

# Bandwidth-Tuned Mott Transition and Superconductivity in Moiré WSe<sub>2</sub>

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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:

The emergence of semiconductor moiré materials provides a new platform to simulate the Hubbard model, which is believed to capture the essential physics of high- $T_c$  superconductivity. In this study, by tuning the twist angle of two WSe<sub>2</sub> layers, we reach the intermediate-coupling regime, where we observe a range of high- $T_c$  phenomenology. By further tuning an out-of-plane electric field, we modify the band structure and find that the superconducting  $T_c$  rises as the Mott insulator weakens, peaking near the electric-field-driven Mott transition.

## Summary of Research:

The Hubbard model is believed to capture the essential physics of high- $T_c$  superconductivity [1-3]. In cuprates, the bandwidth  $W$  and the interaction strength  $U$  are comparable, placing these materials in the moderate-correlation regime [3]. Despite its simple appearance, the model is extremely difficult to solve in this regime, which makes a controllable quantum simulator highly desirable. Semiconductor moiré superlattices provide one such platform, realizing the model on a triangular lattice [4]. Although hallmarks such as the Mott insulator have been observed for years, superconductivity was demonstrated only recently [5,6]. In this study, by tuning the relative twist angle in two WSe<sub>2</sub> layers, we reach a regime close to that of the cuprates and observe a series of high- $T_c$  phenomena.

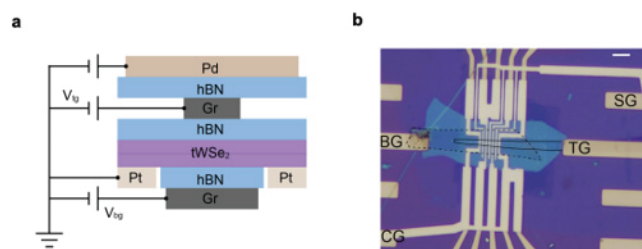


Figure 1. A, Schematic of the dual-gated device structure. B, Optical microscope image of a 4.6° tWSe<sub>2</sub> device. The scale bar is 4  $\mu\text{m}$ .

Figure 1 shows the device structure and an optical image of a twisted WSe<sub>2</sub> bilayer (tWSe<sub>2</sub>) device. The encapsulated twisted bilayer is transferred onto prepatterned platinum electrodes; a top and bottom gate form a dual-gated geometry that independently control the hole filling factor  $\nu$  (in moiré density) and the out-of-plane electric field  $E$ . The latter creates an energy offset between the two layers, thereby modifying the moiré band structure.

Figure 2 shows the resistance as a function of  $\nu$  and  $E$  for devices with twist angle ranging from 2.1° to 4.7°. The twist angle sets the moiré period and therefore controls the bandwidth relative to and correlation strength. The correlated insulators at  $\nu = 1, 1/3$  and  $1/4$  are observed at small twist angles ( $\leq 4.3^\circ$ ); they weaken as the angle increases, showing that the correlation effect weakens. Superconductivity emerges near 3.5° around  $E = 0$  mV/nm and shifts to higher  $E$  field following the Mott insulator. We focus on the 4.6° device, for which  $U$  and  $W$  are comparable which is most relevant to the physics of cuprates.

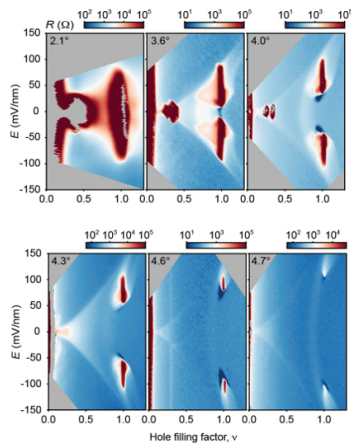


Figure 2: Twist-angle-dependent resistance as a function of filling factor  $\nu$  and electric field  $E$  for devices with twist angle from  $2.1^\circ$  to  $4.7^\circ$  at  $T = 50$  mK and  $B = 0$  T.

