Single photon emitters in sc-TMD (WSe_2) structures

(and in hexagonal boron nitride)

M. Koperski,[1,2] K. Nogajewski,[1] A. Arora,[1] V. Cherkez,[3] P. Mallet,[3] J.-Y. Veuillen,[3] J. Marcus,[3] P. Kossacki,[1,2] and M. Potemski[1]

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MOMB

LNCMI

http://lncmi.cnrs.fr/

- Development of high magnetic field installations & instrumentation
- In house research in high magnetic fields
- Give access to all qualified French and European high field users

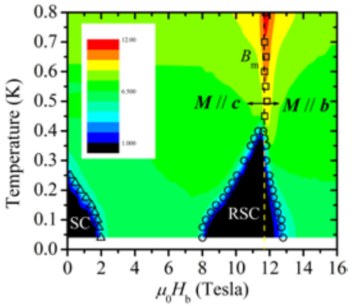
Grenoble; DC fields

37 T / 43 T in project

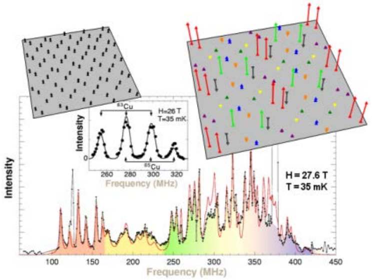
Toulouse; Pulsed fields

91 T 10 ms

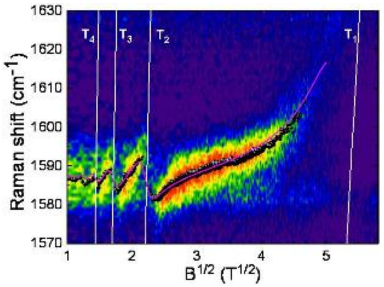
Research topics at LNCMI-Grenoble



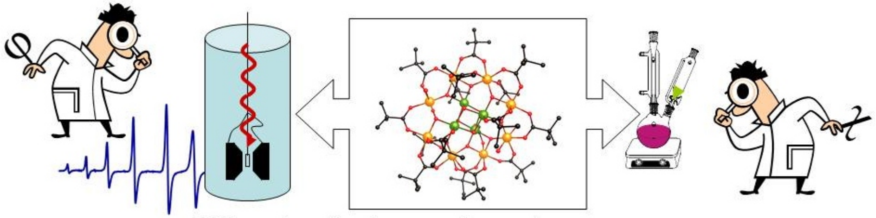
Correlated fermions,
superconductivity



Quantum magnetism



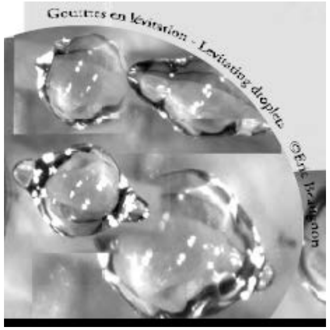
Semiconductors and nanophysics
atomically thin 2D systems (graphene, TMDs)
Dirac matter, topological insulators
quantum dots
optics and transport



Different methods, complementary concerns

Chemistry

Applied superconductivity



Magnetoscience levitation,
elaboration under magnetic field

Acknowledgements

+ research groups from

Warsaw
NEEL Grenoble

Manchester
Columbia
Geneva
Münster

Beyond graphene; other layered compounds, e.g., TM Dichalcogenides

Advances in Physics

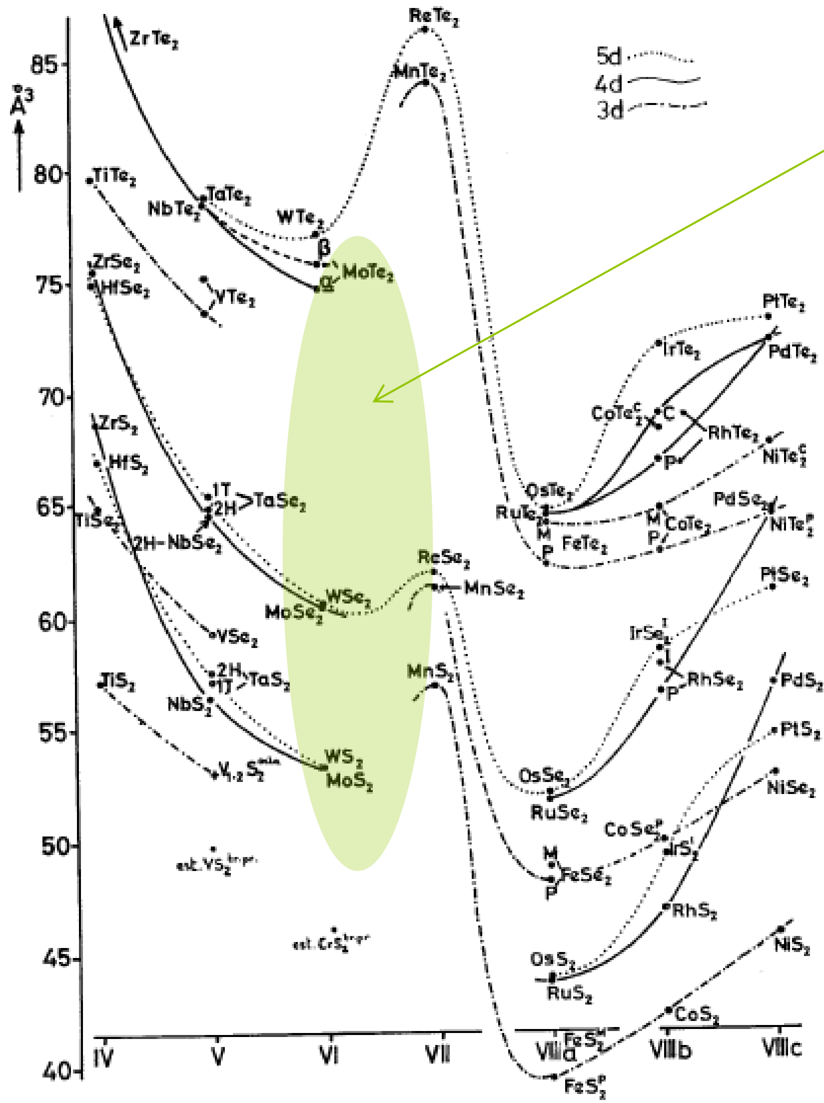
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tadp20

The transition metal dichalcogenides discussion and interpretation of the observed optical, electrical and structural properties

J.A. Wilson [a] & A.D. Yoffe [a]

