Lecture 2:
Tunable quantum confinement of excitons using electric fields

Atac Imamoglu

ETH Zurich

Co-workers:

Ankur Thureja, Puneet Murty

Ivan Amelio, Martin Kroner

Song Liu, Katuyan Barmak (Columbia)

Kenji Watanabe, Takashi Taniguchi (NIMS)

A key goal of solid-state quantum optics:

- Realizing an array of anharmonic quantum emitters whose properties - such as resonance energy & photon emission rate – are set through electric field tunable quantum confinement

A key goal of solid-state quantum optics:

- Realizing an array of anharmonic quantum emitters whose properties - such as resonance energy & photon emission rate – are set through electric field tunable quantum confinement

- 2D excitons are weakly interacting: reduced dimensionality + strong-coupling to cavities are key for realizing strong interactions - photon blockade effect

A key goal of solid-state quantum optics:

- Realizing an array of anharmonic quantum emitters whose properties - such as resonance energy & photon emission rate – are set through electric field tunable quantum confinement

- 2D excitons are weakly interacting: reduced dimensionality + strong-coupling to cavities are key for realizing strong interactions - photon blockade effect

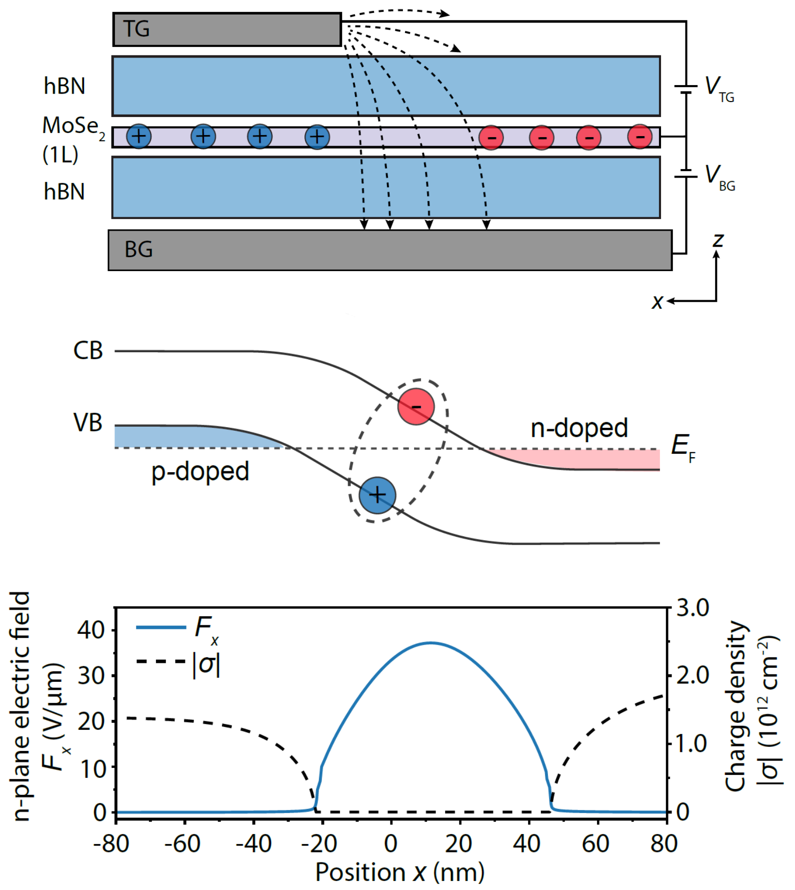
- How to go from 2D excitons to isolated 1D or 0D excitons?

  - excitons are neutral but are polarizable using dc electric fields (*F*): $\Delta E_S = -\frac{1}{2}\alpha F^2$

  - Spatially inhomogeneous strong in-plane electric fields *F*(r) could confine excitons at the field maxima

Our approach: electric-field confinement of exciton center-of-mass motion using gated TMD structures

- Strong inhomogeneous electric fields can be generated using proximal gates which effect a monolayer p-i-n diode
- Strong exciton binding (E_x = 200 meV) ensures that excitons are resilient against ionization
- Peak in-plane fields of F = 0.1 V/nm extending over 50 nm create a harmonic potential with length scale $\ell_x = \sqrt{\frac{\hbar}{m\omega_x}} \leq 10$ nm.

