Quantum confined excitons in two-dimensional materials

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Many discussions with:

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Congratulations Eugene!

Outline

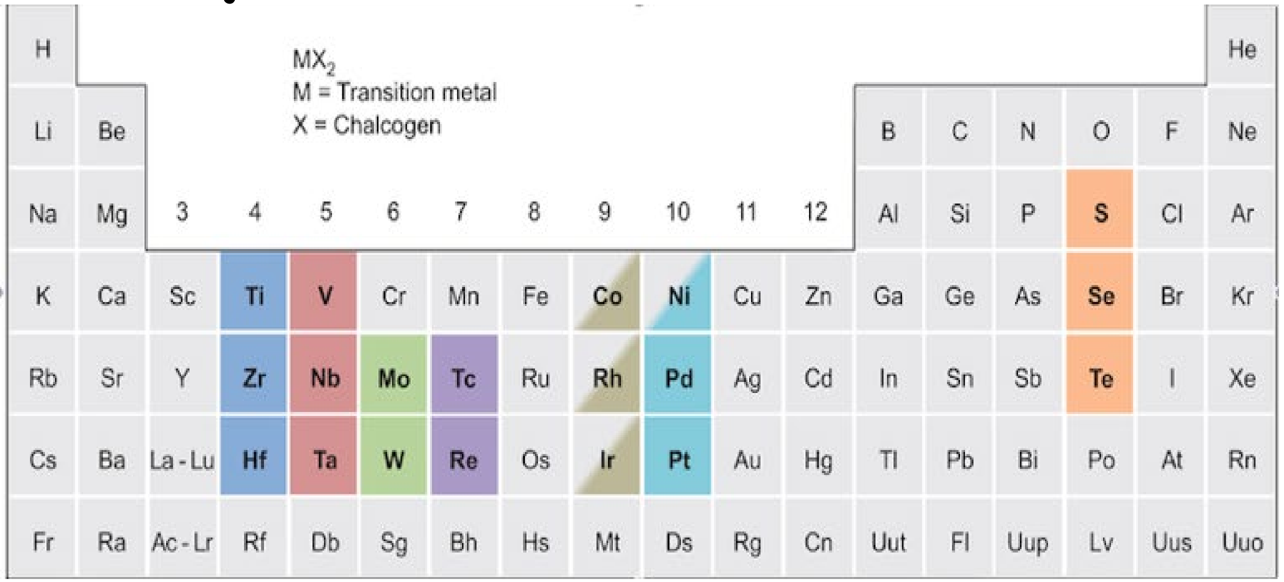
- Elementary optical excitations of transition metal dichalcogenide (TMD) monolayers
- Electrical control of optical properties: realization of quantum confined excitons in a monolayer p-i-n junction
- Prospects for strongly interacting excitons and polaritons

Materials: Transition metal dichalcogenides (TMD) - layered 2D semiconductors

Formula: MX_2

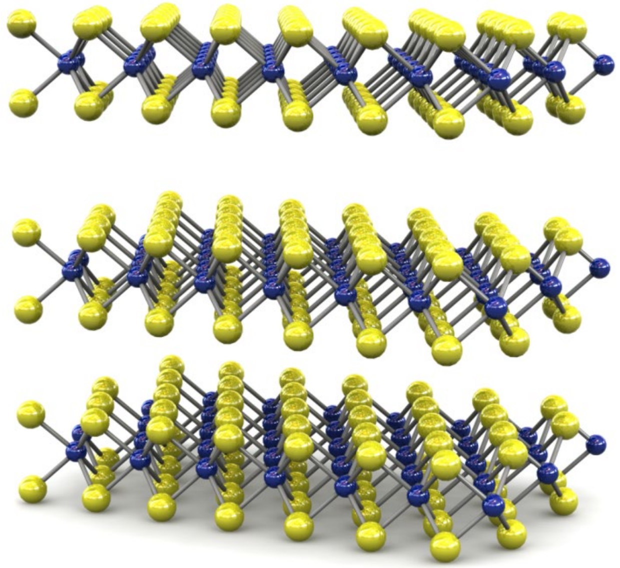
M = Transition Metal

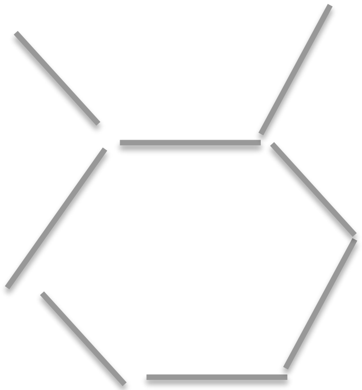
X = Chalcogen

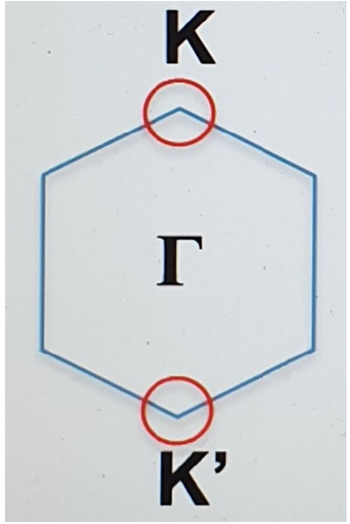


Electrical property	Material
Semiconducting	MoS_2 $MoSe_2$ WS_2 WSe_2 $MoTe_2$ WTe_2
Semimetallic	TiS_2 $TiSe_2$
Metallic, CDW, Superconducting	$NbSe_2$ NbS_2 $NbTe_2$ TaS_2 $TaSe_2$ $TaTe_2$

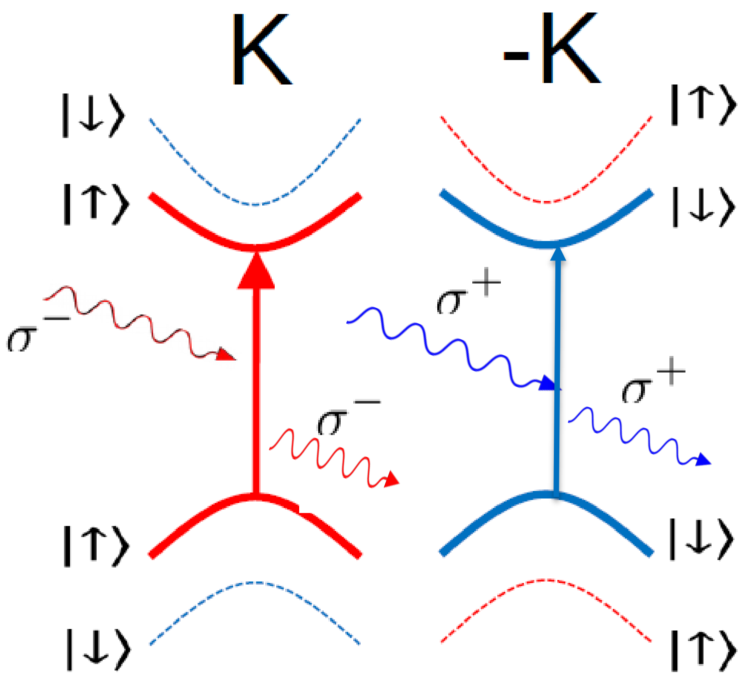
Layered materials







TMD monolayers: direct band-gap semiconductors with a valley degree of freedom

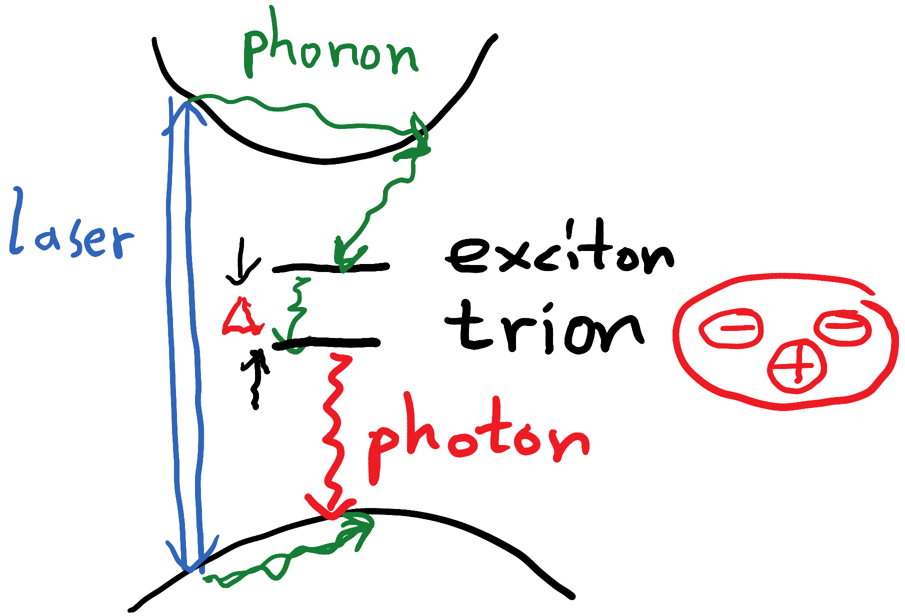


TMD monolayers: direct band-gap semiconductors with a valley degree of freedom

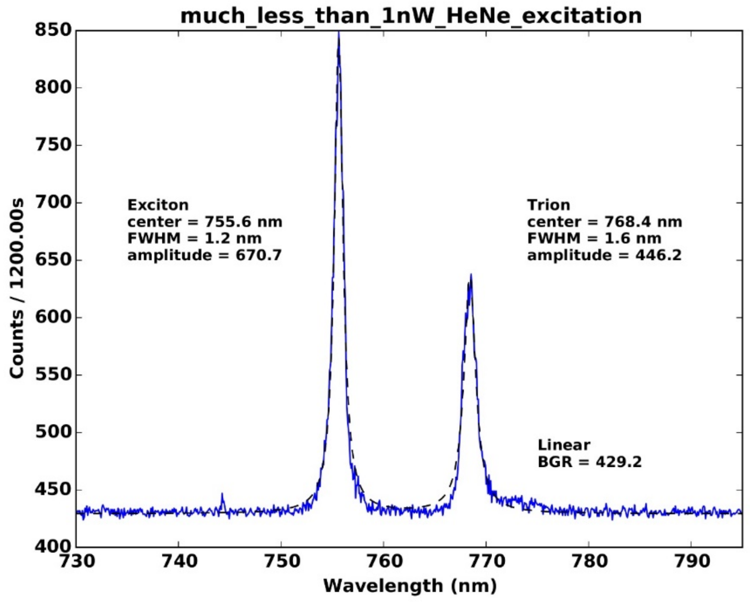
For $MoSe_2$ in hBN, E_B = 230 meV, a_B = 1.1 nm

Photoluminescence (PL) from 2D materials

- Due to strong Coulomb interactions, electrons and holes form strongly bound states before they recombine: PL is dominated by decay of an exciton or a trion if QW has very low density electrons (trion osc. str. is much smaller).

