

Transport and Scanning Tunneling Microscopy Devices Based on van der Waals Heterostructures

CNF Project Number: 3162-24

Principal Investigator(s): Xiaomeng Liu

User(s): Zhida Liu, Alexander Sanchez, Jiabin Xie

Affiliation(s): Laboratory of Atomic and Solid State Physics, Department of Physics, Cornell University

Primary Source(s) of Research Funding: National Science Foundation, College of Arts and Sciences

Contact: xiaomengliu@cornell.edu, zl2293@cornell.edu, aes444@cornell.edu, jx399@cornell.edu

Research Group Website: <https://www.xiaomengliu.com/>

Primary CNF Tools Used: Heidelberg MLA 150 Maskless Aligner, Heidelberg DWL 2000, Zeiss Supra Scanning Electron Microscope, Nabity Nanometer Pattern Generator System, Oxford 81/82 Reactive Ion Etchers, Oxford FlexAL Atomic Layer Deposition System, SC4500 Electron-Beam Evaporators

Abstract:

This report describes three van der Waals device efforts: low-temperature transport in rhombohedral graphene, a twisted ABC graphene device, and a scanning tunneling microscopy (STM)-compatible device. The transport platforms use multiterminal geometries to measure longitudinal and Hall responses, whereas the STM platform preserves a clean, exposed surface for local spectroscopy. CNF lithography, plasma etching, microscopy, dielectric deposition, and metal deposition are central to all three efforts.

Summary of Research:

Our work combines electrical transport with local tunneling spectroscopy to study correlated and topological states in two-dimensional materials. The projects share a fabrication platform based on dry-transferred van der Waals stacks, alignment to pre-patterned markers, plasma etching, and metal deposition. The transport devices remain encapsulated, whereas the STM device must retain electrical connectivity while exposing a clean surface to the tunneling tip.

Project 1: Rhombohedral Graphene Transport

Rhombohedral (ABC-stacked) graphene provides an intrinsically rich platform for correlated-electron physics because its low-energy bands can become narrow and interaction-dominated, while electrostatic gates independently control carrier density and displacement field. In our heterostructures, a nearby twisted transition-metal dichalcogenide stack generates a remote, long-wavelength modulation in the ABC graphene. Combining this engineered periodic potential with the native correlated states of ABC graphene offers

a route to reconstruct the electronic spectrum and explore emergent correlated and topological phases. We fabricate encapsulated heterostructures and pattern them into Hall bars with longitudinal and transverse voltage probes. Four-terminal measurements separate longitudinal resistance from the Hall response, while electrostatic gates tune carrier density and, when applicable, displacement field. Figure 1 shows a completed device after metal liftoff. Before cooldown, we check contact continuity, gate leakage, and channel resistance. At low temperature, multiple probe pairs and forward/reverse sweeps of density, magnetic field, temperature, and DC bias help distinguish intrinsic features from contact mixing, inhomogeneity, or metastability. The CNF-fabricated devices are subsequently measured in a dilution refrigerator.

Project 2: Twisted ABC Graphene Device

Stacking two sets of multilayer rhombohedral graphene one on top of the other at a slight twist angle modifies

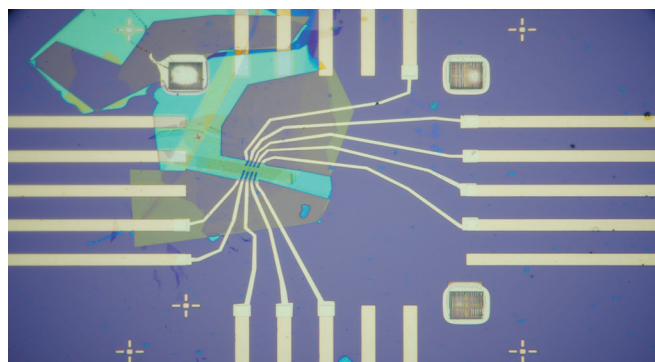


Figure 1: Optical micrograph of the completed multiterminal Hall-bar device after metal liftoff. The central van der Waals heterostructure is connected to multiple longitudinal and transverse voltage probes for low-temperature transport measurements.

the band structure of the graphene, potentially further flattening it. These flat bands can exhibit various quantum states which could be precursor states to those necessary for stable quantum computers. We are exploring different device configurations by varying layer number and twist angle to stabilize these states in twisted rhombohedral graphene heterostructures. By patterning our devices into Hall bars for electronic measurements using the methods heretofore described, we can probe the quantum states of our devices. Figure 2 shows a completed twisted rhombohedral graphene device patterned into a Hall bar geometry for measurement.

