Long-lived quantum emitters in hBN-WSe_2 van der Waals heterostructures

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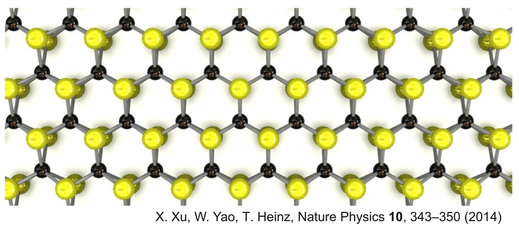
Motivation

Why two-dimensional layered materials?

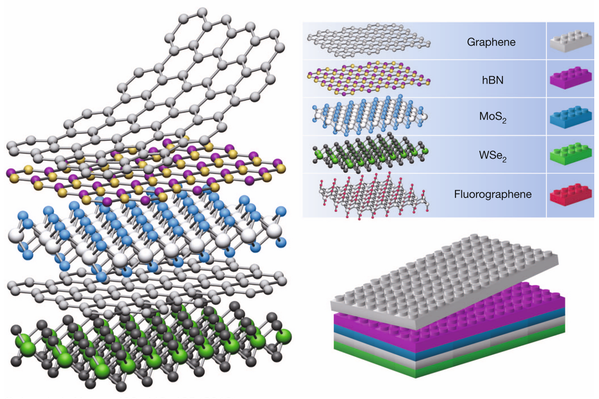
- Direct electronic band gaps in monolayer transition metal dichalcogenides (MoS_2, $MoSe_2$, WS_2, WSe_2)
- Strong coupling to light
- Giant spin-orbit splitting, therefore excellent candidates for spintronic devices



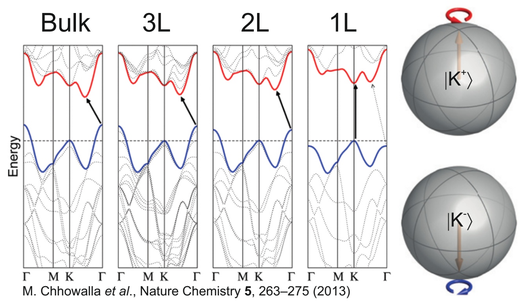
X. Xu, W. Yao, T. Heinz, Nature Physics **10**, 343–350 (2014)

Novel and ultrathin optoelectronic devices

- Stackable 2D heterostructures
- High On/Off-ratios in MOSFET devices



Geim *et al.*, Nature **499**, 419–425 (2013)



M. Chhowalla *et al.*, Nature Chemistry **5**, 263–275 (2013)

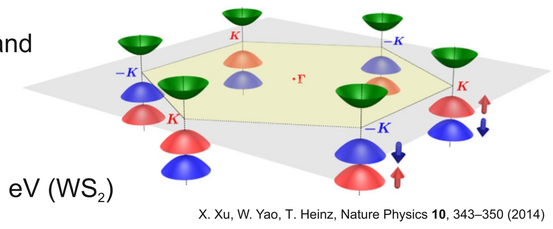
Unexplored physics

- Valley structure properties
- Exciton binding energies and Bohr radii
- Spin relaxation and valley dephasing times

Physical and electrical properties

Bandstructure

- Hexagonal Brillouin zone with 6 valence band minima at high symmetry K-points
- Spin-orbit interaction from metal d-orbitals
- Valley contrast from inversion symmetry breaking
- Optical band gaps of 1.6 eV ($MoSe_2$) to 2.1 eV (WS_2)



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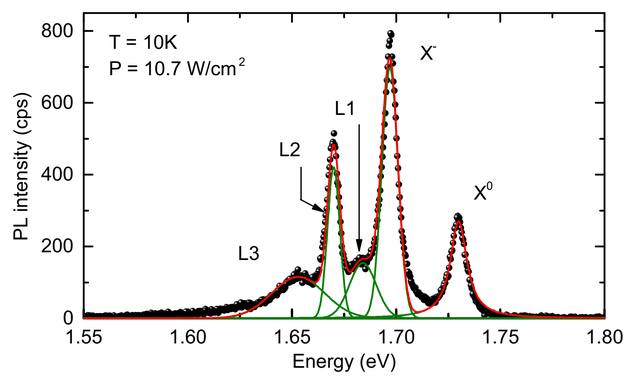
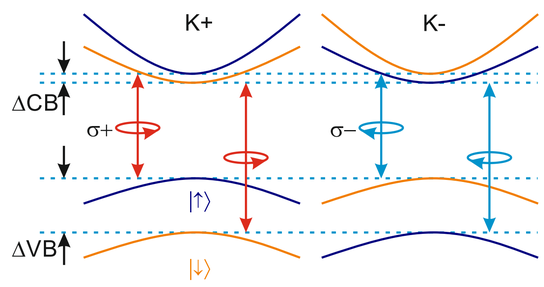


WSe_2 photoluminescence

- Neutral and charged excition lines at 1.72 eV and 1.70 eV
- Exciton linewidths in the order of 9 meV
- Pronounced bound defect luminescence below 1.7 eV
- Exciton lifetimes below 20 ps
- Dark exciton states are lowest energy levels

