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Direct visualization of topological superconducting states in the GHz regime

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Direct visualization of topological superconducting states in the GHz regime

ABSTRACT
The objective of this project is to utilize high-frequency scanning probe microscopy techniques to visualize topological electronic states in quantum materials, with particular focus on two-dimensional systems that host one-dimensional chiral edge modes. During this project, we developed a state-of-the-art microwave impedance microscope (MIM) integrated into a cryogen-free dilution refrigerator, which images the local microwave response from electronic states at low temperatures below 100 mK. To complement this experimental effort, we developed models that quantify the MIM response of chiral edge modes propagating at the boundary of a Chern insulator, which provide a general framework for understanding the response of topological edge modes using the technique of microwave impedance microscopy. During the final year of the project, we developed a suite of complementary scanning probe microscopy tools to both image and dynamically manipulate the twist angle of a moiré crystal in-situ, which may be useful for systematically mapping the phase diagram of correlated and topological states in this family of materials.

I. Accomplishments

1.1. Research Objectives.
The proposed research seeks to identify and probe the fundamental electronic properties of edge states and Majorana zero modes in two-dimensional topological materials. Majorana modes are non-abelian excitations could be leveraged to store quantum information nonlocally using braiding operations, potentially enabling a more robust form of quantum computing.

This study focuses on the modeling and readout of chiral edge modes that propagate along the boundaries of two-dimensional topological insulators. Our technical approach involves the development of a state-of-the-art dilution refrigerator microwave impedance microscope (MIM) to achieve visualization of one-dimensional topological boundary states at milliKelvin (mK) temperatures. It aims to expand the physicist's toolbox by opening up a new suite of sensing tools that probe quantum materials in the frequency domain at ultra-low temperatures and unveil the microscopic nature of one-dimensional chiral edge modes that exist at the edges of Chern insulators.

1.2 Accomplishments

Activity 1: Towards milliKelvin microwave impedance microscopy of topological states.
This research thrust strives to employ microwave impedance microscopy (MIM), which characterizes the local complex conductivity of a material, to directly visualize chiral edge states and Majorana zero modes in topological quantum devices. During this reporting period, our group has made progress on the construction of a new milliKelvin MIM, which will support spatially-resolved detection of topological states at ultra-low temperatures. This setup consists of an Attocube tuning-fork-based atomic force microscope (AFM) integrated into a Leiden Cryogenics dilution refrigerator (Figs. 1-2). A small probe is driven by an AC current at microwave frequency is coupled to the AFM and scanned over a sample of interest; using microwave reflectometry, MIM probes the local conductivity and electronic compressibility of the material (Fig. 3). Our group has demonstrated successful MIM imaging of the conductivity contrast between graphite and silicon dioxide down to temperatures of ~70 mK, which provides a proof of concept of the operation of the technique in the <100 mK regime. The results of this work are published in L. Cao *et al.* (2023).

Characterization of mK MIM. To demonstrate low temperature performance, we measured the spatial contrast of the MIM response across the interface between SiO_2 and graphite at 70 mK (Fig. 5). To explain the experimental observations, one can model the MIM tip-sample interaction for this system using finite element analysis, which can be used to calculate the MIM response curves as a function of sample conductivity. At the measurement frequency of 1.8 GHz, the imaginary part of the MIM response should monotonically increase with the sample conductivity, saturating when the resistivity is higher than $10{-}2\Omega \cdot m$ (insulating limit) or lower than $10{-}5\ \Omega \cdot m$ (conductive limit), as shown in Figure 5b. At a temperature of 70 mK, we estimate the spatial resolution to be around 200 nm, constrained by the apex geometry of the etched tungsten tip and mechanical noise from the pulse tube vibrations (Fig. 4).

Challenges and proposed solutions. The main technical challenge of microwave imaging at low temperatures is the emergence of new noise sources, which impact both spatial resolution and the signal-to-noise of the microwave reflectometry measurements. There are two main sources of increased noise: (1) the high Q factor of the tuning fork, which is used for active height feedback, leads to fluctuations in the tip-sample distance, and (2) mechanical pulse tube vibrations at 1.4 Hz, which are associated with the cooling mechanism of the dilution fridge, places limits on the lateral spatial resolution and adds noise to the MIM readout. To mitigate these noise sources, we damped the tuning fork with glue to decrease its Q factor and physically decoupled the pulse tube motion from the microscope by unscrewing the rotary valve from the fridge and putting isolation foam in between. The high-pressure helium lines to the compressor are also wrapped with acoustic pipe lagging for noise mitigation.

We also found that performing AC-mode MIM imaging, in which the MIM signal is monitored and the tuning fork resonance frequency using lock-in techniques, increased the signal-to-noise ratio and largely eliminated modulations in the images due to pulse tube vibrations (Fig. 6). In height-modulated imaging mode, a low frequency lock-in amplifier is added to the output of the GHz frequency mixer to demodulate the reflected MIM signal at the tuning fork resonance frequency (~30 kHz), after which high and low pass filters can be used to attenuate signals at other frequencies.

During AC-mode MIM imaging, the tip is typically lifted 60-100 nm above the surface and scanning is performed with the tip floating a fixed distance above the sample ("floating mode"). At this distance, the AFM channel will not be modulated due to the topography feedback, but the MIM tip can still interact with the sample via the electromagnetic fields in the vicinity of the tip (when operated in the near-field regime). Because periodic oscillations in the tip-sample distance at the tuning fork resonance are decoupled from the surface roughness of the sample, noise in the MIM response can be dramatically reduced in "floating mode." Figure 6 shows a floating MIM scan performed at 3 GHz, with the tip lifted 100 nm above an hBN-covered graphite layer.

Activity II. Microwave impedance microscopy of chiral edge modes at the boundary of a Chern insulator.

The objective of this project is to connect theoretical predictions of interesting two-dimensional topological phases to experimental detection via MIM. We developed a theoretical model that quantifies the MIM response of one-dimensional topological edge modes that propagate along the boundaries of a Chern insulator state, which constitutes a promising solid-state platform for topological quantum information. These electromagnetic simulations help shed light on our prior experiments on quantum anomalous Hall insulators; they also establish a groundwork for modeling new topological systems that could guide future microscopy experiments.