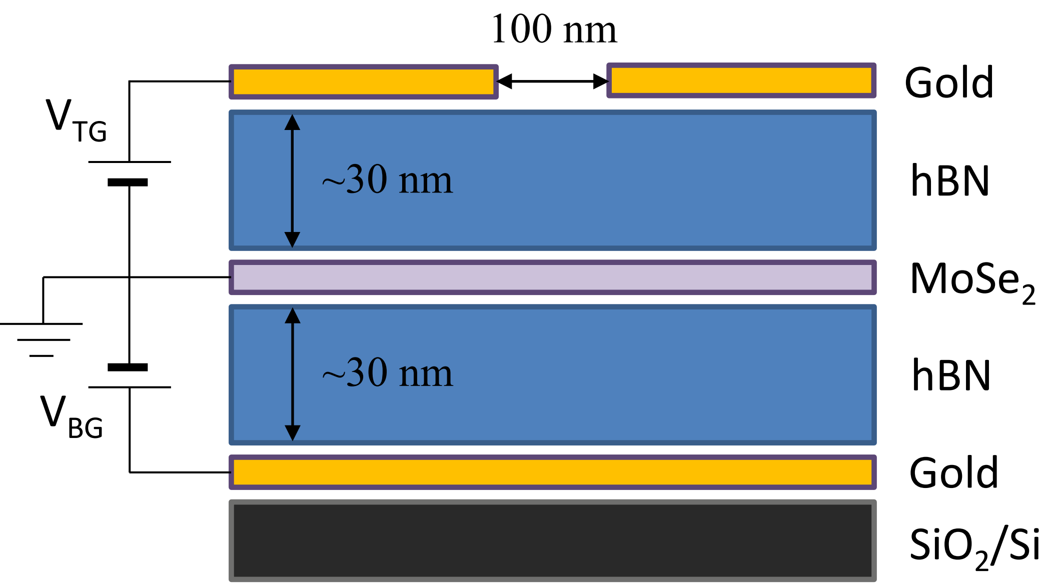


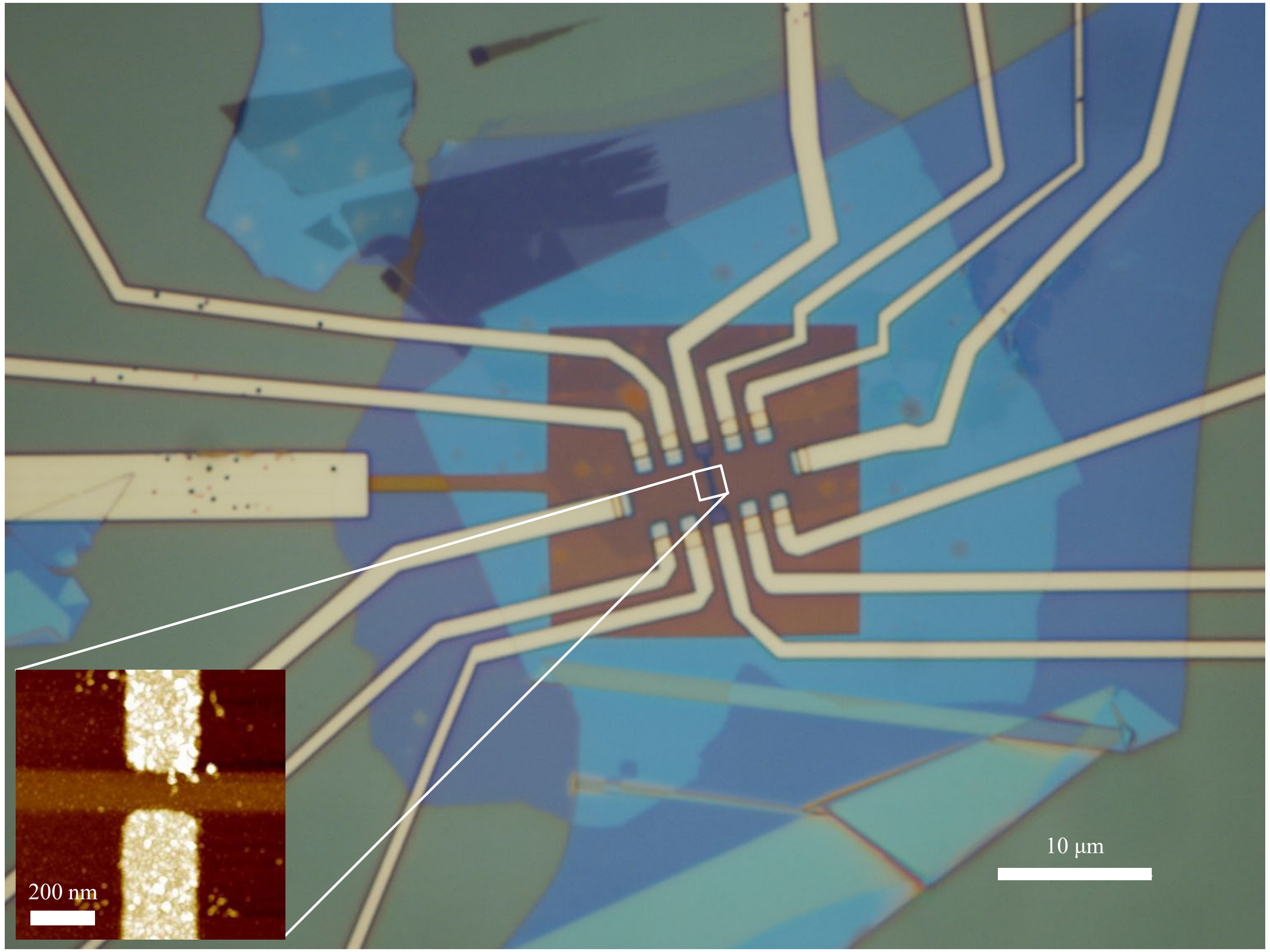
Quantum confinement of neutral excitons using electric fields

Device structure

- Stack:

Au back gate/ hBN / 1L $MoSe_2$ / hBN / Au split gate

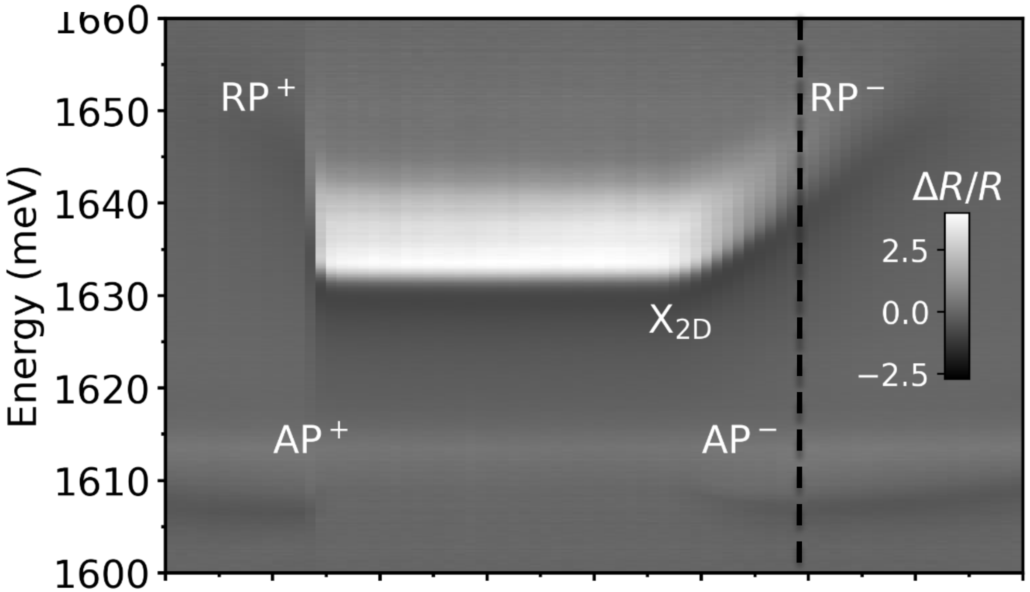




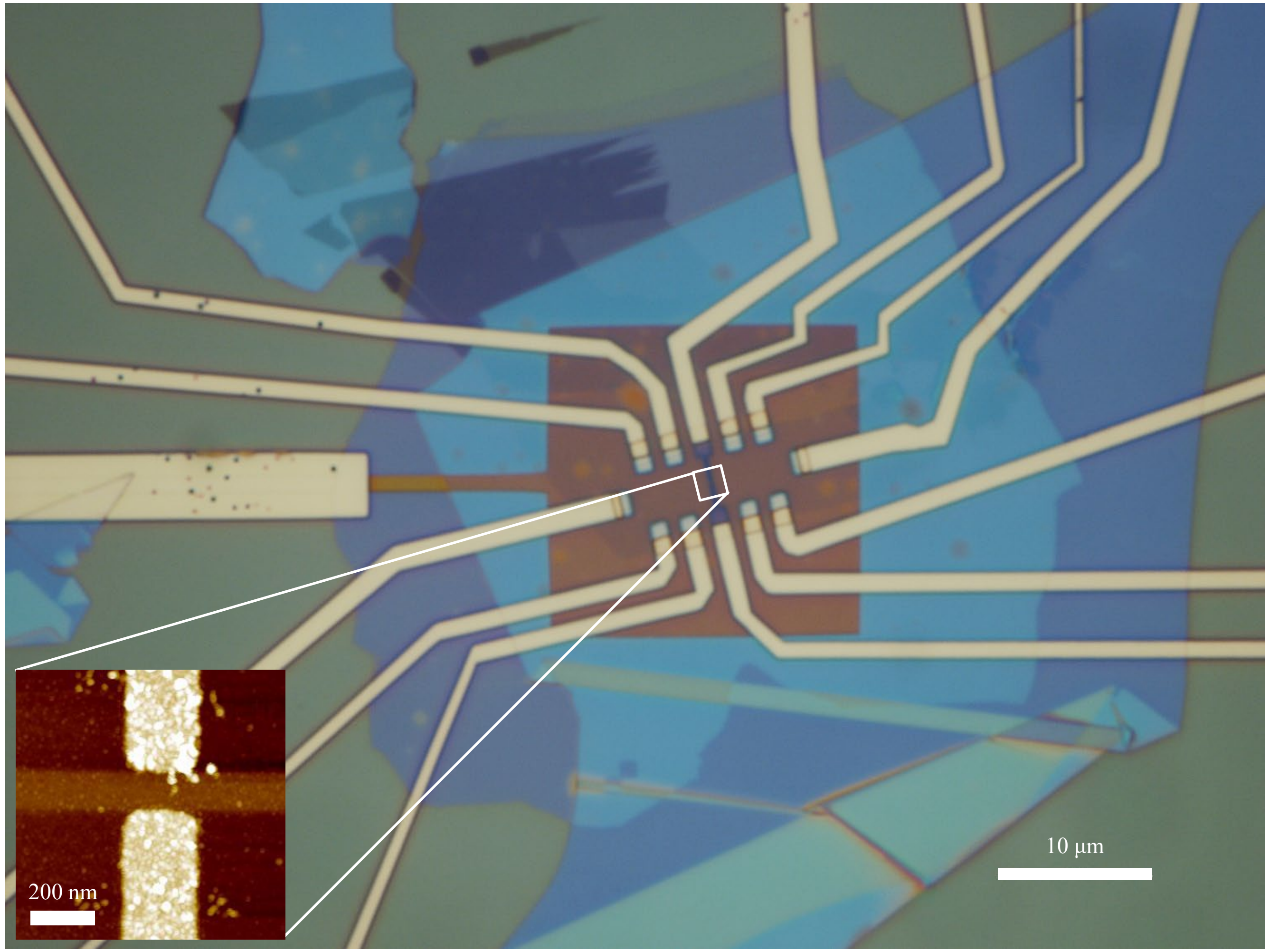
3nm Ti / 7 nm Au split gate ➔ Optically transparent

