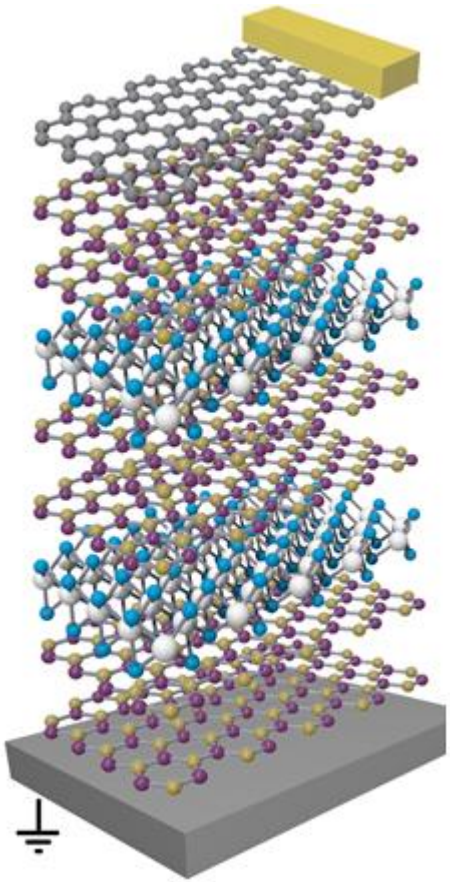
Long-life emission in multi-layer van der Waals heterostructures



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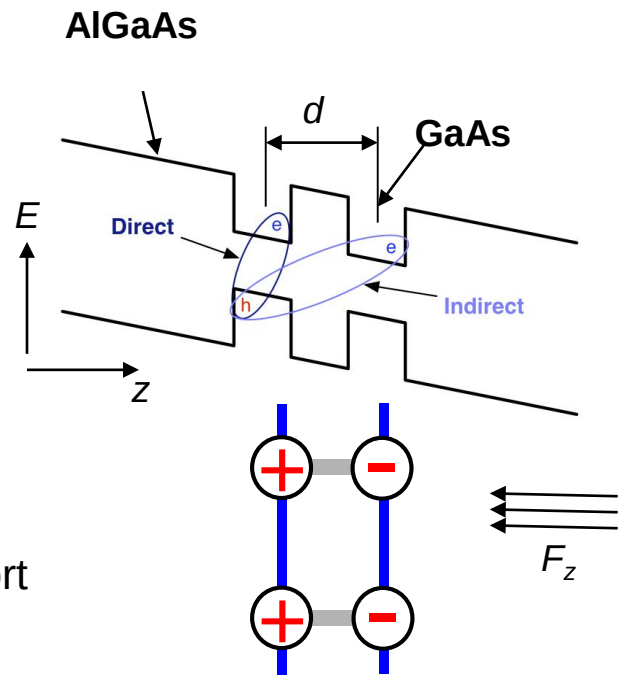
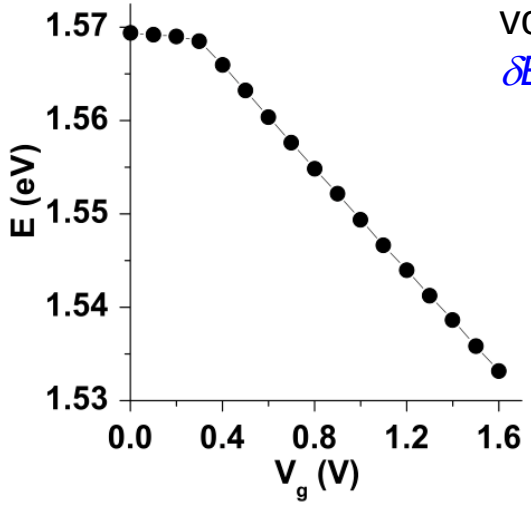
Indirect excitons

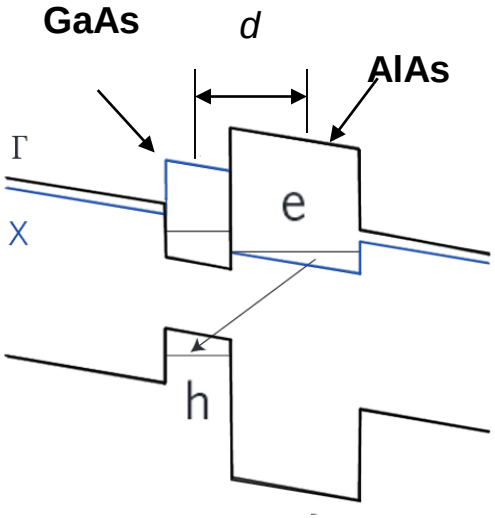
Exciton: bound pair of an electron and a hole.

