Single photon emitters in exfoliated WSe$_2$ structures

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2D materials $\rightarrow$ (1D), 0D materials ?

quantum (single electron) electronics $\sqrt{\text{v}}$
   nano – lithography (~100 nm) + electrostatic gating

quantum (single photon) photonics
single objects (~10nm) ?

making profit of imperfections!
2D $\rightarrow$ 0D (past experience)

semiconductor heterojunctions/quantum wells:
interface imperfections (lattice mismatch)

Effect of Strain on Surface Morphology in Highly Strained InGaAs Films

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FIG. 3. STM images of In$_x$Ga$_{1-x}$As on GaAs(100). (a) 14 ML's, $x = 0.3$ (2.2% mismatch), scan range \(= 154 \text{ nm} \times 130 \text{ nm} \), 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 \(= 150 \text{ nm} \times 154 \text{ nm} \), 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 x 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 $\rightarrow$ 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

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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 $\rightarrow$ 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

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

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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.

FIG. 2. Nonresonant PL spectra excited and detected through apertures with diameters listed.
Single photon sources \((\text{narrow emission lines, } \sim 0.1\text{meV})\)  
**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
Can we find single photon emitters in WSe$_2$ (MX$_2$) flakes?

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)

( Nature Nanotechnology, in print)

Who are those emitters?
2D WSe$_2$ monolayer

typical photoluminescence/absorption response

broad (10-20meV) emission/absorption peaks

"localized, bound excitons"

"negatively charged exciton" "X$^{-}$" (free)
M. Koperski et al.,
Single photon emitters in exfoliated WSe$_2$ structures (France, Poland)

( Imperfections at edges ? )
M. Koperski et al.,
Single photon emitters in exfoliated WSe$_2$ structures (France, Poland)

( Imperfections at edges ? )

Narrow line emitting centers appear at the edges of WSe$_2$ flakes (monolayer and thick flakes)
Photon antibunching
= an unambiguous attribute of single photon emitters
Photon antibunching = an unambiguous attribute of single photon emitters

Characteristic of single photon emitters

line jittering effect (less pronounced at low excitation level)
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 QDots)
Pronounced (sometimes) linear anisotropy:

Similar to fine structure splitting in QDots with anisotropic shape
Who are they?

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

STM: Monolayer nanoflake at the edge of a thicker flake
Who are they?
Monolayer "nanoflakes" at the edges of monolayers and thicker flakes?
An attempt to correlate PL and STM
Near band edge electronic bands in monolayers of semiconducting TMDCs

Direct gap semiconductor
MoSe₂, …

"Quasi direct gap" semiconductor
WSe₂, …

Defect activated "forbidden emission" in WSe₂ ? ?
Single photon emitters in exfoliated WSe$_2$ structures
= nano-flakes of monolayer at the edges of WSe$_2$ films?