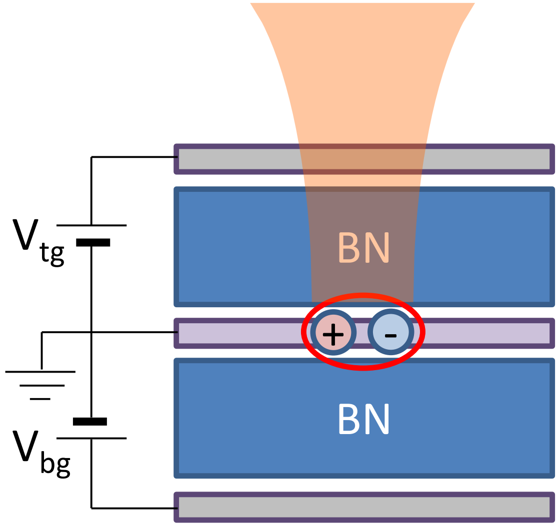


Exciton linewidth of neutral $MoSe_2$ is comparable to the radiative decay rate

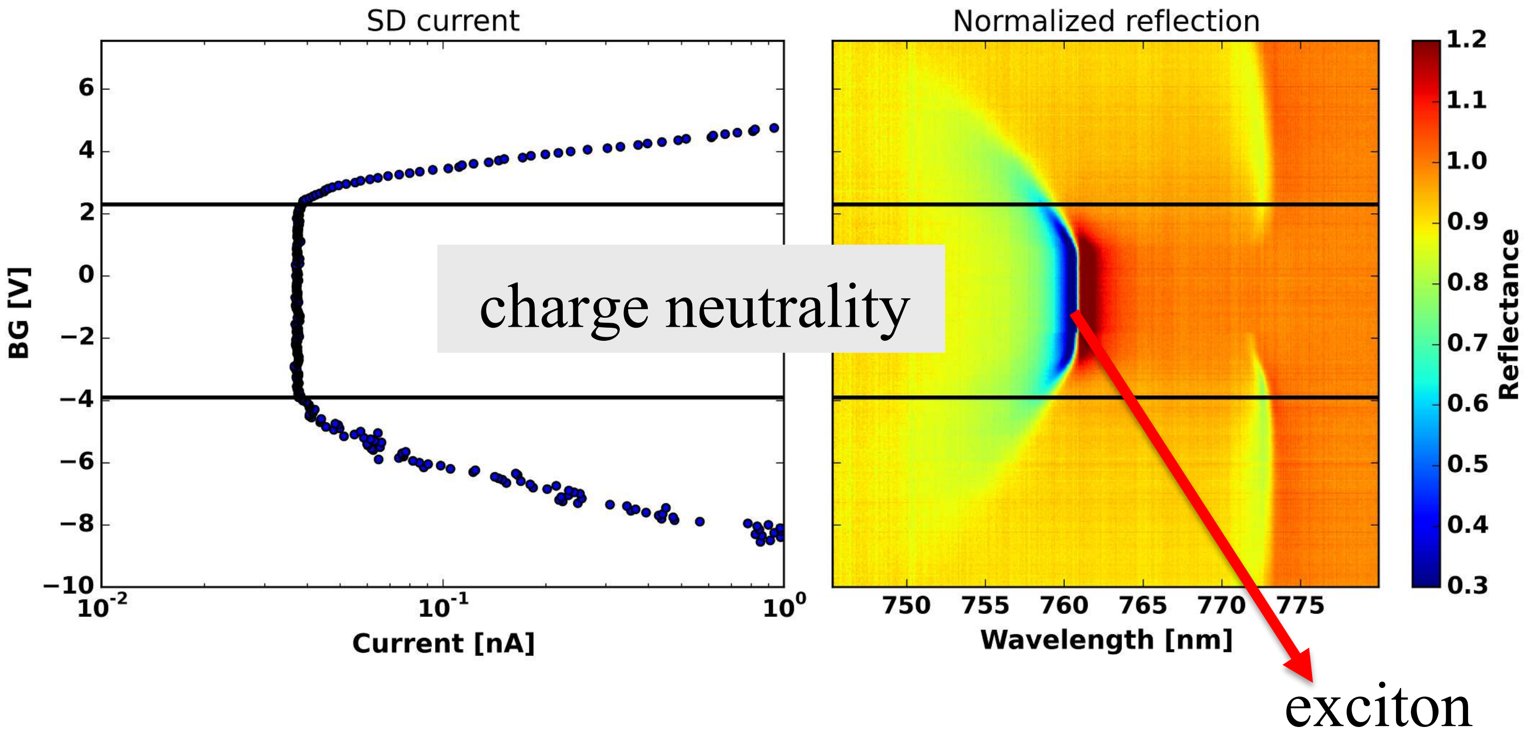


Charge tunable van der Waals heterostructures

- Exfoliation of and stacking of monolayers of semiconducting TMDs and graphene, together with ~50 nm thick insulating boron nitride (BN) layers
- A gate voltage applied between the top/bottom (transparent) graphene gate and the MoSe2 layer allows for tuning the electron/hole density



Carrier density dependent reflection



- Sharp increase in conductance indicates free carriers
- Reflection is strongly modified as electrons or holes injected
- A new red-shifted resonance – **attractive polaron** - if electrons/holes are present

Exciton-electron scattering in a monolayer TMD

- Excitons are neutral bosonic optical excitations (quanta of electronic polarization wave) that interact with itinerant electrons or holes and form a bound molecular state termed “trion”

Exciton as a mobile impurity in a degenerate electron system

Interacting exciton-electron system (with Eugene)

$$H = \sum_k \epsilon_k c_k^\dagger c_k + \sum_k \omega_k x_k^\dagger x_k + \sum V_q c_{k+q}^\dagger c_k x_{k'-q}^\dagger x_{k'}$$

Contact interaction strength determined by the trion binding energy

$$\frac{1}{V_q} = \frac{1}{V} = -\sum_k \frac{1}{\quad + \hbar^2 k^2/(2\mu)}$$

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Approximate form of eigenstates of H in the truncated Hilbert space:

$$|\Psi\rangle = \left(x_0^\dagger \phi_0 + \sum_{k>k_F, q<k_F} \phi_{kq} c_k^\dagger c_q x_{k-q}^\dagger \right) |0_x\rangle |FS\rangle$$

Polaron Chevy-Ansatz

bare exciton

Exciton + Fermi-sea electron-hole pair

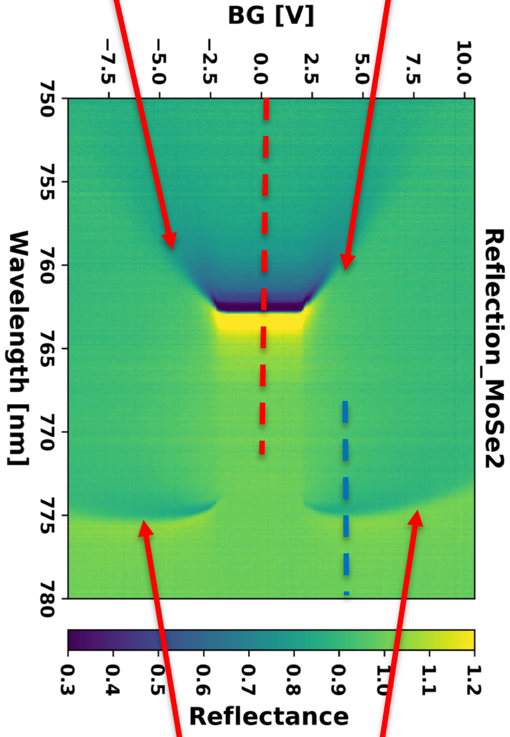
Eigenstates with a large spectral weight:

attractive (AP) and repulsive (RP) polarons

Sidler, Cotlet, Demler, AI Nat. Phys (2017)
Efimkin&MacDonald PRB (2017)

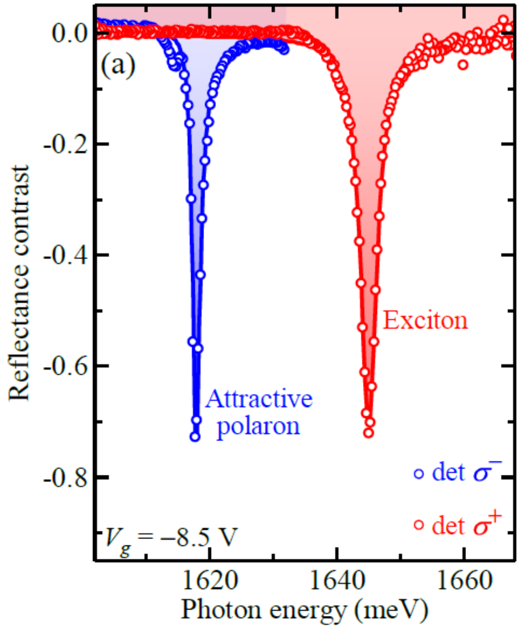
Exciton-(Fermi)-polaron: exciton dynamically screened by itinerant electrons

Repulsive polaron (RP) branch



Attractive polaron (AP) branch

- Existence of a bound trion state is crucial for attractive polaron formation
- For vanishing electron density, attractive polaron & trion are indistinguishable
- Excitons in K-valley can only be dressed to form AP by electrons in K'-valley



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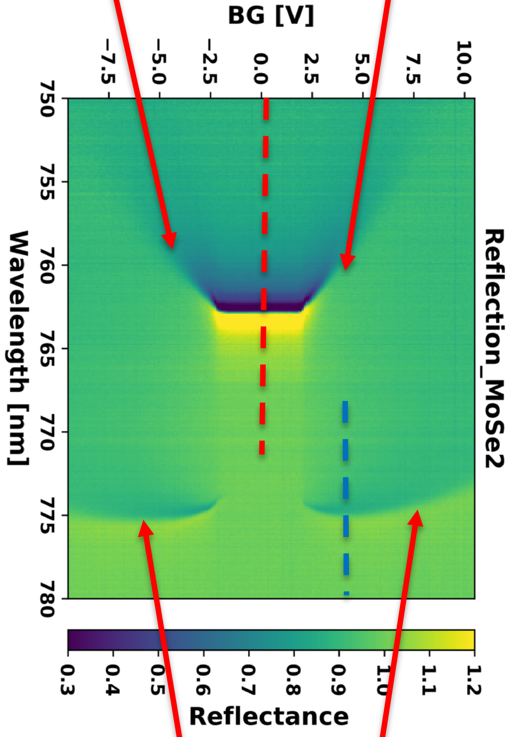

