Strongly Correlated Excitonic Insulator in Atomic Double Layers

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Nabity Nanometer Pattern Generator System (NPGS)

Abstract:

Excitonic insulators (EIs) arise from the formation of bound electron-hole pairs (excitons) in semiconductors and provide a solid-state platform for quantum many-boson physics. Here, we demonstrate a strongly correlated two-dimensional (2D) EI ground state formed in transition metal dichalcogenide (TMD) semiconductor double layers, where spatially indirect excitons form. We construct an exciton phase diagram that reveals both the exciton Mott transition and interaction-stabilized quasi-condensation through a quantum capacitance measurement.

Summary of Research:

In bulk materials, excitonic insulators (EIs) can occur in small band gap semiconductors and small band overlap semimetals [1]. In the semiconductor limit, EIs occur when the electron-hole binding energy of an exciton exceeds the charge band gap. The ground state exciton population is determined by balancing the negative exciton formation energy against the mean exciton-exciton repulsion energy.

Although the concept has been understood for a long time, establishing distinct experimental signatures of the EIs has remained challenging.

In this experiment, we employ the atomic double layer structure to establish electrical control of the chemical potential of interlayer excitons (by making separate electrical contacts to isolated electron and hole layers). Since the electron and hole wavefunctions do not interfere, macroscopic phase coherence is spontaneous, allowing exciton superfluidity.

The dipolar nature of the interlayer excitons and the reduced dielectric screening in our devices also favor strong exciton-exciton repulsion.

Figure 1 shows the device schematics and optical image of a typical device. The device is made of a $WSe_2/MoSe_2$ bilayer separated by a thin hexagonal boron nitride (h-BN) spacer. It is also encapsulated by two gates made of h-BN and graphite. Atomically thin samples of WSe_2, $MoSe_2$, h-BN and graphite were first exfoliated from their bulk crystals onto silicon substrates. Selected thin flakes of appropriate thickness and geometry were picked up one-by-one by a stamp consisting of a thin layer of polycarbonate on polydimethylsiloxane (PDMS). The complete heterostructure was then deposited onto the substrates with pre-patterned Pt electrodes.

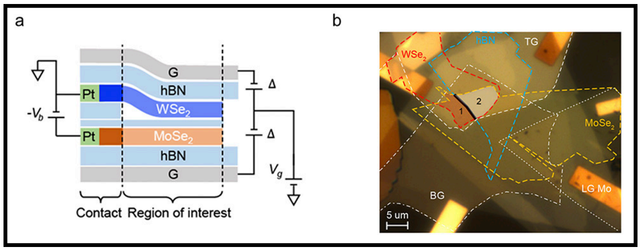

Figure 1: a, Device schematics. b, Optical microscope image of a dual-gated device. Scale bar is 5 µm.

Figure 2 (top row) shows schematics of the penetration (a) and interlayer (b) capacitance measurements. A commercial high electron mobility transistor is used

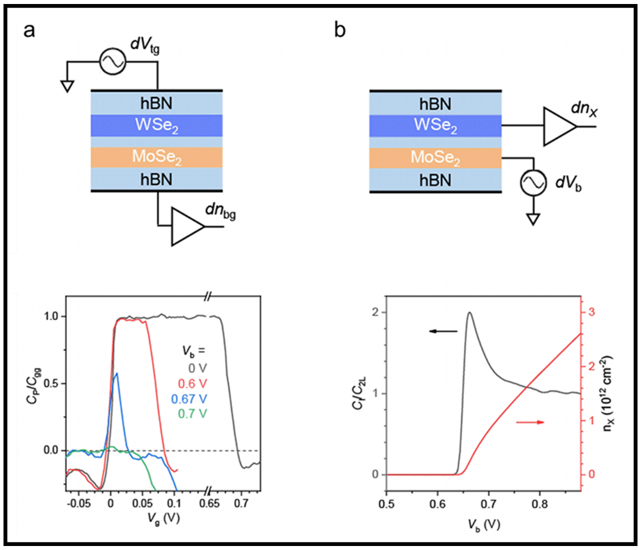

Figure 2: a, Normalized penetration capacitance as a function of gate voltage for representative bias voltages. b, Normalized interlayer capacitance (left axis) and exciton density extracted from the interlayer capacitance (right axis) as a function of bias voltage. Top row shows the schematics of the corresponding capacitance measurements.

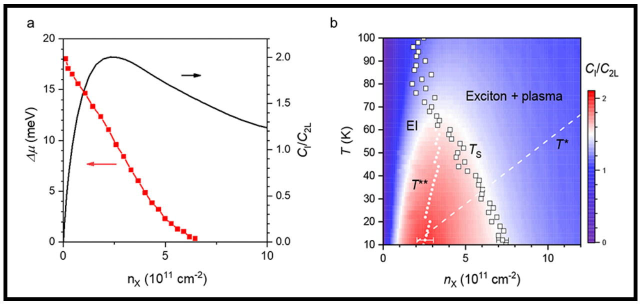

Figure 3: a, Charge gap and exciton compressibility as a function of exciton density at 15 K. b, Exciton compressibility as a function of temperature and exciton density.

as the first-stage amplifier to effectively reduce the parasitic capacitance from cabling [2]. To obtain the penetration capacitance, we apply an AC voltage (5 mV in amplitude) to the top gate and collected the signal from the bottom gate. For the interlayer capacitance, we apply an AC voltage (5 mV in amplitude) to the $MoSe_2$ layer and collected the signal from the WSe_2 layer. The measured penetration capacitance signal (Figure 2a) tracks changes in the charge gap when a bias is applied between WSe_2 and $MoSe_2$. The interlayer capacitance signal directly measures the formation of electron-hole pairs, or exciton compressibility, from which the exciton density can be obtained by integration with respect to bias voltage (Figure 2b).

We obtained exciton phase diagram in Figure 3 by combining the two measurements. The charge gap under various electron-hole pair density is measured by penetration capacitance (Figure 3a). Nonzero gap at finite density indicates that the electron-hole pairs are in the EI phase. With increasing density, the charge gap decreases to zero gradually at a critical density (the Mott density), at which the excitons are dissociated into electron-hole plasma [3]. Figure 3b shows the constructed exciton phase diagram from the measured exciton compressibility as a function of temperature and density.

The density dependence of the exciton compressibility in Figure 3 indicates the importance of exciton-exciton interactions. We consider an interacting Bose gas model [4] below the exciton ionization temperature T_s. The effective interaction strength extracted from our result is an order of magnitude larger than in other systems such as cold atoms and helium. The strong correlation is expected to suppress exciton density fluctuations [5] and enhance the effective degeneracy temperature from the degeneracy temperature T^* for non-interacting bosons to T^{**}. The region bound by T^{**} and T_s represents a degenerate exciton fluid with suppressed density fluctuations (i.e., a quasi-condensate). The strong correlation is also expected to suppress phase fluctuations and enhance the exciton superfluid transition temperature.

Our experiment paves the path for realizing the exotic quantum phases of excitons, as well as multi-terminal exciton circuitry for applications.

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