Analyzing Penetration Field Capacitance in Twisted Double-Bilayer WSe_2

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Studying the electronic properties of materials is essential for creating specialized equipment, like an ideal dielectric for experiments. In this work, we examined the penetration field capacitance of a device made with twisted double heterobilayer WSe_2 with $\sim 3^\circ$ twist angle. Similar studies have revealed techniques to achieve superconductive graphene, and there are theoretical reasons to believe the same may be achievable with WSe_2. With the recent rise in quantum computing, knowing how electrons interact within materials may be crucial to constructing high-quality, precise devices.

Keywords: *twisted WSe_2, fabrication, materials science, penetration field capacitance*

I. INTRODUCTION

The emergence of moiré superlattices in van der Waals heterostructures has revolutionized our understanding of strongly correlated electron phenomena in 2D materials. Moiré superlattices are a "hidden" lattice periodicity in the interface between twisted stacked layers at a larger scale than the individual crystal lattice. The resulting Moiré pattern creates a periodic modulation of the electronic potential, restricting electrons to periodic regions and generating flat bands. These effects amplify electron-electron interactions, allowing for thorough examination [1].

Twisted metal dichalcogenides (TMDs) are particularly attractive for these studies, as they exhibit strong spin-orbit coupling and tunable band gap [2]. This, together with the tunability of Moiré lattices by varying the twist angle, allows for a wide range of phenomena under the right conditions. WSe_2 is one of the most promising TMDs, with properties such as superconductivity observed in twisted double bilayers [3].

There are many types of measurements that can be used to assess these properties, but the one used in this study is penetration field capacitance (PFC). PFC is essentially a measure of how much an applied displacement field penetrates the material. In a material with an infinite density of states (DOS) — an ideal conductor — the electrons rearrange themselves until the electric field inside the material is zero, so the conductor will completely screen an applied field. On the other hand, a material with zero DOS allows the entire field to pass. Therefore, measuring the PFC allows one to determine the DOS of a material.

Knowing the density of states provides a detailed understanding of the overall electronic properties of the material [4]. These can be characteristics from the existent dispersion relations, to the effective mass and scale of electrons in the analyzed system [4].

In this research, we utilize penetration field capacitance (PFC) measurements to probe the impact of the Moiré-induced band structure on the electronic properties of twisted double bilayer WSe_2 (tdbWSe_2). By analyzing the capacitance's dependence on twist angle and stacking configuration, we aim to examine the many-body effects and improve our understanding of electron interactions in materials. The specific configuration studied is ABBA stacked WSe_2 with a twist angle of $\sim 3^\circ$.

This twist angle was chosen based on the behavior of Moiré patterns for different twists. The amplitude of the pattern decreases as the twist angle increases, making it ideal for imaging to have lower twist angles, allowing for measurable phenomena. However, when the angles are too low ($\sim 1^\circ$) the material is more likely to rearrange itself, deforming or even destroying the pattern, ruining the effects the experiments aim to study [5].

Furthermore, the ABBA stacking configuration was chosen in lieu to ABAB mainly because of the specific interlayer interactions in ABBA. The natural configuration (ABAB) is more prone to dipolar excitons because of the mismatched crystal arrangement. ABBA on the other hand, suppresses these interactions and enhances carrier hopping between the intermediate layers, increasing interlayer coupling [6]. Lastly, the modifications to the band structure and increased coupling (relative to ABAB) may be avenues that lead to discoveries in topological states, a current frontier in quantum computing.

The recent developments in the fabrication techniques, as well as the results involving TMDs and WSe_2 itself [3, 7–10] show promise in the further examination of WSe_2. Then, with these background concepts in mind, we will work through the device fabrication techniques and procedure to allowed us to study WSe_2. Further, though data had yet to be gathered, an outline of the experimental setup and an overview of the research will also be discussed.

II. DEVICE FABRICATION

The first and longest part of the experiment is the device fabrication process. The micrometer-scale of the two-dimensional crystals makes the samples and devices prone to breaking at all steps, thus requiring extreme care when manipulating anything during the fabrication process. One may also note that some 2D materials are sensitive to the presence of air, thus requiring additional measures and care so that all steps are performed inside an argon-filled glove box. This is not the case for WSe_2, with all the steps performed inside a glove box being simply due to where the equipment is located. Then, no distinction will be made between steps taken inside and outside the glove box. Before detailing the procedure, note that there are numerous ways to produce stacks of 2D materials. These are reviewed in an article by Chen et al (2024) [11], with the approach adopted in this experiment being briefly described in the section labeled "Atomic layer aligned stacking".

The fabrication begins with exfoliating pure crystals of the desired material. The desired device is illustrated in figure 1. We exfoliated crystals of hBN, graphite, and WSe_2 to get pieces of the desired thickness for each of these. While the desired pieces of WSe_2 needed to be bilayers, hBN and graphite had no specific required thickness. Graphite thickness is mostly based on uniformity and robustness, as few layers allows for adequate conductivity and screening. hBN thickness is chosen such as to optimize capacitance (note that hBN acts as a dielectric) and screening capability [12].

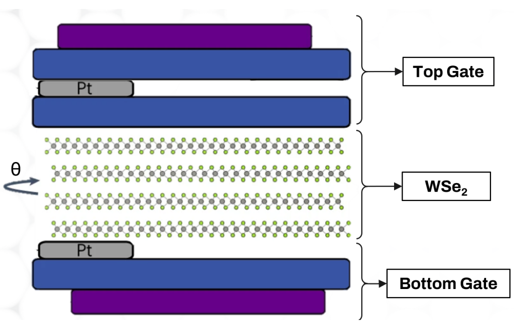

FIG. 1. Illustration of a completed device of twisted double bilayer WSe_2 with twist angle θ. The purple corresponds to a graphite gate, and the blue corresponds to an hBN dielectric. The platinum (Pt) is used as contacts to perform the measurements (figure modified from [13]).

The exfoliation process consists of using adhesive tape to shear some layers of the crystal, as illustrated in Figure 2. A SiO2 chip is then pressed onto the tape and put on a hot plate for a little over one minute. The ideal time on the hotplate depends on the material being exfoliated. Once the chips are removed from the hotplate, the tape is peeled off, leaving some crystals on the SiO2 substrate. The chips are then examined in an optical microscope to identify suitable pieces. Once a good piece of WSe_2 is identified, it is then cut in half so it and stacked with a known twist angle.

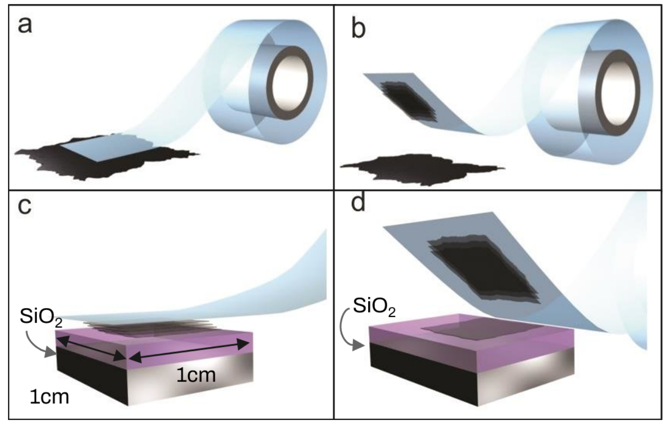

FIG. 2. Illustration of the process of acquiring 2D crystals by exfoliating them with adhesive tape [14]. Panels (a) and (b) show the first steps of exfoliating the crystals onto the tape, from where it is laid down on the substrate in panel (c). Usually, between steps (c) and (d) the chips are placed on a hotplate to loosen the glue, reducing the contamination of the sample.

The stacking process starts with picking up a piece of hBN with an adhesive polymer, and using it to pick up graphite, thus forming the bottom gate of the device 3. This is then laid on a fresh chip and thoroughly cleaned. With a clean gate, platinum contacts can then be evaporated by means of photolithography. With this done, another piece of hBN is used to now pick up the WSe_2. After the first piece is picked up, the chip is rotated by $\sim 63°$ so as to achieve a $\sim 3°$ twist in the ABBA configuration 4.

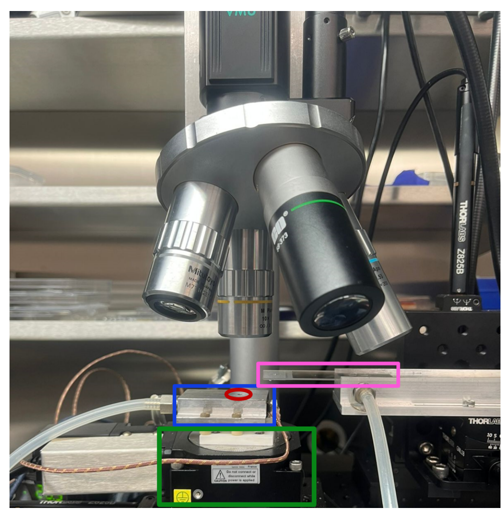

FIG. 3. Picture of the stacking setup. In pink is the slide with the adhesive polymer at the tip. In green is a heating pad attached to a platform with ability to rotate (blue) and a vacuum pump to hold the slide shut at the hole in the center (red).

Before setting the tdbWSe_2 on the bottom gate, it is useful to image it on the polymer by means of Torsional

Force Microscopy (TFM), by following the adequate procedure [15]. Should substantial resonance be detected 4, showing that there is significant coupling between the layers and a pronounced Moiré pattern, the stack is good to be laid down on the bottom gate, though taking care so that the contacts are touching the region with $tdbWSe_2$.