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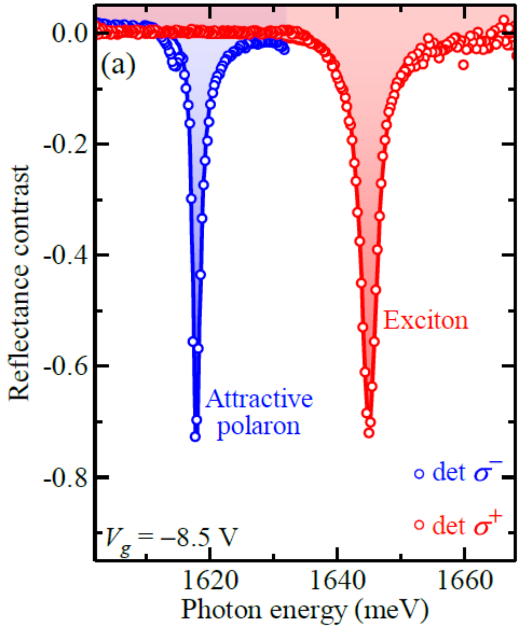


Note the strong electron (hole) density dependence of repulsive polarons:

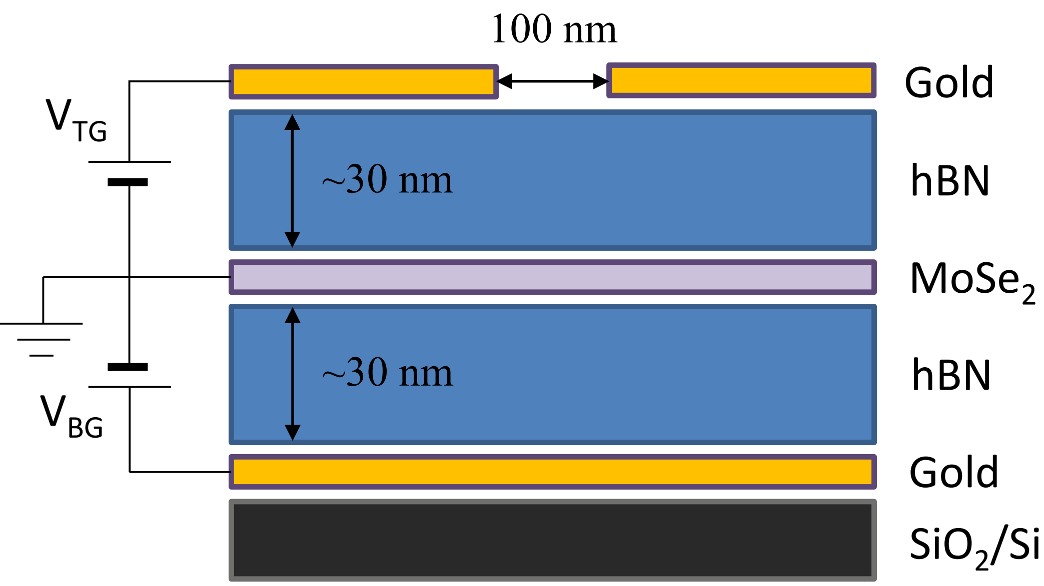
Exciton as a «quantum sensor» of correlated electron states

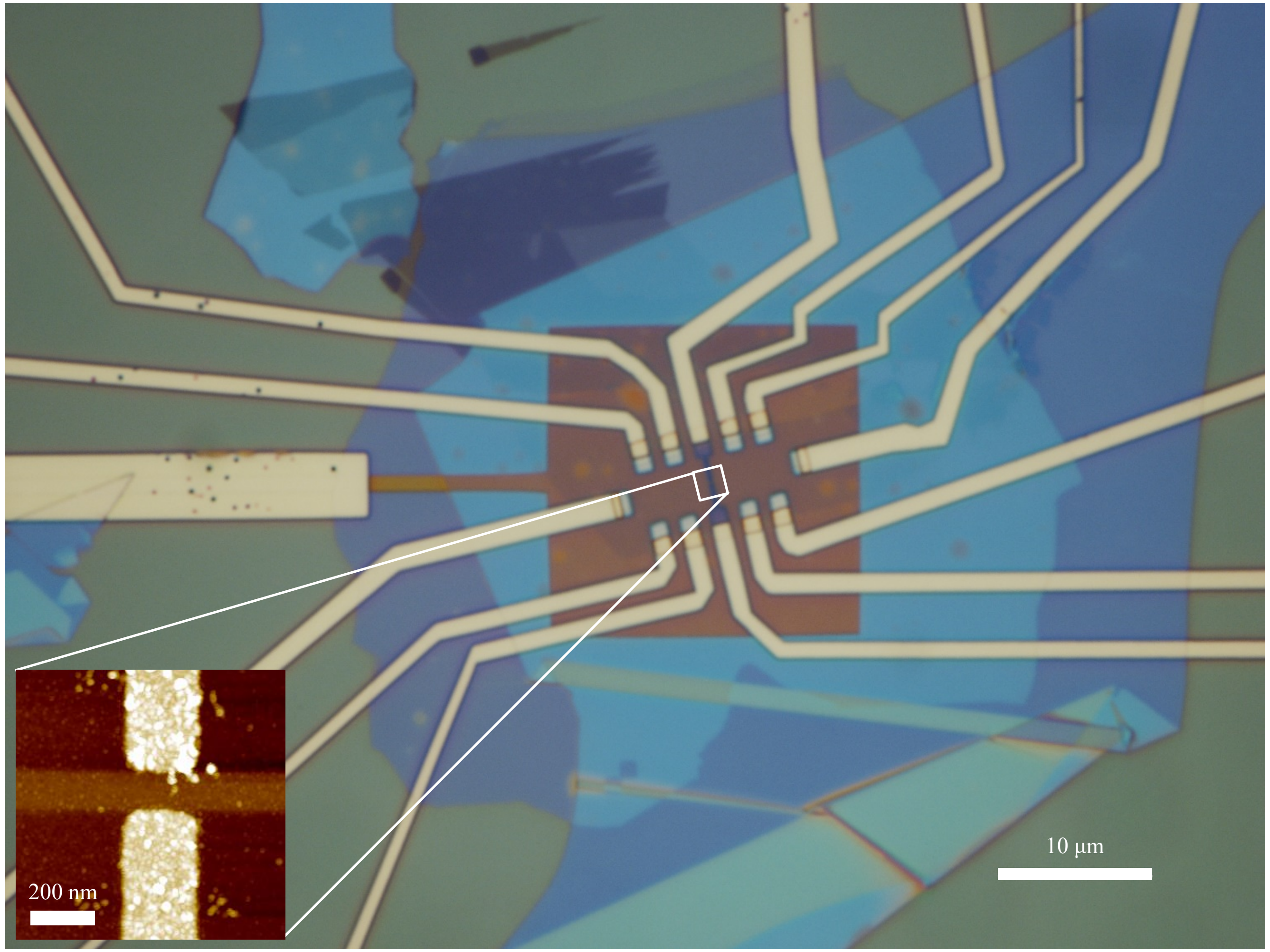
Quantum confinement of neutral excitons using electric fields

Device structure

- Stack:

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

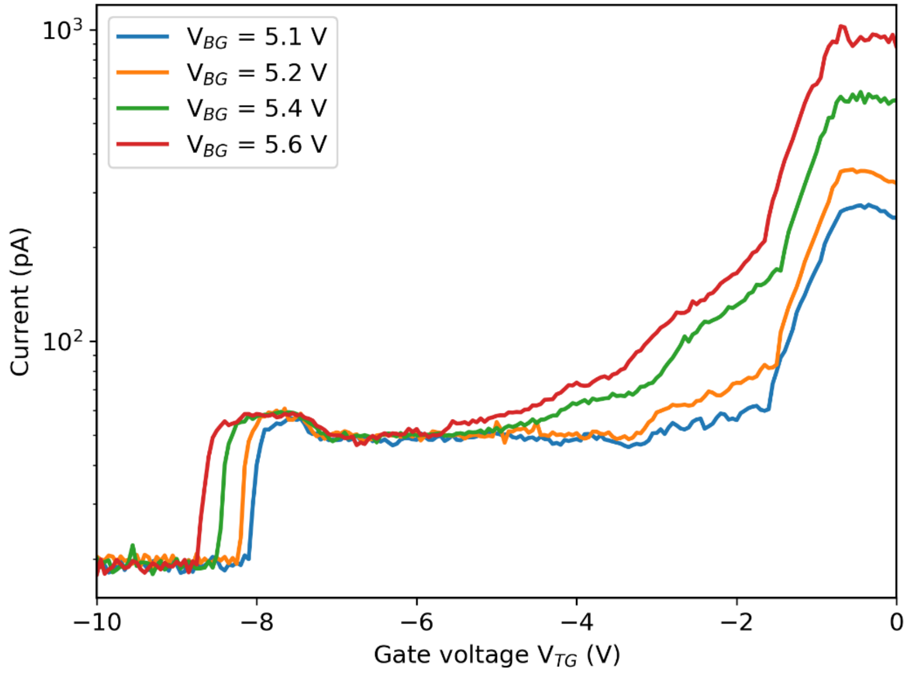


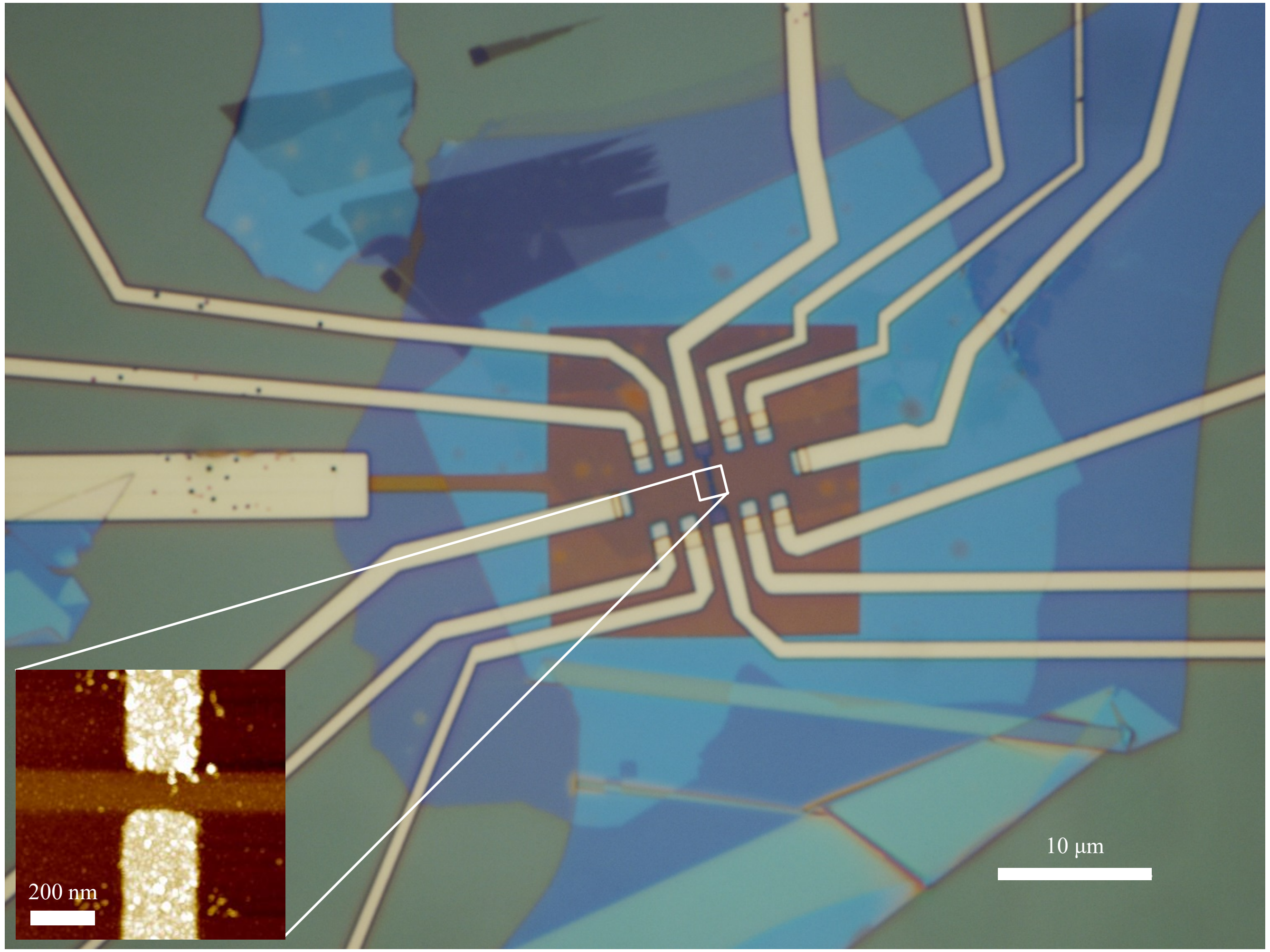


3nm Ti / 7 nm Au split gate ➔ Optically transparent

Quantum confinement of neutral excitons using electric fields

Quantized 2P-current measurement T = 4 K, B = 7 T





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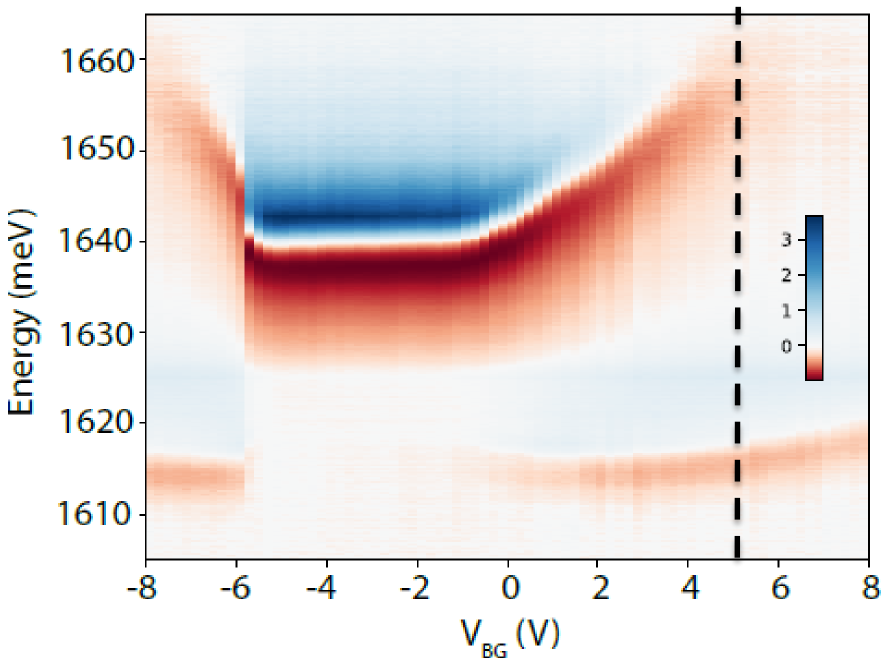
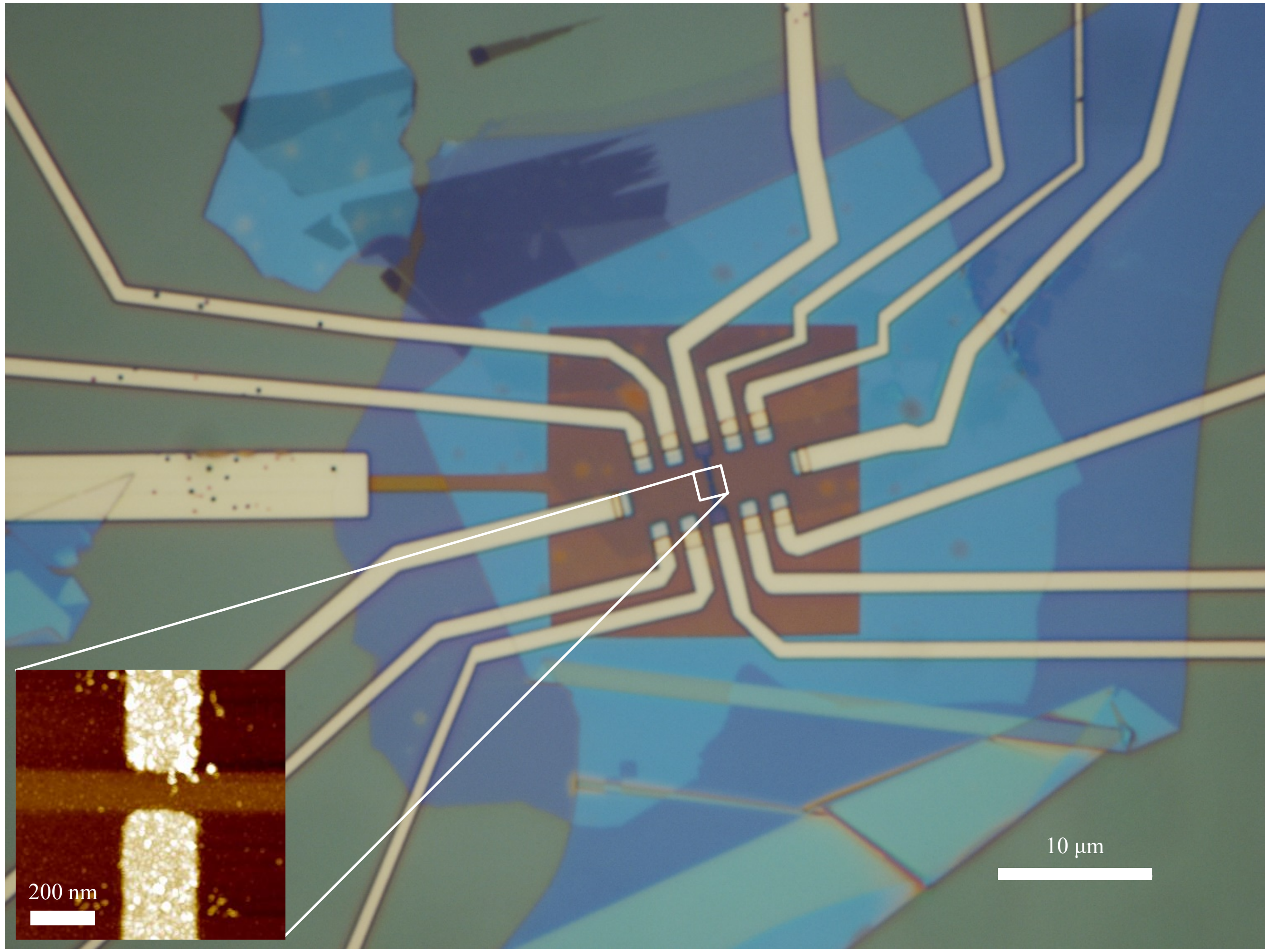
Quantum confinement of neutral excitons using electric fields

Set top gate to 0 V



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



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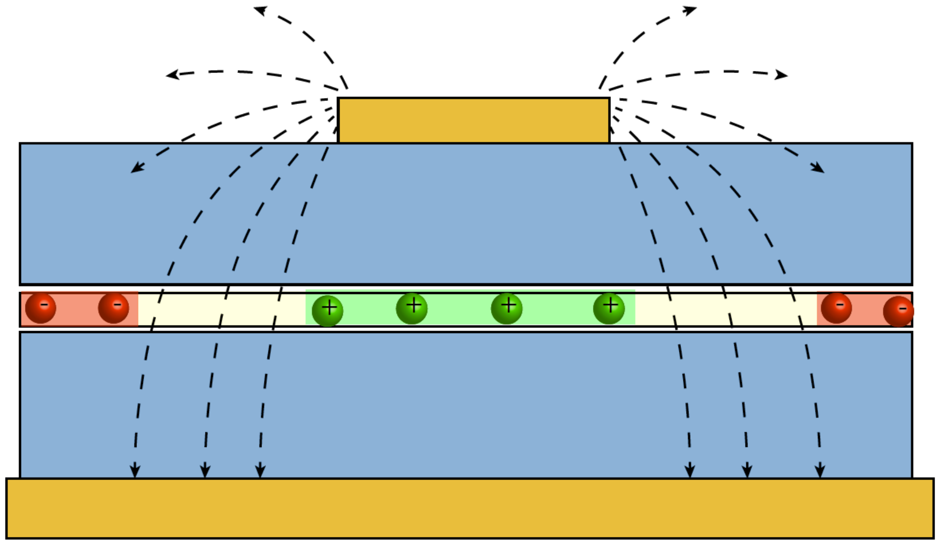
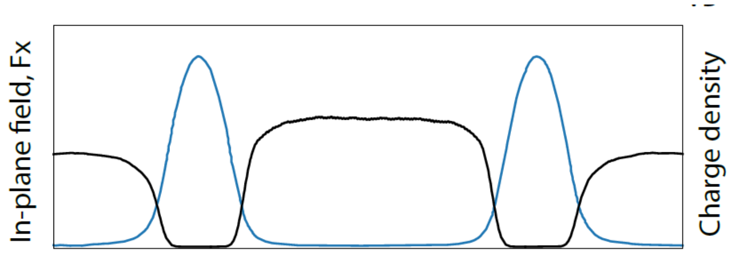
Reflection spectrum– Top gate dependence for V_{BG} = 5V