Indirect excitons: electron and hole are confined to spatially separated quantum wells. Properties:

- bosons
- long and controllable lifetime → long-range exciton transport
- built-in dipole moment → excitons screen disorder
- built-in dipole moment → control of excitons by voltage: $\delta E = edF_z$







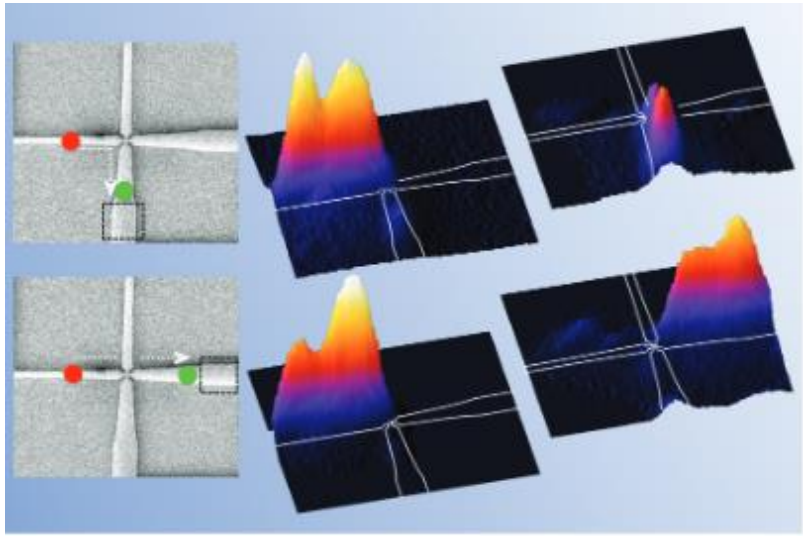
Opto-Electronic Devices with Indirect Excitons

- Exciton devices for basic study
  - Artificial lattices
  - Traps

- Exciton circuit devices
  - Exciton transistors
  - Exciton ramps
  - Exciton conveyers (CCD)
  - Exciton memory cells
  - Exciton integrated circuit

- For temperatures $k_B T \gtrsim E_{binding}$ excitons dissociate

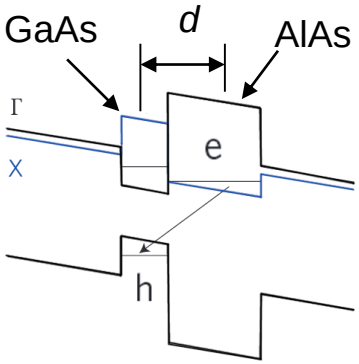
Operation of exciton transistor and router



P. Andreakou, S.V. Poltavtsev, J.R. Leonard, E.V. Calman, M. Remeika, Y.Y. Kuznetsova, L.V. Butov, J. Wilkes, M. Hanson, A.C. Gossard. Optically controlled excitonic transistor, *Appl. Phys. Lett.* 104, 091101 (2014).

GaAs/AlAs devices can operate up to ~100K

Grosso, et al., *Nat. Photonics* 3, 577 (2009).

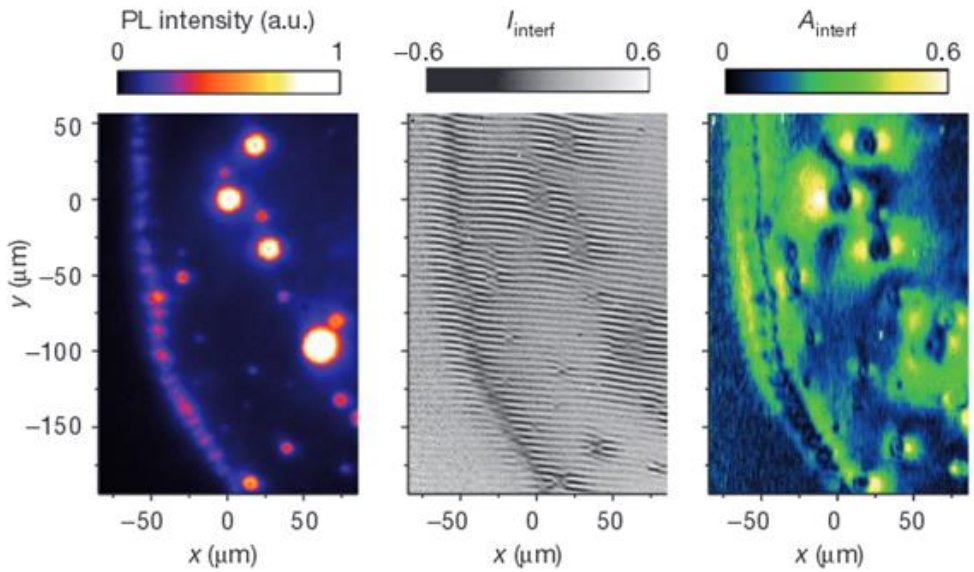


Quantum Degenerate Gas of Indirect Excitons

- Basic studies of exciton transport, spin transport, correlation, coherence, condensation, strong magnetic field regime