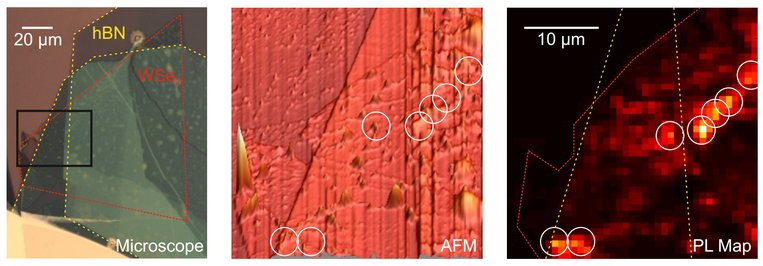


Spin-Valley coupling

- Valley optical selection rules
- Controllable spin and valley polarization
- Polarization contrast

$$\eta = (I_{\sigma+} - I_{\sigma-}) / (I_{\sigma+} + I_{\sigma-})$$

Quantum emitters in WSe_2

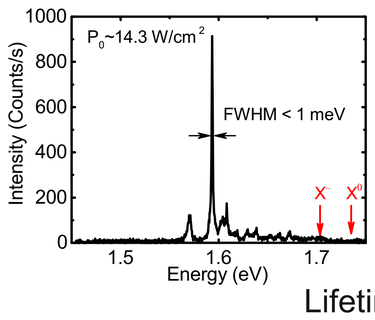


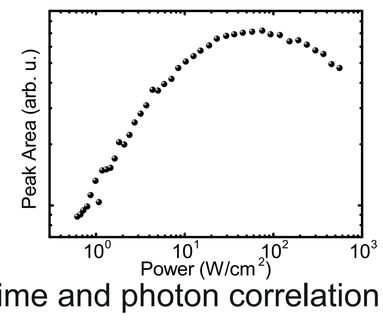
Topologically induced emitters

- Sharp emission lines near bubbles in the hBN/WSe_2/hBN structure
- Possible strain effects induce more favourable low energetic radiative decay channels
- Bubble formation with up to 100 nm height and 2 µm diameter

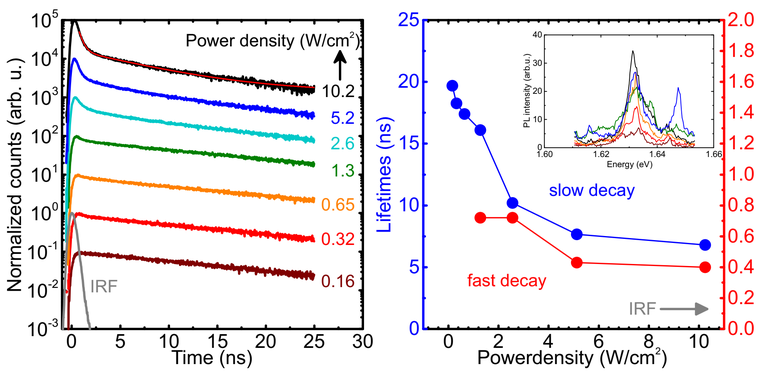
Photoluminescence properties

- Localized hot spots on WSe_2
- Sharp emission lines 120 meV redshifted to the bulk exciton lines
- FWHM below 1meV
- Saturation powerdensities in the order of 10-50 W/cm²
- Decrease in intensity in the high power regime

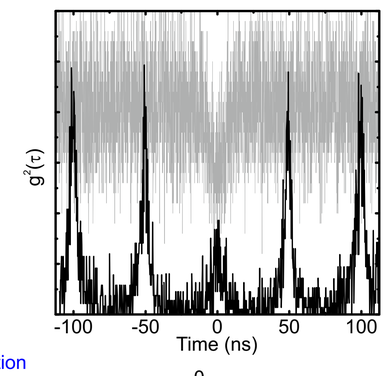




Lifetime and photon correlation

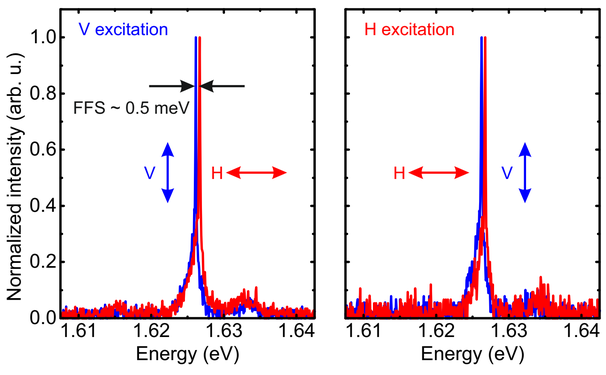


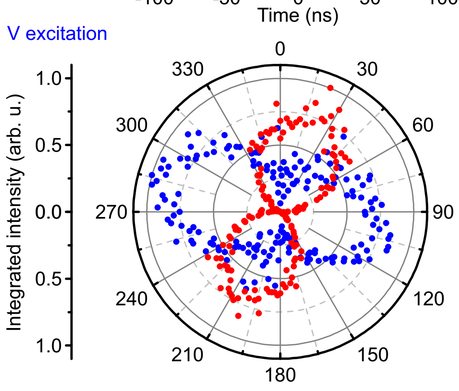
- Long lifetime (5 ns to 20 ns) compared to neutral and charged excitons in WSe_2 (10 ps)
- Fast (0.5 ns) component with increasing excitation power density due to Auger processes
- Clear anti-bunching behaviour in cw and pulsed HBT measurements