Modeling the MIM response of a Chern insulator. Using finite element analysis software (COMSOL), we modeled the GHz response of topological edge states as probed by MIM. Here a small metallic probe is driven by an AC current at microwave frequency and placed near a quantum anomalous Hall insulator sample, whose Chern number is quantified by a conductivity tensor. Our models interpret the experimentally-measured change in the MIM response near the edge of topological insulator as a sign of an off-diagonal, in-plane component of the conductivity tensor. We calculated the resonant frequencies of standing waves that can occur at the edge of a topologically non-trivial Chern insulator. In the case of a quantum Hall sample, these waves are called "edge magnetoplasmons", and can be understood as oscillations simultaneously in the electromagnetic field and in the local chemical potential (Figs. 7-8). In future experimental work, we seek to probe the discrete resonant frequencies, as these might be accessible to MIM measurements. We also expanded our simulations to understand the frequency-dependent broadening of the edge signal detected in our prior experiments. The results of this work are published in T. Wang *et al.* (2023).

Towards time-resolved microwave imaging of topological insulator edge states. Motivated by these theoretical developments, our group is developing a new time-resolved pump-probe MIM measurement scheme that can map out the time evolution of the topological plasmonic edge excitations in the MHz-GHz regime. This approach has the potential to detect the unique experimental signature of the chirality and topological invariant of the state, which is critical for distinguishing topologically non-trivial modes from their trivial counterparts.

Activity III. In-situ twisting and imaging of moiré crystals.

In the final project, we developed a suite of complementary scanning probe microscopy tools to both image and dynamically manipulate the twist angle of a moiré crystal in-situ, enabling continuous control of the electronic band structure. The methods developed in this work may potentially be useful for systematic manipulation and readout of the phase diagram of topological states in a moiré device. This is achieved via nanomechanical manipulation of one atomic layer with respect to another, which can be performed in real-time inside a microscope (see Figures 9-10). This approach achieves the collective rotation of a single layer of atoms with millidegree control and minimal distortion of the superlattice, which contrasts other methods for manipulation of van der Waals heterostructures that simultaneously introduce stretching or strain in the process. Furthermore, unlike highly specialized methods that are tailored for inter-layer tunneling spectroscopy our approach leaves the superlattice accessible during the rotation process. This allows for interrogation using a variety of optical, electronic and scanning microscopy probes, which could be useful for a range of experiments. The results of this project are reported in the paper Q. Zhang *et al.* (2023).

As illustrated in Figures 9-10, a nanostructured metal rotor is patterned on the top monolayer of the twisted heterostructure using lithographic methods, allowing it to rotate freely with respect to the bottom flake. The rotor frame provides structural support that enables rigid rotation of the entire top atomic layer, minimizing the likelihood of stretching or tearing during the mechanical manipulation process. When the moving AFM probe comes into contact with the metal rotor, it will exert a horizontal force on the structure, leading to in-situ twisting of the double-layer stack. The PI has demonstrated in-situ rotation of twisted bilayer graphene with a precision of a fraction of a degree, as illustrated in Figure 10.

To complement our *in-situ* twisting technique, we employ PFM to image the spatial structure of the moiré crystal, providing quantitative readout of the twist angle (Fig. 10). PFM maps the structure of the superlattice with nanoscale resolution by detecting the local mechanical response of the sample induced by an AC bias on the tip, allowing for extraction of the twist angle locally at every point on the twisted vdW heterostructure. This imaging method can therefore provide real-space visualization of lattice reconstruction, local strain, and angle disorder, all of which can have a critical impact on the electronic band structure. Guided by the PFM maps of a moiré crystal, we will later use MIM to image the low-energy electronic ground states at specific locations on the superlattice at low temperatures. This combination of microscopy tools provides a new route for the real-time rotation of semiconductor moiré crystals and should allow us to precisely map the phase diagram of gapped and topological states as a function of twist angle in the family of twisted transition metal dichalcogenide (TMD) homobilayers, including $tMoTe_2$ and $tWSe_2$.

1.3. Dissemination of Results.
The PI gave invited talks at the Simons Ultra Quantum Matter Workshop at Harvard University, the Thouless Institute for Quantum Matter Winter Workshop: New Developments in Fractionalization, and the IR/THz/Microwave Nanoscopy for Quantum Information Science Workshop.

The PI also delivered seminars on the results of this project at the NSA's Laboratory of Physical Sciences, Oxford University, UC Santa Barbara, and UC Davis.

The results from this project have been shared with the research community in the following papers:

- T. Wang, C. Wu, M. Mogi, M. Kawamura, Y. Tokura, Z.-X. Shen, Y.-Z. You, and M. T. Allen. Probing the edge states of Chern insulators using microwave impedance microscopy. *Phys. Rev. B* **108**, 235432 (2023).
- L. W. Cao, C. Wu, R. Bhattacharyya, R. Zhang, and M. T. Allen. MilliKelvin microwave impedance microscopy in a dry dilution refrigerator. *Review of Scientific Instruments* **94**, 093705 (2023).
- Q. Zhang, T. Senaha, R. Zhang, C. Wu, L. Lyu, L. W. Cao, J. Tresback, A. Dai, K. Watanabe, T. Taniguchi, and M. T. Allen. Dynamic twisting and imaging of moiré crystals. arXiv:2307.06997 (2023).

II. Impacts

2.1. Impact on the principal discipline(s) of the project.
Our group develops high-resolution scanning probe microscopy techniques to visualize electronic states in quantum materials, with particular focus on two-dimensional materials that may exhibit topological physics. During this funding period, our group set up a novel microwave impedance microscope integrated into a cryo-free dilution refrigerator (delivered in January 2022), which images the local microwave response from electronic states at low temperatures down to 50 mK (published in L. Cao *et al.* (2023)). These imaging methods are naturally suited for detecting topological states at domain walls, interfaces, and crystal boundaries. We anticipate that our technique has the potential to broadly impact the base of knowledge and research across experimental condensed matter physics and quantum materials. A few examples of applications of our ultra-low temperature instrumentation to topics of interest to this community include:

- Mapping the phase diagram of correlated states and metal-insulator transition in twisted transition metal dichalcogenides (TMDs), which can be challenging to electrically contact and probe using transport techniques

- Visualization of chiral one-dimensional modes that propagate along the interface of magnetic domains that emerge at phase transitions in magnetic topological materials (such as quantum anomalous Hall insulators and Weyl semimetals)
- Real-space imaging of topological superconductivity in 3D crystals or topological insulator Josephson junctions. We are currently collaborating with theorists to better quantify the expected MIM response of topological modes in these systems and distinguish them from trivial states. Systems that host topological superconductivity are of interest due to potential applications in the area of topological quantum computation.