- At $T \lesssim T_0 = \frac{2\pi\hbar^2 n}{m}$ excitons form a quantum degenerate gas of bosons

- GaAs strucures have shown spontaneous coherence of excitons at low temperatures around 1K



Regions of spontaneous coherence

High, et al. *Nature* 483, 584 (2012)

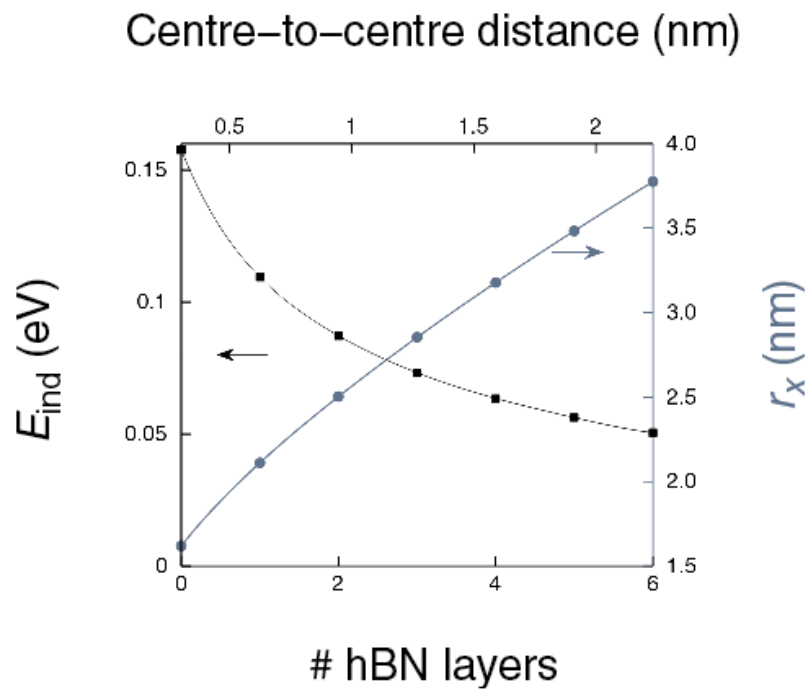
Indirect Excitons in van der Waals heterostructures

- Effective mass and small ε result in binding energy $E_{IX} \gg k_B T_{room}$ which keeps excitons bound at high temperatures
- Theory predicts superfluidity in a quantum degenerate exciton gas at high temperatures

$$T_0 = \frac{2\pi\hbar^2}{m_x} n = \frac{4\pi m_e m_h}{m_x^2}\left(n a_x^{\,2}\right) Ry_x$$

