Exciton Density Waves in Coulomb-Coupled Dual Moiré Lattices

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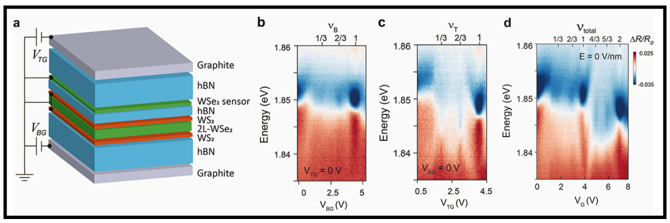

Figure 1: a, Schematic of a dual-gated device. b-d, Reflectance contrast spectrum of the sensor 2s exciton as a function of gate voltage and filling factor. In b, c one of the lattices is empty and in d two lattices are equally populated.

Abstract:

Strongly correlated bosons in a lattice are a platform to realize rich bosonic states of matter and quantum phase transitions, but in a solid-state system they are challenging to realize [1]. Here we trap interlayer excitons (bosons composed of bound electron-hole pairs) in a lattice provided by an angle-aligned WS_2/bilayer WSe_2/WS_2 heterostructure. We observe correlated insulating states when the combined electron filling factor of the two lattices equals to 1/3, 2/3, 4/3, and 5/3. These new states can be interpreted as exciton density waves in a Bose-Fermi mixture. Our results demonstrate that Coulomb-coupled moiré lattices are fertile ground for correlated many-boson phenomena.

Summary of Research:

Two-dimensional moiré materials have emerged as a highly tunable platform for the study of strongly correlated phases of matter. However, compared to fermionic systems, strongly correlated bosonic systems are much less explored. Here, we demonstrate the realization of a Coulomb-coupled dual-moiré lattice where electrons in one lattice bind with holes in the other forming bosonic particles (excitons). In such a system, we achieve independent control of the electron and exciton densities. When the combined electron filling factor of the two lattices is tuned to 1/3, 2/3, 4/3, and 5/3, we observe a new exciton density wave phase where an exciton fluid breaks the translational symmetry.

Figure 1a illustrates a dual-gated device of an angle-aligned monolayer WS_2/bilayer WSe_2/monolayer WS_2 structure. The WSe_2 bilayer provides nearly identical triangular moiré lattices of period $a_M \approx 8$ nm at the top and bottom WS_2/WSe_2 interfaces [2] and also acts as a tunnel barrier. For the relevant density range, the electrostatically doped electrons are in the WS_2 layers. The two graphite gates independently control the combined filling factor ν (doping density per moiré lattice) and the out-of-plane electric field E in two moiré lattices. The latter tunes the distribution of electrons between the two lattices. To probe the insulating states in the coupled moiré lattices, we employ an optical sensing technique [3] by placing a WSe_2 monolayer above the top WS_2 layer. Figure 1b-d show the reflectance contrast (RC) spectrum of the sensor 2s exciton as a function of gate voltage (lower axis) and total filling factor (upper axis). An insulating state in the sample is identified when the 2s exciton resonance exhibits a blueshift and an enhanced spectral weight 11. When the electrons are in one of the lattices solely (Figure 1b, c), insulating states are observed at $\nu = 1/3, 2/3, 1, 2$. When the electrons are introduced equally in two lattices by setting $E \approx 0$ V/nm (Figure 1d), we observe additional insulating states at $\nu = 4/3, 5/3$.

We use the amplitude of the sensor 2s exciton RC, R_{2s}, to identify insulating states. The largest R_{2s} is observed in Figure 2a when both lattices have integer fillings (ν_t and ν_b denoting the filling factor of the top and bottom lattices, respectively). We also observe extended regions with enhanced R_{2s} when the top lattice is insulating, and the bottom generally charge-compressible. They correspond to the red regions in Figure 2c. Similarly, one can find the blue regions in the electrostatic phase diagram in Figure 2c when the bottom lattice is insulating, and the top is generally charge-compressible. The result is fully consistent with an independent measurement based on the moiré excitons in WS_2 (Figure 2b).

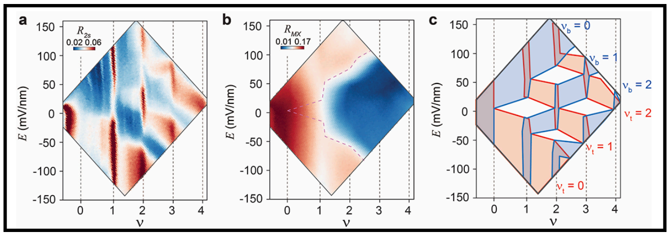

Figure 2: a,b, Reflectance contrast amplitude of the sensor 2s exciton R_{2s} (a) and WS_2 moiré exciton R_{MX} (b) as a function of total filling factor and electric field. c, Electrostatic phase diagram includes regions of gapped top lattice (red-shaded) and bottom lattice (blue-shaded).

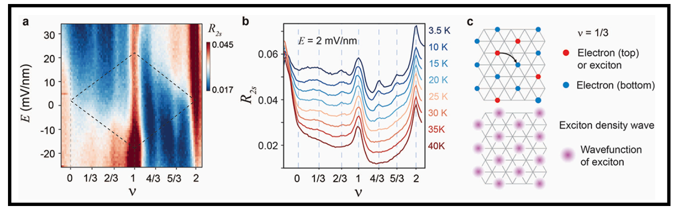

Figure 3: a, R_{2s} as a function of total filling factor and electric field. b, Horizontal linecut of a near zero field at representative temperatures. c, Schematic representation of the inter-layer Wigner crystal at v=1/3.

Upon a closer examination, we identify incompressible states from the enhanced R_{2s} at $v = 1/3, 2/3, 1, 4/3, 5/3$ for a wide range of electric field (Figure 3a). As temperature increases, the incompressible states at the fractional fillings disappear around 30-35 K (Figure 3b). The nature of these insulating states inside the dashed box is completely different from outside the box. We focus on the exotic fractional fillings. They are generalized Wigner crystals when electrons reside in a single lattice (outside the box). Inside the box, electrons are continuously transferred from the generalized Wigner crystal to the empty lattice as a function of electric field but remain bound to the empty sites in the original lattice by the inter-lattice long-range Coulomb repulsion. They form an "inter-layer" Wigner crystal to minimize the total intra- and inter-lattice Coulomb repulsions and can also be viewed as excitonic insulators [4]. The interlayer excitons hop along the channels defined by the Wigner crystal (Figure 3c), therefore dubbed exciton density wave (EDW). In the weak-disorder limit, EDWs are expected to possess finite superfluid densities in the ground state and are supersolids, as predicted by theoretical studies on atomic Bose-Fermi mixtures. This is an interesting direction for future studies.

References:

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