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



$V_{BG} > 0$: overall electron doping

$V_{TG} + V_{BG} < 0$: hole doping under the top gate

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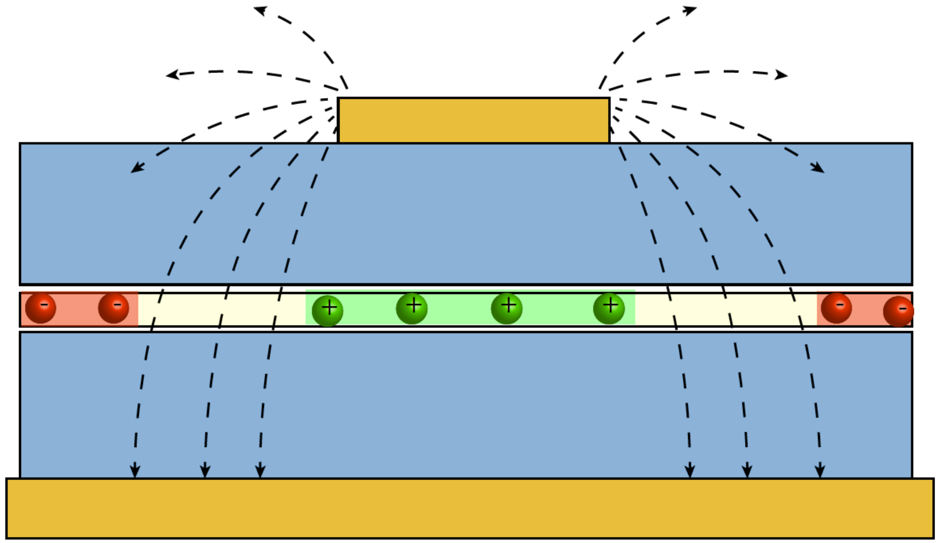

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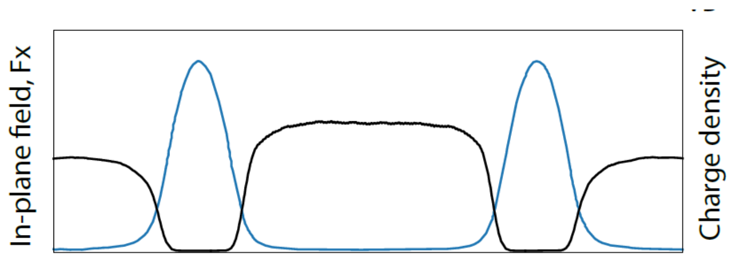

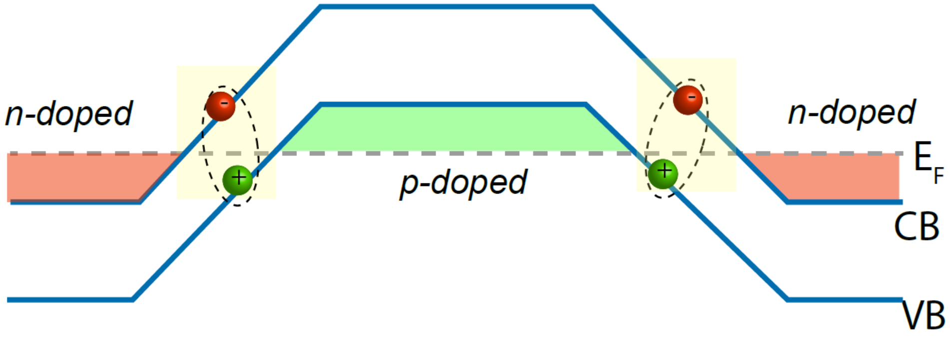

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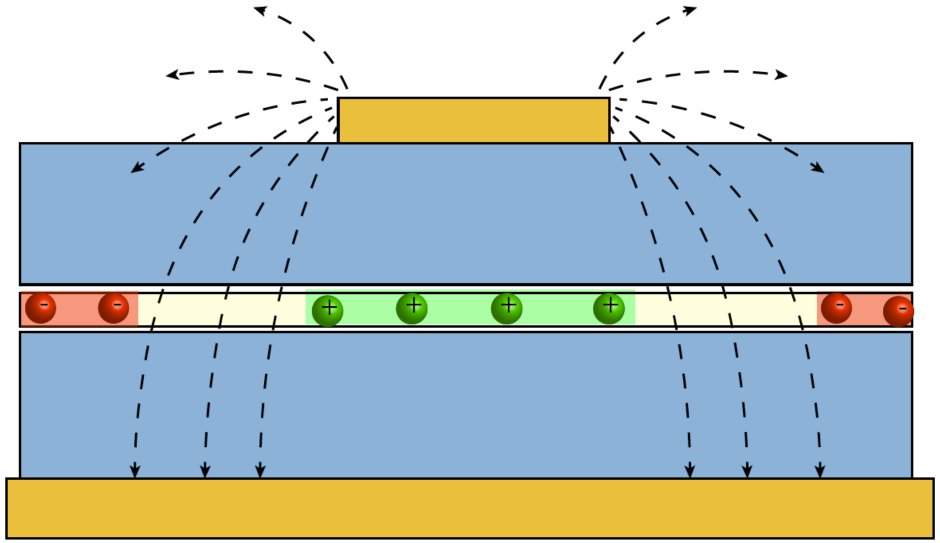

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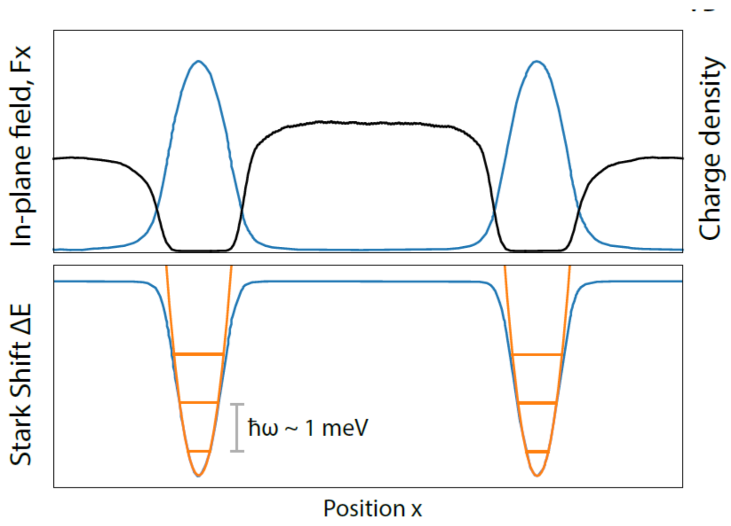
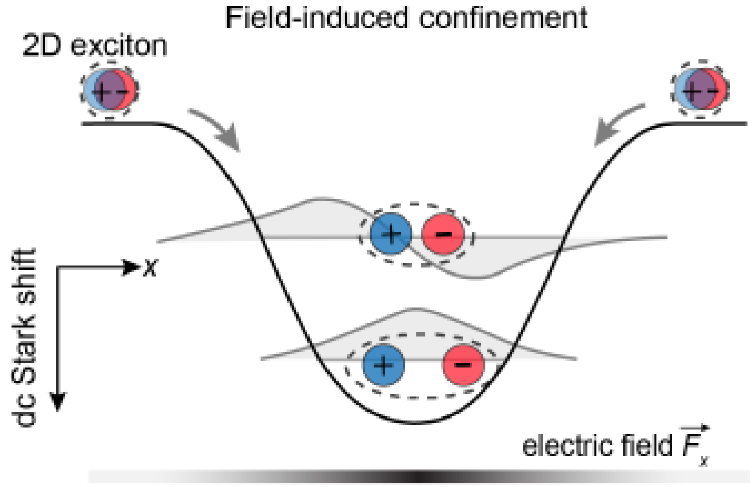


$$\Delta E_S = -\frac{1}{2}\alpha F_x(x)^2$$



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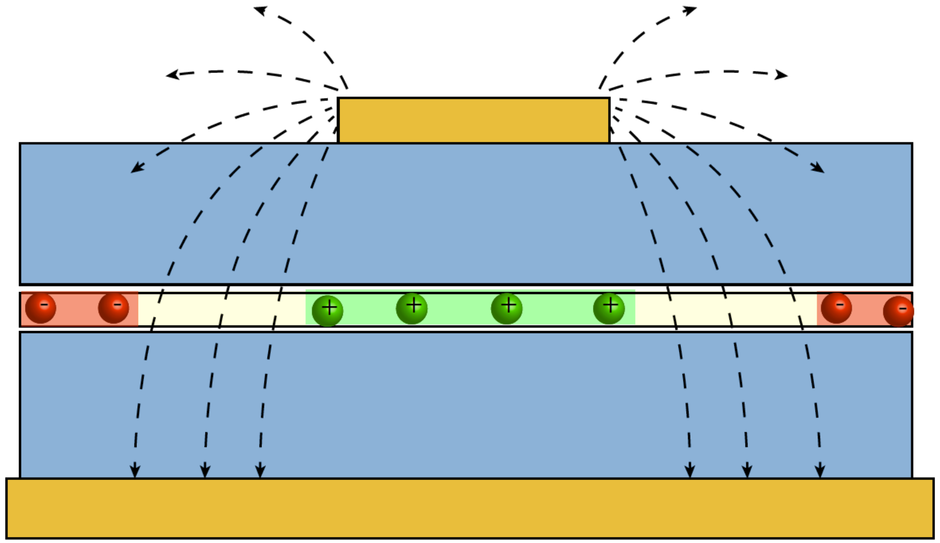

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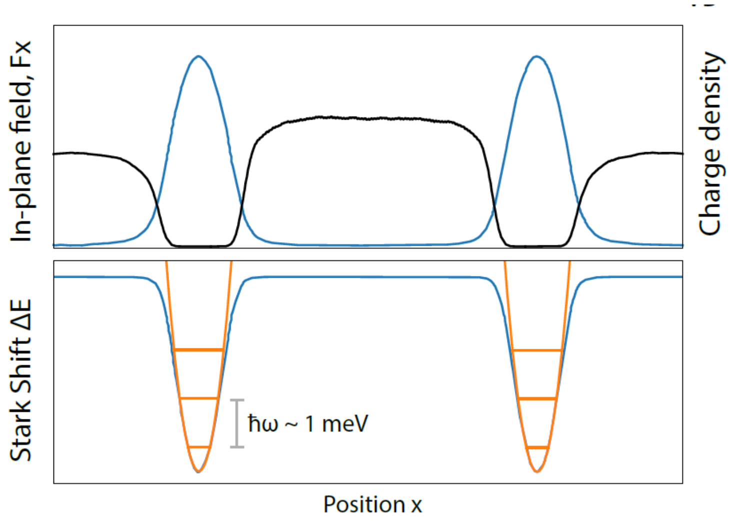