On the modeling side, our simulations of the MIM response of quantum Hall states lay the general groundwork for extraction of the Chern number of topological edge modes using the technique of microwave impedance microscopy, though specific case studies will require additional theory work to incorporate materials-specific parameters (published in T. Wang *et al.* (2023)). This measurement capability is potentially useful for characterization of other topological phases in emerging quantum materials.

2.2. Impact on other disciplines.

Bio-imaging. The room temperature MIM system we developed supports nanoscale imaging under ambient conditions, which can enable exploration of biological systems. A potential application would be spatially-resolved imaging of electrical signals in neurons and cardiac tissue. Also, our recent COMSOL simulations indicate that MIM can be used to probe systems described by non-trivial conductivity tensors, so another new application of this technique would be the detection of anisotropic conductivity in muscles and other tissue with a directional structure.

Imaging nanomechanical motion. Our dilution refrigerator microscope supports MIM experiments under high vacuum, which could offer a new method for imaging nanomechanical motion of suspended 1D or 2D materials. The technique of MIM provides a capacitance-based method for visualizing the modal responses of atomically thin membranes with nanoscale resolution. Using COMSOL, we have developed preliminary electromagnetic models that predict the local microwave response of a gated nanomechanical graphene resonator placed in proximity to a scanning probe tip. In this configuration, the MIM signal is modulated in response to changes in the tip-sample capacitance as the membrane vibrates. In this way, the MIM acts as an electromechanical transducer by converting mechanical movement into electrical signal in the MHz-GHz regime. This novel (and currently unexplored) application of MIM may open the door to spatially-resolved, time-domain imaging of nanomechanical devices over a broad temperature range, which has not been achieved using other readout methods.

2.3. Describe the impact in this reporting period on the development of human resources.

During this funding period, the PI served as a faculty mentor for the Summer Training Academy for Research Success (STARS) and Cal-Bridge's CAMPARE, a jointly sponsored summer research program that provides research opportunities for underrepresented students from community colleges and minority-serving institutions. Cal-Bridge is a bridge program that serves as a pipeline facilitating the advancement of undergraduates from underrepresented groups into PhD programs in physics. The program pairs students from the network of California State Universities and California community colleges with research labs in the UC system. Cal-Bridge has supported over 125 scholars, including women, African American, Hispanic American, Native

American, LGBTQ+, and first-generation college students.

Over the course of this grant, the PI mentored four graduate students and three undergraduate students, who contributed to this research. All three undergraduate researchers were admitted to competitive Physics PhD programs this year, including Princeton, Cornell, UC Berkeley, Columbia and others.

2.4. Impact on teaching and educational experiences.
The PI developed and taught a new advanced undergraduate laboratory course on condensed matter physics at UCSD, which focused on quantum materials characterization, nanoscale systems, and scanning probe microscopy. The lab employs an inquiry-based approach to learning, which strives to emulate a realistic research environment in a classroom setting. Projects are designed to focus on simple ideas that illustrate key physics concepts: topics include Hall effects, superconductivity, low-temperature electronic measurement techniques, and nanoscale imaging using atomic force microscopy (AFM) and microwave impedance microscopy (MIM).

The first half of the course is structured into lecture (1 hour/week) and lab components (2 hours/week). Students are grouped into small teams of 3-4 and pursue several supervised experiments under the direction of a Teaching Assistant. During the first few weeks, we introduced students to basic materials characterization techniques using the Versalab physical property measurement system from Quantum Design. Each research team was required to learn some of the basic background and methodology of electronic transport and vibrating sample magnetometry, completing two experimental modules.

To expand the scope of the course, the PI developed a new instructional microscopy module that provides students with hands-on experience with the techniques of AFM and MIM, utilizing home-built equipment in my lab. During the second half of the course, students had the opportunity to pursue a focused research project using this state-of-the-art microscopy instrumentation. Examples of final research projects include:

- Microwave impedance microscopy of graphene and van der Waals heterostructures
- Atomic force microscopy of nanoscale patterns in data storage discs
- Electronic transport and magnetometry measurements high T_c superconductor YBCO

2.5. Impact on physical, institutional, and information resources that form infrastructure.
Due to delays in the construction of the PI's lab at UCSD, the building facilities (cooling water, electrical power, high ceiling space, etc.) required for the projects described in this proposal were unavailable for the majority of Years 1-2 of the award. To overcome this obstacle, we sought out and renovated temporary lab space located in the Center for Magnetic and Recording Research. During Y2 of this reporting period, our research group devoted a significant amount of manpower and resources to facilities upgrades that would support operation of our low-temperature microscopy and electronic transport equipment in temporary space.

Our renovation work included: (1) clearing out old equipment in the space, (2) cutting open the ceiling and rearranging overhead ductwork, electrical conduits, and light fixtures to provide high ceiling (~12 ft) space for top-loading dilution refrigerator and cryostat probes, (3) upgrading a cooling water manifold with pressure gauges, flowmeters, water filters, valves, piping, and hosing to interface our equipment with the building cooling water, (4) installation of high voltage electrical outlets, (5) design and construction of two acoustic isolation chambers for pulse tube compressors, which ensures a low noise environment for imaging, and (6) design and machining of overhead support beams for operation of top-loading measurement probes for a Leiden Cryogenics dilution refrigerator and an Oxford Instruments cryostat.

An expanded discussion and justification for the renovations described above is provided in *Section 3.2: Problems and Delays* in this report. Renovations of temporary lab space were paid for using my startup funds; the AFOSR YIP grant was not billed for these additional expenses.

2.6. Impact on society beyond science and technology.

This project takes steps towards the development of novel materials platforms for topological quantum computing, an exceptionally robust form of quantum computation that is less sensitive to environmental noise and perturbations. Development of a quantum computer would impact the areas of computer security and cryptography and would be important for strengthening national security. Quantum algorithms could also accelerate solving complex problems in biology and medicine, especially drug design, which would have broader social impact.

III. Changes

3.1. Changes in approach.

We adjusted our research focus in response to lengthy delays in the delivery of our cryogenic measurement equipment, which stemmed from COVID travel restrictions during Years 1-2 of the grant. Because low temperature microscopy was not possible during that time, we instead focused our efforts on finite element modeling of the MIM response of topological states, as well as the development and testing of a room temperature microwave impedance microscope.

