Perfect Coulomb Drag in a Dipolar Excitonic Insulator

CNF Project Number: 263318
Principal Investigator(s): Jie Shan, Kin Fai Mak
User(s): Raghav Chaturvedi, Phuong X. Nguyen, Jinwoo Yu

Affiliation(s): Laboratory of Atomic and Solid State Physics, School of Applied and Engineering Physics; Cornell University

Primary Source(s) of Research Funding: DOE, NSF, AFOSR, Moore Foundation

Contact: jie.shan@cornell.edu, kinfai.mak@cornell.edu, rc669@cornell.edu, pxn2@cornell.edu, jy968@cornell.edu

Website: https://sites.google.com/site/makshangroup/

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. In systems where the exciton binding energy exceeds the single particle band gap, excitons spontaneously form, and the new ground state is an excitonic insulator (EI): conducting for excitons but insulating for free electrons or holes. In this work, we realize a dipolar EI in MoSe2/WSe2 double layers. The formation of excitons results in perfect Coulomb drag, that is, driving a charge current in one layer induces an equal and opposite drag current in the other layer. Upon increasing exciton density beyond the critical Mott density, excitons dissociate into an electron-hole plasma and the drag current becomes negligible. Our work opens pathways to realize exciton superfluidity and other exotic phases of correlated excitons.

Summary of Research:

Excitonic insulators (EIs) [1] form when the binding energy of bound electron-hole pairs exceeds the single particle bandgap in a semiconductor. Unlike charge insulators, where the charges are immobile, excitons can flow. However, excitons are charge neutral which makes driving an exciton current impossible in bulk EIs. Using van der Waals (vdW) semiconductors it's possible to fabricate independent electron and hole contacts by separating the electrons and holes to dilerent layers of material. This approach has been used to flow an exciton current in coupled GaAs quantum wells [2] and graphene double layers [3], however, only in the quantum Hall regime. In our work, we use dipolar EIs observed in Coulomb-coupled double layers [4] to flow an excitonic current in the absence of magnetic field [5].

Figure 1A and 1B show a schematic cross-section and an optical image of our device, respectively. The device consists of WSe2/MoSe2 double layers separated by a thin hexagonal boron nitride (hBN) barrier. WSe2 and MoSe2 form a type-II band alignment as shown in Figure 1C, that is, the lowest (highest) energy conduction (valence) band lies in the MoSe2 (WSe2) 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 WSe2 layer and electrons in the MoSe2 layer, respectively. An interlayer bias, V_b, is applied between the layers to tune electron-hole pair density, n_p, and the gate voltages allow to tune electron-hole density imbalance. Our experiment is performed at equal electron and hole densities.

Figure 2A shows the configuration for the Coulomb drag measurement. An electron current is driven in the $MoSe_2$ layer while WSe2 layer is connected to an ammeter. In this configuration, when an exciton current flows in the system, it's expected that the drive current in the $MoSe_2$ layer will induce an equal and opposite drag current in the WSe_2 layer. This is because a flowing electron in the $MoSe_2$ layer will drag along a hole in the WSe2 layer.

The results for the Coulomb drag measurement are shown in Figure 2B. Drive current in the $MoSe_2$ layer (black line) is observed when V_b crosses a threshold value and injects electron-hole pairs into the double layer. At low n_p, the drag current (red line) in the WSe_2 layer exactly traces the drive current. The ratio of the drag and drive current (blue line) persists to 1 for exciton density up to ~ 4 x 10^{11} cm^{-2}. Upon further increasing N_p beyond this density, the drag current abruptly drops to zero. This corresponds to the Mott limit, beyond which excitons unbind into an electron-hole plasma due to larger screening of the electron-hole interaction at higher densities.