Project 3: Direct-Write STM Device

STM requires atomic-scale access to the sample surface, but conventional lithography can leave polymer residue in the scan region. We therefore use a top hBN layer as

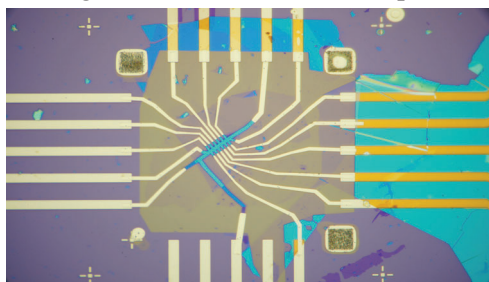


Figure 2: Optical micrograph of a twisted rhombohedral graphene device which has been etched into a Hall bar geometry for transport measurements, using nanofabrication facilities.

a temporary protective cover during fabrication. Direct-write photolithography defines the alignment marks, contact pads, and routing. After completing the electrical structure, we translate the top hBN laterally to expose the active device while preserving the contacts and gate architecture. Graphene on hBN provides a low-disorder platform for local spectroscopy [3], and edge contacts provide robust electrical access [4]. Figure 3 shows the device after hBN displacement. Optical registration locates the exposed window relative to the contacts, and electrical checks confirm continuity and gate isolation. These steps allow the STM tip to approach a clean, electrically tunable region without contacting a metal lead or remaining hBN terrace.

CNF Nanofabrication Workflow

The Heidelberg MLA 150 and DWL 2000, together with photolithography spinners, define direct-write patterns and large alignment features. Fine patterns are written using the Zeiss Supra SEM and Nabity Nanometer Pattern Generator System after resist preparation on the

E-Beam Lithography Spinners. Oxford 81/82 etchers provide CHF_3/O_2 or O_2 plasma processes for mesas and contact edges; the Oxford FlexAL supports dielectric deposition when required; and the SC4500 Even/Odd evaporators deposit contact metals. Microscopy between steps verifies alignment, channel geometry, contact continuity, and the position of the movable top hBN

Conclusions and Future Steps:

The three projects establish complementary routes for probing two-dimensional quantum materials. The rhombohedral-graphene and twisted-ABC platforms enable longitudinal and Hall measurements, while the STM design adds spatially resolved access to an electrically tunable device. Near-term work will complete low-temperature transport characterization, compare contact pairs and sweep directions, and refine hBN displacement to maximize the clean STM-accessible area. We will then evaluate tunneling stability and spectroscopic quality. CNF alignment, etching, deposition, and inspection capabilities remain central to converting assembled flakes into reliable devices.

References:

- [1] Park, H. et al. Observation of fractionally quantized anomalous Hall effect. *Nature* 622, 74-79 (2023).
- [2] Zeng, Y. et al. Thermodynamic evidence of a fractional Chern insulator in moiré MoTe_2 . *Nature* 622, 69-73 (2023).
- [3] Xue, J. et al. Scanning tunnelling microscopy and spectroscopy of ultra-flat graphene on hexagonal boron nitride. *Nature Materials* 10, 282-285 (2011).
- [4] Wang, L. et al. One-dimensional electrical contact to a two-dimensional material. *Science* 342, 614-617 (2013).

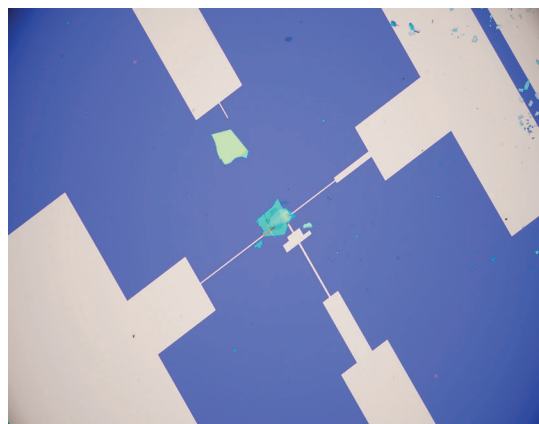


Figure 3: Optical micrograph of the laser-direct-written STM device after lateral displacement of the protective top hBN. The central heterostructure remains electrically connected while an exposed region is made accessible to the STM tip.