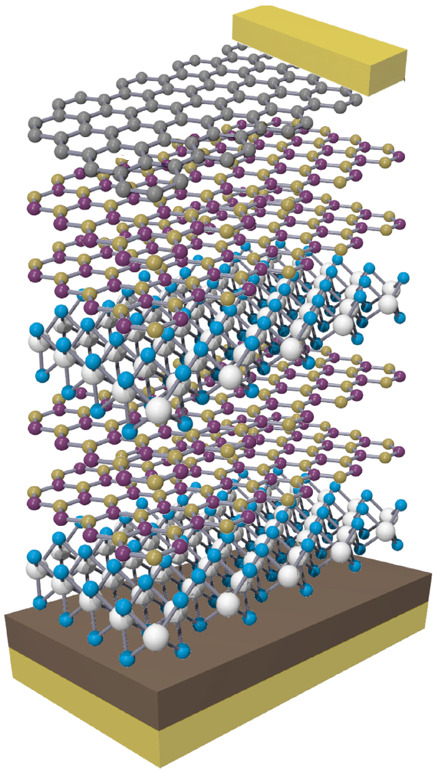
Control of excitons in multi-layer van der Waals heterostructures



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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:

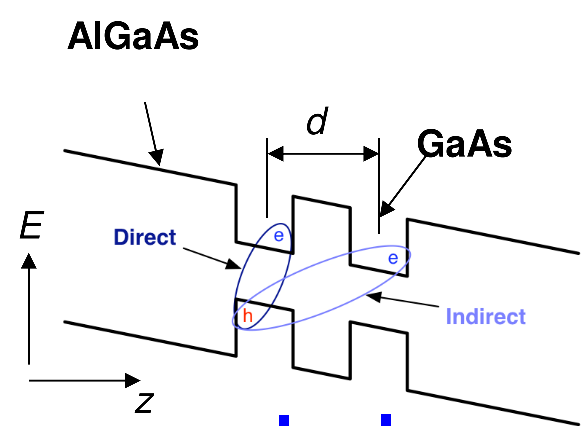
- bosons

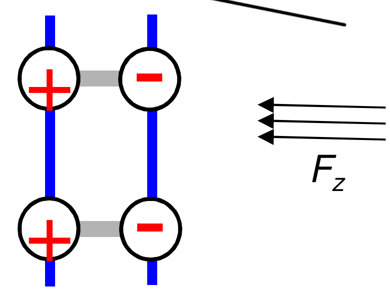
- long and controllable lifetime → long-range exciton transport

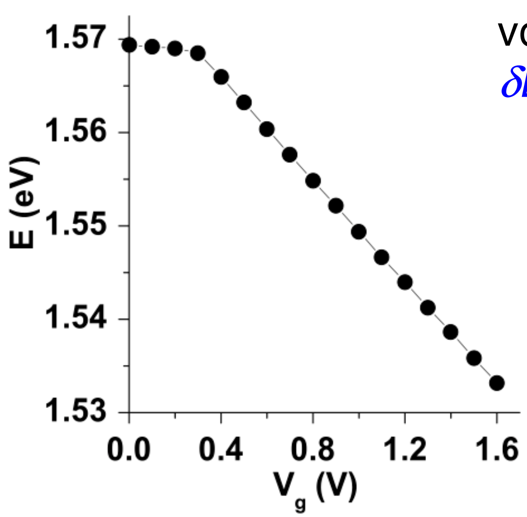
excitons screen disorder

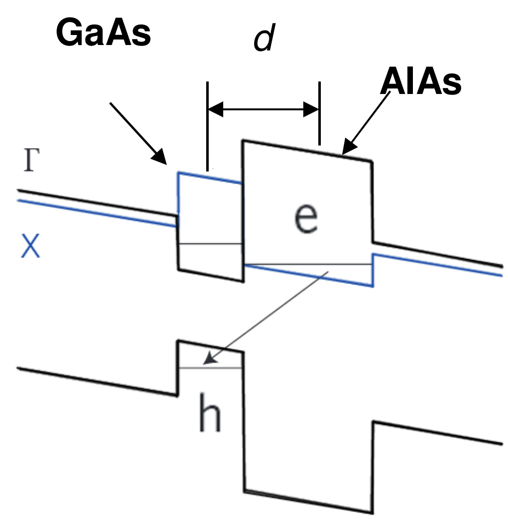
- built-in dipole moment

control of excitons by voltage:
$\delta E = edF_z$







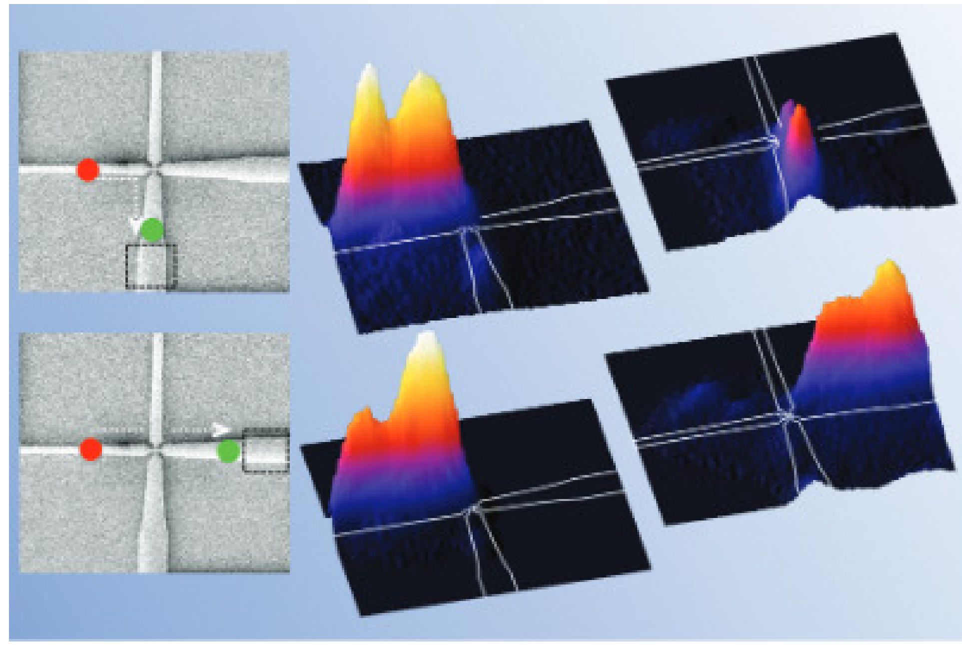


Opto-Electronic Devices with Indirect Excitons

- 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 $\mathrm{k}_B T \gtrsim E_{binding}$ excitons dissociate
- GaAs/AlAs devices can operate up to ~100K

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

Operation of exciton transistor and router

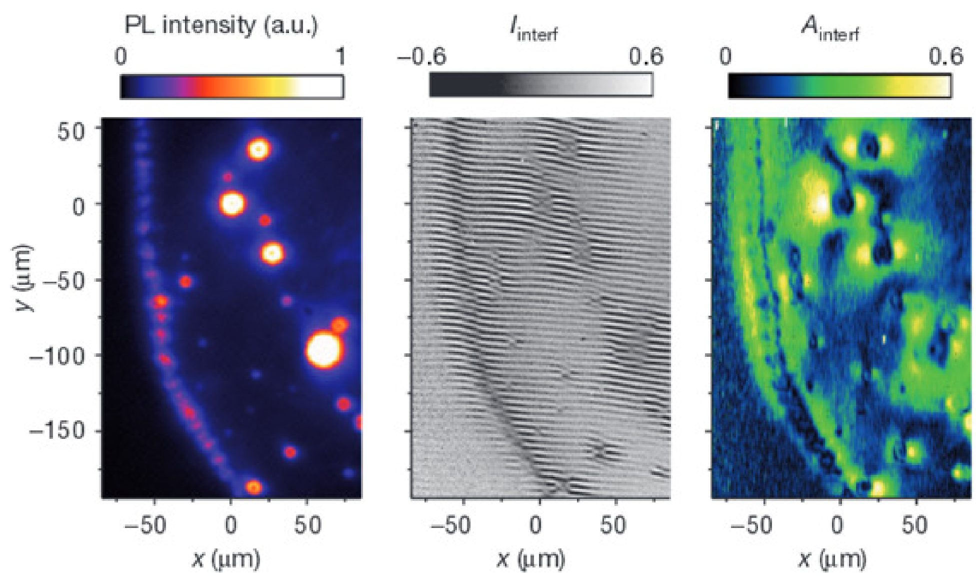


P. Andreakou, S.V. Poltavtsev, J.R. Leonard, E.V. Calman, M. Remeika, Y.Y. Kuznetsova, L.V. Butov, J. Wilkes, M. Hanson, A.C. Gossard. Optically controlled excitonic transistor, *Appl. Phys. Lett.* 104, 091101 (2014).