[a] Cavendish Laboratory, Cambridge

Available online: 02 Jun 2006



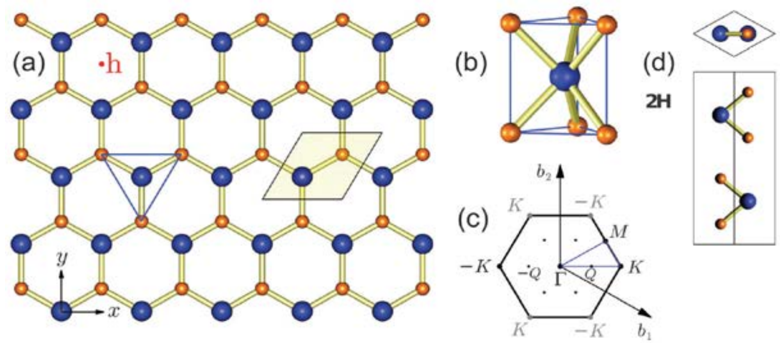
semiconductors

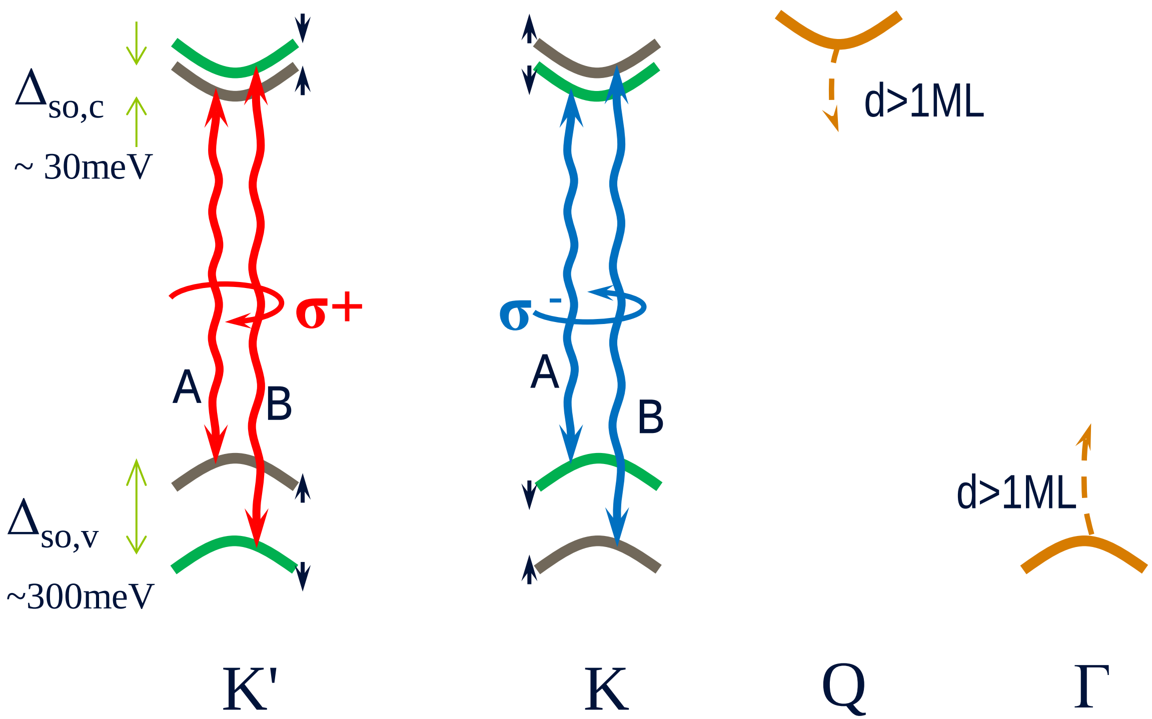
properties of mono layers ?

to be or not to be discovered ?

Atomically thin semiconducting transition metal dichalcogenides

WSe_2, $MoSe_2$, WS_2, MoS_2, $MoTe_2$, … (S-TMDs)





light emitting devices
(optically bright monolayers)
+
opto-valley-tronics
(robust valley pseudospin ?)

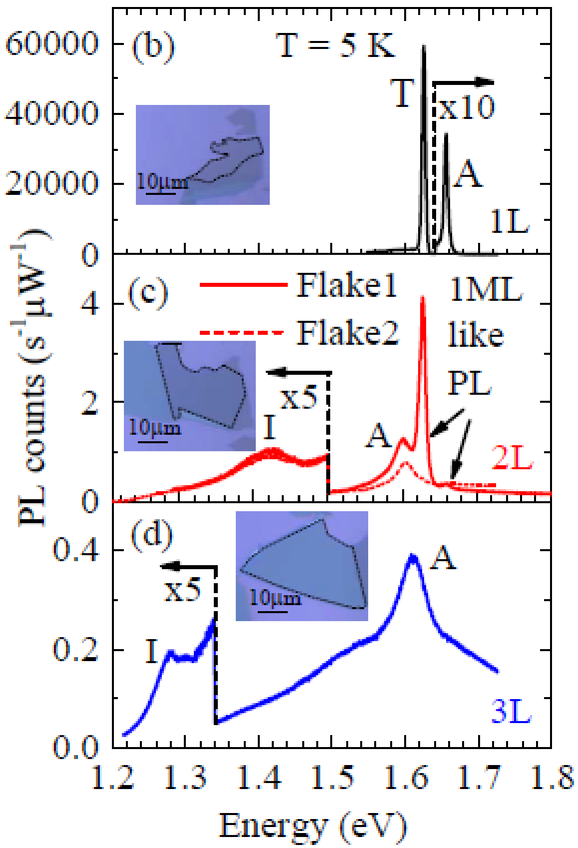
+
…., interesting physics

Direct gap monolayers and indirect gap N-layers

A. Splendiani *et al.*, Nano Lett. 10, 1271 (2010).
F.K. Mak *et al.*, Phys. Rev. Lett. 105, 136805, (2010).

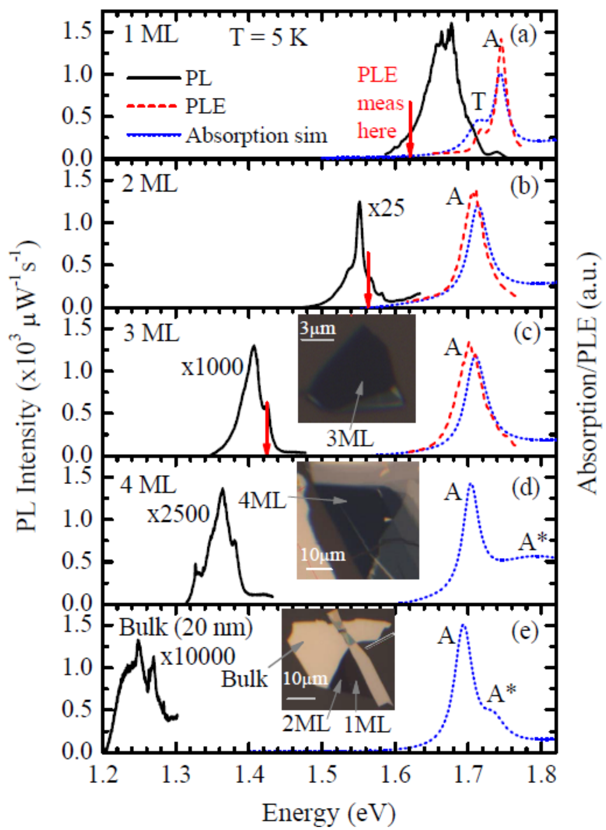
LNCMI:

$MoSe_2$



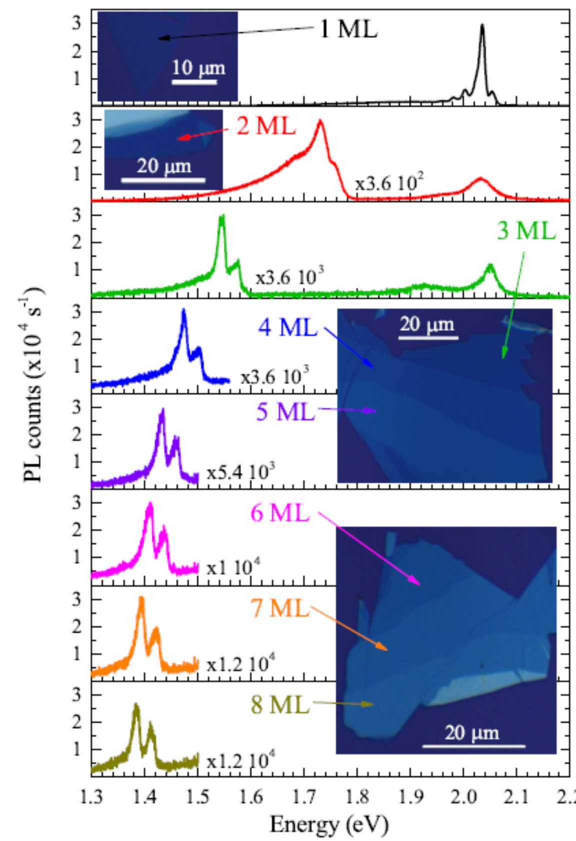
A. Arora *et al.*
Nanoscale (2015)

WSe_2



A. Arora *et al.*
Nanoscale (2015)

WS_2



M. Molas *et al.*
to be published

LNCMI

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2D materials → (1D), 0D materials ?

quantum (single electron) electronics **(graphene)** √

nano – lithography (~100 nm) + electrostatic gating

quantum (single photon) photonics

single objects (~10nm) ?

making profit of imperfections !