$$n^{\max} a_x^{\,2} \sim 0.02$$

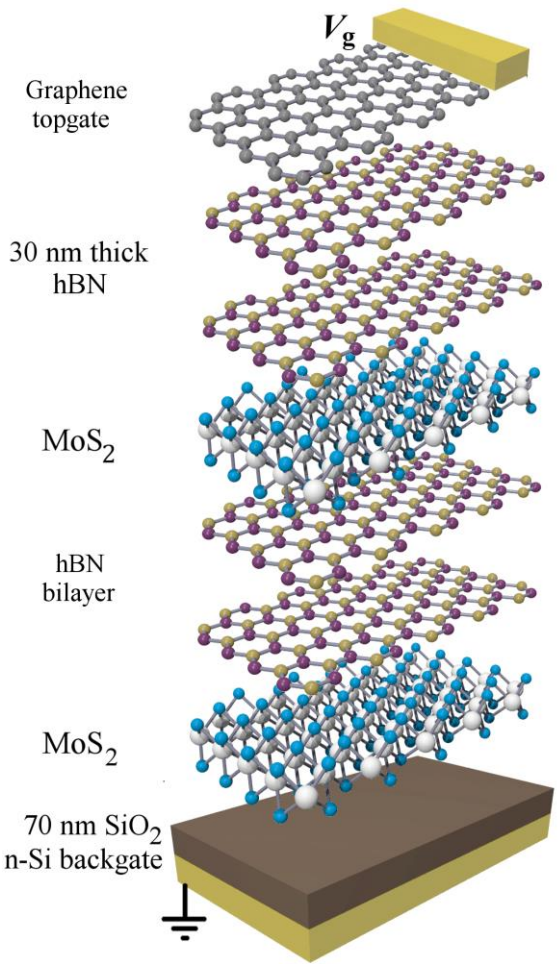
$$T_0^{\max} \sim 0.06 Ry_x$$

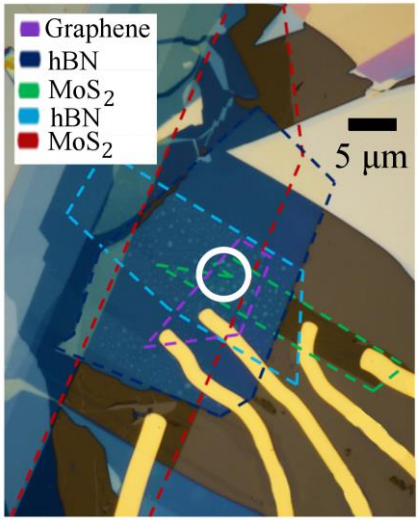


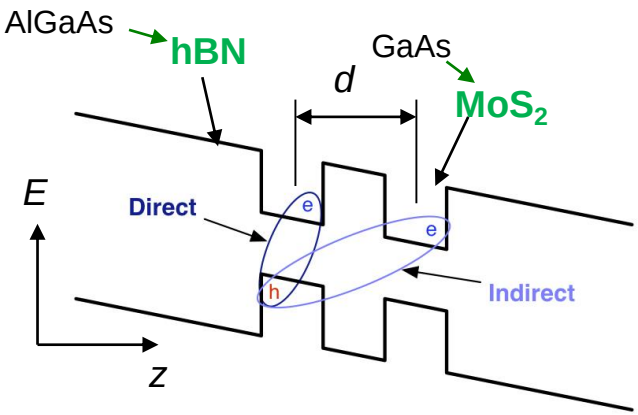
Fogler, Butov, Novoselov *Nat. Commun.* 5, 4555 (2014).

Indirect Excitons in Transition Metal Dichalcogenide Structures (TMD)

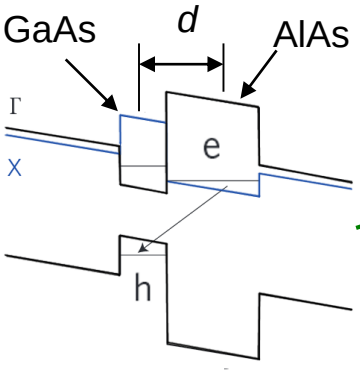
- Exciton binding energy is much greater than for GaAs and can support excitons up to room temperature and above

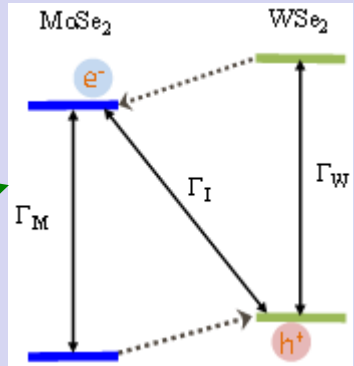






Calman, et al, *APL* 108, 101901 (2016).



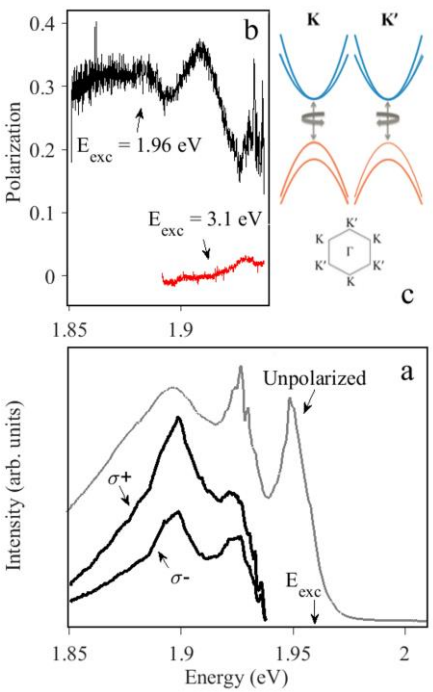


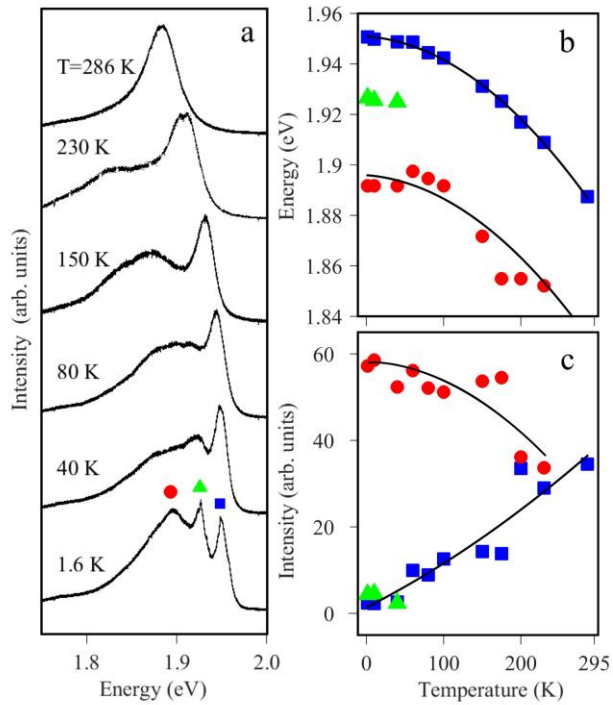
Fang, et al *PNAS* 111, 6198 (2014)