Due to a 3+ year delay in the construction of our lab at UCSD, the building facilities required for the proposed research were also unavailable during Years 1-2. To overcome this obstacle, we identified alternative space in the Center for Magnetic and Recording Research and performed renovations of this space during Year 2. Design work included rearranging ceiling ductwork and overhead electrical work to provide clearance for top-loading measurement probes, planning the installation of high voltage electrical outlets, and the design and construction of home-built acoustic isolation chambers for pumps and compressors. A more complete description of these infrastructure upgrades is provided in the following section.

3.2. Problems or delays.

Impact of the COVID-19 pandemic. The most significant delays stemmed from research disruptions due to the COVID-19 pandemic. The campus' temporary shutdown of on-site research, followed by a reduction of on-site personnel, impacted my group's experimental efforts, particularly the installation and testing of cryogenic measurement equipment.

The proposed experiments require low temperature measurement equipment developed by Oxford Instruments and Attocube Systems. However, the installation of both of these measurement systems were significantly delayed due to COVID-related travel restrictions and delays in the manufacturing process. In particular, the installation of the Oxford system was postponed to

September 2021 and the installation of the Attocube system was postponed to January 2022. The Oxford Instruments system was not delivered in working condition and required replacement parts for the repairs. Supply issues have also slowed down our ability to purchase/repair components that support our measurement equipment, including turbo pumps, vacuum flange feedthroughs, a nitrogen pre-cooling line for the dilution fridge, and replacement parts. Due to COVID-related travel restrictions and embassy closures, the start date of my postdoctoral fellow had been delayed significantly (by 6 months); he was expected to play a key role in the construction and testing of the low temperature measurement equipment.

Lab renovation delays at UC San Diego. The PI's lab renovation at UCSD was delayed by 3+ years, with the completion date postponed to Spring 2023. Due to this situation, we lacked the building facilities (high ceiling space, high voltage electrical outlets, cooling water, etc.) to support operation of the cryogenic measurement equipment needed for the proposed work. In an effort to overcome these obstacles, our research group sought out temporary space across campus in the Center for Magnetic and Recording Research. For roughly one year of this project, my students and I spent considerable time and resources on renovating this space to meet the facilities needs of the proposed project. The renovation work included: (1) clearing out old equipment, (2) cutting open the ceiling in select locations, (3) measuring and moving ceiling ductwork, overhead lights, support beams, and electrical work to provide clearance for top-loading electronic transport and microscopy probes, (4) installation and testing of cooling water manifolds, (5) installation of high voltage electrical outlets, (6) design and construction of home-built acoustic isolation chambers for pumps and compressors, in lieu of using a separate pump room, and (7) designing and machining overhead crane booms for operation of top-loading measurement probes. The PI paid for renovations of temporary space using my startup funds; the AFOSR account was not billed for these additional expenses.

Note: At the time this AFOSR YIP proposal was submitted, the completion of our lab renovation and the arrival of the Attocube equipment were both slated for February 2020, which aligned with the start date of the award. Due to delays, the facilities and equipment listed in the original proposal were unavailable for the majority of Years 1-2 of this award.

3.3. Expenditure Impacts.

Our group experienced significant delays in hiring personnel, including postdoctoral fellows and graduate students, due to COVID travel restrictions, which resulted in lower spending rates on Years 1-2 of the award. Additionally, our expenditures on supplies/equipment were slowed down due to UCSD lab construction delays and COVID-related equipment delivery delays (described in the previous section).

3.4. Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards.

Nothing to report.

3.5. Changes to the primary place of performance from that was originally proposed.

The primary place of performance has been changed to UCSD's Mayer Hall 3318/3322 and the Center for Magnetic and Recording Research 1E. Research is currently performed in temporary space due to a 3+ year delay in the construction of the PI's lab at UCSD, whose completion date was postponed from February 2020 to Spring/Summer 2023. Due to this situation, the required space and facilities (cooling water, electrical power, ceiling height, etc.) needed for the experiments described in this proposal were unavailable for the majority of this award.

IV. Technical information and Figures

Technical description of the mK microwave impedance microscopy setup: This setup consists of an Attocube tuning-fork-based atomic force microscope (AFM) integrated into a Leiden Cryogenics CF-CS110 dilution refrigerator (Figures 1-2). The microscope housing is in thermal equilibrium with the mixing chamber (MC) plate on the cold-insertable probe, which is loaded into the dilution refrigerator. Figure 3a shows the design of the microscope tip holder, which houses an etched tungsten wire mounted onto to the end of one prong of a tuning fork (TF) mechanical resonator. The oscillation amplitude of the TF is measured for continuous height feedback, which enables tapping-mode topography imaging. An optical image of the tungsten tip glued on the TF is shown in Figure 2(a). Below the tip holder, the sample stage is mounted on a stack of piezoelectric scanners (Attocube AN-Sxyz100) and the positioners (ANPx(z)100), which control fine xyz scanning (up to 40 μm × 40 μm scan window) and coarse positioning (5 mm × 5 mm travel distance), respectively.

On the MIM circuitry side, GHz signals are generated by an analog signal generator, and one split branch of the signal is coupled to the tip via an impedance matching network. The reflected signal from the tip travels to the probe-MC plate, passes through two directional couplers sitting on the probe-still plate, and then it gets amplified by a cryogenic amplifier on the 3K stage, after which the signal propagates out of the probe and gets further amplified and demodulated at room temperature (as shown in Fig. 3).

We characterized the low temperature performance of the AFM on a sample consisting of an array of etched SiO2 holes patterned on a Si wafer, as depicted in the topographic profile in Figure 3. Cryogenic AFM measurements were performed over the same 5 μm × 5 μm scan window at 70-80 mK (Fig. 4). To assess the magnitude of z-noise during AFM scanning, we performed 96x96-pixel noise scans over a 1 nm × 1 nm area, such that the spatial profile is irrelevant. Root mean square (RMS) roughness was calculated using Gwyddion after line fitting, which gives z-noise levels in the range of 1.8 nm (at 9 T) to 2.2 nm (at 0 T). Note that a tilted stripe pattern is visible in the large area 5 μm × 5 μm AFM images: taking a Fourier transform of this data reveals that the stripe pattern has a frequency of 1.4 Hz, consistent with the frequency of the pulse tube.