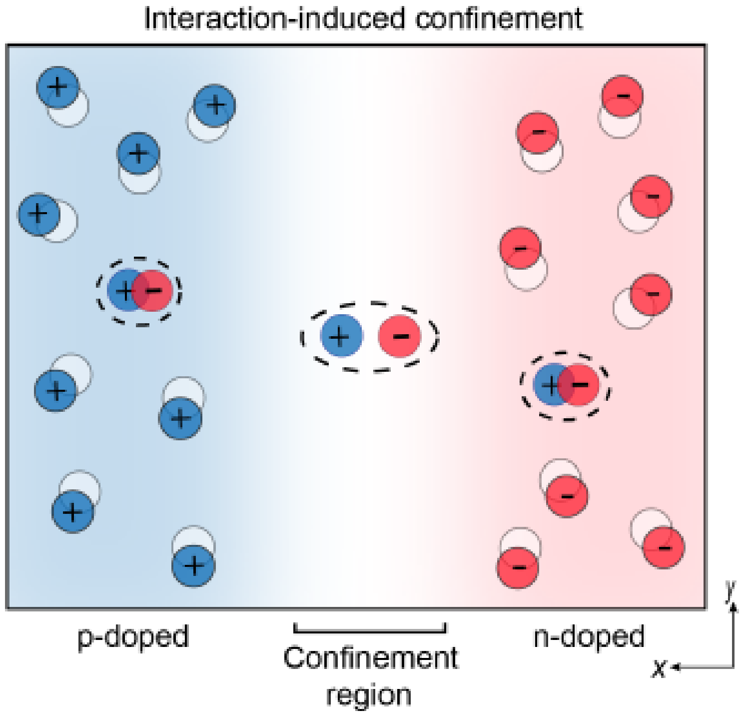

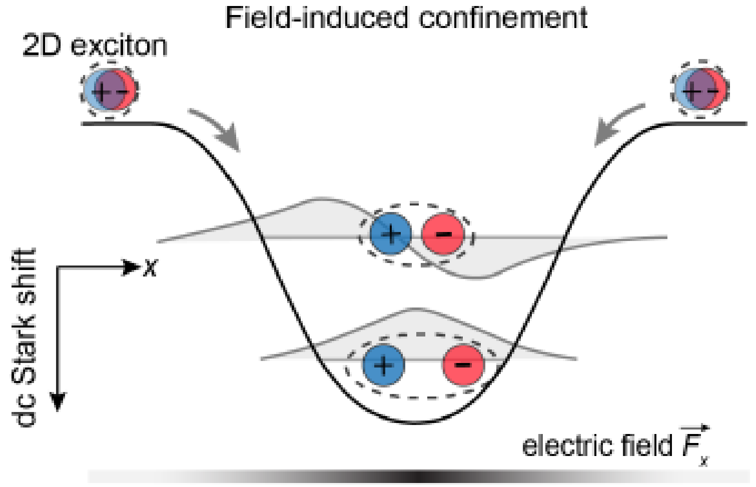

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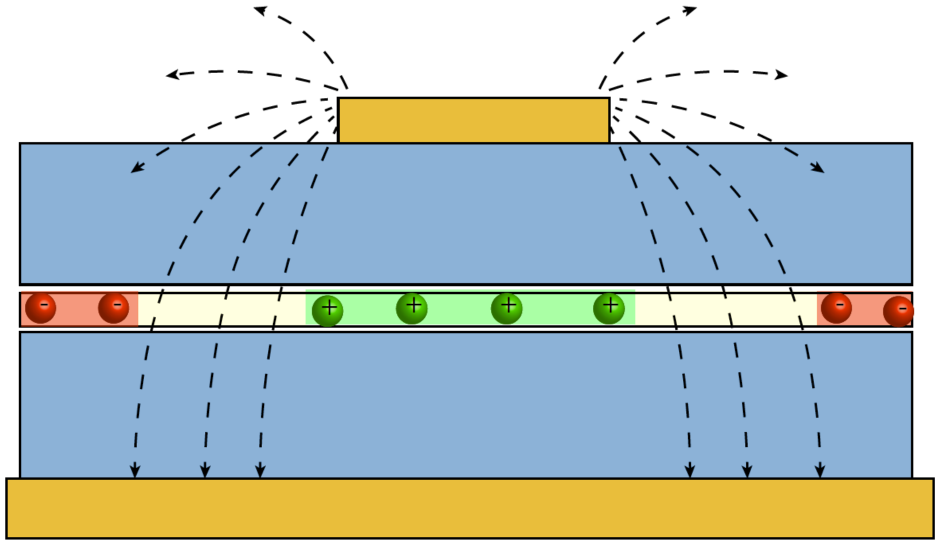

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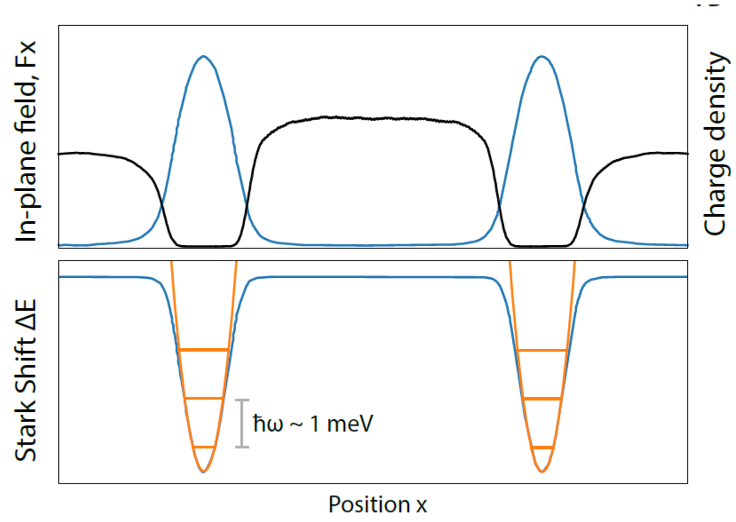

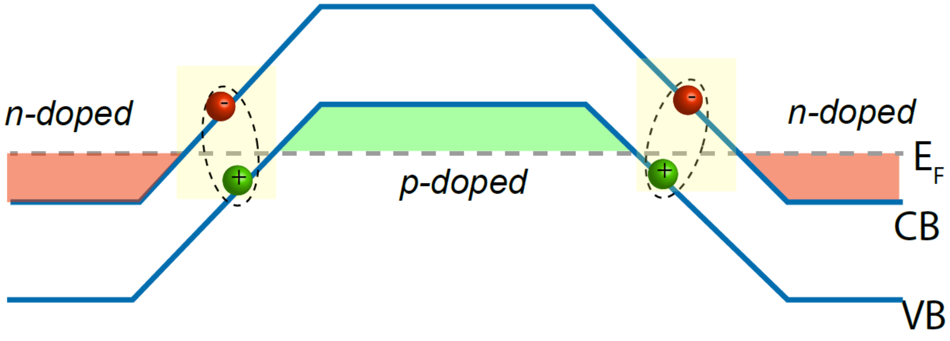

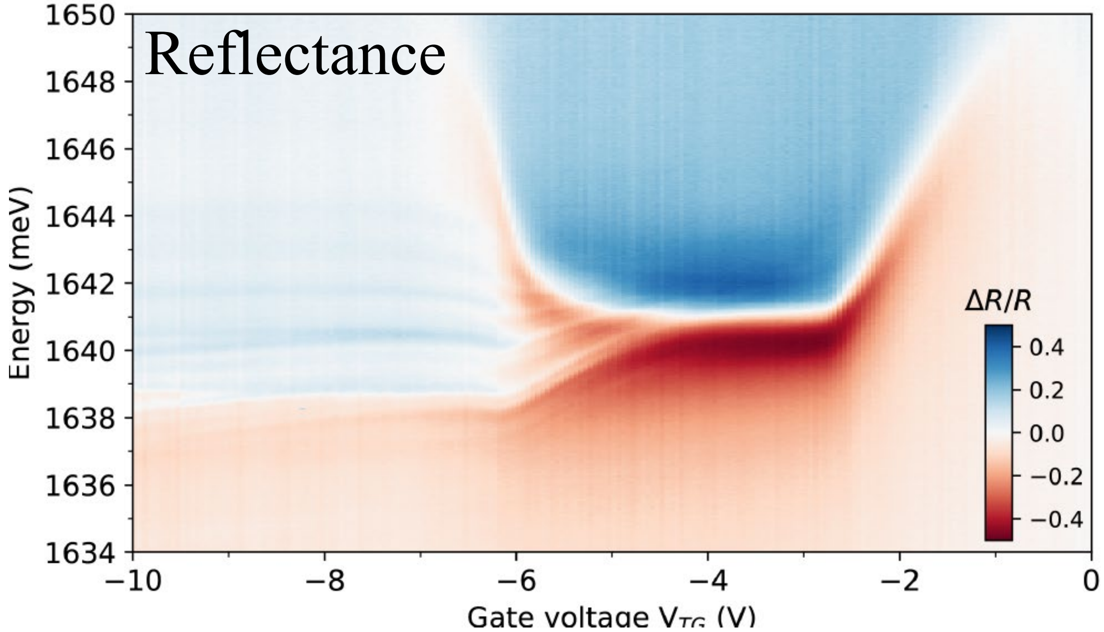

Neutral excitons are confined in the i-region by dc-Stark effect and repulsive exciton-carrier interactions: dipolar excitons in a 1D wire

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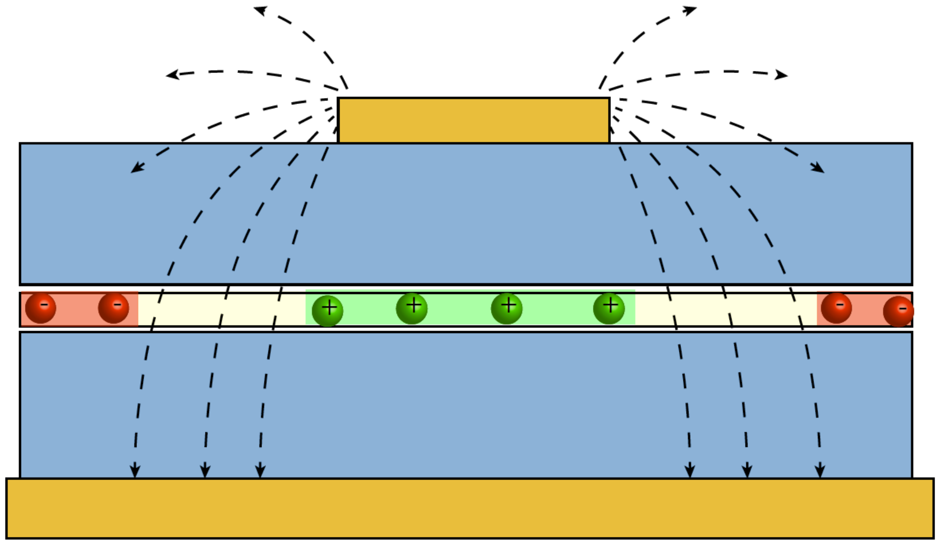

