Exciton Density Waves in Coulomb-Coupled Dual Moiré Lattices

**CNF Project Number:** 2633-18

**Principal Investigator(s):** Jie Shan, Kin Fai Mak

**User(s):** Yihang Zeng, Zhengchao Xia

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

**Primary Source(s) of Research Funding:** NSF, DOE, ONR

Contact: jie.shan@cornell.edu, kinfai.mak@cornell.edu, yz425@cornell.edu, zx287@cornell.edu

**Primary CNF Tools Used:** Autostep i-line Stepper, Hamatech Wafer Processor Develop, Heidelberg Mask Writer - DWL2000, Photolithography Spinners, SC4500 Odd/Even-Hour Evaporator, Dicing Saw - DISCO, Zeiss Supra SEM, Nabit Nanometer Pattern Generator System (NPGS)

**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 $v$ (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 $v = 1/3$, $2/3$, $1$, $2$. When the electrons are introduced equally in two lattices by setting $E \approx 0$ V/nm (Figure 1d), we observe additional insulating states at $v = 4/3$, $5/3$.

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 ($v_1$ and $v_2$ 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).
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: