Finding Ordered State in a Disordered Jungle

Xiaodong Zhou(周晓东)[1,2] and Jian Shen(沈健)[1,2,3*]

[1]*State Key Laboratory of Surface Physics and Institute for Nanoelectronic Devices and Quantum Computing, Fudan University, Shanghai 200433, China*
[2]*Zhangjiang Fudan International Innovation Center, Fudan University, Shanghai 201210, China*
[3]*Shanghai Research Center for Quantum Sciences, Shanghai 201315, China*

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A rich portfolio of emergent phenomena has been discovered in twisted two-dimensional (2D) moiré systems, including strongly correlated insulators,[1] superconductivity,[2] integer and fractional Chern insulators (ChIs),[3–5] magnetism,[6] and interfacial ferroelectricity.[7,8] The twist angle is a critical knob to modulate the properties of moiré materials. However, such a small twist angle (1°–2°) is often not thermodynamically stable for the moiré systems leading to strong reconstruction of the moiré lattice, which introduces an unconventional type of twist angle disorder.

Recently, Hu *et al.*[9] performed scanning microwave impedance microscopy (sMIM) measurements to directly visualize the spatial distribution of twist angle in a twisted bilayer graphene targeted at the magic angle ($\sim 1.1°$). sMIM is a newly developed scanning probe microscopy utilizing the interaction between the microwave and the material.[10,11] In practice, sMIM shines a microwave to the sample (3 GHz in that work) locally through the tip of an atomic force microscopy, and measures its reflected microwave signal. The knowledge of electromagnetic physics tells us that, the more conductive the sample is, the more microwave it will reflect. Therefore, being a local conductivity imaging probe with spatial resolution typically lower than 50 nm, sMIM has been widely used to visualize the edge states in topological materials,[12–16] and has also recently been applied in twisted WS_2/WSe_2 moiré lattice to reveal abundant correlated insulating states.[17] In Ref. [9], Hu *et al.* took advantage of such local transport measurements to collect single point spectrum sMIM (B, V_g, r) as a function of external magnetic field and the back gate voltage at different locations of the device, from which they can identify the feature of moiré band gaps, quantum Hall states and ChIs, and more importantly, their spatial distribution. By using the relation between the twist angle θ and the gate voltage of moiré band gaps, they extracted the spatial distribution of such twist angles within their mesoscopic device $\theta(r)$. They found that such $\theta(r)$ not only varies abruptly across a structural domain, but also changes gradually within the domain. They also revealed the close correlation between the twist angle value and the ChIs.

Given that twisted 2D moiré systems are inherently subjected to twist angle disorder, the power of sMIM is manifest in their study by directly visualizing the spatial variation and dependence of quantum phases. Similar observation of twist angle disorder has been reported by several scanning probe microscopy studies before.[18–20] The community has now acknowledged the universality of such twist angle disorder in twisted 2D moiré systems. A more pressing issue is to elucidate how such structural disorder modifies the electronic structure of moiré systems as a whole. More importantly, how can one correlate the observed $\theta(r)$ disordered pattern to the global transport characteristics of moiré systems? Notably, sMIM has a unique position to address this issue. Also, sMIM can be taken as a scanning near-field optical microscopy (SNOM) working at the microwave frequency. Therefore, it beats the diffraction limit ($\sim$ 0.1 m for 3 GHz) to achieve nanometer scale spatial resolution. Unlike SNOM working at the infrared or terahertz regime, sMIM senses the response of the material to a microwave excitation ($\sim$ 100 MHz to 10 GHz) which is mainly a Drude response. Therefore, sMIM is more close to conventional DC transport measurement which is still the dominant experimental method to detect various quantum states in twisted 2D moiré systems. On the other hand, sMIM is capable of providing a local transport characterization of the device as manifested by the single point spectrum sMIM (B, V_g, r). Similar global transport phase diagram has been routinely displayed in the study of 2D moiré systems. In future, once global transport measurements have been performed in their device, the comparison between global and the sMIM obtained local transport characteristics is highly valuable. For example, are the ChIs detected by sMIM completely missed by the global transport if they are so fragile against the twist angle disorder? For devices that do show quantized transport of topological phases in a global measurement, what is the spatial distribution of topological channels amidst this jungle of moiré lattice reconstruction to sustain the quantized transport? Another important twisted 2D moiré system is twisted bilayer $MoTe_2$ which shows fractionally quantized anomalous Hall effect with filling factor $\nu = -2/3$ and $-3/5$.[4,5] The dilution refrigerator based sMIM system used in the current work has the capability (9 T and 100 mK) to detect these

*Corresponding author. Email: shenj5494@fudan.edu.cn
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intriguing topological phases. Following the same logic as argued above, is it possible by sMIM to find out more fractional phases which are otherwise missed by the global measurements? In particular, is it possible for the twisted 2D moiré systems to host 5/2 fractional quantum anomalous Hall state which possesses non-Abelian statistics and finds applications in topological quantum computation? It is realized that sMIM is the right tool at hand to find such an ordered state in a disordered jungle.

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