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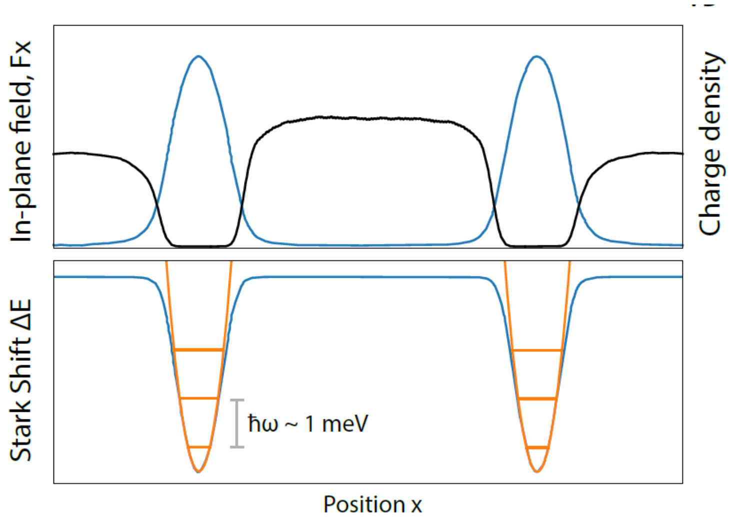
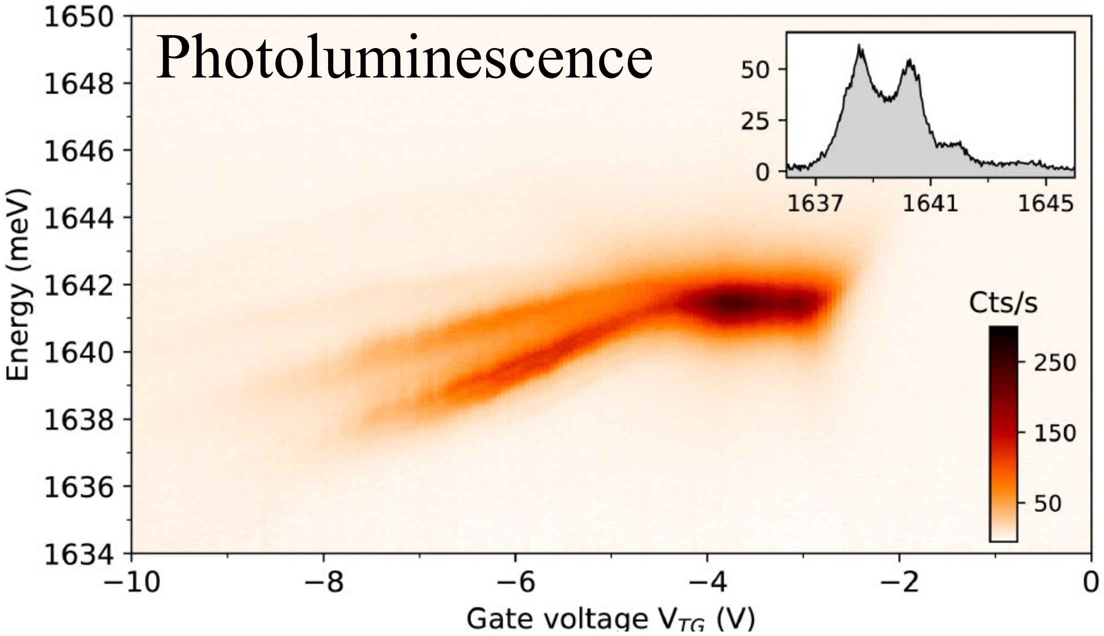
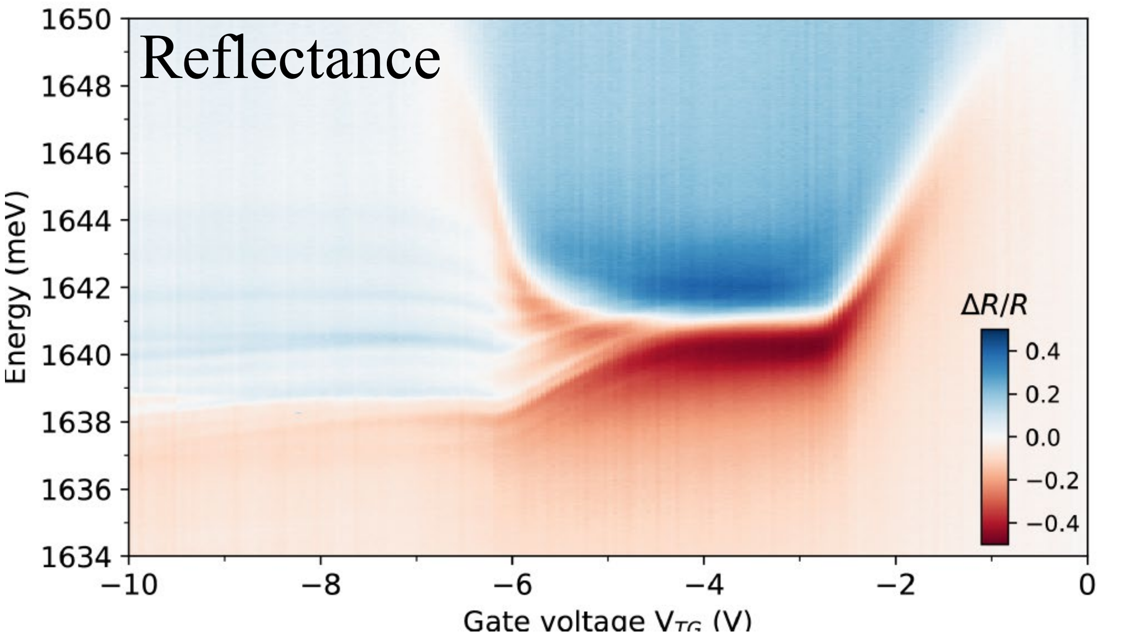
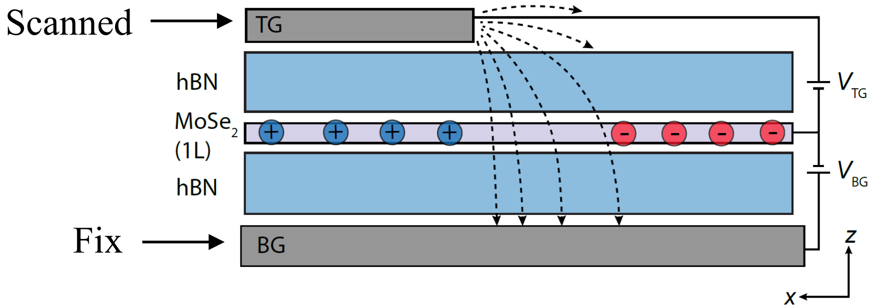
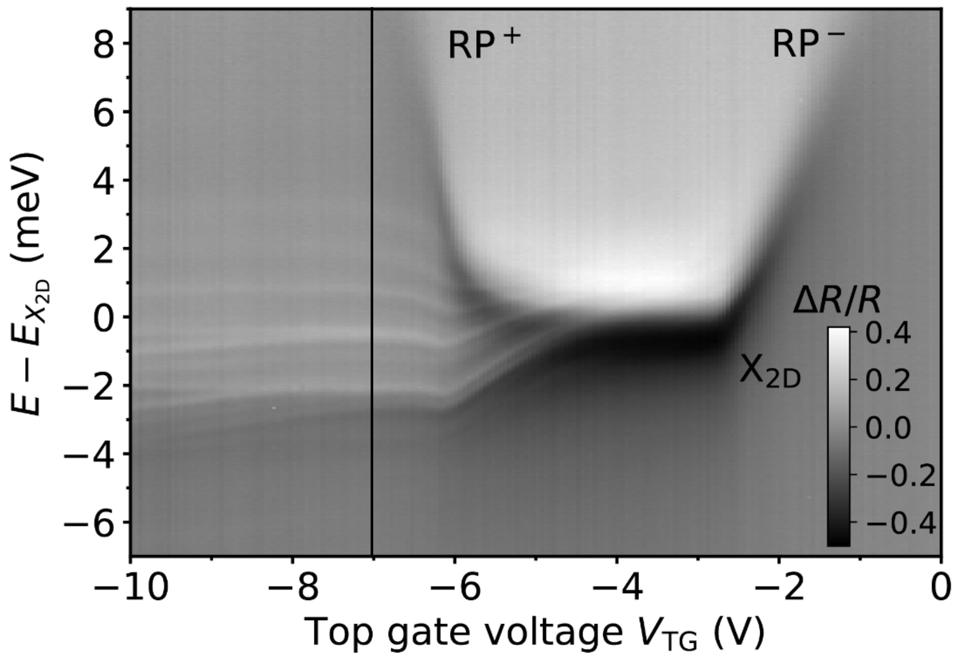