- talk today by Chelsey Dorow at 5:30 on potential energy gradients for excitons

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

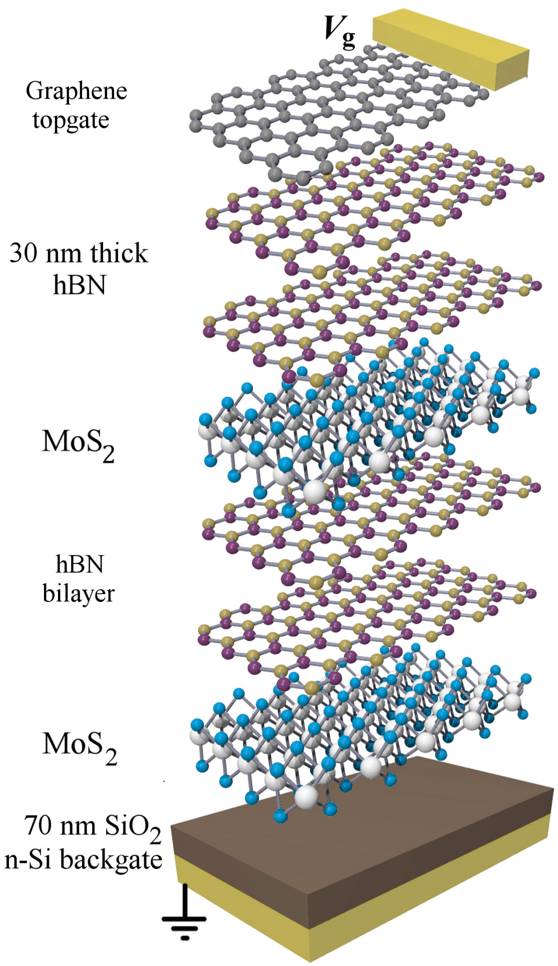


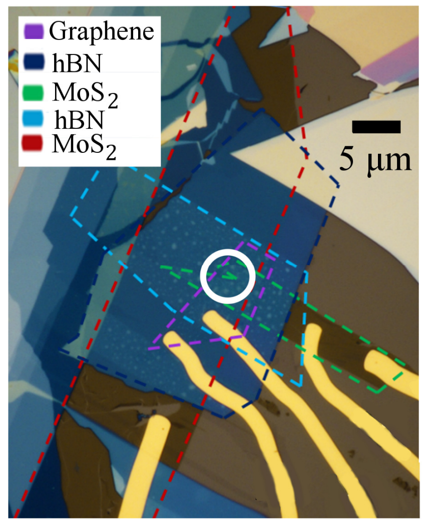
Regions of spontaneous coherence

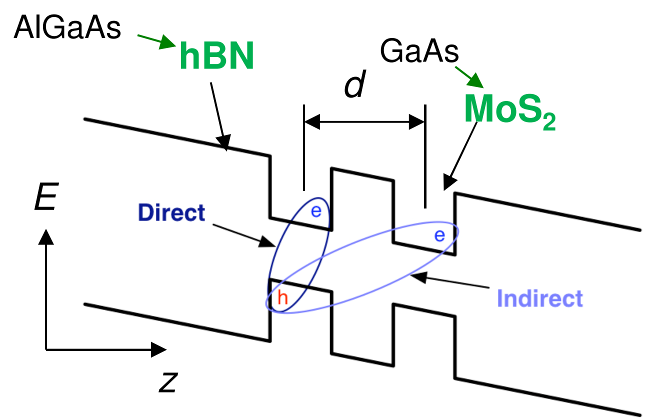
High, et al. *Nature* 483, 584 (2012)

Indirect Excitons in Transition Metal Dichalcogenide Structures

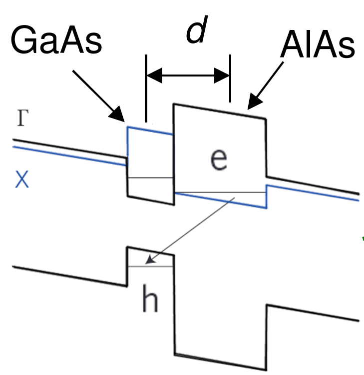
- Exciton binding energy is much greater than for GaAs and can support excitons up to room temperature and above