2D → 0D (past experience)

semiconductor heterojunctions/quantum wells :

interface imperfections (lattice mismatch)

VOLUME 66, NUMBER 23 PHYSICAL REVIEW LETTERS 10 JUNE 1991

Effect of Strain on Surface Morphology in Highly Strained InGaAs Films

C. W. Snyder, B. G. Orr, D. Kessler, and L. M. Sander

H. M. Randall Laboratory, University of Michigan, Ann Arbor, Michigan 48109-1120

(Received 28 February 1991)

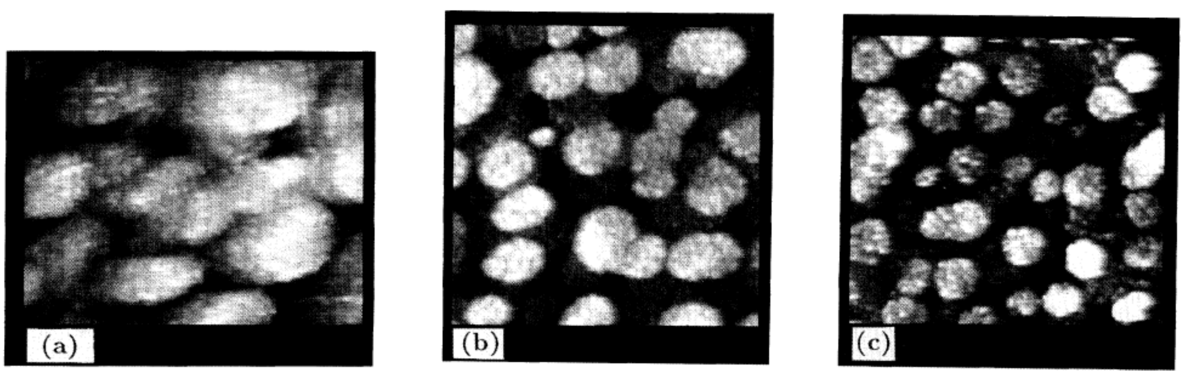

FIG. 3. STM images of $In_xGa_{1-x}As$ on GaAs(100). (a) 14 ML's, $x=0.3$ (2.2% mismatch), scan range $=154$ nm$\times$130 nm, full-scale height range (from black to white) is 8.0 nm, $V_t=2.6$ V, $I_t=0.4$ nA. (b) 11 ML's, $x=0.4$ (2.9% mismatch), scan range $=150$ nm$\times$154 nm, full-scale height range is 8.5 nm, $V_t=2.6$ V, $I_t=60$ pA. (c) 12 ML's, $x=0.5$ (3.6% mismatch), 150 nm$\times$147 nm, full-scale height range is 9.0 nm, V_t $=2.7$ V, $I_t=20$ pA. For the films represented in (b) and (c), 4–5 ML's of additional material were deposited after the RHEED pattern became spotty. During this extra growth the pattern sharpened. For the film represented in (a) there was no extra growth.

2D → 0D (past experience)

semiconductor heterojunctions/quantum wells :
self assembled InAs/GaAs quantum dots

Photoluminescence of Single InAs Quantum Dots Obtained by Self-Organized Growth on GaAs

J.-Y. Marzin, J.-M. Gérard, A. Izraël, and D. Barrier

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G. Bastard

Laboratoire de Physique de la Matière Condensée, Ecole Normale Supérieure, 24 rue Lhomond, F75005 Paris, France

(Received 11 March 1994)

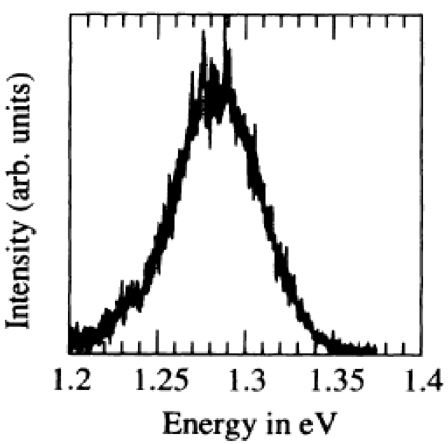


FIG. 1. 10 K PL spectrum of a 5000 nm mesa in sample A.

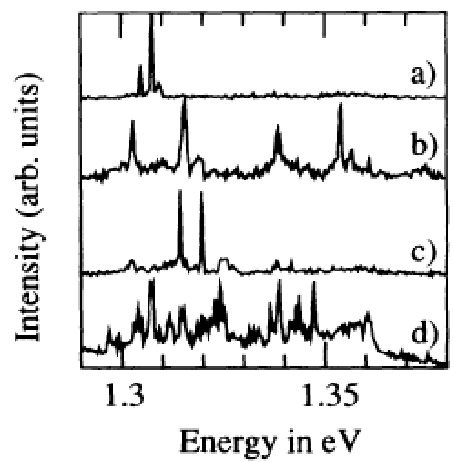
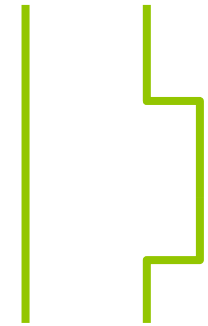


FIG. 5. (a), (b), and (c): 10 K PL spectra of three different 200 nm mesas of sample B. (d) sum of 20 spectra recorded on different such mesas.

2D → 0D (past experience)

semiconductor heterojunctions/quantum wells :
well width fluctuations (monolayer steps)



Quantum Dots Formed by Interface Fluctuations in AlAs/GaAs Coupled Quantum Well Structures

A. Zrenner, L. V. Butov,* M. Hagn, G. Abstreiter, G. Böhm, and G. Weimann
Walter Schottky Institut, Technische Universität München, D-85748 Garching, Germany
(Received 21 December 1993)

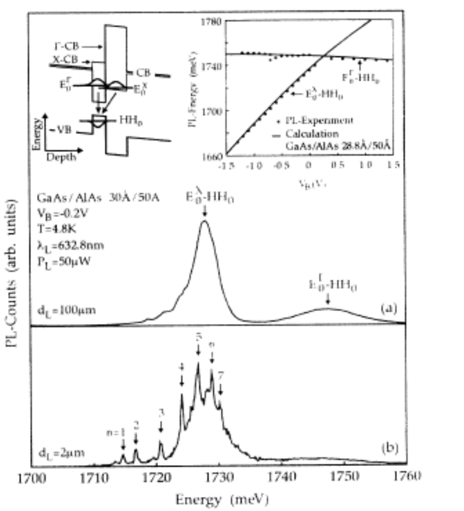


FIG. 1. (a) PL response of a GaAs/AlAs 30 Å/50 Å coupled QW structure in the indirect regime for $V_B = -0.2$ V. The diameter of the optically probed area d_L is 100 μm. A schematic band diagram of the structure and the observed PL energies as a function of V_B are shown in the inset. (b) Same as (a) only with higher spatial resolution ($d_L = 2$ μm). New narrow emission lines (labeled from $n = 1$ to 7) appear in the region of the indirect PL.

