

Trion Hall Effect in Electron-hole Double Layers

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Primary CNF Tools Used: Zeiss Supra SEM, Nabity Nanometer Pattern Generator System (NPGS), Angstrom E-Beam Evaporator, SC4500 Odd/Even-Hour Evaporator, Oxford 81/82 RIE, YES Asher, Autostep i-line Stepper, Hamatech Wafer Processor Develop, Heidelberg Mask Writer - DWL2000, Photolithography Spinners, Dicing Saw - DISCO

Abstract:

Exciton is a quasiparticle made of one electron and one hole bound by Coulomb attraction. Doping an exciton fluid with excess electrons or holes creates a fluid of trions that are bound states of two electrons and one hole or vice versa. Since trions carry a net charge, they can experience a Lorentz force under finite magnetic field and exhibit a Hall effect. In this work, we observe a trion Hall effect in Coulomb-coupled $\text{MoSe}_2/\text{WSe}_2$ double layers. Through magneto-transport measurements, we find that an electron-like Hall effect can emerge in the hole doped layer because of Coulomb drag of negatively charged trions. Our work opens pathways to realize trion-based quantum Hall phenomena.

Summary of Research:

Excitonic insulators (EIs) [1] form when the binding energy of electron-hole pairs exceeds the single particle bandgap in a semiconductor. EIs provide an ideal platform for studying bosonic quantum states of matter, such as exciton condensates [2]. Using van der Waals (vdW) semiconductors it's possible to study exciton transport by separating the electrons and holes to different layers of material. This approach has been used to flow an exciton current in Coulomb-coupled double layers [3] in the absence of magnetic field. Doping the exciton fluid with excess carriers creates a Bose-Fermi mixture. In the limit of strongly attraction between free carriers and excitons, an equilibrium fluid of

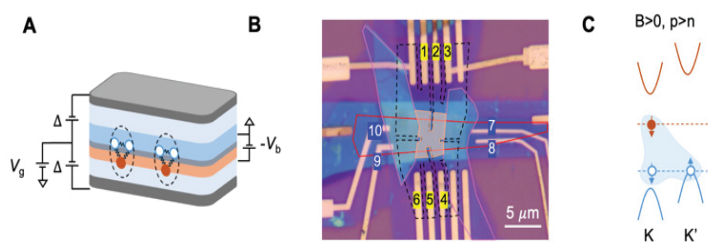


Figure 1: **A**, Schematic cross-section of the device. **B**, Optical microscope image of a device. Scale bar is 5 μm . **C**, Type-II band alignment of MoSe_2 and WSe_2 .

trions has been observed [4]. Since these trions are charged, they are subject to Lorentz forces under a perpendicular magnetic field [5].

Figure 1A and 1B show, respectively, a schematic cross-section and an optical image of our device. It consists of $\text{WSe}_2/\text{MoSe}_2$ double layers separated by a thin hexagonal boron nitride (hBN) barrier. WSe_2 and MoSe_2 form a type-II band alignment (Fig. 1C), that is, the lowest (highest) energy conduction (valence) band lies in the MoSe_2 (WSe_2) layer. The double layer is further encapsulated by two gates made of hBN and graphite. We use Pt and Bi electrodes that make Ohmic contacts to holes in the WSe_2 layer and electrons in the MoSe_2 layer, respectively. An interlayer bias, V_b , is applied between the layers to tune the electron-hole pair density, n_p , and the gate voltage V_g tunes electron-hole density imbalance. For negative V_g , excess holes are added to the WSe_2 layer and for positive V_g , excess electrons are added to the MoSe_2 layer.

Figure 2A and 2B show longitudinal (R_{xx}) and Hall (R_{xy}) resistances measured at $B = 4$ T in the

W-layer while the Mo-layer was in open-circuit. Since electrons are not allowed to flow, interlayer bound states in this measurement configuration are insulating states. The triangular insulating region near $V_g = 0$ is the EI. There are two additional insulating states that appear upon doping the EI with excess holes or electrons and are denoted by $(X+X^+)$ and $(X+X^-)$, respectively. These regions consist of bound excitons and trions – positive trions for $(X+X^+)$ and negative trions for $(X+X^-)$. Hall resistance is large inside the trion regions and changes sign for negative trions while measuring R_{xy} in the hole-doped layer. This effect can be explained by a Hall effect of trions since the hole in the hole layer experiences

trion region; n_H decreases monotonically due to free carriers forming bound trions. In the negative trion region, n_H becomes negative and jumps back to the hole density as the density increases and trions ionize. Figure 3B shows the temperature dependence of the Hall resistance in the positive and negative trion regions. Above 8 K, trions ionize into free carriers providing an estimate of the trion binding energy (~ 0.7 meV). The negative Hall resistance vanishes and the Hall resistance approaches the value corresponding to free hole density at high temperature.

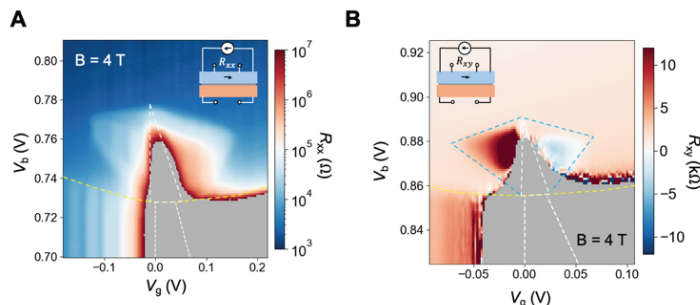


Figure 2: **A**, R_{xx} at $T = 1.5$ K as a function of V_g and V_b under $B = 4$ T, where R_{xx} is the longitudinal resistance measured on the hole layer with the electron layer in open circuit (inset). Blue dashed lines: boundary of the $(X+X^{\pm})$ regions. **B**, R_{xy} at $T = 1.5$ K as a function of V_g and V_b under $B = 4$ T.

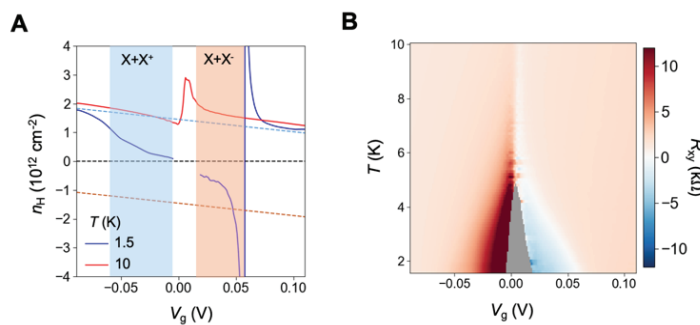


Figure 3: **A**, Hall density as a function of V_g at $V_b = 0.88$ V and $T = 1.5$ K and 10 K. The $(X+X^+)$ and $(X+X^-)$ regions are shaded in blue and orange, respectively. **B**, R_{xy} as a function of V_g and T at $V_b = 0.88$ V.

opposite Lorentz force when it's bound to two electrons in the electron layer.

Figure 3A shows Hall density, n_H , at $T = 1.5$ K and 10 K along $V_b = 0.88$ V which cuts through regions of positive trions, excitonic insulator, and negative trions. The dashed lines are the expected density of holes (blue) and electrons (orange) in respective layers, evaluated from the device capacitances. At 10 K, trions are ionized and n_H traces the expected Hall density. At 1.5 K, n_H deviates from the hole density as the system enters the positive

References:

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