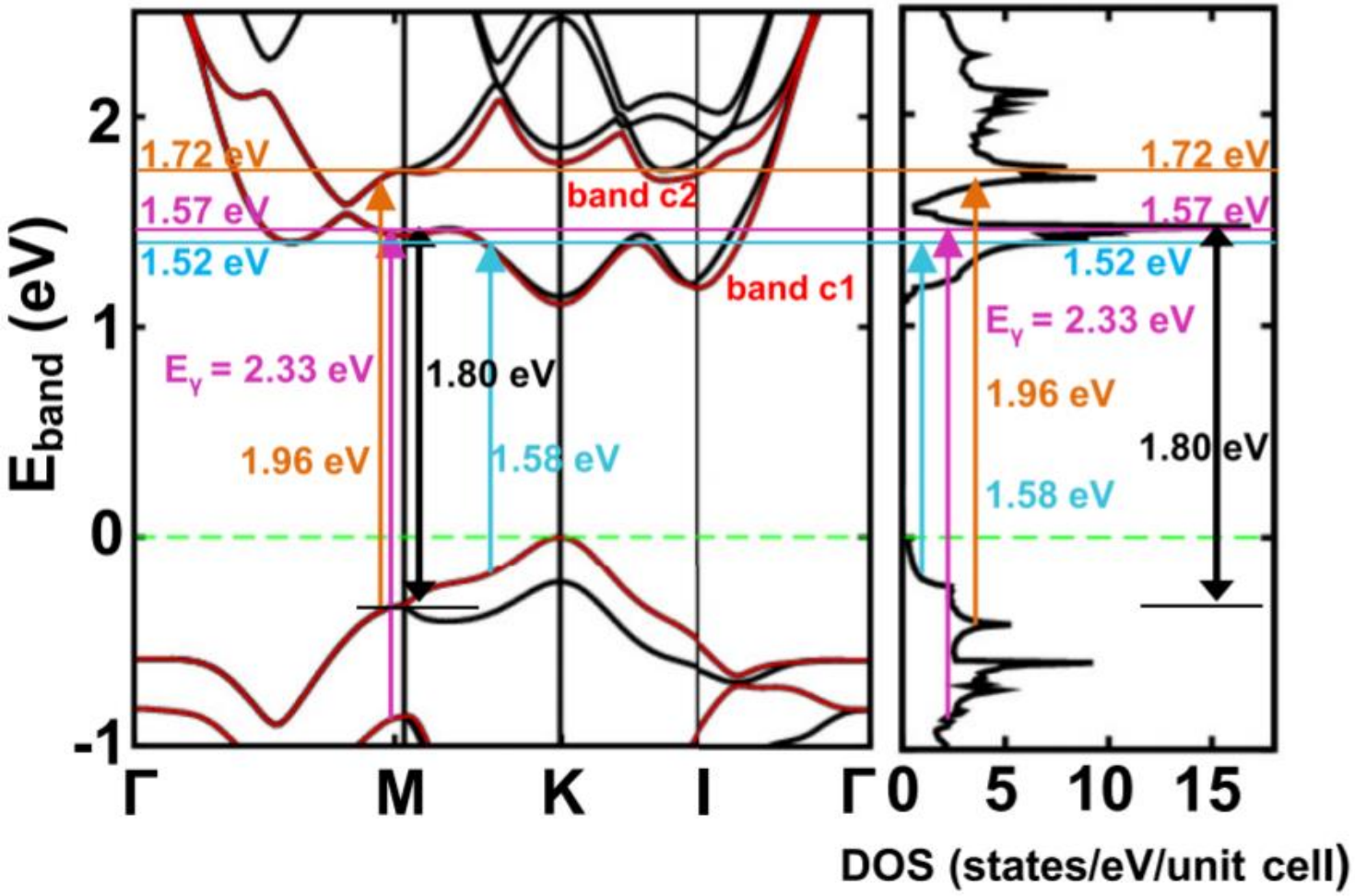
exc. 532 nm

Resonant effect





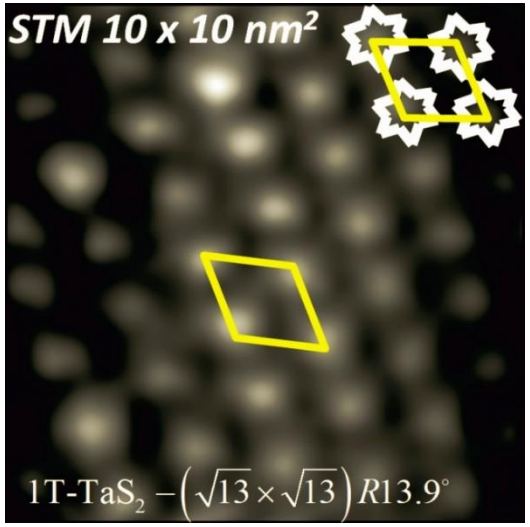
M. Furman et. al (2019)



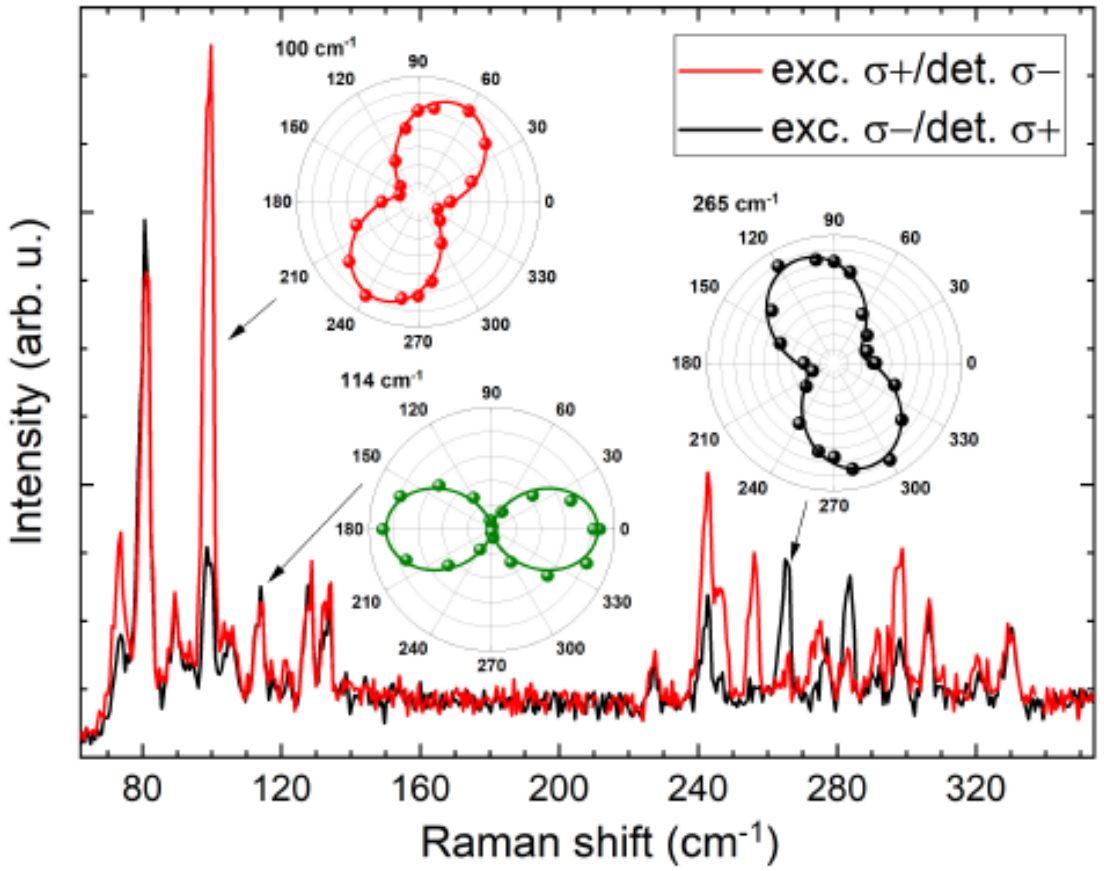
Huaihong Guo et al., Double resonance Raman modes in monolayer and few-layer $MoTe_2$, Physical Review B 91, 205415 (2015)

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!