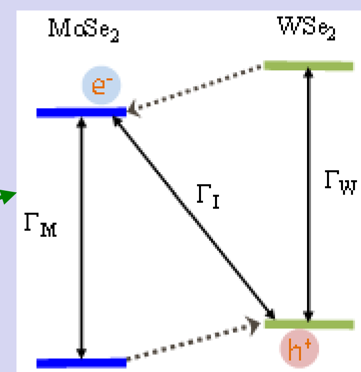






Calman, et al, *APL* 108, 101901 (2016).





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

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

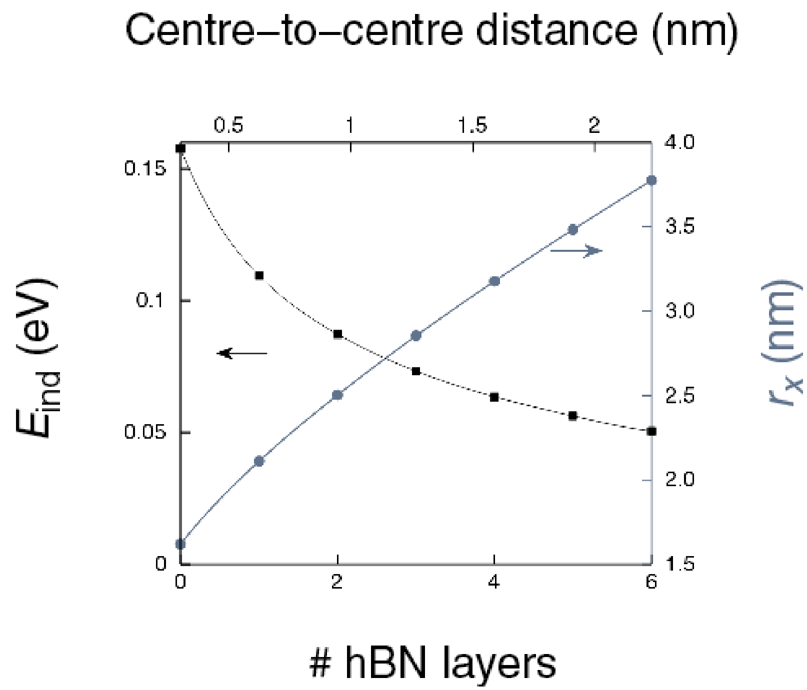
Indirect Excitons in van der Waals heterostructures

- Theory predicts superfluidity in a degenerate exciton gas at $T \sim 100\ K$

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

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

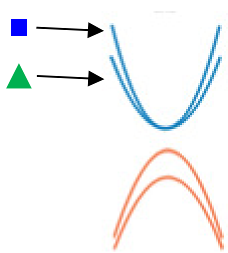
$$T_0^{\max} \sim 0.06 Ry_x$$

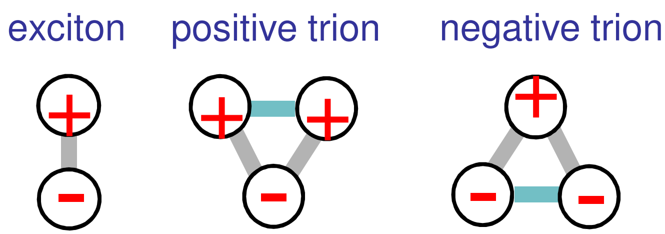


Fogler, Butov, Novoselov *Nat. Commun.* 5, 4555 (2014).