Figures

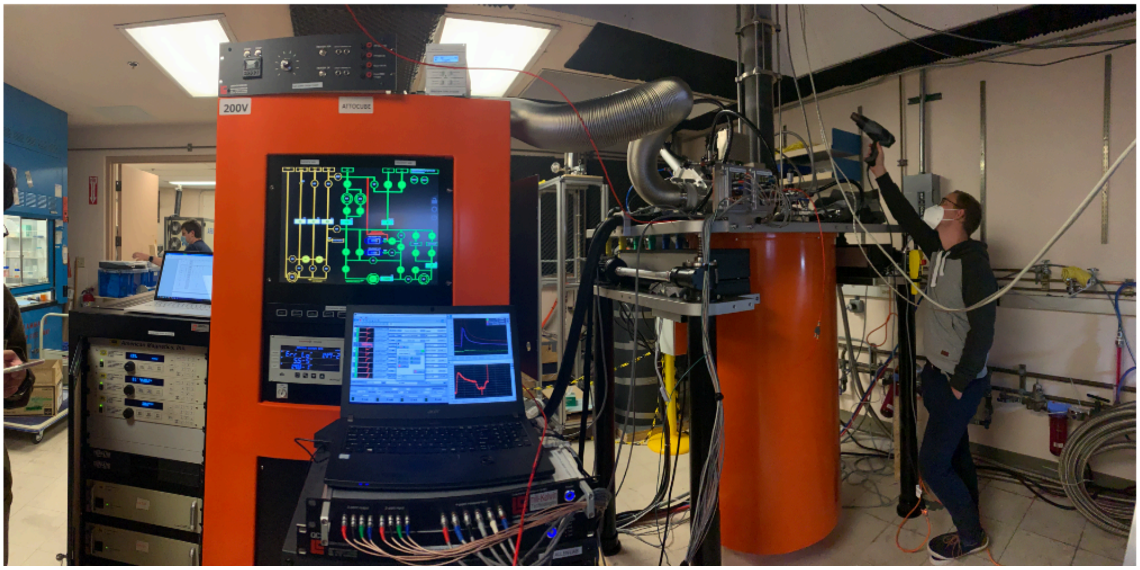


Figure 1. Installation of the Attocube/Leiden milliKelvin scanning probe microscope (delivered January 2022).

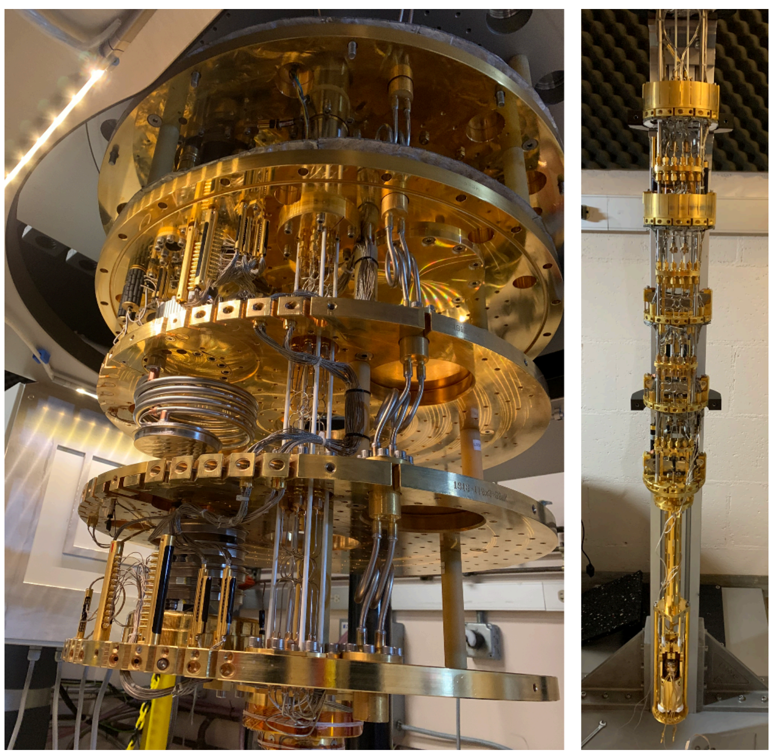


Figure 2. Leiden Cryogenics dilution refrigerator (left panel) and top-loading probe with integrated atomic force microscope (right panel)