Quantum confinement of neutral excitons using electric fields

Set top gate to 0 V

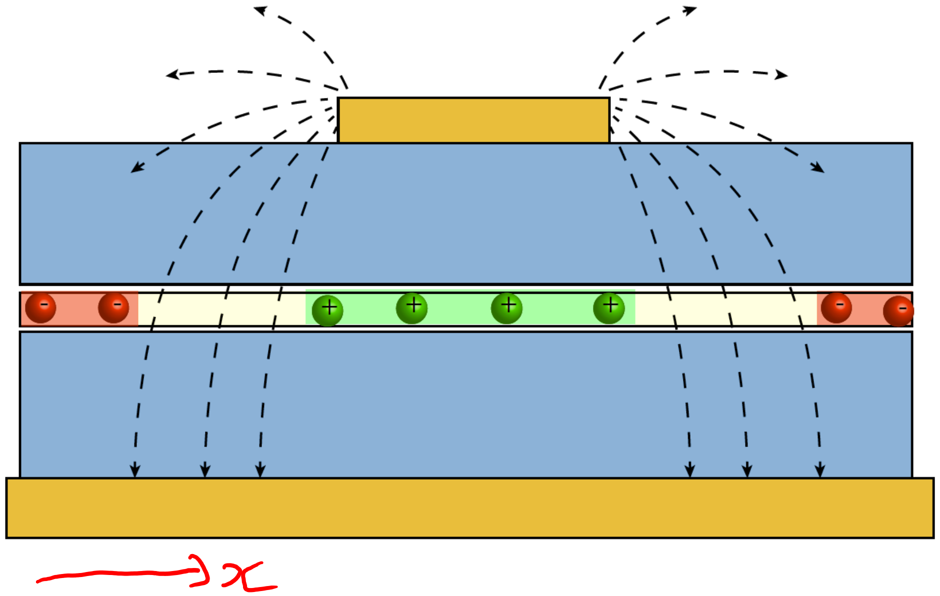


For V_{BG} = 5V (black dashed line), the sample is electron doped

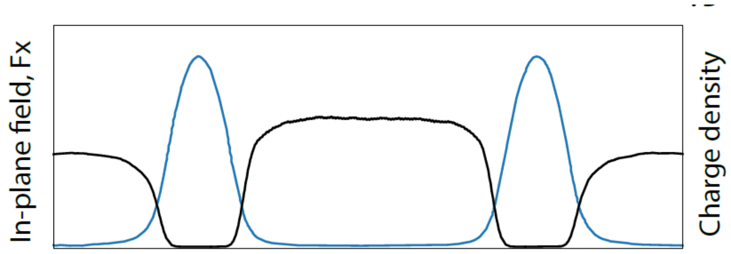


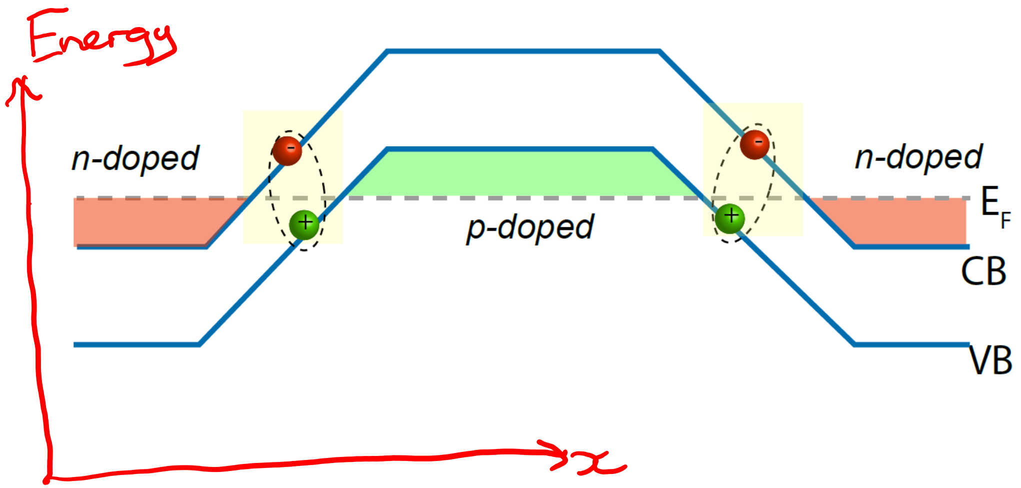
3nm Ti / 7 nm Au split gate ➔ Optically transparent

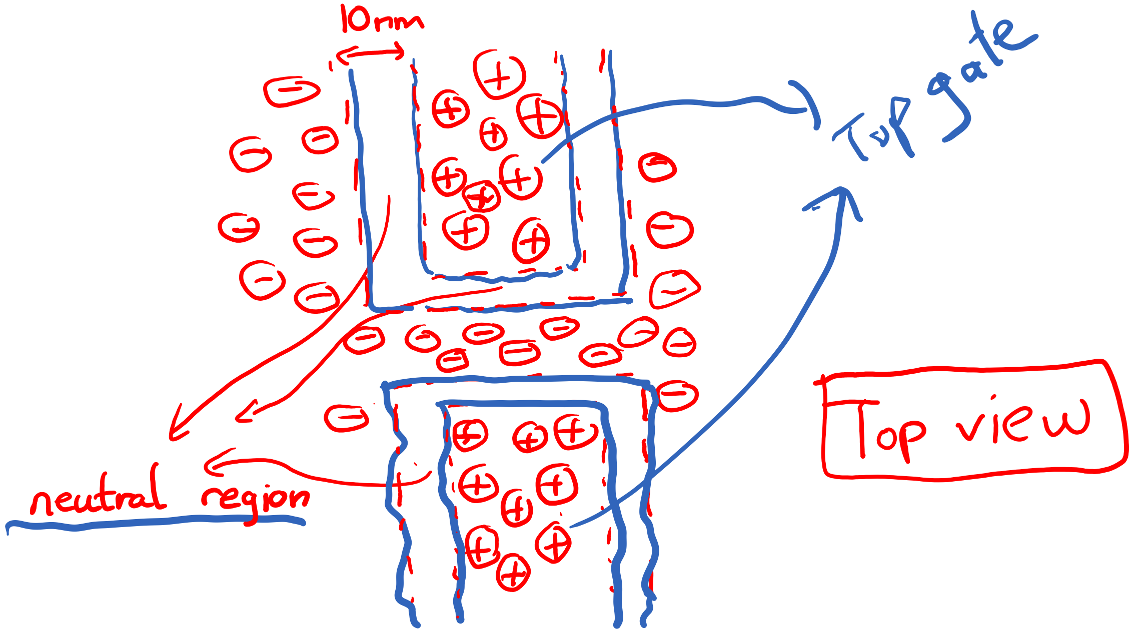
Quantum confined excitons in a p-i-n diode