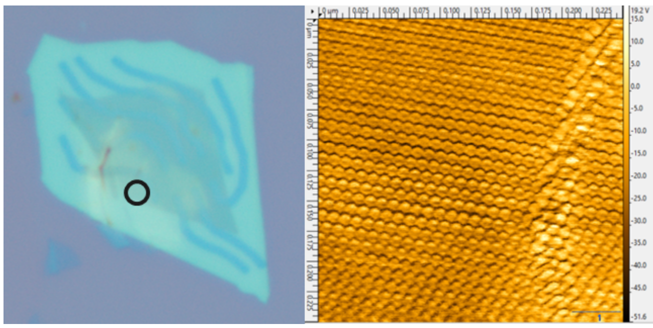

FIG. 4. (left) Image taken in an optical microscope of one of the devices during the fabrication process. So far it has a complete bottom gate with contacts and the $tdbWSe_2$. The circled region was probed via TFM to produce the plot (right) across the surface. Note the hexagonal pattern, which is the Moiré superlattice. The line on the bottom right is $40\mu m$.

After properly cleaning the combined stack, platinum contacts are evaporated onto the hBN, and then topped with another piece of hBN and graphite, thus completing the top gate and the device. It is crucial throughout the stacking process that at least some of the contacts remain exposed and accessible, otherwise no voltage can be applied to perform the measurements.

III. EXPERIMENTAL SETUP AND EXPECTATIONS

Though we have yet to analyze the fabricated devices, there are known ways to perform PFC measurements that we can use. Here we outline one such procedure gone through in more detail in [16]. Note that specifics may vary and alternative procedures exist.

First, the device is put into a superconducting coplanar waveguide (SCWP) cavity and cooled using a liquid helium bath. Next, independent DC biases are applied to the top and bottom gates to generate a displacement field perpendicular to the 2D material, here $tdbWSe_2$. Based on how much the material screens (i.e. how conducive it is), we get a measure of the capacitance that is comprised of two parts: a fixed contribution from the hBN dielectric layers and a varying contribution, the PFC. As the displacement field is tuned, the material's electronic properties vary. This can be done, for instance, by changing the band gap. Such changes impact the field's screening, hence changing the PFC.

A low-power microwave signal is then sent into the SCPW cavity using a vector network analyzer. The resonant frequency is sensitive to capacitance, so as we vary the displacement field, so does the resonant frequency. This allows us to record the cavity's transmissions over a range of displacement fields and study how the frequency shifts. If we fit this data into an appropriate model, we can infer how the penetration field capacitance depends on the displacement field. In general, a higher PFC implies a lower resonant frequency [16].

With this setup in mind, we can hypothesize what results one could expect to obtain in this experiment. While this is a difficult thing to do, there are some aspects we can be reasonably confident about. The existing experiments on ABBA stacked WSe_2 clearly show highly tunable band gaps [2, 10]. When it comes to PFC measurements, this could manifest in periodic capacitance minima with narrow band gaps, and maxima with high density of states. It's is difficult to know beforehand whether the regions with high density of states would approach divergence (hence be indicative of superconductivity), but since this phenomenon has been observed in WSe_2 [3, 7] it is not a far-fetched guess.

This type of measurement has been done in other materials, with a good breakdown and visualization of the results presented in [17]. This paper shows a thorough examination of graphene monolayers, akin to what could be done on WSe_2 (note that the data on graphene isn't expected to be indicative of any trends in TMDs, with this paper presented for illustrational purposes).

IV. DISCUSSION

Although no PFC measurements have yet been made, a discussion is still warranted. There was considerable difficulty during the initial phases of the experiment due to the time-consuming nature of the fabrication process.

The manual exfoliation technique is quite inefficient, especially when it comes to WSe_2, with sometimes there not being a single large enough piece in an entire chip. Furthermore, the stacking process isn't precise, occasionally leading to misalignment of the crystals and little overlap with the contacts, making measurements impossible.

Furthermore, since the $tdbWSe_2$ can't be imaged with a piece of hBN on top, it must be probed while still on the polymer. This material is prone to having air bubbles and is not rigid itself, leading to lower resonance during TFM. The highest quality imaging 4 was acquired by picking the WSe_2 directly, setting it down on the bottom gate, and then imaging it. Though this has proved effective, it has been difficult to replicate.

Lastly, some technical difficulties took considerable work to address. Prior to the adoption of TFM, piezoresponse force microscopy (PFM) was used, but it was significantly less efficient in yielding high-quality pictures. A couple of devices also unfortunately broke during fabrication, leading to setbacks.

V. CONCLUSION

Improving our understanding of electron interactions can have large implications for fields such as quantum computing. Two-dimensional materials stacked in ways that exhibit pronounced Moiré patterns are among the best ways to study these interactions. Measuring penetration field capacitance is one way to observe these effects, making it an appropriate avenue of study for tdbWSe_2.

The fabrication process of these devices is still cumbersome, leading to difficulties in acquiring measurements. New techniques have recently been developed that allow for consistently higher-quality microscopy data [15], thus making it so the lengthy measurements are only performed on devices known a priori to be high-quality. More sophisticated techniques such as gold tape exfoliation [18] produce even higher-quality samples, although these were inaccessible due to technical and equipment limitations.

After undergoing this fabrication process for numerous devices and successfully obtaining quality samples, the next logical step is finishing the metal contacts and realizing the PFC measurements in a helium dunker. The data gathered from these experiments is hoped to shed light on additional properties of WSe_2 or, more fundamentally, electron-electron interactions, allowing for a deeper understanding of how to tune a material's properties.

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