Fine Structure Splitting in the Optical Spectra of Single GaAs Quantum Dots

D. Gammon, E. S. Snow, B. V. Shanabrook, D. S. Katzer, and D. Park
Naval Research Laboratory, Washington, D.C. 20375-5347
(Received 17 August 1995)

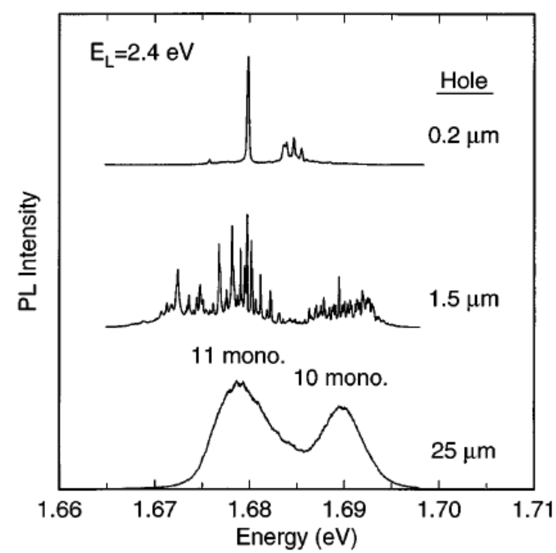
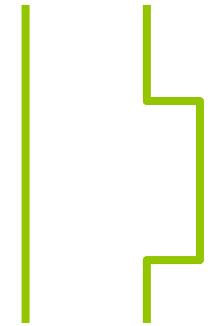


FIG. 2. Nonresonant PL spectra excited and detected through apertures with diameters listed.

2D → 0D (past experience)

semiconductor heterojunctions/quantum wells :
well width fluctuations (monolayer steps)



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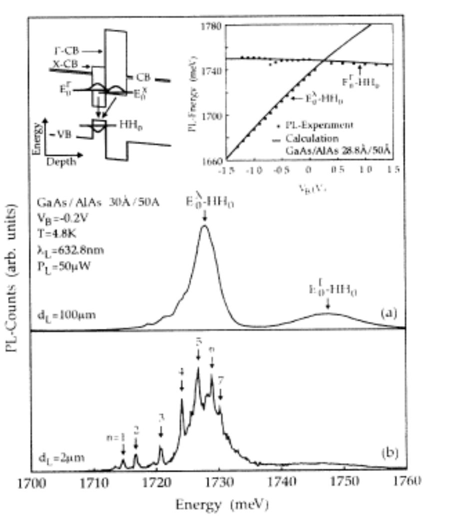

FIG. 1. (a) PL response of a GaAs/AlAs 30 Å/50 Å coupled QW structure in the indirect regime for $V_B = -0.2$ V. The diameter of the optically probed area d_L is 100 μm. A schematic band diagram of the structure and the observed PL energies as a function of V_B are shown in the inset. (b) Same as (a) only with higher spatial resolution ($d_L = 2$ μm). New narrow emission lines (labeled from $n = 1$ to 7) appear in the region of the indirect PL.

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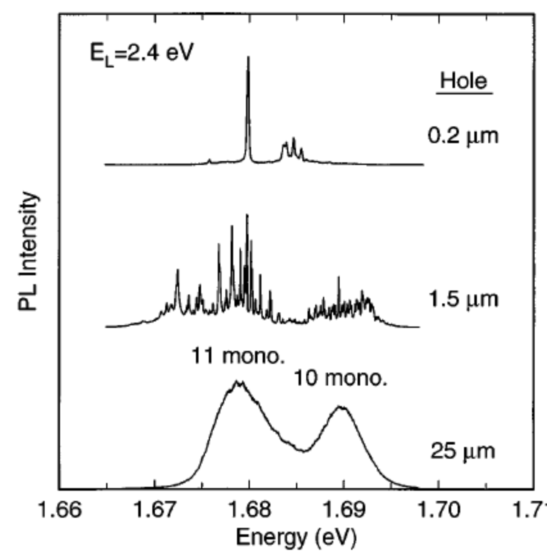
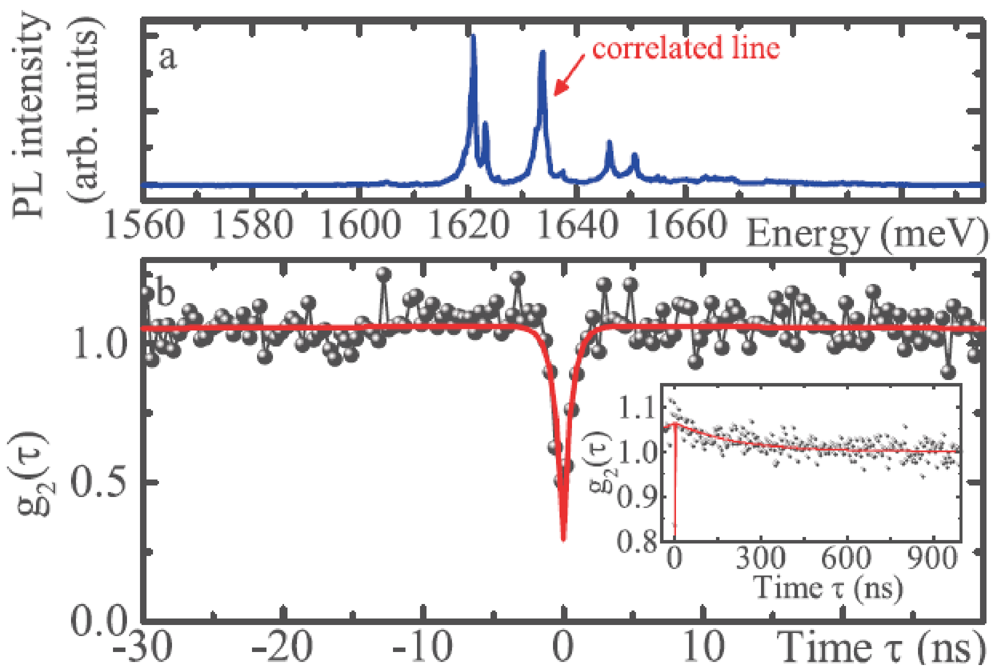


FIG. 2. Nonresonant PL spectra excited and detected through apertures with diameters listed.

Single photon sources (narrow emission lines, ~0.1meV))
fingerprint: photon antibunching
photon correlation measurements



semiconductor (single) quantum dots, nanocrystals (colloidal dots)
NV centers in diamond (SiC), organic molecules
interesting applications; issues: stability, room temperature operation, electrical pumping

Single photon emitters in WSe_2 (MX_2) flakes ?

(Nature Nanotechnology, 2015)

A. Srivastava et al., Optically active quantum dots in monolayer WSe_2 (Switzerland)

M. Koperski et al., Single photon emitters in exfoliated WSe_2 structures (France, Poland)

Y-M, He et al., Single quantum emitters in monolayer semiconductors (China, USA)

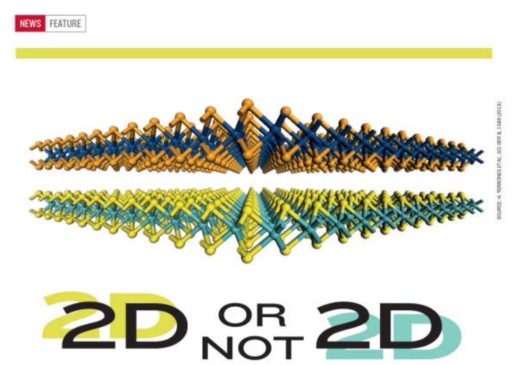
C. Chakraborty et al., Voltage controlled of quantum light from an atomically thin semiconductor (USA)

news & views

METAL DICHALCOGENIDES

Two dimensions and one photon

Single-photon sources have been demonstrated in two-dimensional semiconductors.