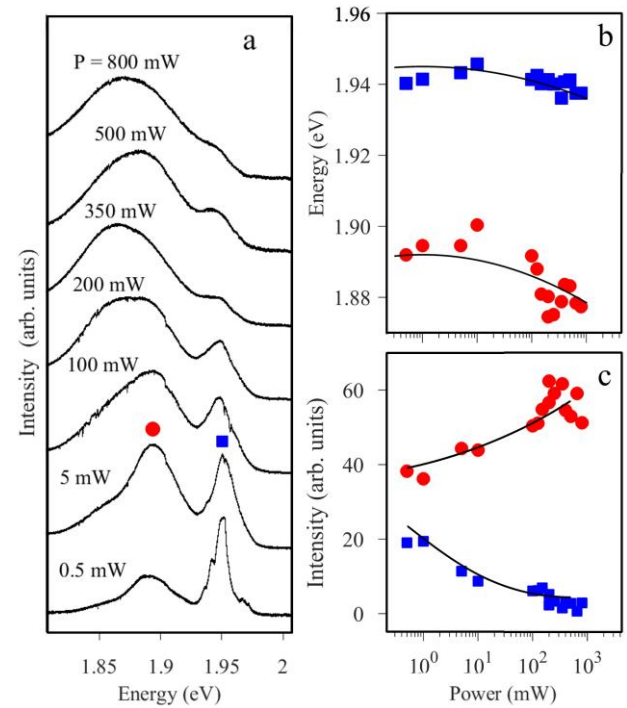
Rivera, et al, *Nat. Commun.* 6 (2015).

Control of Excitons in MoS_2

Calman, et al, *APL* 108, 101901 (2016).





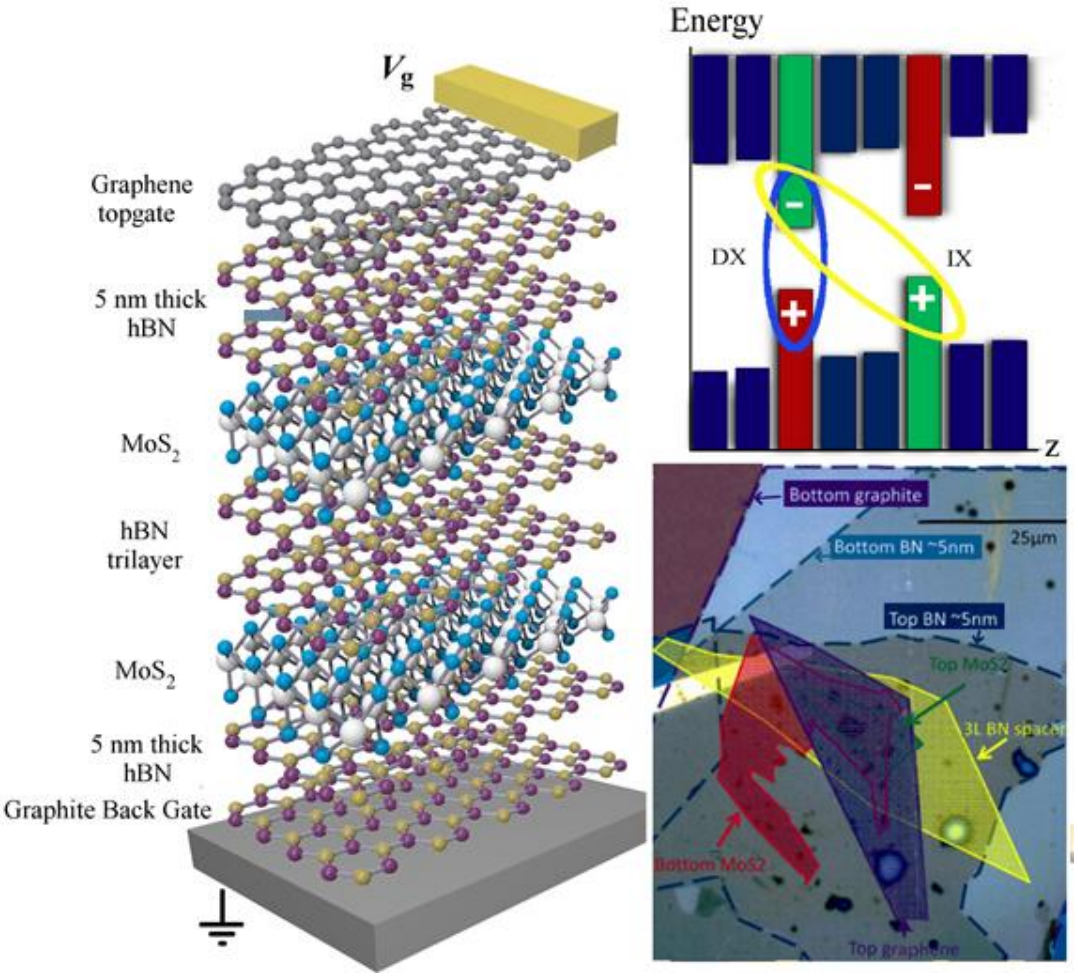


- Exciting with circularly polarized light near exciton resonance produces polarized emission
- $\tau_{spin} > \tau_E$ for nearly resonant excitation because spin and valley indices are coupled