Excitons in MoS_2 structures: Temperature dependence

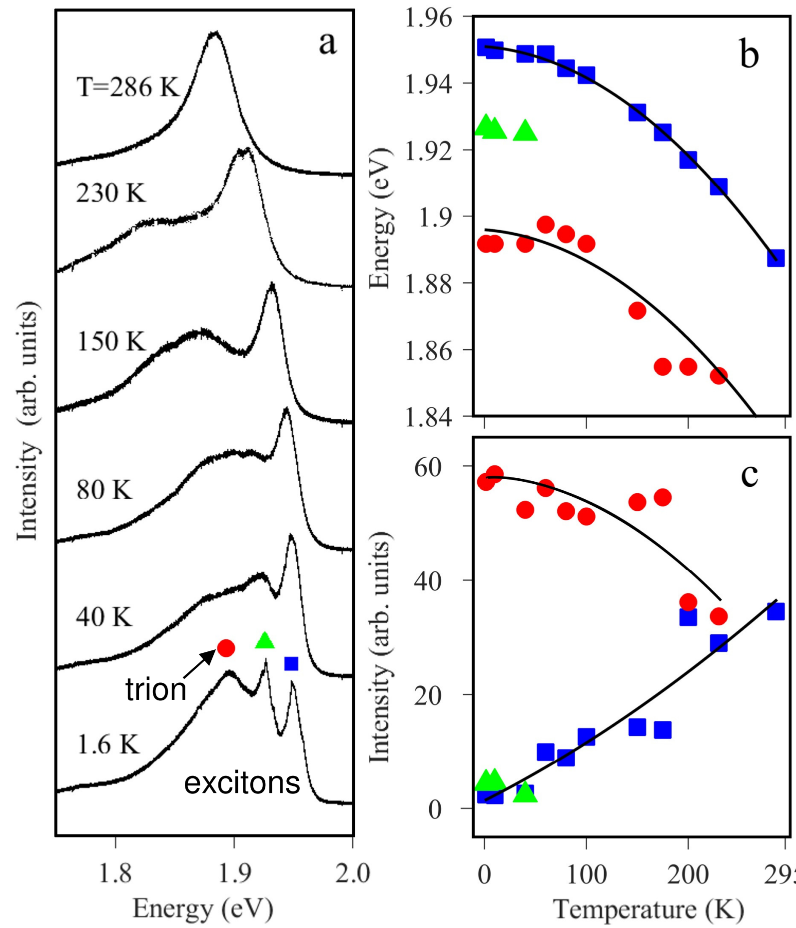
- 3 emission lines: 2 high energy exciton lines, 1 low energy trion line





- Exciton emission at room temperature

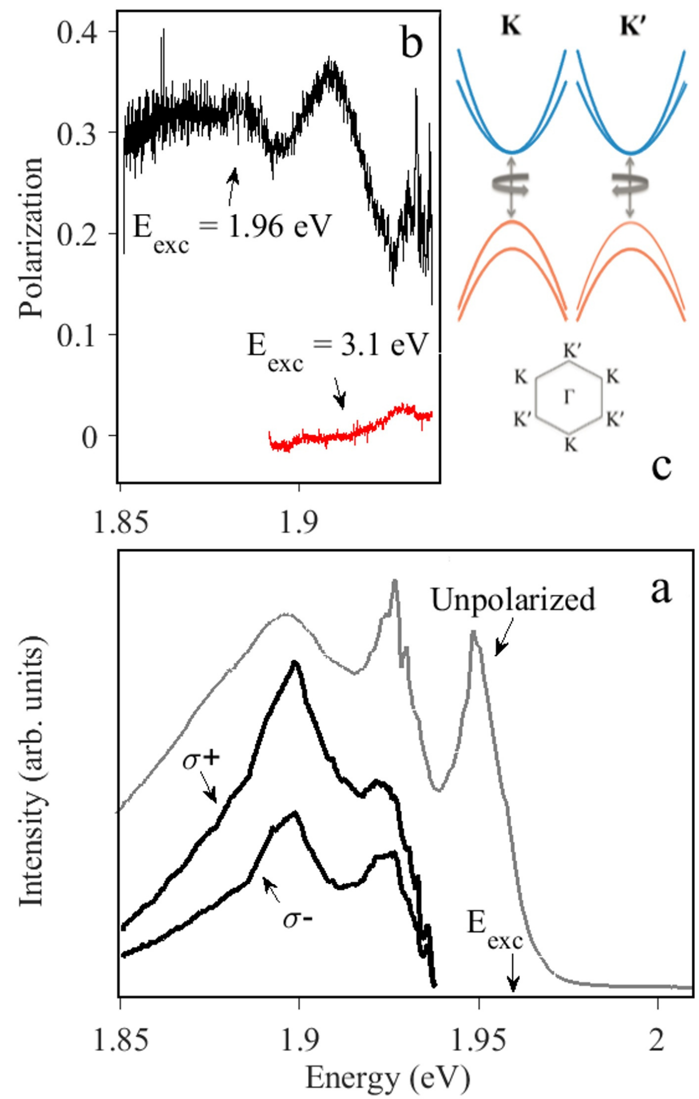
- The relative intensity of the high-energy exciton lines increase with T, consistent with the thermal dissociation of trions due to their smaller binding energy



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, *APL* 108, 101901 (2016).