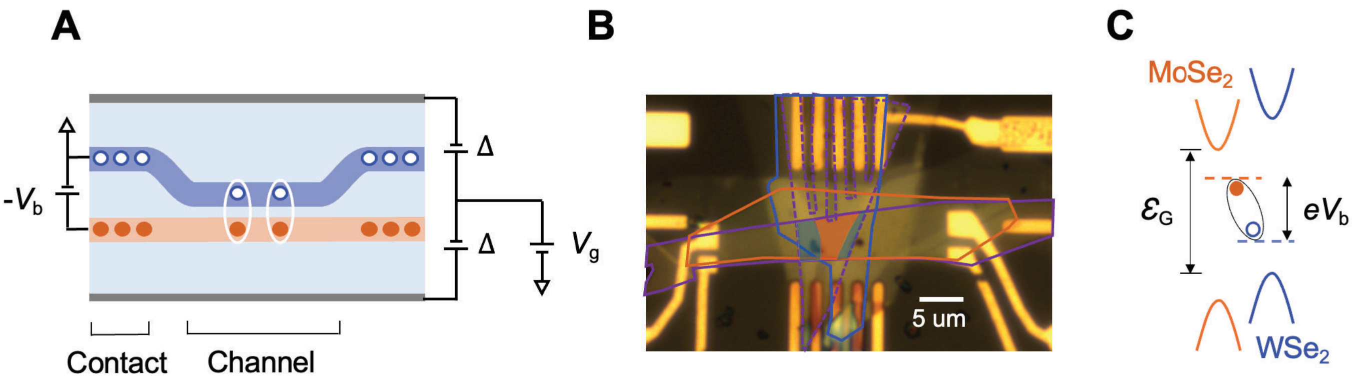

Figure 1: a, Schematic cross-section of the device. b, Optical microscope image of a double layer device. Scale bar is 5 µm. c, Type-II band alignment of $MoSe_2$ and WSe_2.

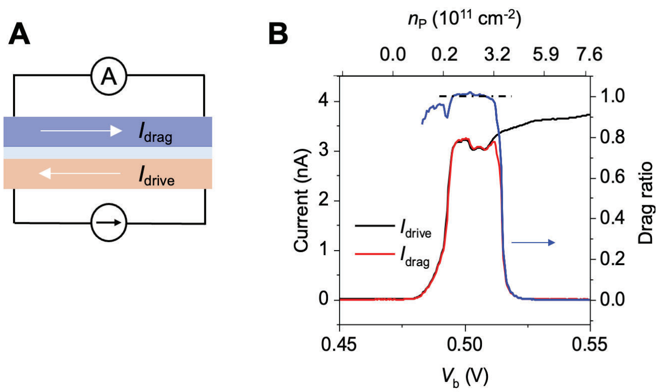

Figure 2: a, Circuit for Coulomb drag measurement. b, Drive (black line) and drag (red) currents in the MoSe2 and WSe2 layers respectively measured as a function of V_b. The ratio of the currents is plotted in blue. The black dashed line marks drag ratio = 1.

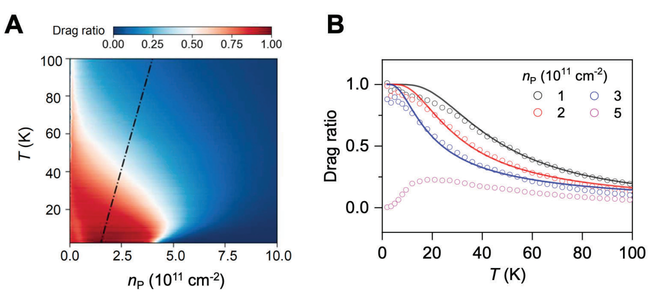

Figure 3: a, Drag ratio as a function of temperature and n_p . Black dashed line corresponds to the degeneracy temperature. b, Linecuts of drag ratio as a function of temperature for dilerent n_p. Solid lines are fit to the Saha equation.v

We measure the temperature dependence of the drag ratio for varying n_p as shown in Figure 3. The drag ratio remains above 0.9up to 20 K at low n_p. When excitons are dissociated above the Mott limit, only frictional drag is observed with a characteristic quadratic temperature dependence as expected for two independent Fermi liquids. Furthermore, the temperature dependence of the drag ratio can be largely captured by a simple ionization model (solid lines in 3B) based on the Saha equation. We also plot the degeneracy temperature (black dashed line) obtained through compressibility measurements for each density in Fig 3A. Below the degeneracy temperature, the exciton fluid is expected to become a quantum fluid.

Our work successfully realizes exciton circuitry in the absence of a magnetic field and enables future studies of exciton transport, including a four-terminal measurement of the exciton chemical potential that can directly detect exciton superfluidity.

References:

[1] D. Jérome, T.M. Rice & W. Kohn, Excitonic Insulator, Physical Review 158, 462–475 (1967).

[2] D. Nandi, A. D. K. Finck, J. P. Eisenstein, L. N. Pfeiler & K. W. West, Exciton condensation and perfect Coulomb drag. Nature 488, 481–484 (2012).

[3] X. Liu, K. Watanabe, T. Taniguchi, B. I. Halperin & P. Kim, Quantum Hall drag of exciton condensate in graphene. Nat. Phys. 13, 746–750 (2017).

[4] L. Ma, P. X. Nguyen, Z. Wang, Y. Zeng, K. Watanabe, T. Taniguchi, A. H. MacDonald, K. F. Mak & J. Shan, Strongly correlated excitonic insulator in atomic double layers. Nature 598, 585–589 (2021).

[5] P. X. Nguyen, L. Ma, R. Chaturvedi, K. Watanabe, T. Taniguchi, J. Shan & K. F. Mak, Perfect Coulomb drag in a dipolar excitonic insulator. Science 388, 274–278 (2025).