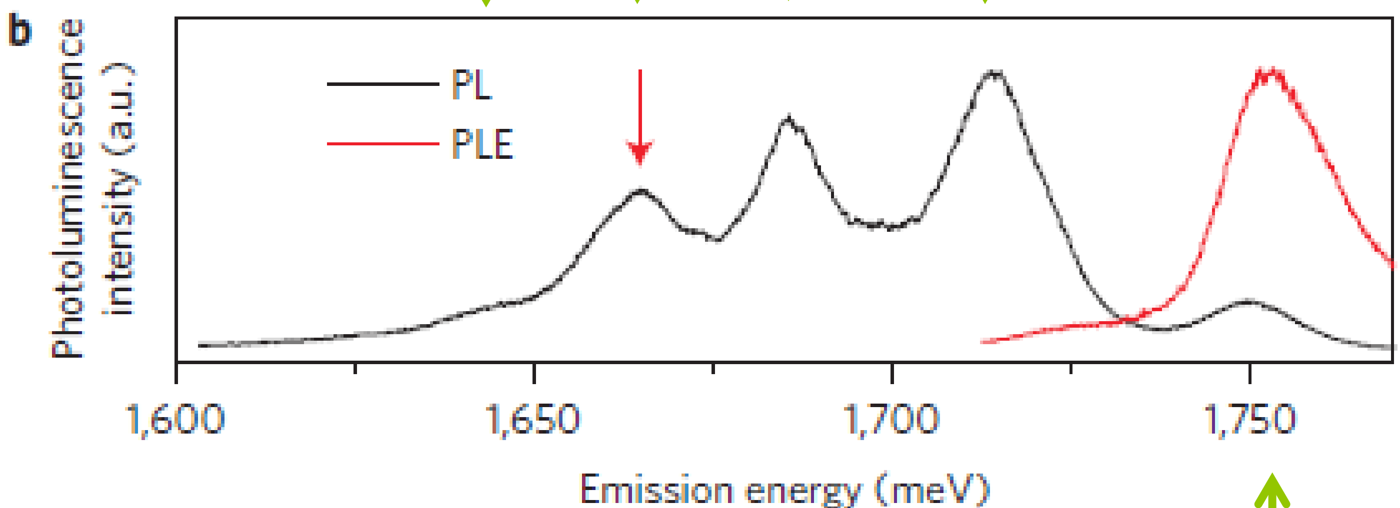
2D WSe_2 monolayer

typical photoluminescence/absorption response

broad (10-20meV) emission/absorption peaks

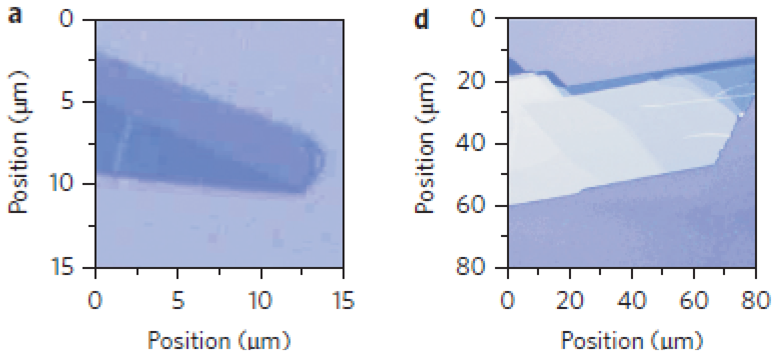
"localized, bound excitons"

"negatively charged exciton" "X^- " (free)

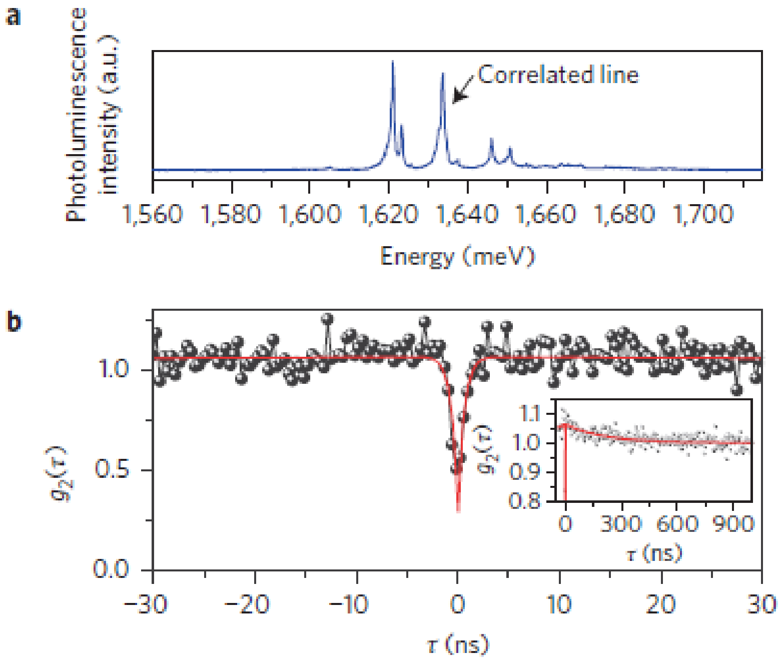


exciton (free)

M. Koperski et al.,
Single photon emitters in exfoliated WSe_2 structures



(Imperfections at edges ?)