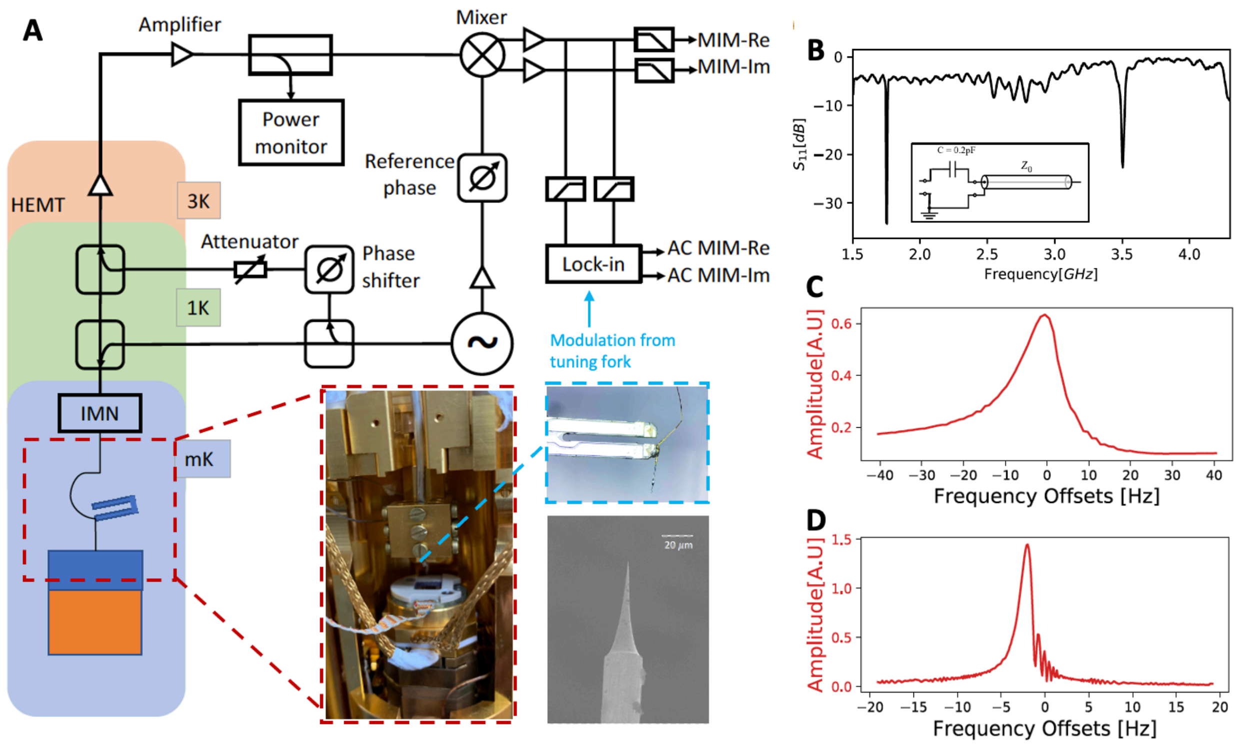


Figure 3. Scanning probe microscopy system with combined AFM and MIM readout, integrated into a dilution refrigerator. (A) Schematic illustration of the scanning microwave impedance microscopy (MIM) readout electronics and hardware integrated into a Leiden Cryogenics dilution refrigerator. Insets display a close-up view of the microscope head, scanners, and sample stage (*red*), tuning fork for height feedback (*blue*) and an etched tungsten wire tip. **(B)** Plot of microwave power reflected from the MIM probe showing impedance matching at GHz frequencies. Good impedance matching appears as a dip in power. **(C)** and **(D)** Mechanical resonance peak of the tuning fork at T = 4 K and ~ 70 mK, respectively.

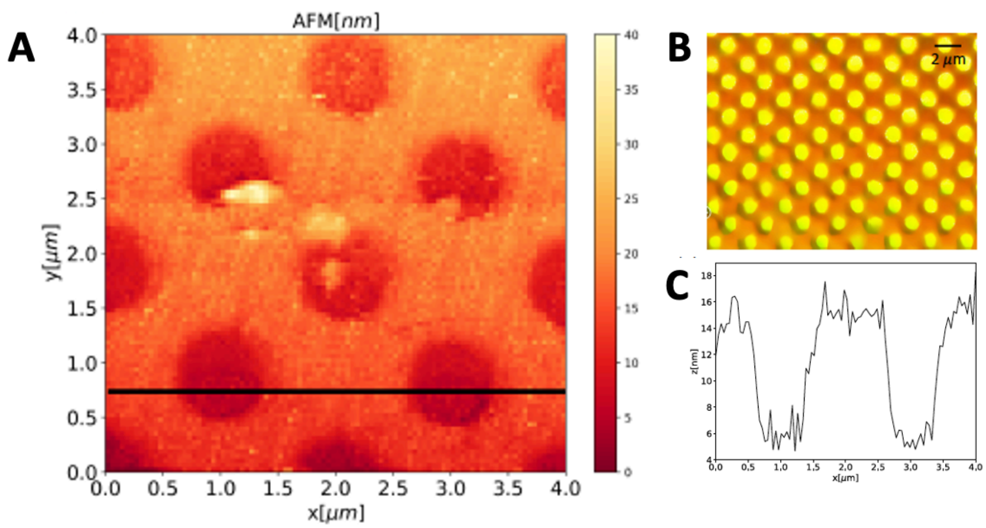


Figure 4. Nanoscale topographic imaging of a micropatterned dielectric film at milliKelvin temperatures using a tuning-fork-based atomic force microscope. (A) Atomic force microscopy image of a nanopatterned dielectric film at ~70 mK**. (B)** Optical microscope image

of the test sample measured in (A). **(C)** Cross-sectional profile of the AFM image in (A): the line cut corresponds to the black line. Spatial resolution in the mK regime is estimated to be ~200 nm based on this data.

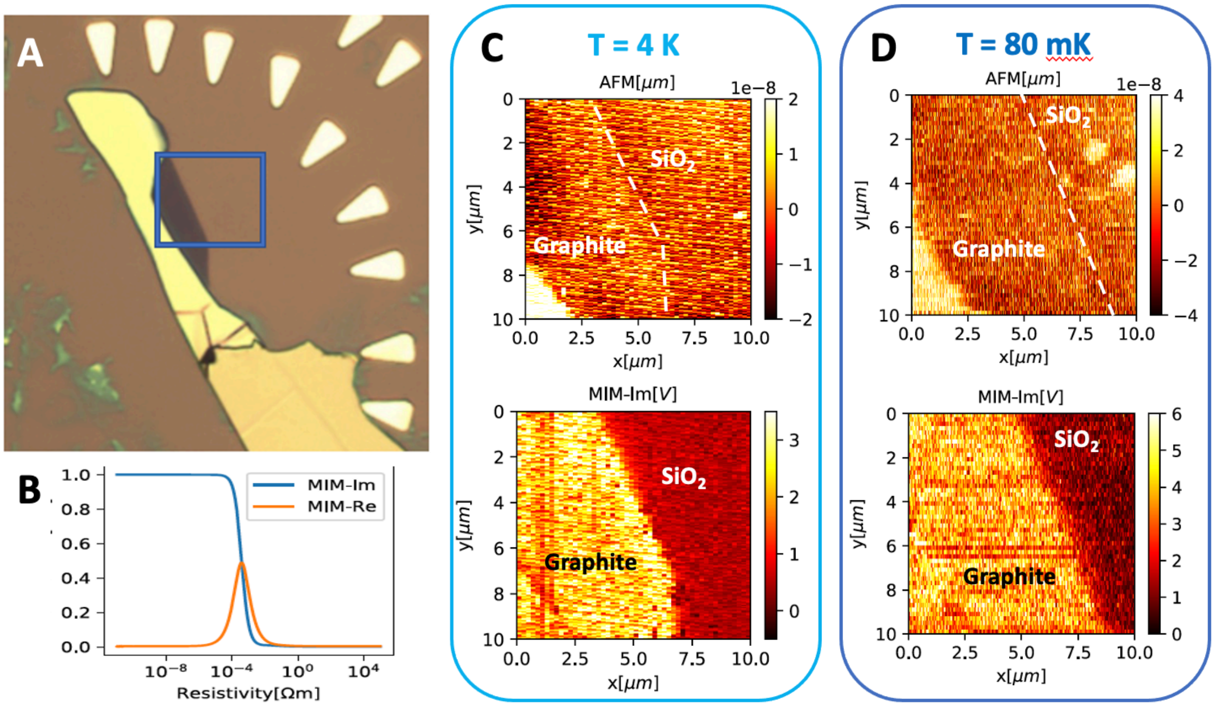


Figure 5. Demonstration of nanoscale microwave imaging of a van der Waals material at milliKelvin temperatures. (A) Optical microscopy image of a graphite flake exfoliated onto an insulating SiO_2 substrate, which is used to test the MIM performance at low temperatures. **(B)** Microwave response curves at 3 GHz, illustrating the evolution of the MIM contrast with the underlying sample conductivity. **(C)** and **(D)** AFM and MIM images of the graphite/SiO2 interface at temperatures of 4 K and 80 mK, respectively. The scan window is labeled by the blue box in (A).