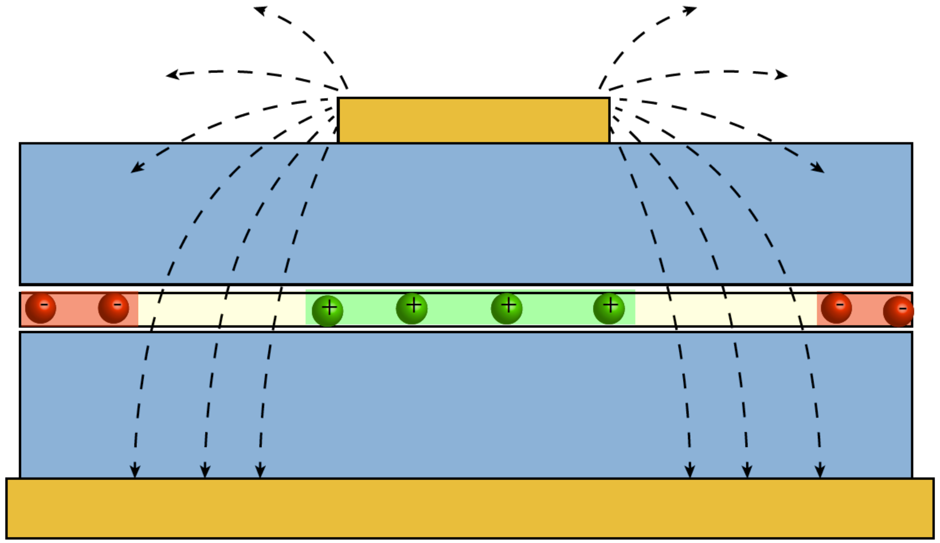
As we reduce V_{TG} we can hole dope under the top gate; there is large electric field in the i-region that separates p- and n-doped regions



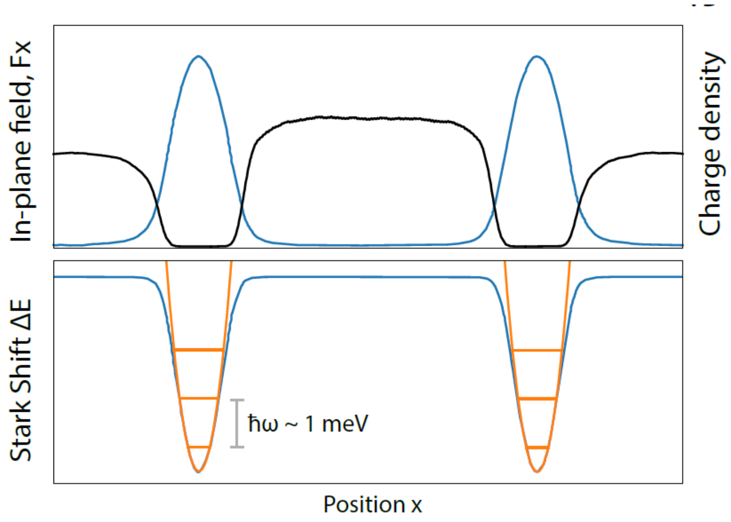




Quantum confined excitons in a p-i-n diode

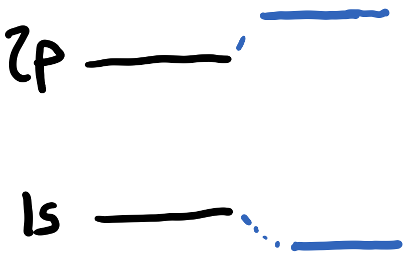


As we reduce V_{TG} we can hole dope under the top gate; there is large electric field in the i-region that separates p- and n-doped regions