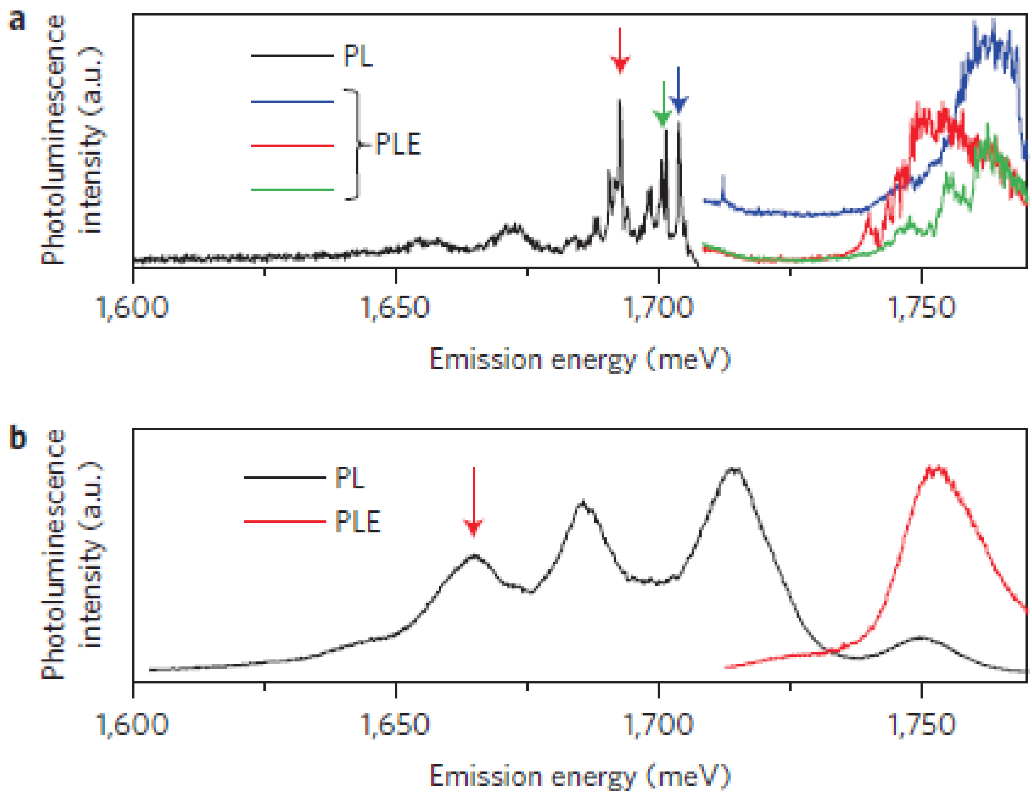


<u>Photon antibunching</u>

=

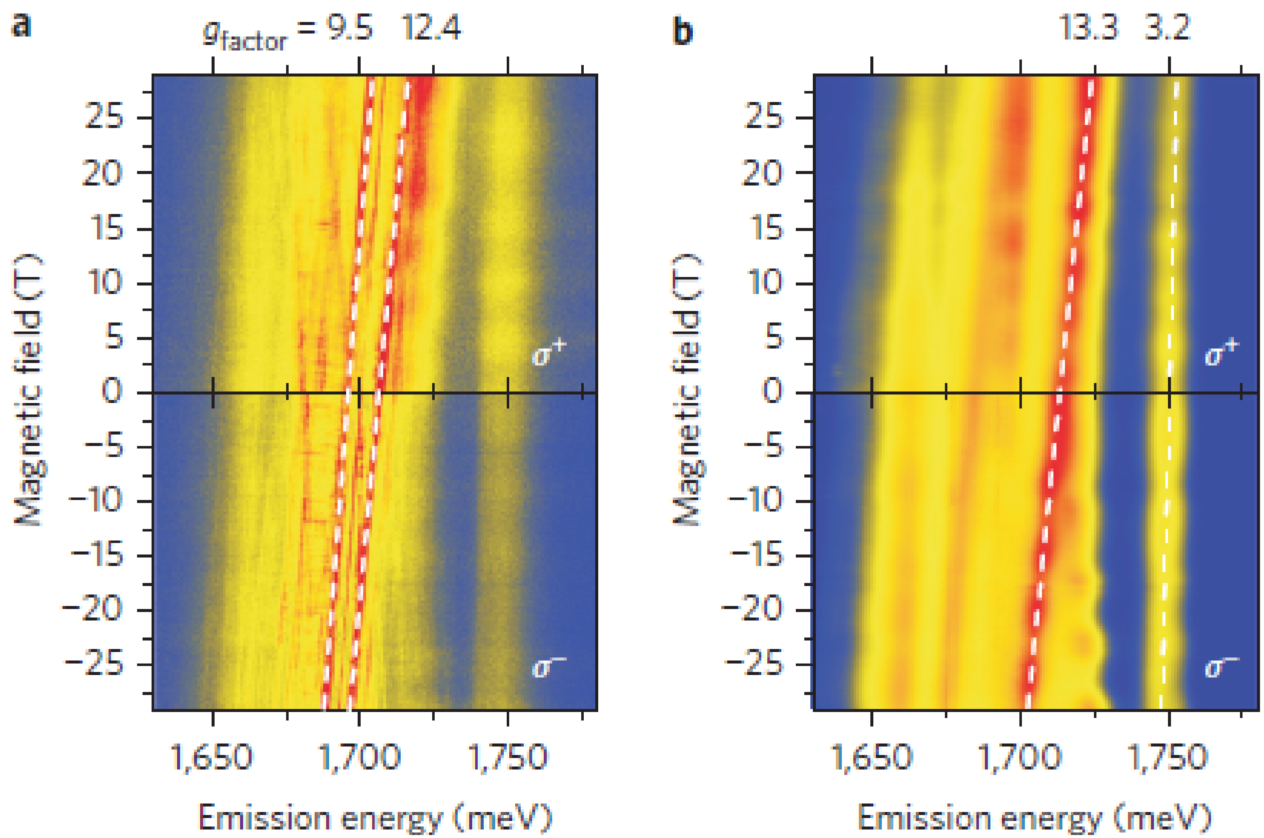
an unambiguous attribute of single photon emitters

Optical response of narrow lines , linked to the 2D properties of a WSe_2 monolayer



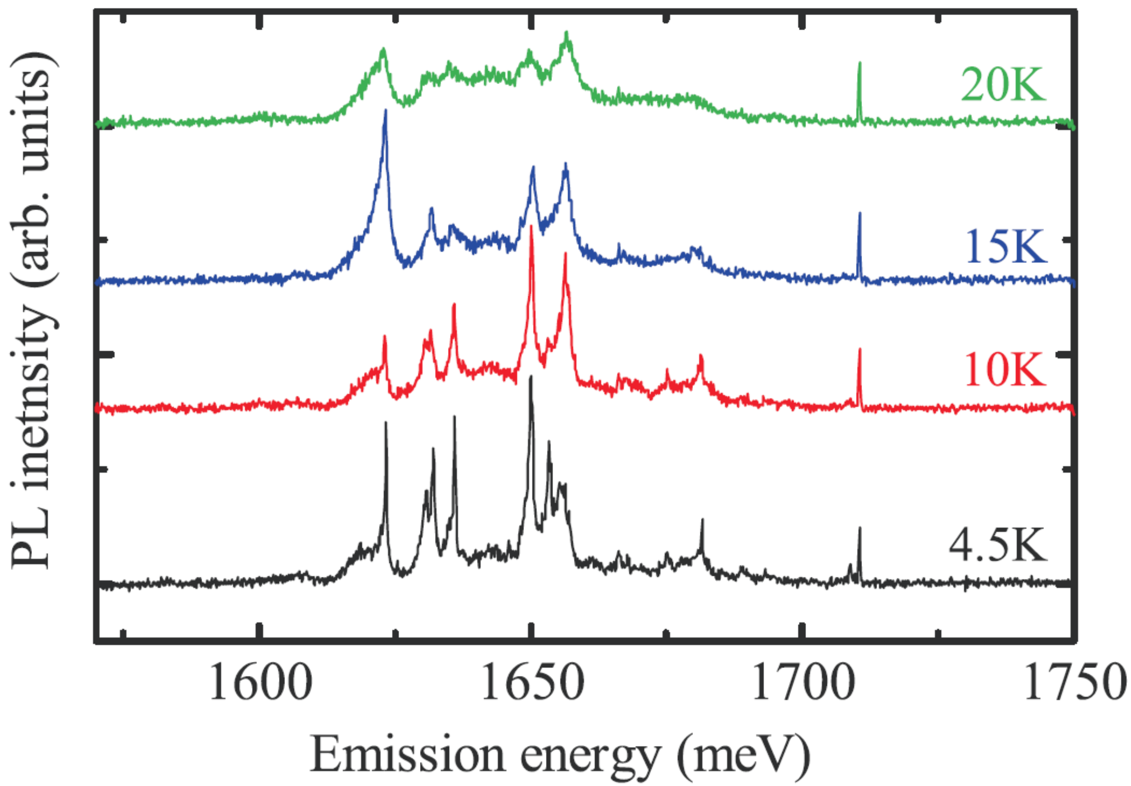
Emission in the same energy range, similar excitation spectra

Optical response of narrow lines , linked to the 2D properties of a WSe_2 monolayer



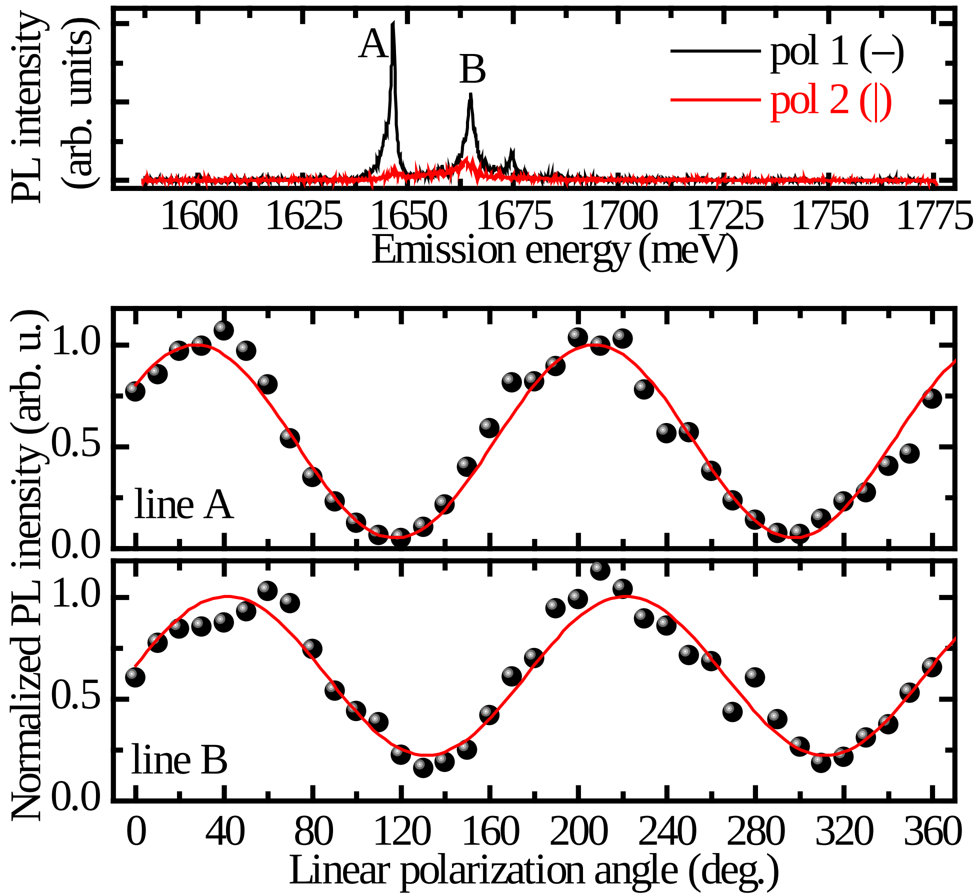
Similar, anomalously large "Zeeman" splitting