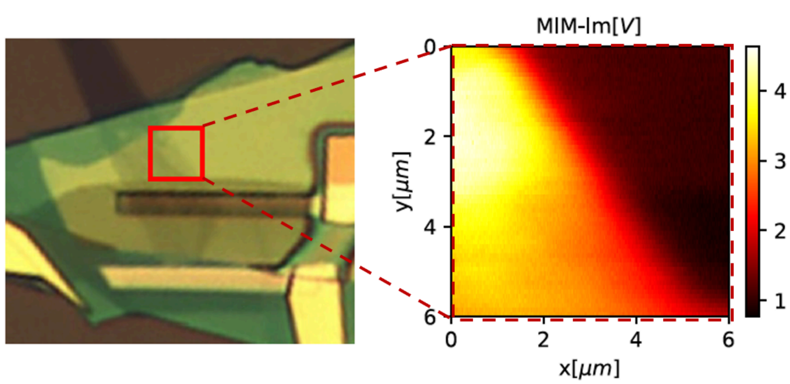


Figure 6. Demonstration of low noise height-modulated MIM in a dry dilution fridge. *Left panel:* optical image of a hBN-encapsulated graphite sample. The MIM scan window is shown in red. *Right panel:* AC-mode MIM image showing the conductivity contrast at the interface between the graphite and hBN.

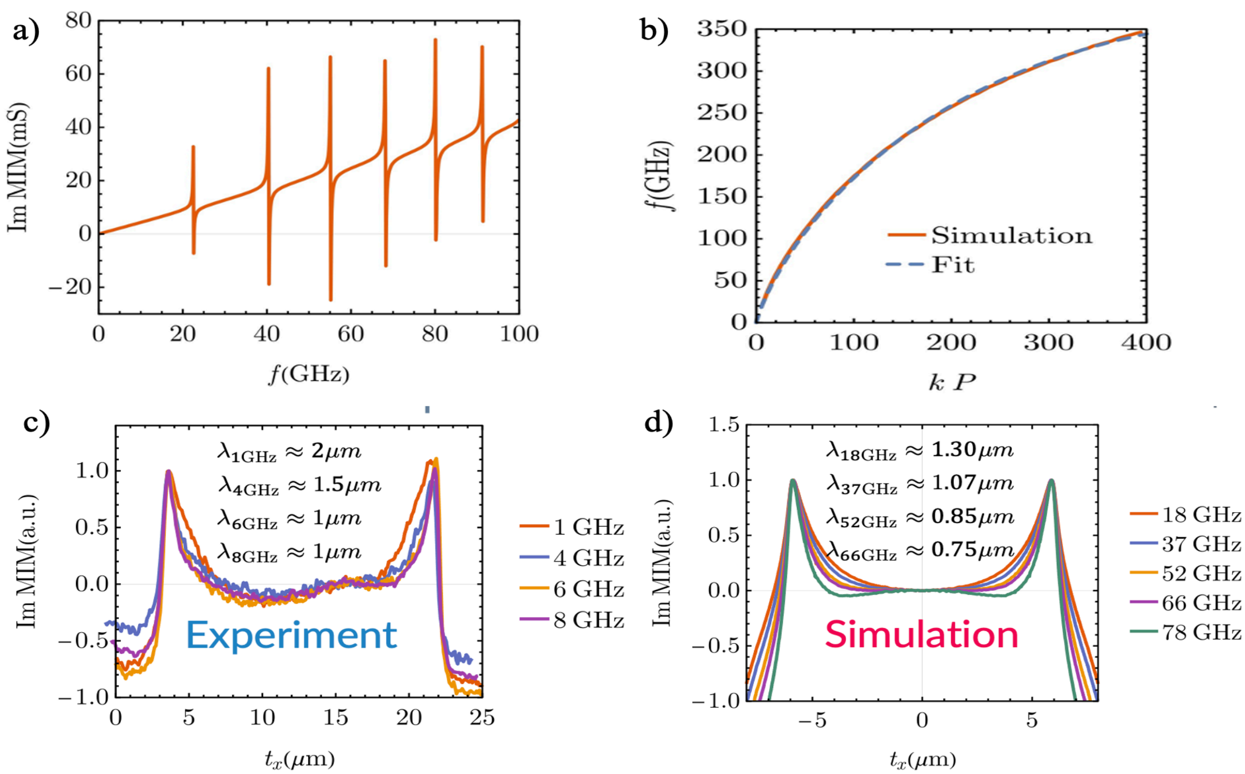


Figure 7. a) EMP mode resonances. b) EMP dispersion relation. c) Experimental results of a 1D MIM spatial sweep across a QAH sample. d) Simulation results corresponding to (c)