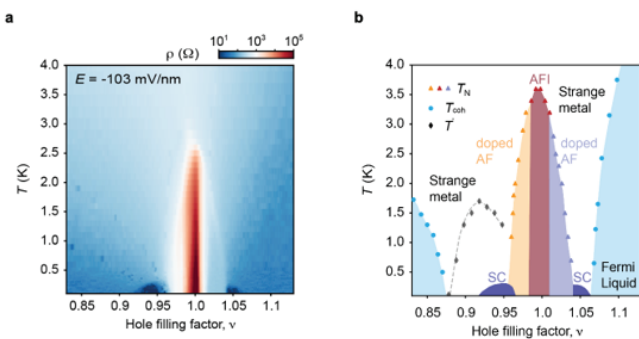


Figure 3: A, Longitudinal resistivity  $\rho$  as a function of filling factor  $\nu$  and temperature  $T$  at  $E = -103$  mV/nm for the  $4.6^\circ$  device. B, Phase diagram constructed from A. It exhibits an AF insulator (AFI) (red), electron-doped AF insulator (yellow), hole-doped AF insulator (purple), superconductors (SC) (dark blue), strange metal and Fermi liquid (light blue) with corresponding temperature scales  $T_N$ ,  $T_{coh}$  and  $T'$  (symbols).

Figure 3 shows  $\rho_{xx}$  as a function of  $\nu$  and temperature  $T$  at a fixed electric field  $E = -103$  mV/nm and the phase diagram constructed from the data. At  $\nu = 1$ , we find an antiferromagnetic Mott insulator: the resistivity rises with  $T < T_N \approx 3.5$  K, with the Néel temperature  $T_N$  defined at the local resistivity minimum. Correspondingly, the magnetic susceptibility shows a cusp at  $T_N$  with a Curie–Weiss behavior above  $T_N$ . Small doping yields an antiferromagnetic metal with a small Fermi surface, for which a local minimum can be identified in the  $\rho$ – $T$  curve at  $T_N$ . Further doping produces a superconducting dome on each side of the insulator. The metallic states adjacent to the superconductor are strange metals, showing  $T$ -linear resistivity from 100 mK to 10 K. A Fermi liquid is recovered at large doping. The resulting phase diagram is reminiscent to that of the high- $T_c$  cuprates.

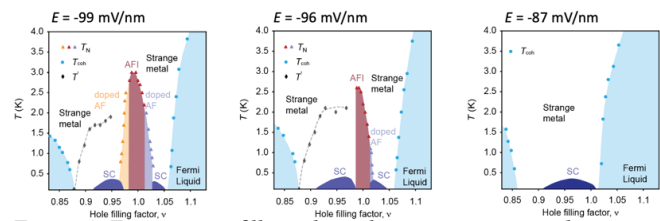


Figure 4: Temperature-filling phase diagrams constructed at different electric fields for the  $4.6^\circ$  device.

Figure 4 shows the phase diagrams constructed at different electric fields.  $E$  tunes the band structure, and thereby effectively tunes the Fermi velocity around filling  $\nu = 1$  as well as the strength of the Mott insulator. As shown in Figure 2, a metal-to-insulator transition is observed near  $\nu = 1$  at a critical field of about  $-92$  mV/nm. As  $E$  increases from the insulating side, the phase diagram evolves continuously: the antiferromagnetic insulator weakens, with  $T_N$  falling and the doped antiferromagnetic regions shrinking, whereas the superconducting domes expand and  $T_c$  increases. Beyond the transition, the insulator vanishes and only one superconducting dome is observed. The highest  $T_c$  occurs near the critical field, close to the  $E$ -field-driven Mott transition.

## Conclusions and Future Steps:

We observe in moiré  $\text{WSe}_2$  a phase diagram resembling that of the high- $T_c$  cuprates. The tunability of this platform offers insight into the high- $T_c$  problems and supports the view that superconductivity is closely related to the Mott transition. As a next step, we will characterize the properties of the novel states. For example, tunnelling experiments in the superconductor and the doped AF state will tell us the gap size of the superconductor, and whether the doped AF state exhibits a pseudogap as seen in the cuprates.

## References:

- [1] Hubbard, J. Proceedings of the Royal Society A 276, 238–257 (1963).
- [2] Anderson, P. W. Science 235, 1196–1198 (1987).
- [3] Lee, P. A., Nagaosa, N., Wen, X.-G. Reviews of Modern Physics 78, 17–85 (2006).
- [4] Kennes, D. M. et al. Nature Physics 17, 155–163 (2021).
- [5] Xia, Y. et al. Nature 637, 833–838 (2025).
- [6] Guo, Y. et al. Nature 637, 839–845 (2025).