- Exciton emission at room temperature
- The relative intensity of the high-energy exciton lines increase with T, consistent with the thermal dissociation of trions due to their smaller binding energy

- The relative intensity of the trion line increases with power
- This effect may be due to an enhanced probability of trion formation at larger carrier density

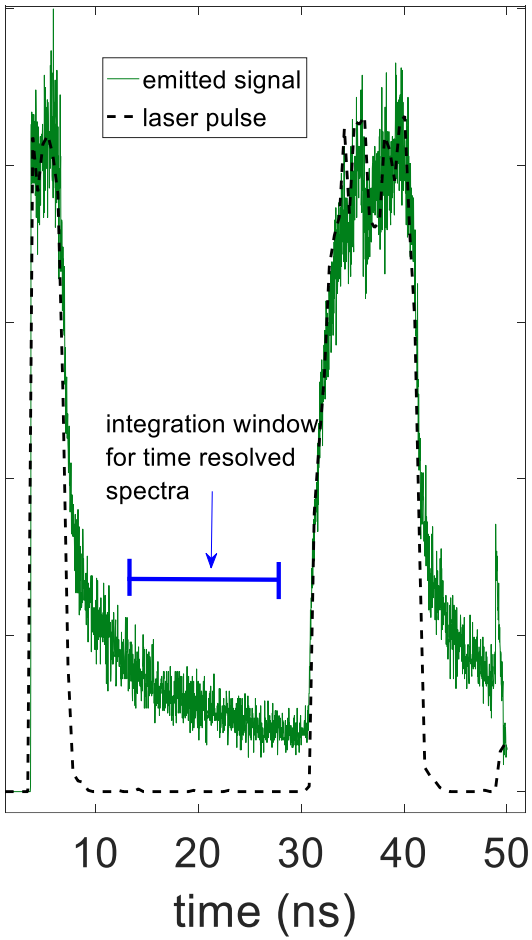
New Sample Design for MoS_2-hBN-MoS_2