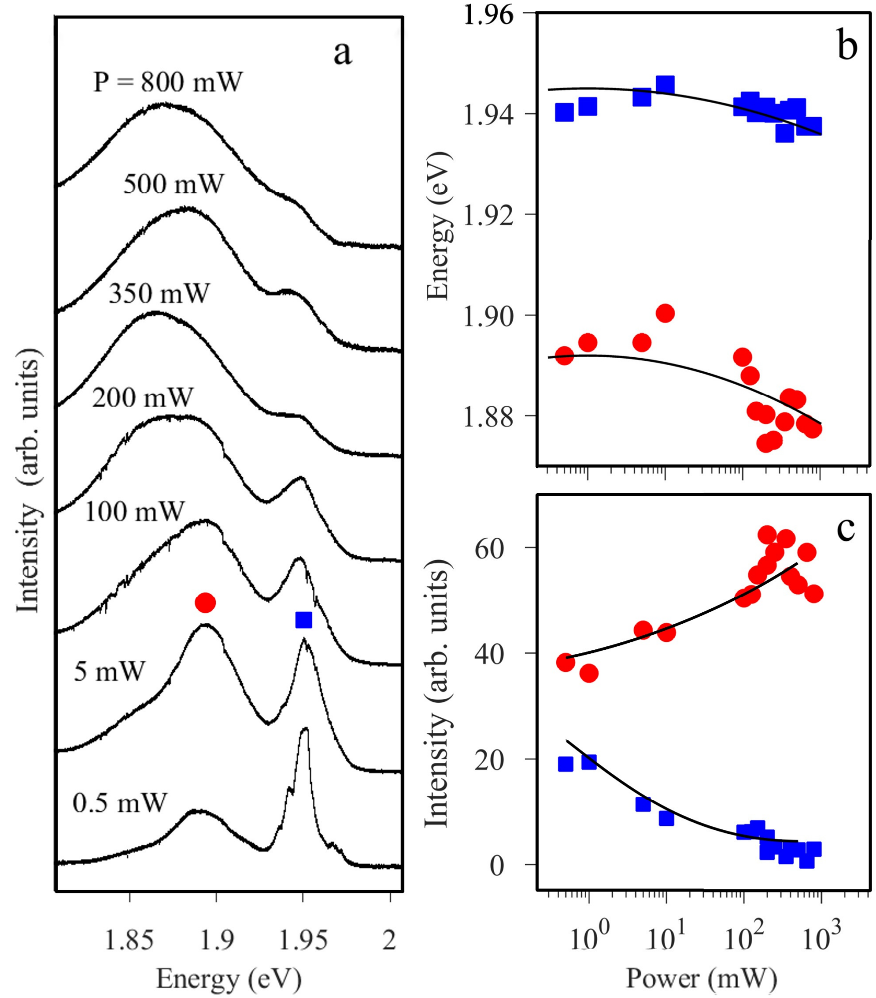
Long Spin Lifetime

- Exciting with circularly polarized light near exciton resonance produces polarized emission
- Indicates that spin lifetime is longer than energy relaxation time and exciton lifetime for nearly resonant $1.96\ \mathrm{eV}$ excitation
- Spin and valley indices are coupled, so that exciton spin relaxation requires inter-valley scattering
    - Exciting far from resonance with polarized light produces no polarization



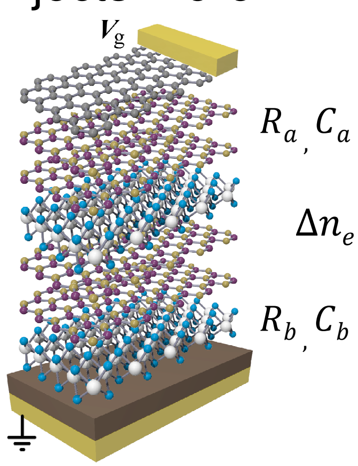
Excitons in MoS_2 structures: Power dependence