Temperature effect:



Quench of intensity (weakly confined electron hole pairs ?)
Broadening (similar to acoustic phonon effect in semiconductor QDs)

Pronounced (sometimes) linear anisotropy:

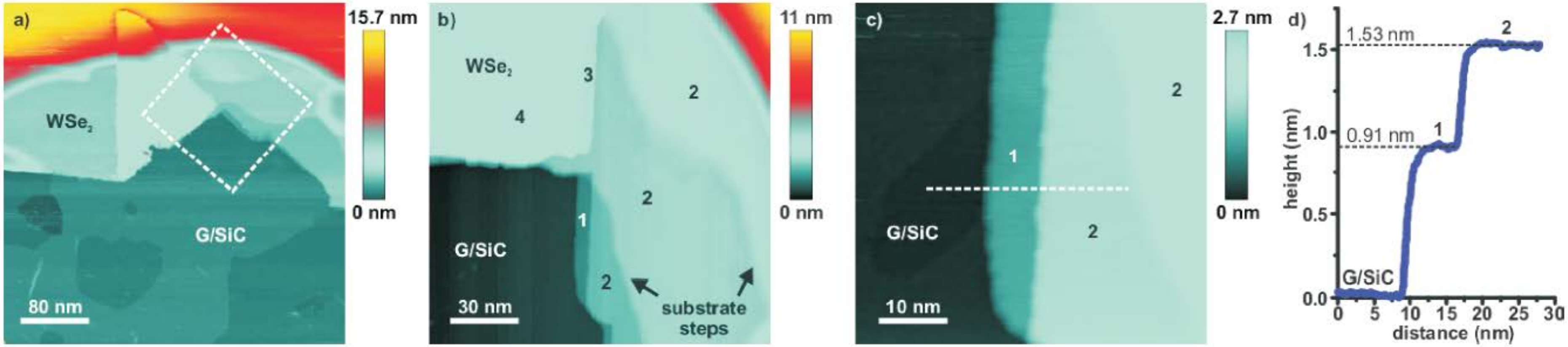


Similar to fine structure splitting in QDots with anisotropic shape

What are they ?

Monolayer "nanoflakes" at the edges of monolayers and thicker flakes ???

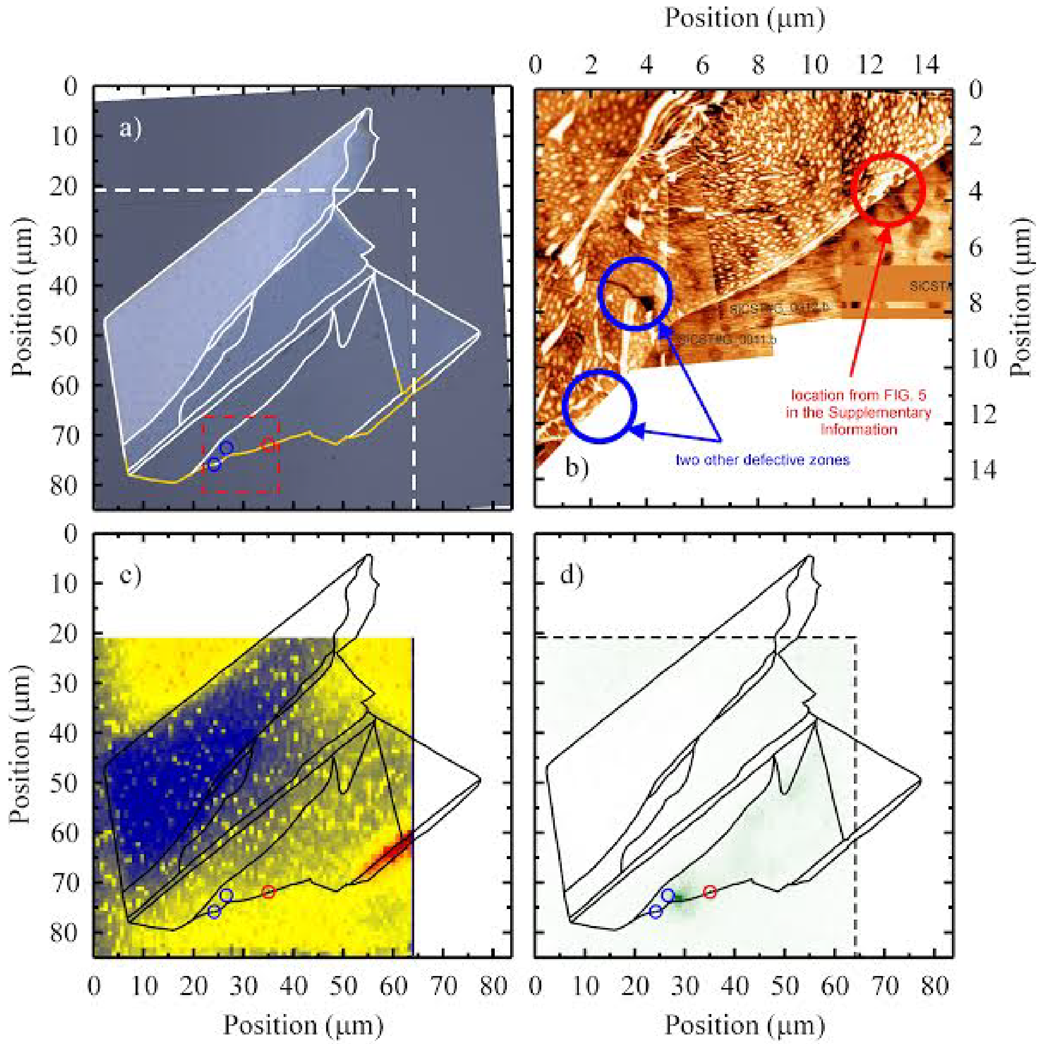
STM: Monolayer nanoflake at the edge of a thicker flake



What are they ?

Monolayer "nanoflakes" at the edges of monolayers and thicker flakes ?

An attempt to correlate PL and STM



Flow of works :

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[119] Schwarz S, Kozikov A, Withers F, Maguire JK, Foster AP, Dufferwiel S, Hague L, Makhonin MN, Wilson LR, Geim AK, Novoselov KS, Tartakovskii AI. Electrically pumped single-defect light emitters in WSe_2. 2D Mater 2016;3:25038.

[120] He Y-M, Iff O, Lundt N, Baumann V, Davanco M, Srinivasan K, Hofling S, Schneider C. Cascaded emission of single photons from the biexciton in monolayered WSe_2. Nat Commun 2016;7:13409.

[121] Palacios-Berraquero C, Barbone M, Kara DM, Chen X, Goykhman I, Yoon D, Ott AK, Beitner J, Watanabe K, Taniguchi T, Ferrari AC, Atatüre M. Atomically thin quantum light-emitting diodes. Nat Commun 2016;7:12978.

[122] Palacios-Berraquero C, Kara DM, Montblanch AR-P, Barbone M, Latawiec P, Yoon D, Ott AK, Loncar M, Ferrari AC, Atature M. Large-scale quantum-emitter arrays in atomically thin semiconductors. ArXiv E-Prints 2016:Preprint at arXiv:1609.04244.