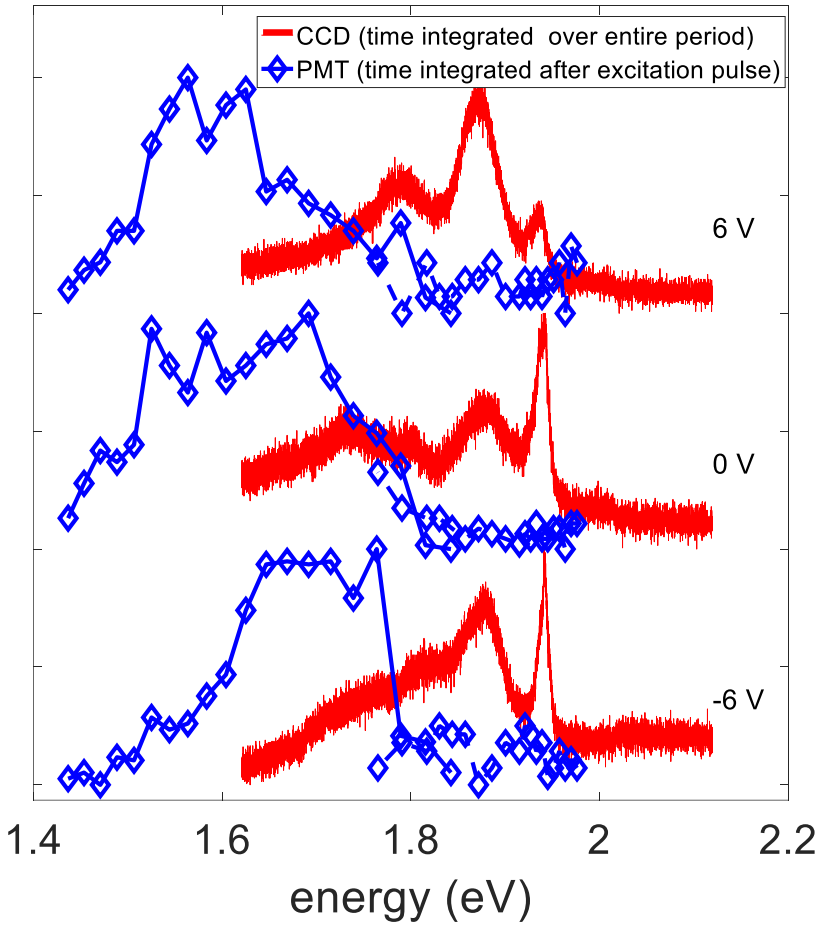


- New sample design can support higher $\vec{E}$ than <u>previous design</u>

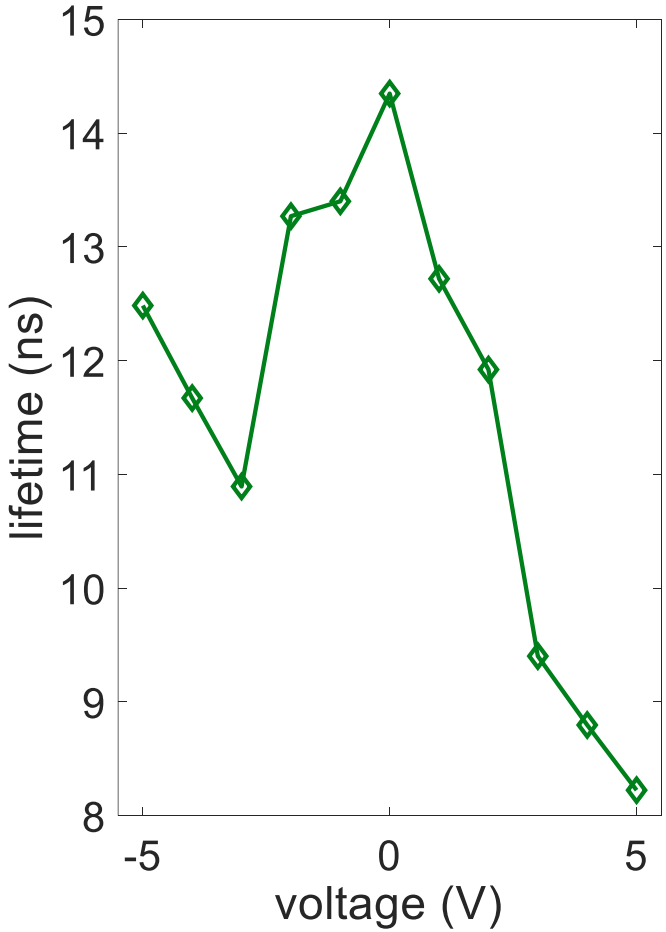
E. V. Calman, C. J. Dorow, M. M. Fogler, L. V. Butov, S. Hu, A. Mishchenko, A. K. Geim. Control of excitons in multi-layer van der Waals heterostructures, Appl. Phys. Lett. 108, 101901 (2016).

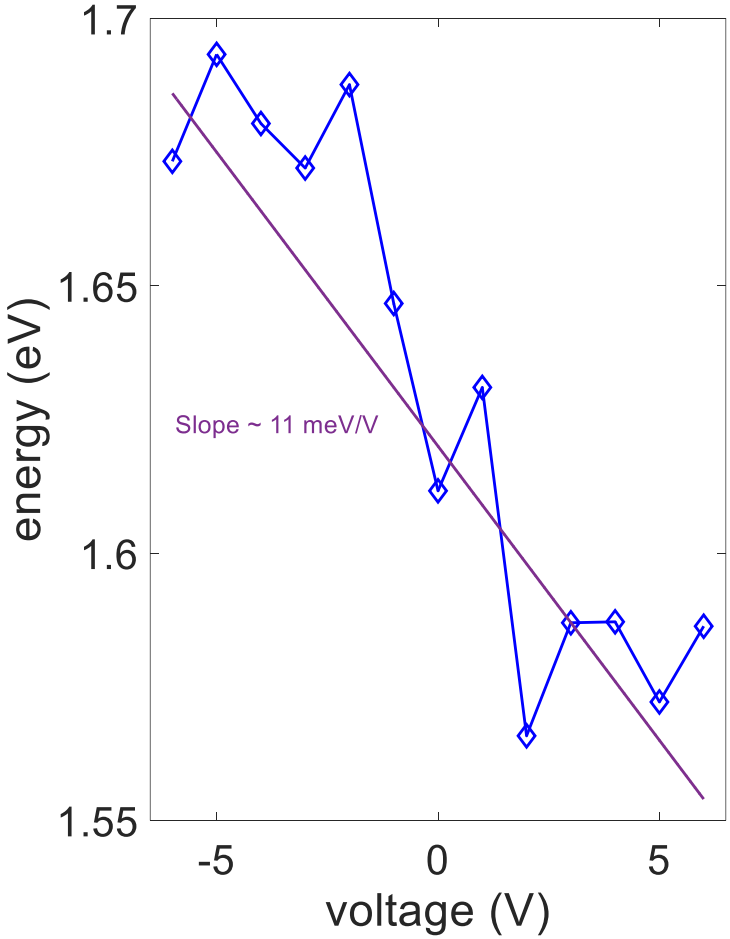
Long Life Emission from MoS_2-hBN-MoS_2 structures