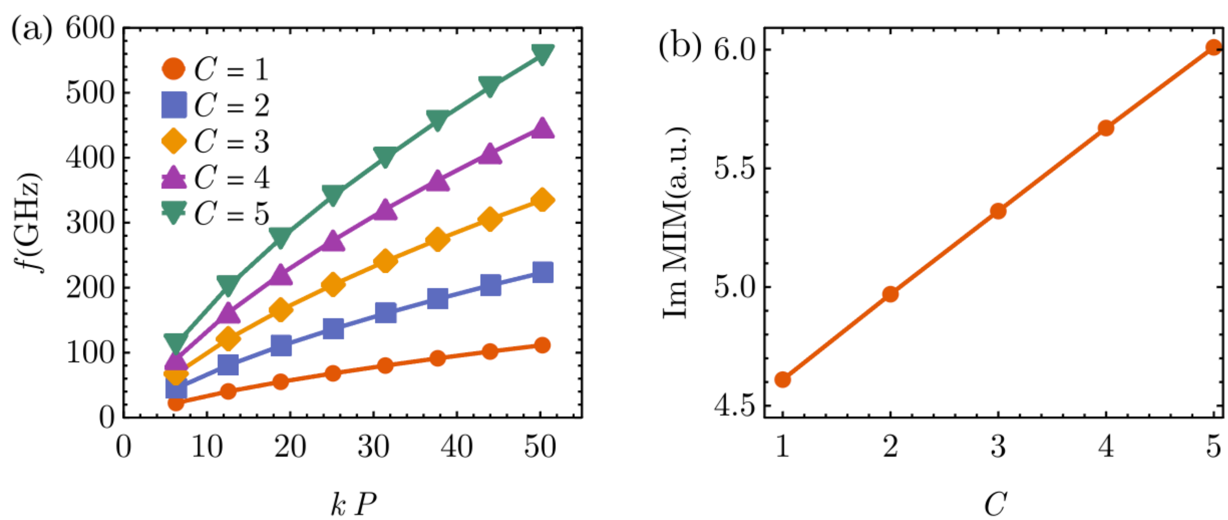


Figure 8. a) Dispersion relation fit for Chern number 1,2,3,4,5. b) MIM-Im channel for Chern number 1,2,3,4,5 at the same frequency.

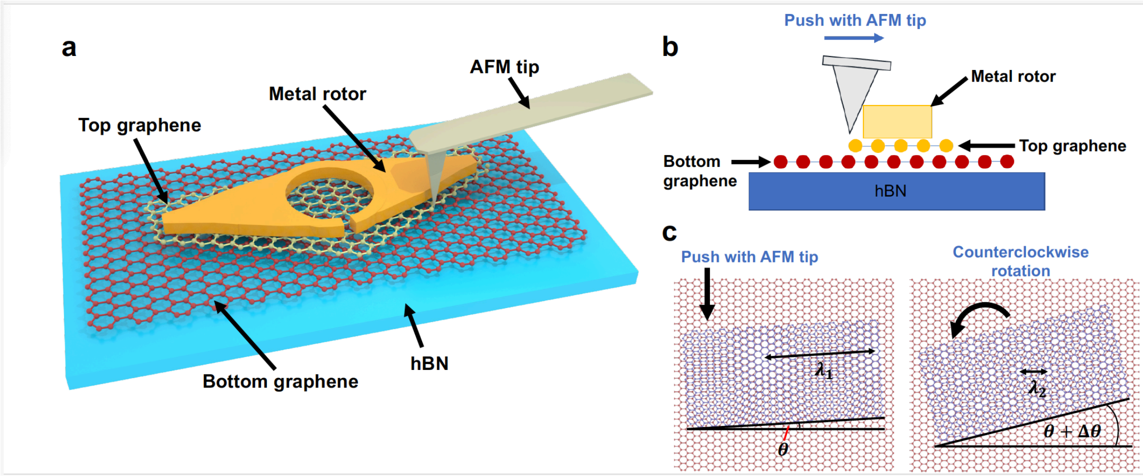
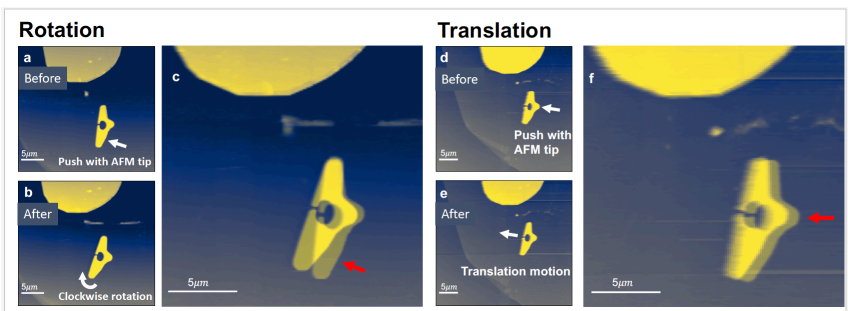


Figure 9. Dynamic manipulation of a moiré superlattice, enabling in situ control over the twist angle. (a) Schematic of a twisted bilayer graphene rotor device and manipulation of the angle using an AFM tip. The circular opening in the rotor frame allows for imaging of the moiré superlattice. (b) Cross-sectional view of the manipulation process. (c) Change in moiré wavelength due to twisting.



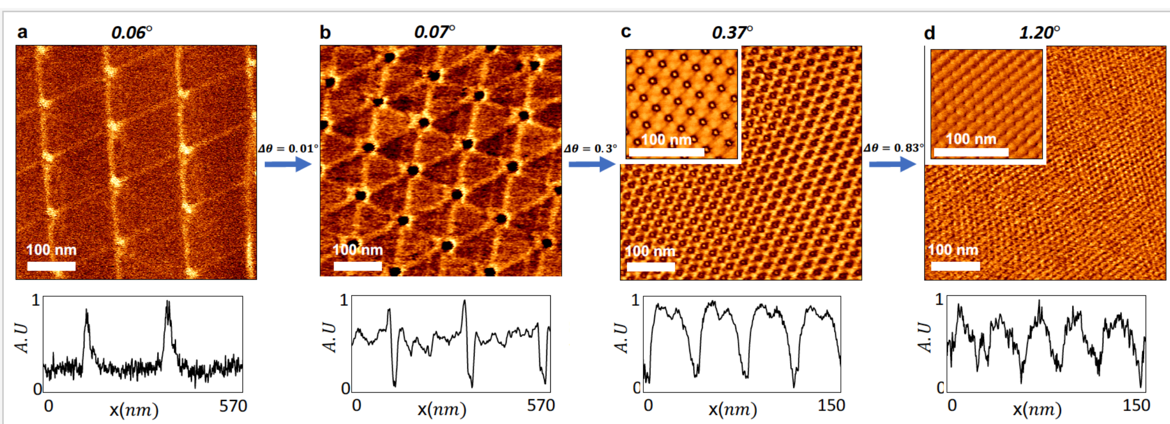


Figure 10. Tunability of the moiré superlattice geometry, achieved via *in situ* rotation of twisted bilayer graphene. *Upper panel:* Tapping-mode AFM images of a rotor device before and after rotational (left) or translational (right) motion. *Lower panel:* Piezoresponse force microscopy (PFM) images showing the change in the moiré wavelength induced by the rotation. The bottom row shows cross-sectional line cuts of modulations in the PFM signal associated with the superlattice.