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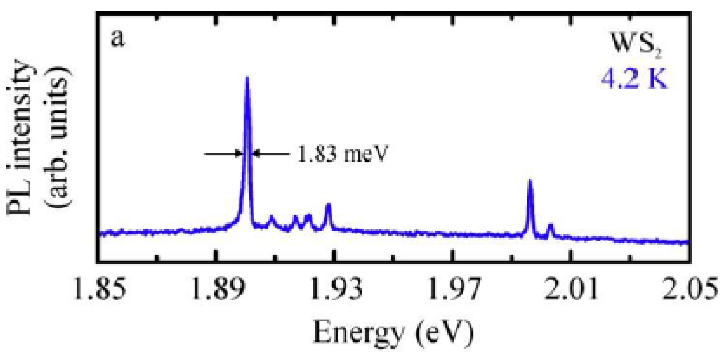
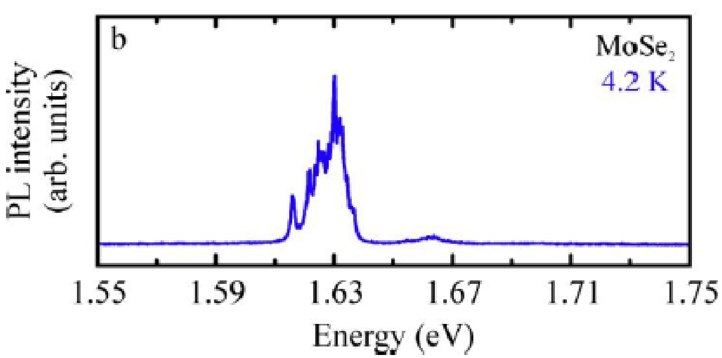
[124] Branny A, Wang G, Kumar S, Robert C, Lassagne B, Marie X, Gerardot BD, Urbaszek B. Discrete quantum dot like emitters in monolayer $MoSe_2$: Spatial mapping, magneto-optics, and charge tuning. Appl Phys Lett 2016;108:142101.

Sharp emission lines in other S-TMDs ? Electric excitation ?

C. Palacios-Berraquero *et al.*, Nat. Commun. (2016)
A. Branny *et al.*, APL (2016)
S. Schwarrz *et al.*, 2D Materials (2016)
………

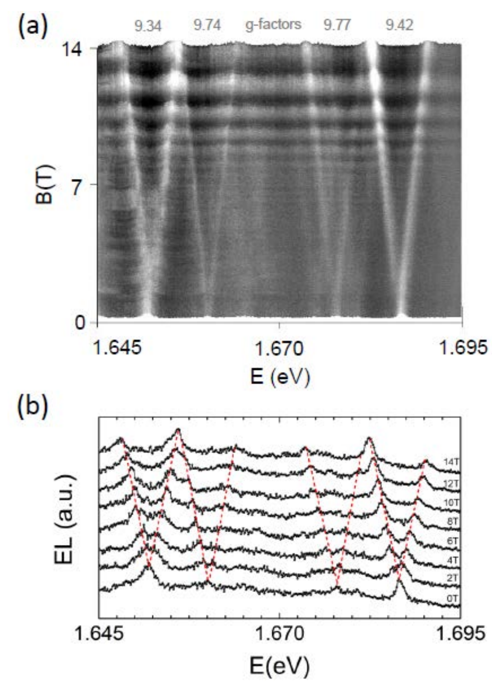




M. Molas, M. Koperski *et al.*, unpublished data

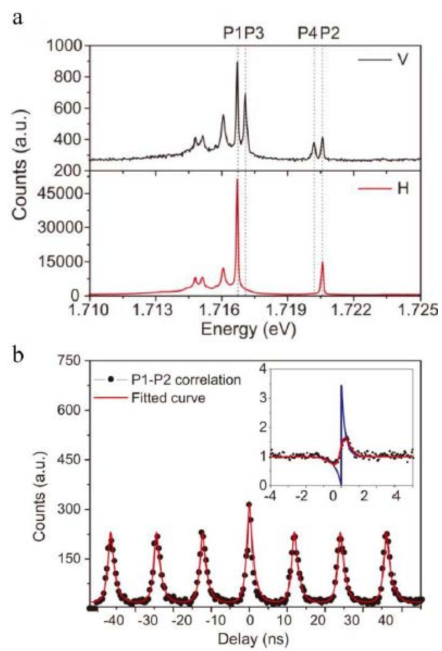
J. Binder *et al.*. unpublished data

electroluminesecnce
hBN/WSe2/hBN LED



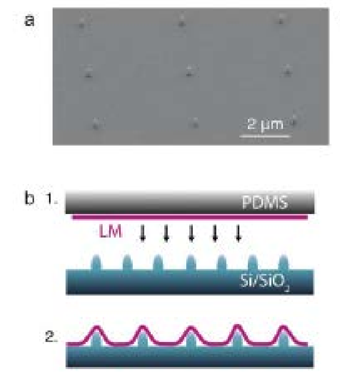
<u>3D confinement</u> (or defects ?)

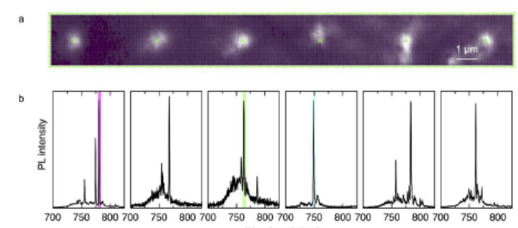
Control,
on demand
- strain engineering



biexciton-exciton cascade ?

Y-M. He *et al.*,
Nat. Commun. (2016)



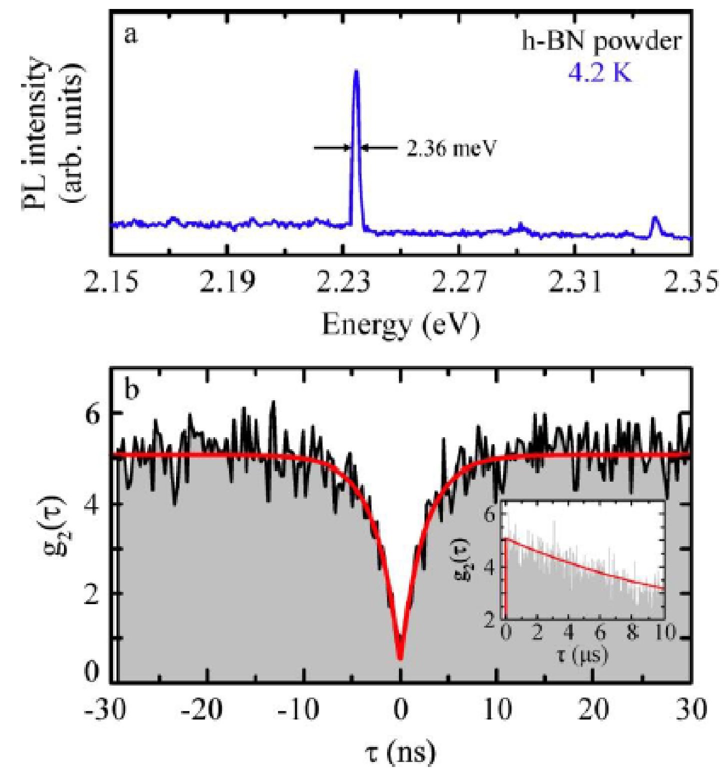


C. Palacios-Berraquero *et al.*
arXiv (2016)

J. Kern *et al.*, Adv. Mater. (2016)

hexagonal boron nitride (hBN):
yet another class of single photon emitters

T.T. Train *et al.,* Nature Nanotech. (2015)
...
N.R. Jungwirth *et al.,* Nano Lett. (2016)
A.W. Shell, et al., APL Photonics (2016)
L.J. Martinez, *et al.,* PRB(2016)
N. Chejanovsky *et al*., arXiv (2016)
A.L. Exarhos *et al.,* arXiv (2016)
…



M. Koperski et al
to be published

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Déjà vu again

Single photon emitters in sc-TMDs

quantum dot like objects

Single photon emitters in hBN

similar to NV centers in diamond/SiC

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