- 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

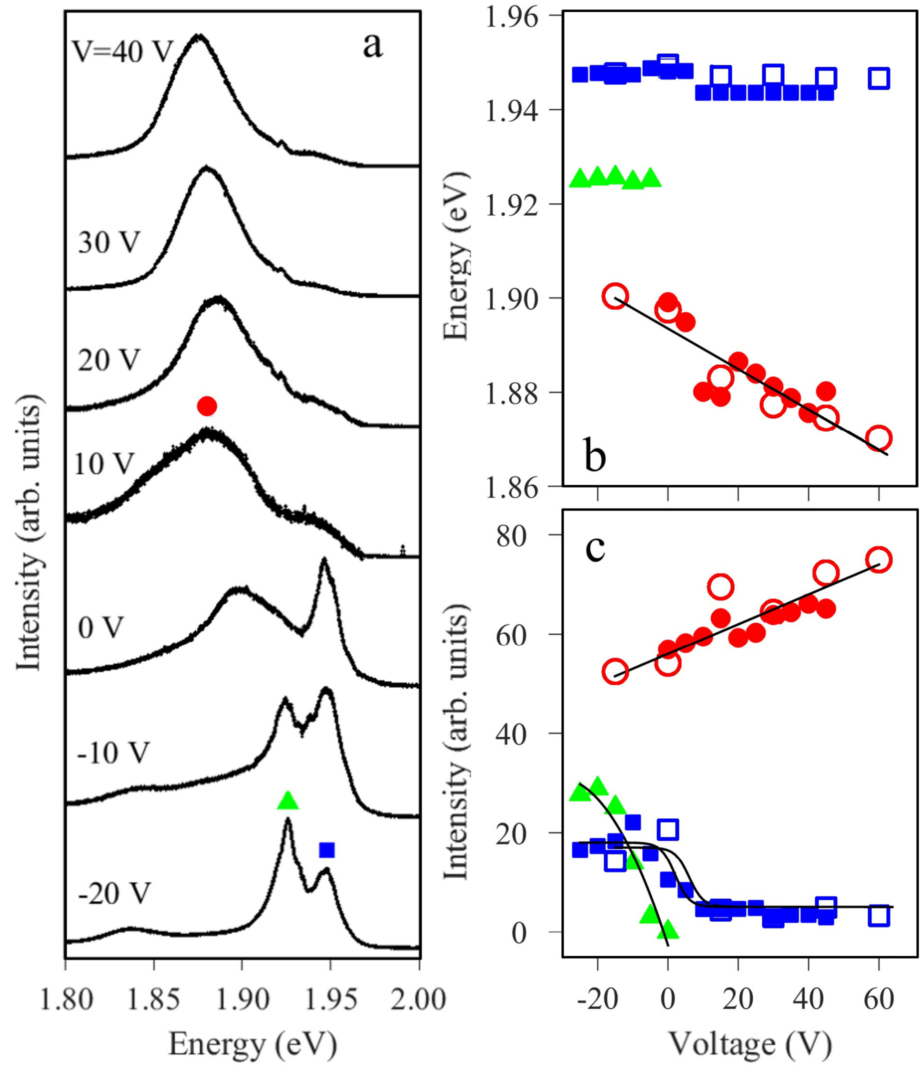


Towards the indirect regime: control of excitons by gate voltage

- Negative voltages suppress low energy (trion) line and enhance high energy (exciton) lines
- Positive voltages suppress high energy (exciton) lines and enhance low energy (trion) line
- System starts with non-zero carrier density, and negative voltage depletes carriers, while positive injects more



$$\Delta n_e = \frac{C_aR_a - C_bR_b}{R_a + R_b}\frac{V_g}{e}$$



Conclusion

- Observed three emission lines in PL spectra of a double quantum well MoS_2/hBN van der Waals heterostructure.
- Dependence of these lines on experimental parameters indicates that the two high energy lines correspond to the emission of neutral excitons and the lowest energy line to the emission of charged excitons (trions).
- Demonstrated control of the exciton emission by:
  - Temperature
  - Helicity of optical excitation
  - Excitation power
  - Gate voltage
- Van der Waals heterostructures provide new prospects for studying excitons at high temperatures

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$$T_0 = \frac{2\pi\hbar 2}{m_x} n_x = \frac{4\pi memh}{m_x} n(a_x)^2 Ry_x$$

$$n^{max} {a_x}^2 \approx 0.02$$

$$T_0{}^{max} \approx 0.06Ryx$$