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PhD THESIS DEFENSE: Optoelectronic probes of quantum geometry and out-of-equilibrium phenomena in graphene moire superlattices

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Two-dimensional moire superlattices have opened a new era in quantum materials, as they provide a versatile platform for engineering electronic bands and accessing correlated and topological phases. Their intrinsically narrow minibands, achieved by twisting or aligning atomically thin two-dimensional crystals, favor strong electronic interactions. Additionally, electrostatic gating further enables in situ control of carrier density, bandwidth, and bandgaps, stabilizing a wide range of quantum phases, including superconductivity, correlated insulating states, ferromagnetism, and Chern and fractional Chern insulators. Most experimental knowledge of these systems has come from quantum transport, scanning-probe, or optical experiments in the linear-response regime. This work extends the experimental toolbox by employing cryogenic nonlinear optoelectronic methods. By applying such techniques to graphene moire materials, we probe two regimes that remain difficult to access with conventional experiments: the quantum geometry of interacting flat bands and the out-of-equilibrium states generated by large in-plane currents.

Using terahertz radiation resonant with the flat bands of magic-angle twisted bilayer graphene (MATBG), we observe a polarization-resolved photocurrent whose principal axis rotates abruptly whenever the carrier density reaches an integer filling of the moire Brillouin zone. We identify this response as a shift current, a second-order photocurrent governed by the interband quantum geometry. Microscopically, the effect arises from the interplay between extrinsic symmetry breaking of the moire crystal, attributed to alignment with hexagonal boron nitride or strain, and Hartree-driven reconstruction of the MATBG flat bands. We further present preliminary mid-infrared photocurrent measurements aimed at resolving the spatial distribution of these broken-symmetry states.

The second part of this work investigates the nonlinear current-voltage response of bilayer graphene aligned to hexagonal boron-nitride under large in-plane bias. Using dual-gated devices, we map the density and displacement-field dependence of the out-of-equilibrium critical transition that occurs when single-band transport breaks down, accompanied by negative differential conductance (NDC). The critical current scales with the miniband bandwidth, a relation verified across multiple devices and moire systems. By combining temperature-dependent measurements with Boltzmann-transport simulations, we find evidence for strong electronic overheating at the transition, followed by the formation of an electron-hole plasma in which electron-hole collisions dominate the transport response. Scanning photocurrent microscopy at 4 K reveals that the transition is localized in a bulk hotspot; at the bistable threshold near the NDC regime, this hotspot also acts as the active region for single-photon detection.

Together, these results demonstrate the value of optoelectronic probes for investigating moire quantum materials, and open multiple directions for future study. Polarization-resolved terahertz photocurrent spectroscopy provides access to the quantum geometry of correlated moire bands, whereas high-bias transport offers a direct handle on superlattice dispersion and nonequilibrium carrier dynamics. These techniques are readily applicable to a vast range of materials. Additionally, our findings pave the way for novel optoelectronic devices based on moire materials operating at long wavelengths.

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