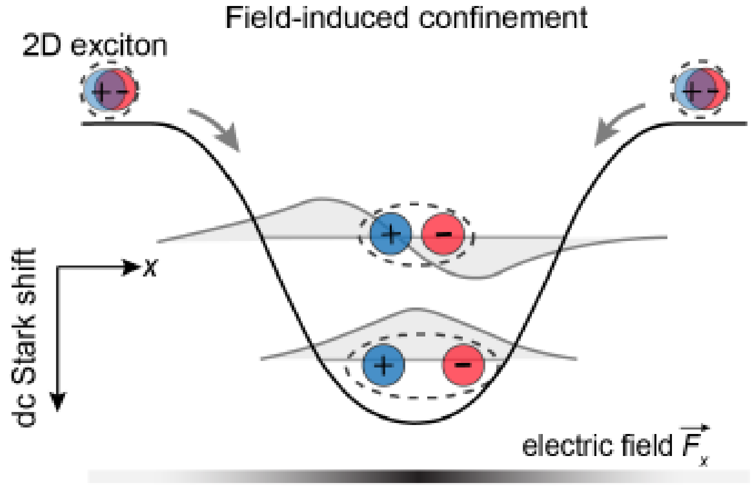
dc - Stark effect

$$\Delta E_S = -\frac{1}{2}\alpha F_x(x)^2$$

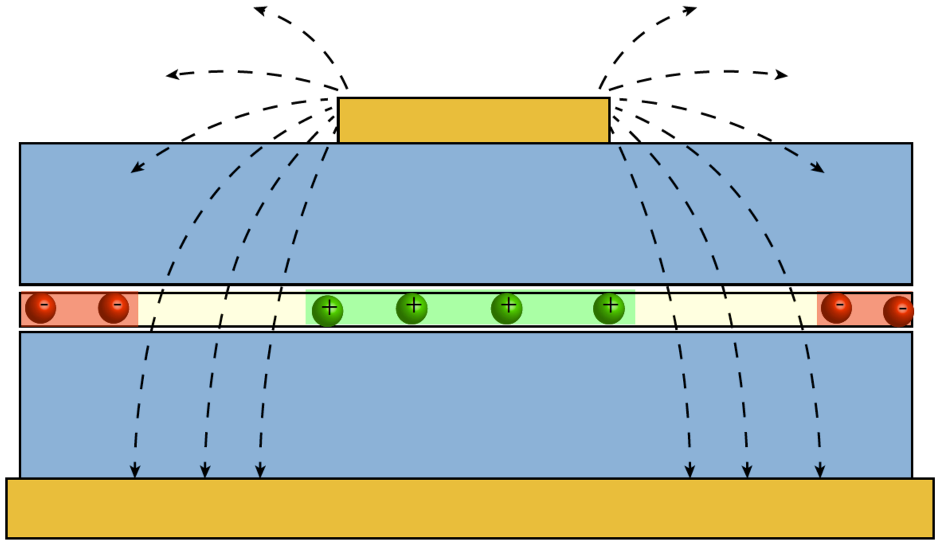


E ≠ 0 mixes 1s & 2p excitons and lowers the 1s exciton energy

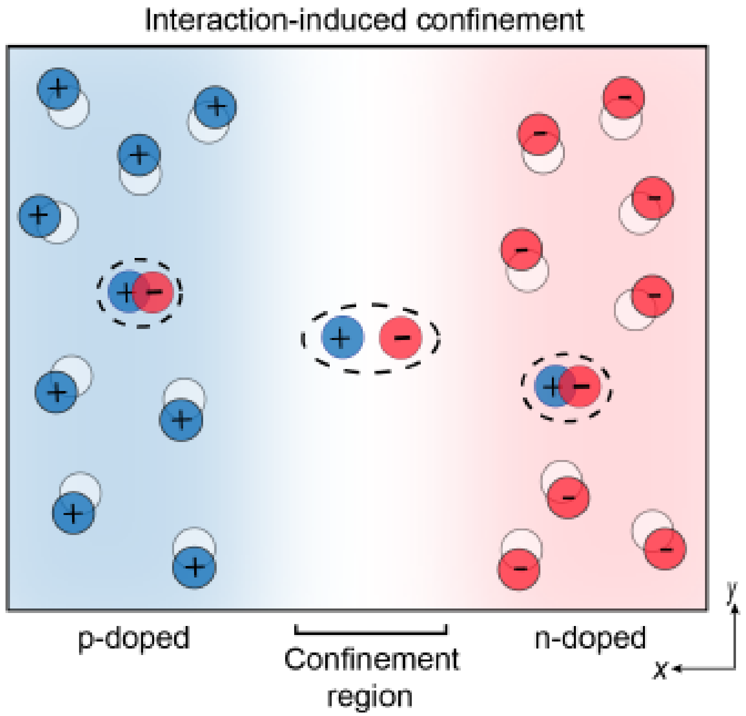
→ A trap for excitons at E = Emax



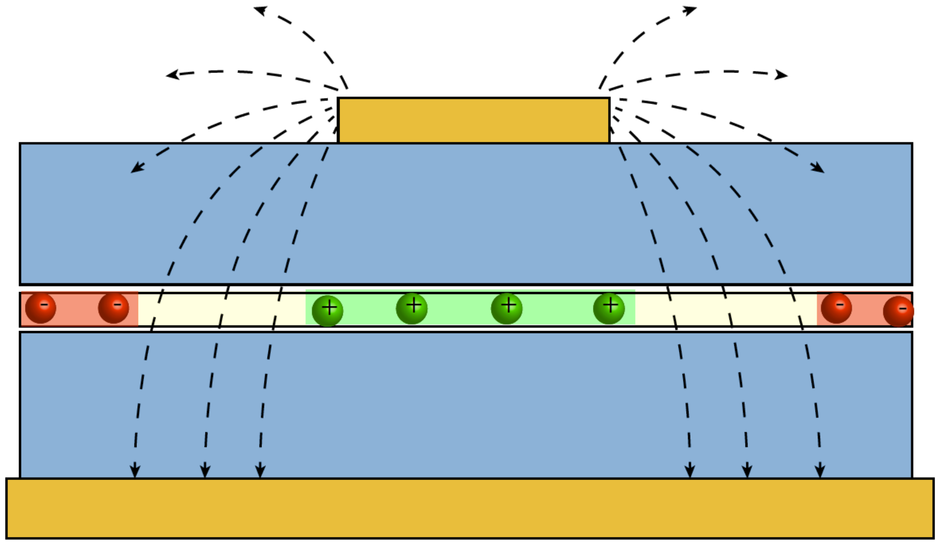
Quantum confined excitons in a p-i-n diode



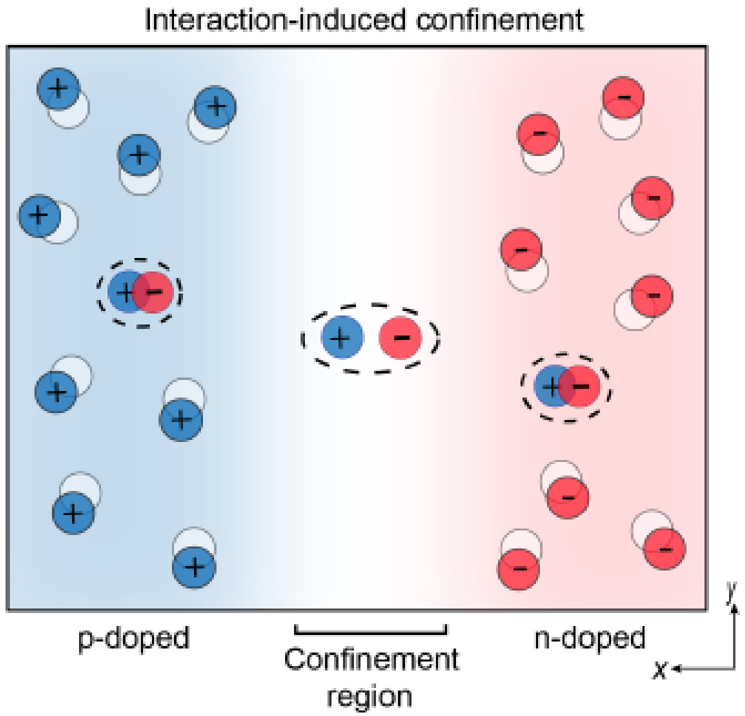
effective repulsive interaction between excitons & charges (leading to repulsive polaron) creates an effective excitonic potential



Quantum confined excitons in a p-i-n diode

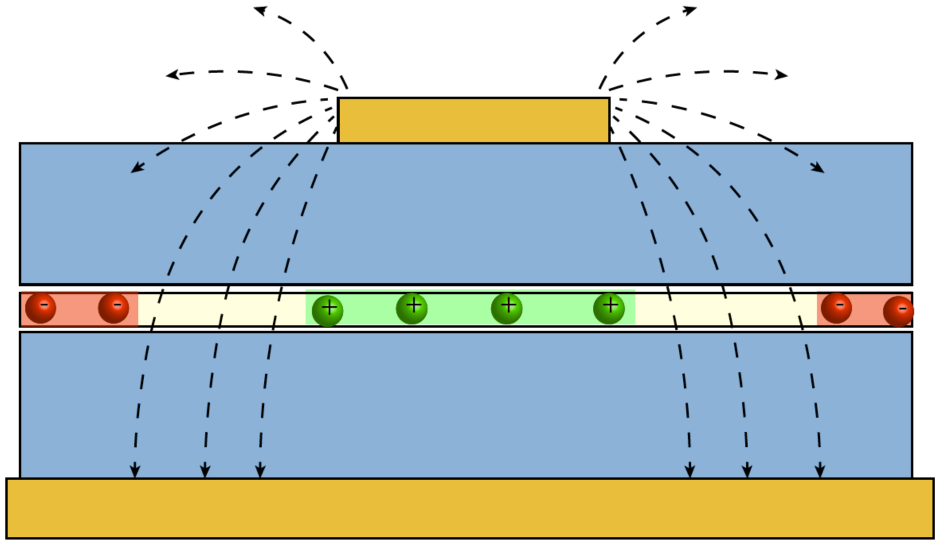


effective repulsive interaction between excitons & charges (leading to repulsive polaron) creates an effective excitonic potential