- Emission persists after excitation pulse has ended
- Spectra measured after optical excitation(◆) reveal long-life emission



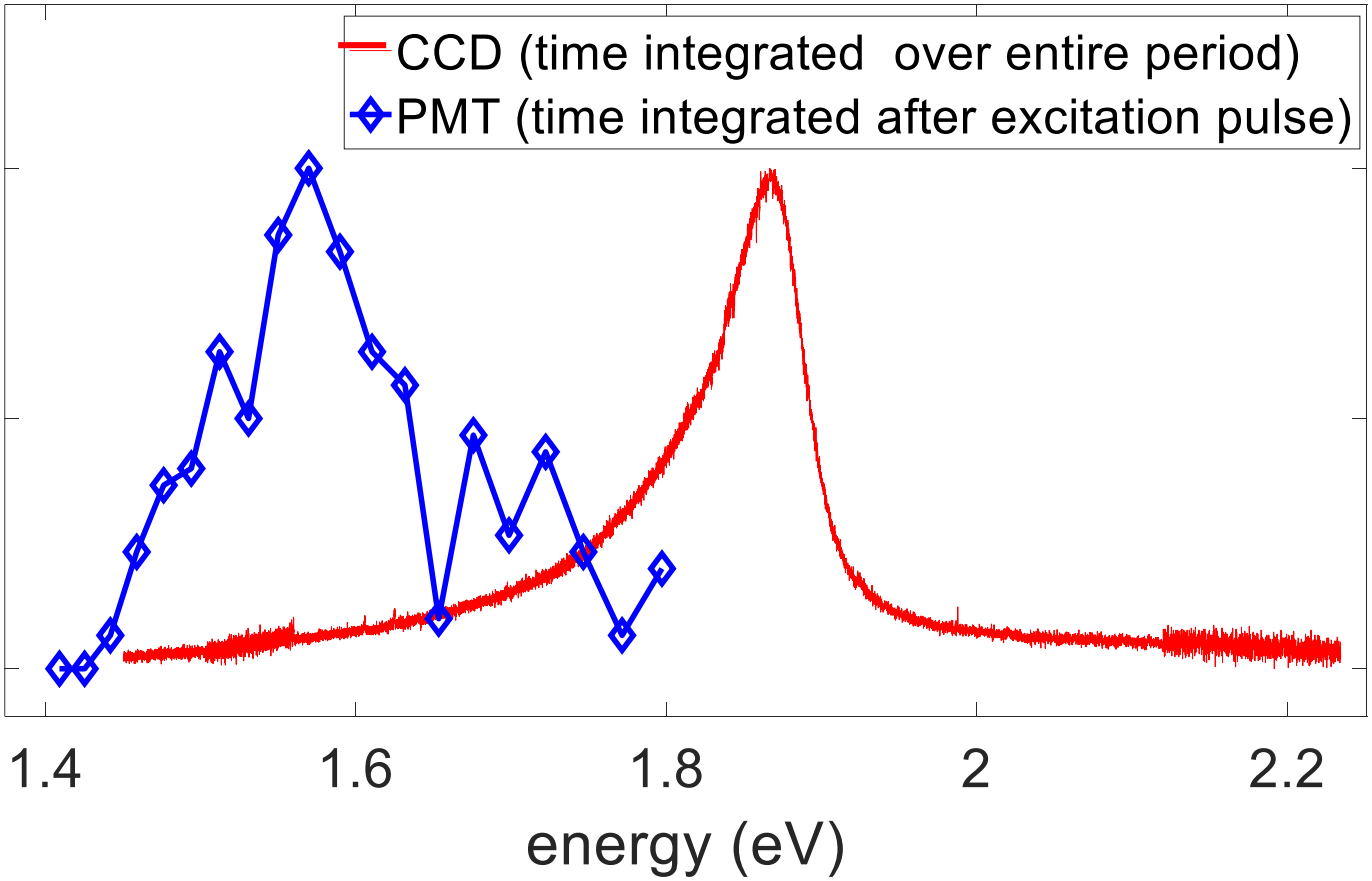


- Lifetime of long-life emission line is ~10 ns, orders of magnitude longer than <u>1.8 ps for direct exciton in monolayer MoS_2</u>

Robert, C., et al. Phys. Rev. B **93**, 205423 (2016).

- Energy of the long-life emission line is controlled by voltage within ~100 meV

T=300 K



- Emission of long-life emission line is observed at room temperature
- Lifetime of ~30 ns

Conclusion

- Observed emission in a MoS_2 van der Waals heterostructure at both cryogenic and room temperatures with a lifetime orders of magnitude longer than for direct excitons in monolayer MoS_2
- Demonstrated control via gate voltage of the energy of a long-life emission line within ~100 meV

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