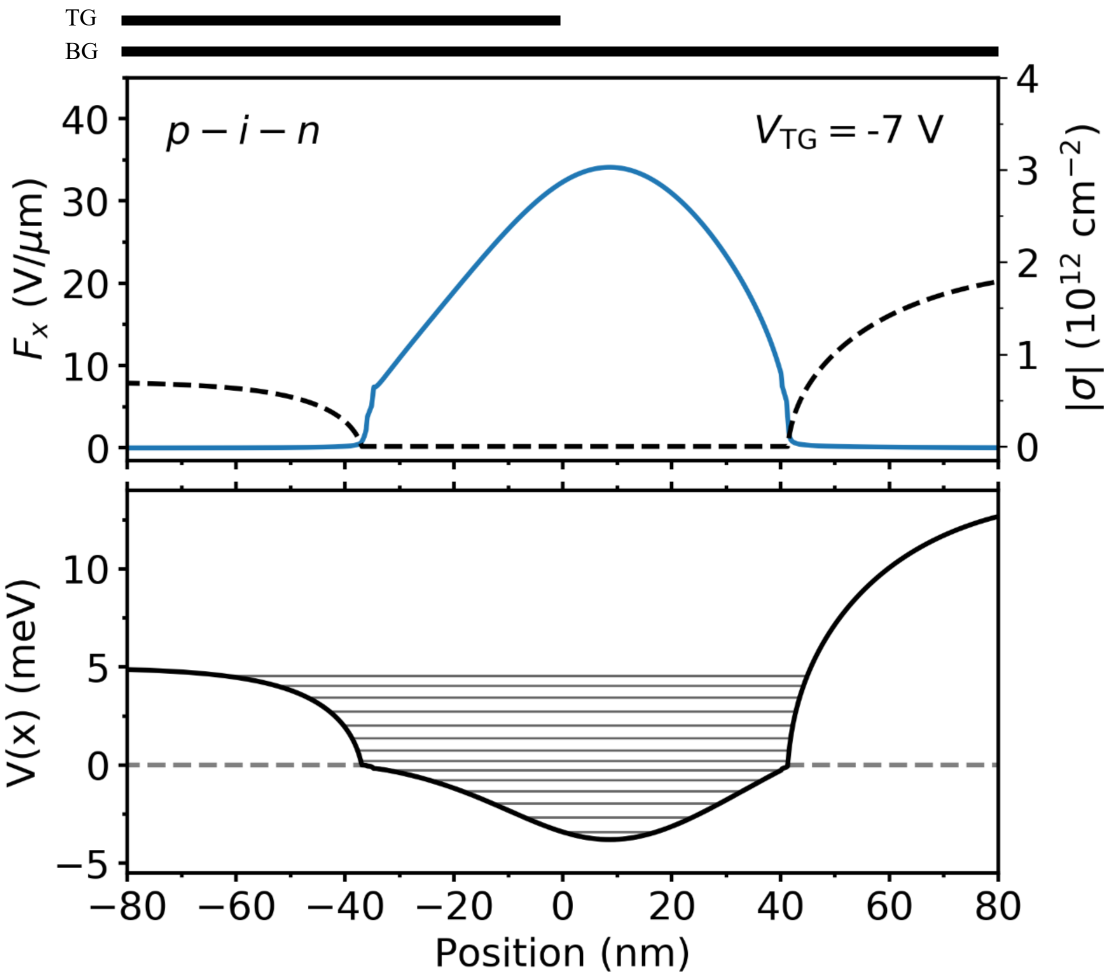




Quantum confined excitons in the p-i-n diode

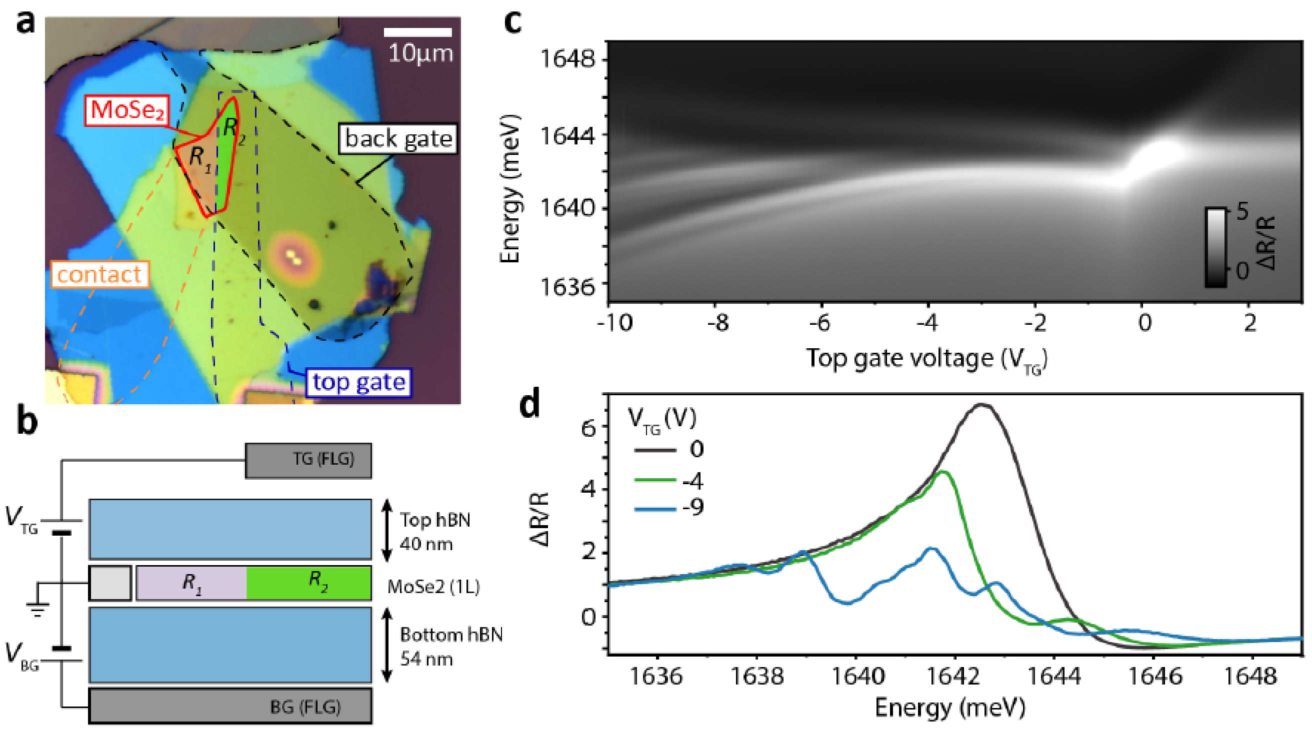




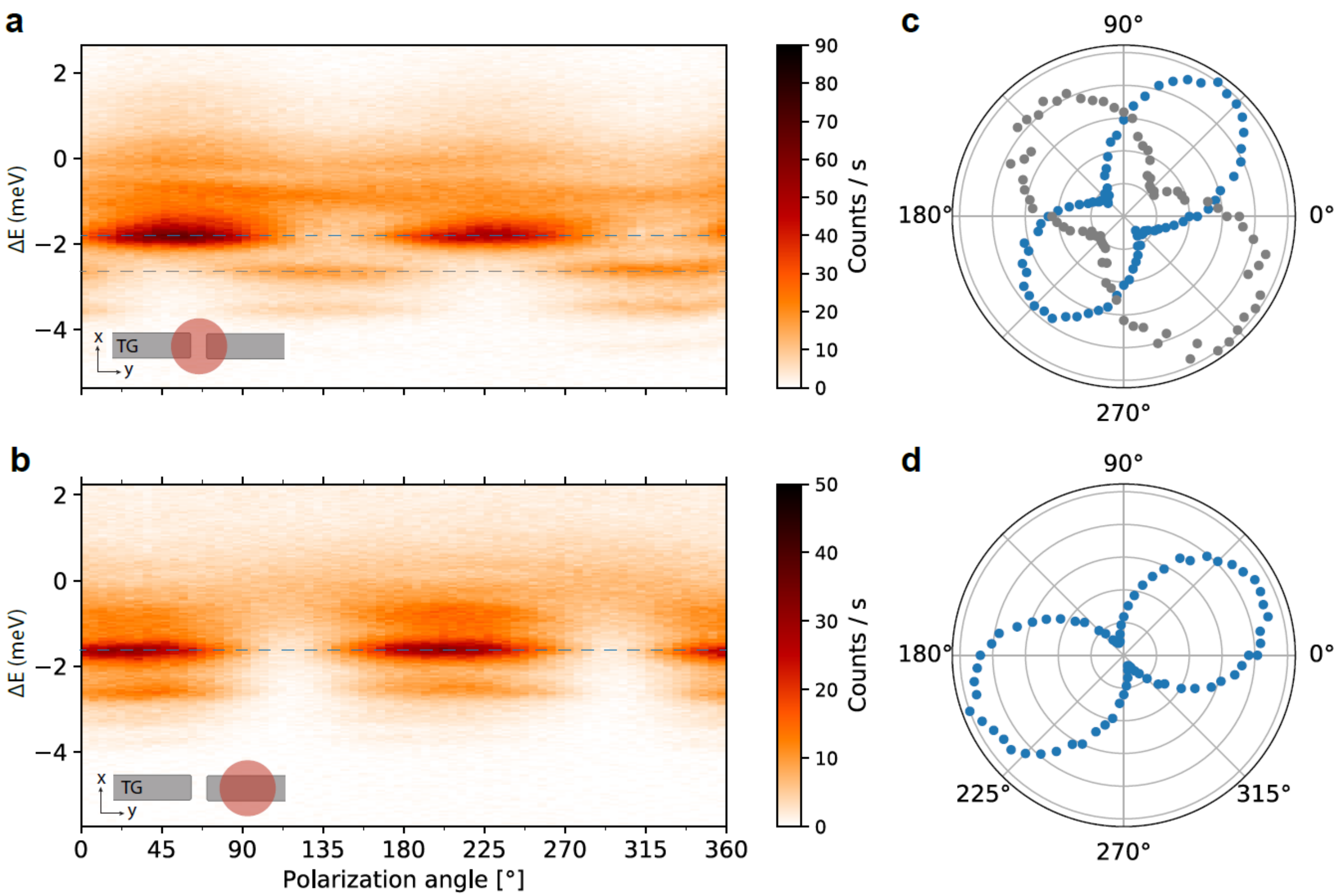


Change in slope of red-shift due to optical charging effects

Quantum confinement of excitons in another device



Evidence for 1D confinement: linearly polarized emission

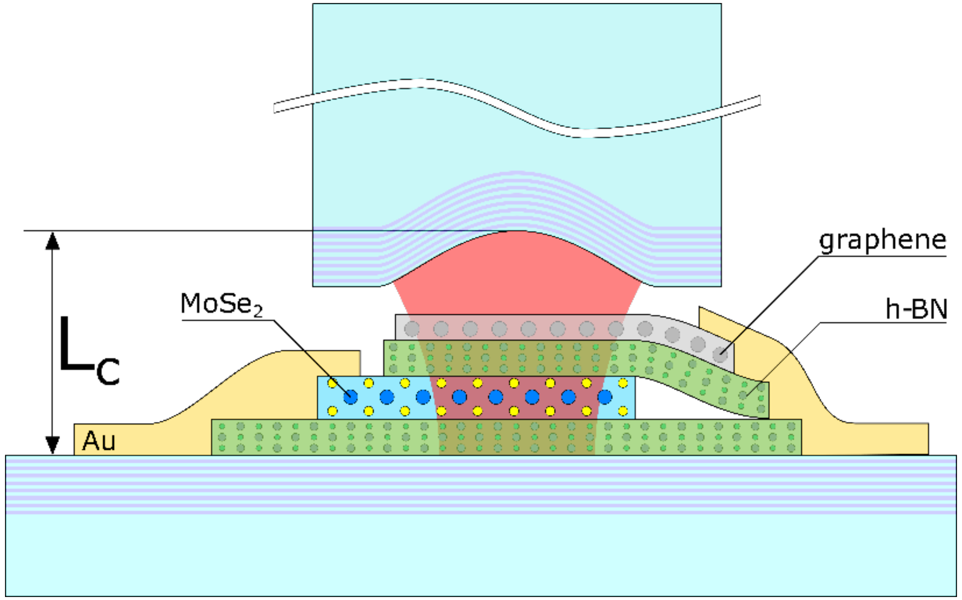


Long-range electron-hole exchange ensures that the exciton emission is polarized along the wire

New directions

- 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 polariton blockade regime



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- Fully electrically defined and tunable quantum dots in monolayer TMDs.