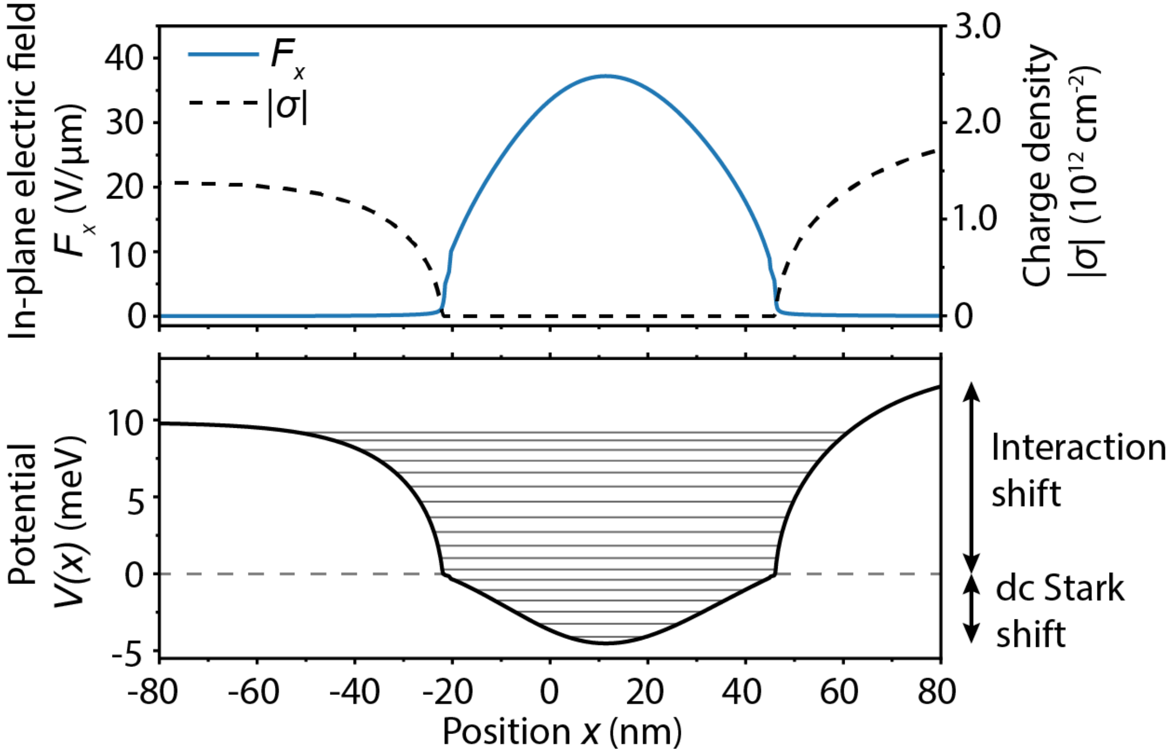


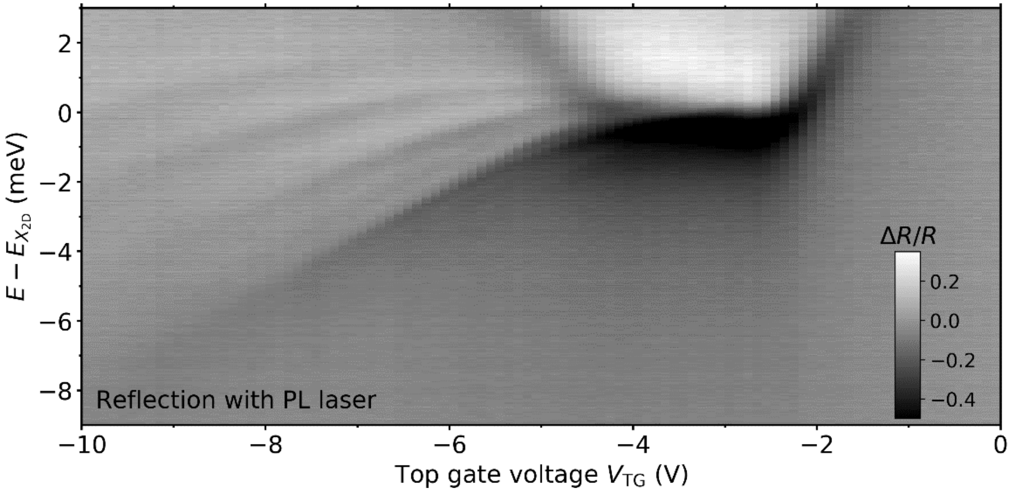
- The large electric field confines the center-of-mass motion but couples the 1s exciton (relative electron-hole motion) state to a continuum of ionized electron-hole states. Yet, small Bohr radius ensures that excitons decay predominantly radiatively.
- The exciton-electron interaction induced confinement potential has an imaginary part due to decay into attractive polaron branch.

Quantum confined excitons in a p-i-n diode



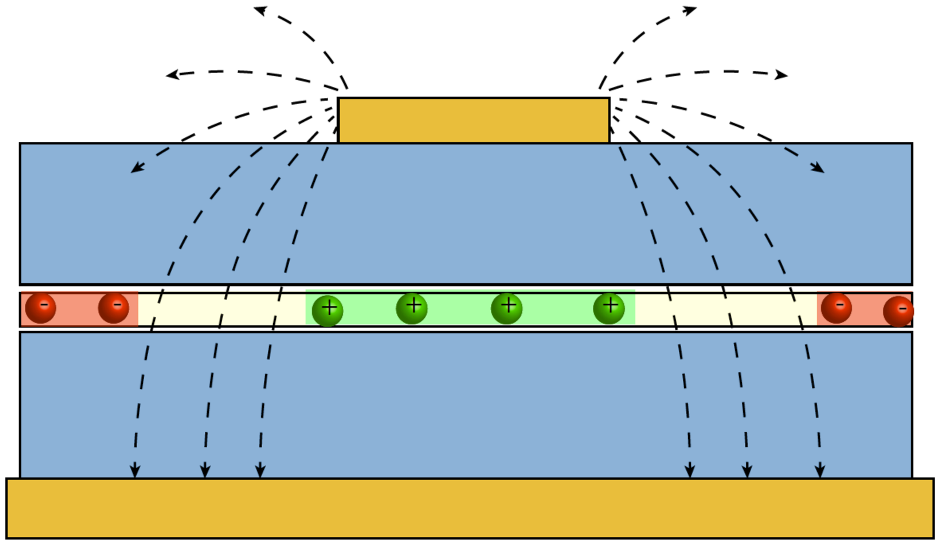
$$V(x) = -\frac{1}{2}\alpha F_x(x)^2 + \beta \cdot \sigma(x)$$