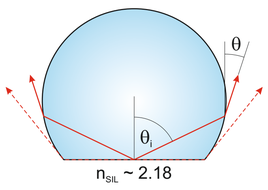
Finestructure splitting

- Energetic splitting between H and V polarized PL components in the order of 0.2 meV to 0.9 meV
- Angular difference 90° ± 15°



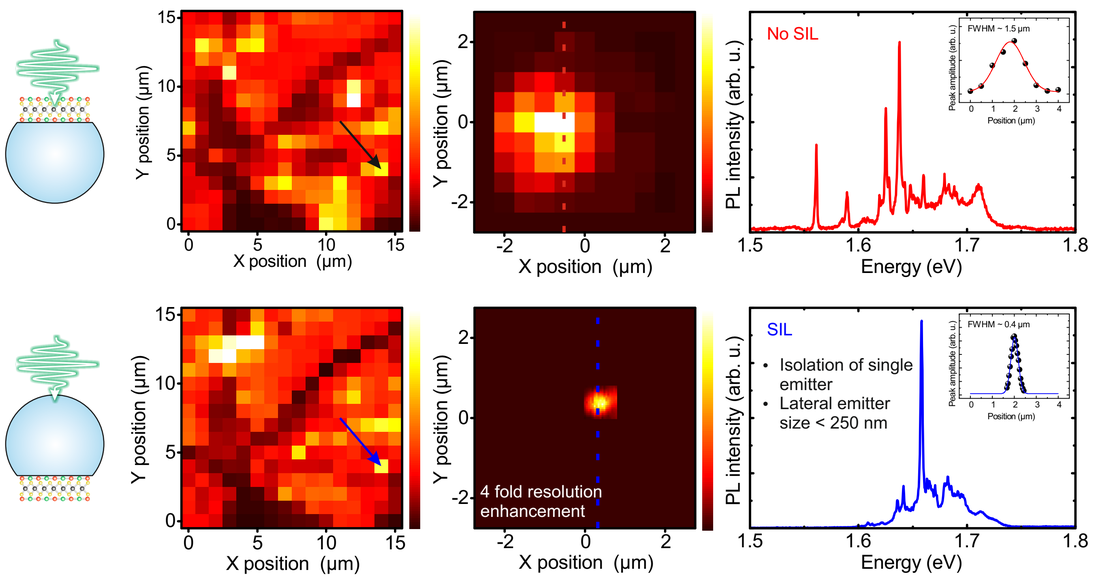


SIL-based spectral isolation

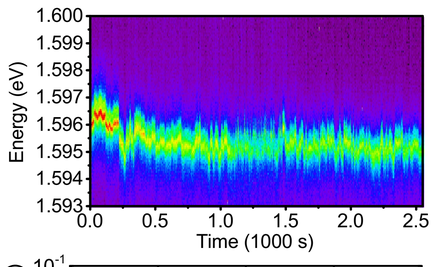


Weierstrass solid immersion lens

- Truncated sphere design: $h = (1+1/n_{SIL})\, r$
- N.A. conversion: $\sin(\theta_i) = n_{SIL}\sin(\theta)$
- Improved spatial resolution: $r_{SIL}=0.51\ \lambda/\text{N.A.}\ n^2_{SIL}$

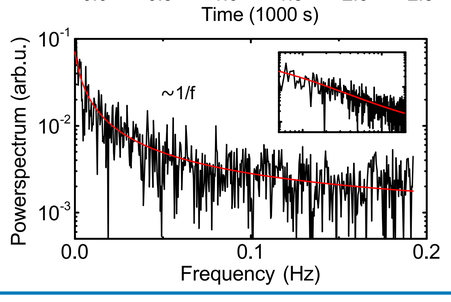


Towards electrical stability of 2D quantum emitters



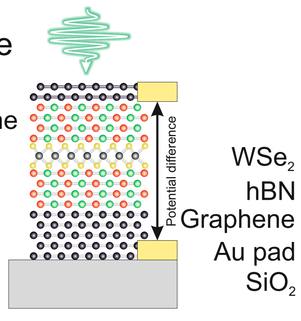
Temporal energy fluctuation

- Discrete changes in emission energy
- Termal 1/f noise within 0.2 Hz (Nyquist limit) for 2 sec integration time
- No clear resonances in frequency domain



Pure 2D capacitor device

- hBN encapulated WSe_2 heterostructure with graphene contacts
- Electric field stabilization of fluctuating environment
- DC-Stark tuneability of QD emission lines



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