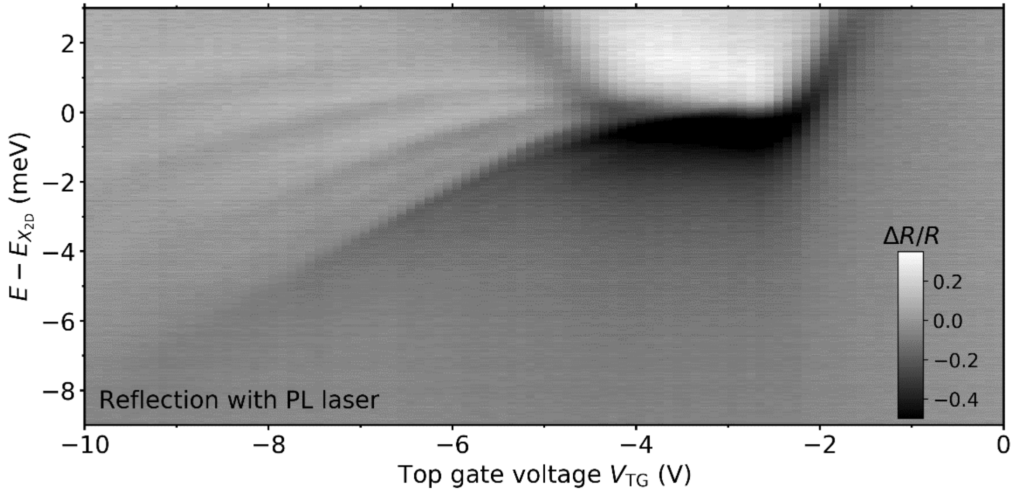




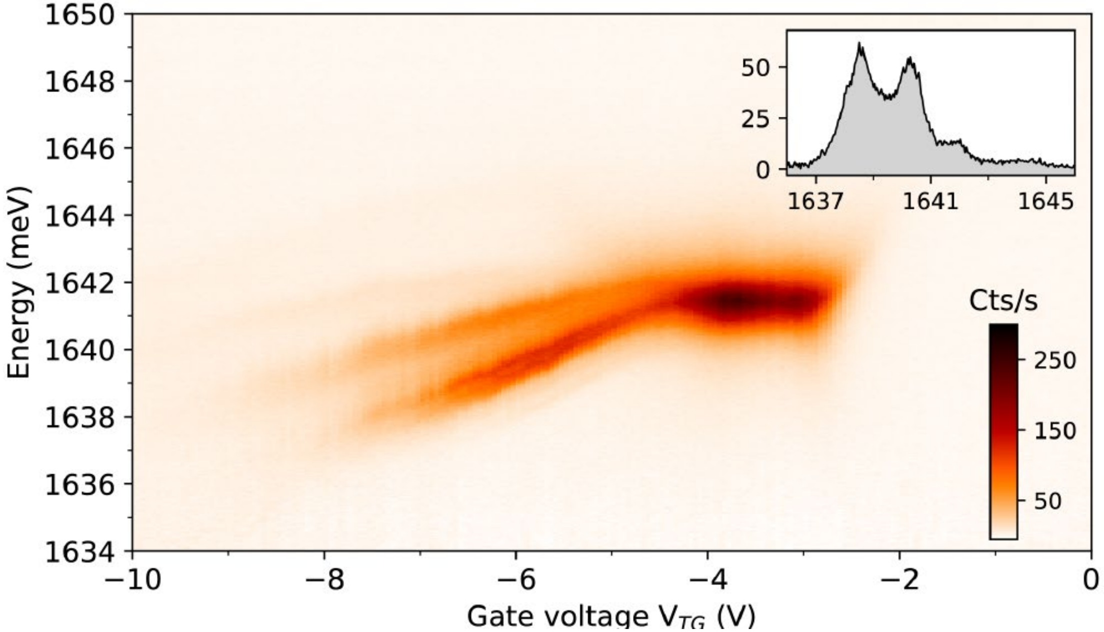
➢ **Confined states with E > E_{2D}!**

Quantum confined excitons in a p-i-n diode

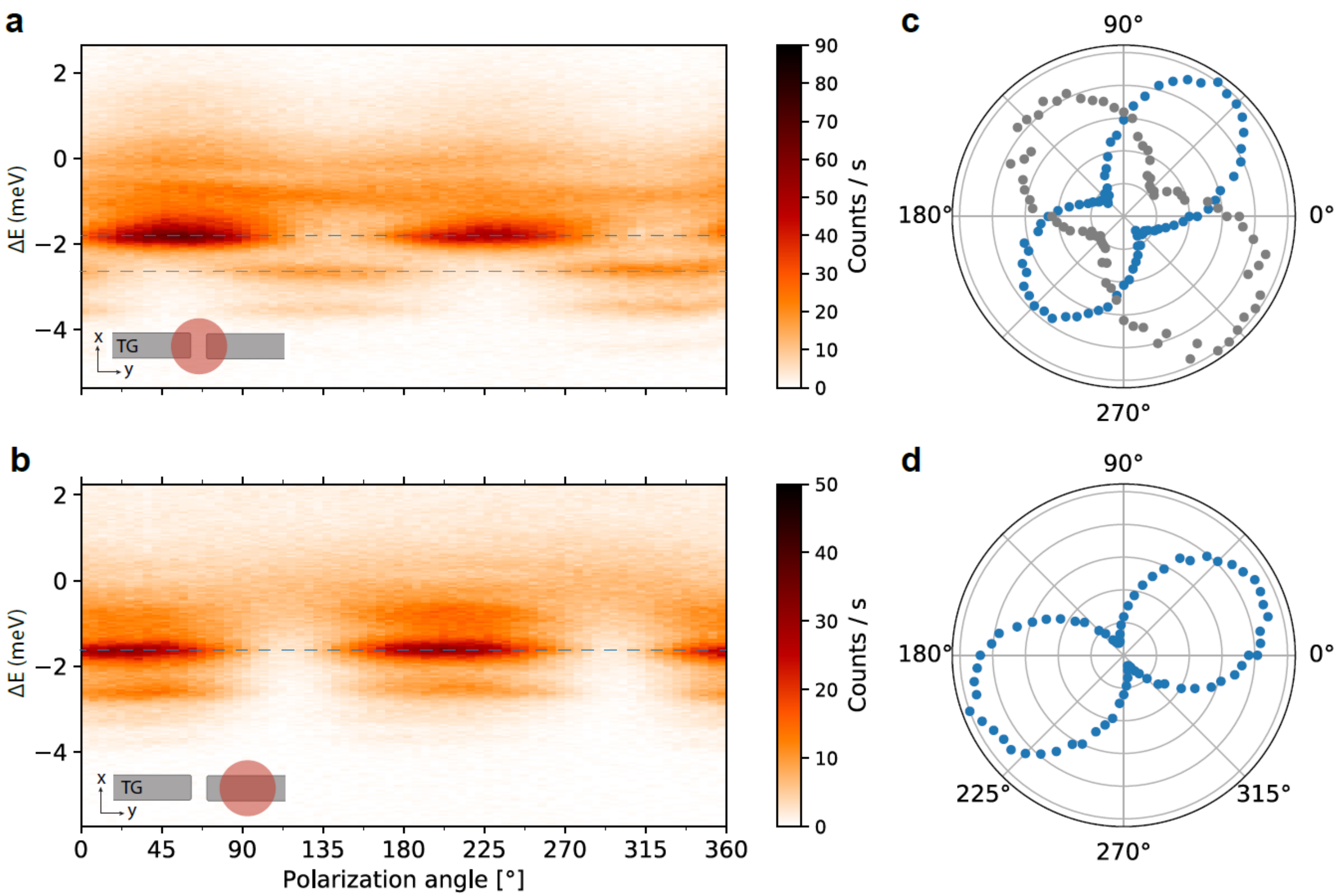




Photoluminescence



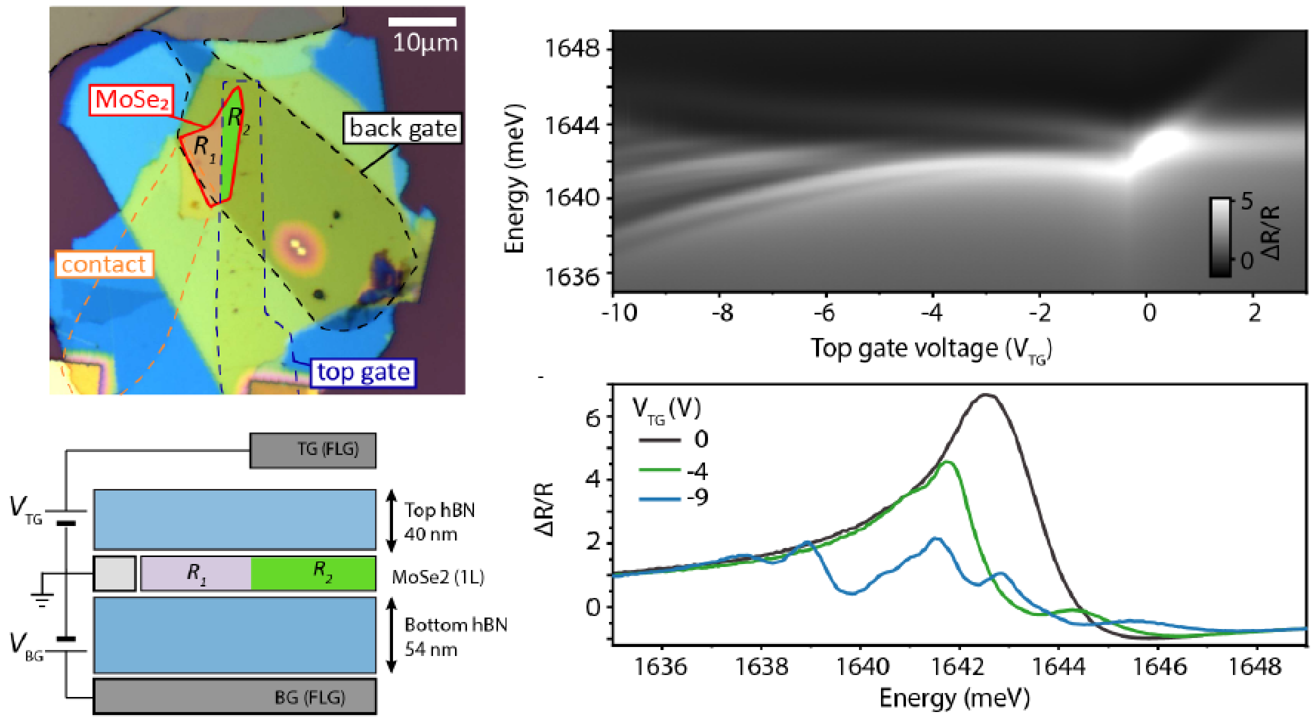
Evidence for 1D confinement: linearly polarized emission



Long-range electron-hole exchange ensures that the exciton emission is polarized along the wire

Quantum confinement of excitons in another device

- Simple structure: a top graphene gate that only partially covers the TMD: 1D excitons along the edge of the top gate

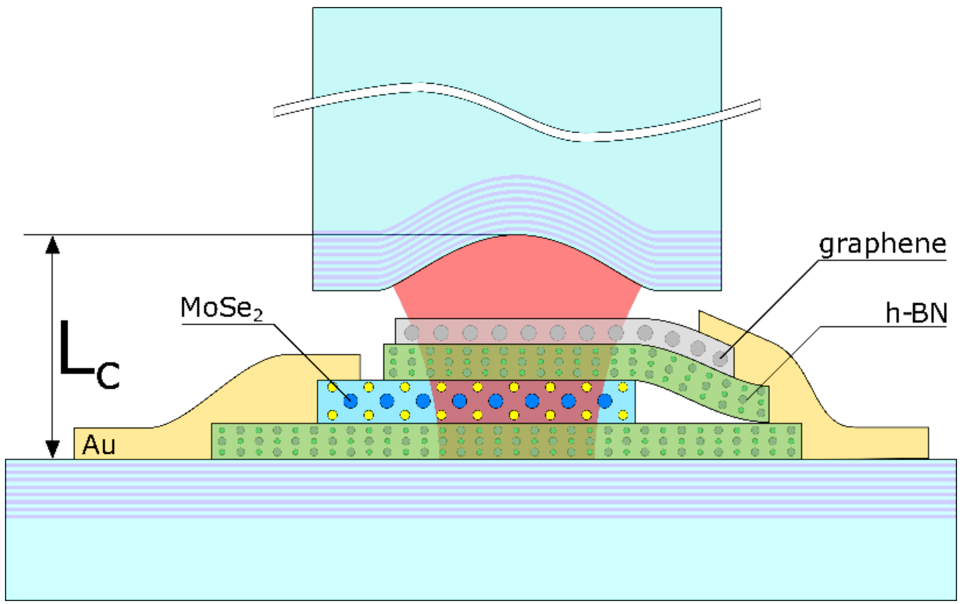


A terrible p-i-n photo-detector but an exciting quantum device!

Next steps

- Strongly interacting photons: so far the successful efforts used either 0D emitters (transmons in circuit-QED) or Rydberg excitations from 3D atomic ensembles.

  - a 1D exciton wire in a 0D cavity as a solid-state photonic system with strong polariton interactions in the photon blockade regime



Next steps

- Strongly interacting photons: so far the successful efforts used either 0D emitters (transmons in circuit-QED) or Rydberg excitations from 3D atomic ensembles).

  - a 1D exciton wire in a 0D cavity as a solid-state photonic system with strong polariton interactions in the photon blockade regime

- 1D excitons could have dipolar length exceeding 100 nm: transition from a Tonks-Girardeau gas to a Wigner crystal of excitons

Next steps

- Strongly interacting photons: so far the successful efforts used either 0D emitters (transmons in circuit-QED) or Rydberg excitations from 3D atomic ensembles).

  - a 1D exciton wire in a 0D cavity as a solid-state photonic system with strong polariton interactions in the photon blockade regime

- 1D excitons could have dipolar length exceeding 100 nm: transition from a Tonks-Girardeau gas to a Wigner crystal of excitons
- Synthetic gauge fields for photons: $qA = \alpha E \times B$

Next steps

- Strongly interacting photons: so far the successful efforts used either 0D emitters (transmons in circuit-QED) or Rydberg excitations from 3D atomic ensembles).

  - a 1D exciton wire in a 0D cavity as a solid-state photonic system with strong polariton interactions in the photon blockade regime

- 1D excitons could have dipolar length exceeding 100 nm: transition from a Tonks-Girardeau gas to a Wigner crystal of excitons
- Synthetic gauge fields for photons: $qA = \alpha\ E \times B$
- Fully electrically defined and tunable quantum dots in monolayer TMDs.