An Overview of Twistronics and Device Fabrication

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1. Theoretical Predictions

2. Experimental Discoveries

3. Twisted 2D Structure Fabrication

Introduction

- **Twistronics:** Studying how the twist angle between the layers of a vertically stacked 2D structure affect its properties.
- **VdW heterostructure**: Reassembling isolated atomic planes layer by layer in a precisely chosen sequence

Moiré Pattern

- A result of interference - the overlapping of 2 layers of atoms rotated by a certain angle
- The moiré pattern is determined by the twist angle
- The moiré pattern forms a new periodicity which could be described as a unit cell with its own vectors

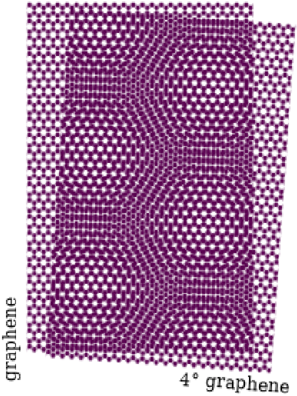


Figure: A moiré pattern.

Modeling Interlayer Coupling

- Twist-dependent effects are produced by the interactions between layers - interlayer coupling
- Interlayer coupling facilitates the hopping of electrons and charge redistribution between layers, forming a distinct material
- A powerful tool to model the interlayer coupling: first-principle density functional theory (DFT) techniques

Probing the Interlayer Region

Two techniques demonstrated to be sucessful in probing the interlayer region:

- **X-ray diffraction**: probe the electron density
- **Selected Area Electron Diffraction (SAED)**: Using high energy and small wavelength of electrons. Make each layer and interlayer region to be probed independently

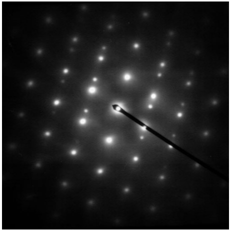


Figure: A SAED pattern.

Charge Redistribution in Interlayer Region

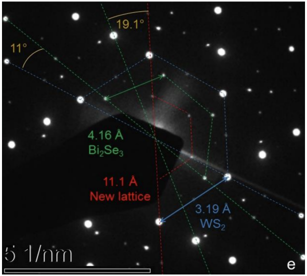
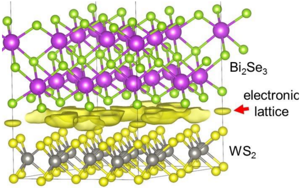
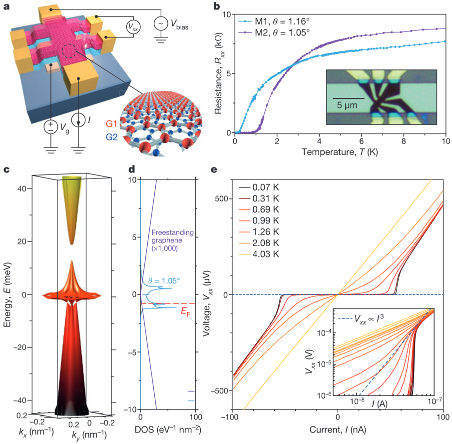


Figure: An SAED image of Bi_2Se_3/WS_2 heterostructure.

- A large lattice doesn't correspond to either parent material
- A new non-atomic lattice composed entirely of charge, called electronic lattice, as predicted by DFT
- A result of charge redistribution



Twist-Dependent Transport: Superconductivity at Magic Angles



- At magic angle about 1.1°, band structure of twisted bilayer graphene (tBLG) exhibits flat bands near zero Fermi energy
- At 70mK, both devices show zero resistance, and therefore a superconducting state ⇒ superconductivity

Hall Effect Family

Recent discoveries:

- **Quantum hall effect**: tBLG (Jurgen H. Smet, 2011)
- **Integer quantum anomalous hall effect**: Twisted $MoTe_2$ (Tingxin Li, 2023)
- **Fractional quantum anomalous hall effect**: Twisted $MoTe_2$ (Tingxin Li, 2023), Twisted $MoTe_2$ (Xiaodong Xu, 2023)
- **Integer quantum spin hall effect**: tBLG (P. San-Jose, 2016)
- **Fractional quantum spin hall effect**: Twisted $MoTe_2$ (Kin Fai Mak, 2024)

Moiré Superlattice Exciton Quasiparticles

- **Exciton**: A bound state formed by an electron and an electron hole that are attracted to each other by the Coulomb force
- When 2 TMD vectically are vertically-stacked, interlayer excitons are produced.
- The electron in one layer forms a bound pair with the hole in the other layer

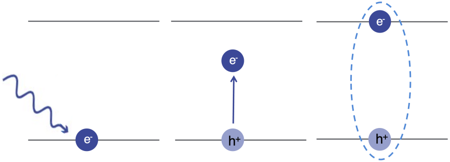


Figure: Formation of an exciton.

Raman Spectroscopy

- Measures the phonon and vibrational modes of a material
- A powerful tool to evaluate 2D material since it's non-destructive, non-instructive, and easy to conduct
- Measure in-plane symmetry, defects, strain, doping, interlayer coupling, charge interactions, charge density waves, and the twist angle.

Summary of Experimental Discoveries

- Superconductivity
- Orbital ferromagnetism
- Moiré excitons
- Hall effects
- Strong electron-electron correlation
- Exciton photoluminescene
- Twist-dependent color
- Raman mode
- Hofstadter butterfly
- 1D topological channel
- Lateral and vertical conductivities
- Spatially-dependent vertical conductivity
- ...

Fabrication

Mechanical transfer by vertically-stacking one material on another

Mechanical Exfoliation

1. Adhesive tape is pressed down to the crystal surface
2. Top few layers are attached to the tape
3. The tape with crystal few layers is pressed down to a substrate surface
4. After peeling off, some flakes are left on the substrate surface

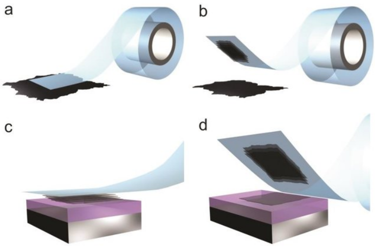


Figure: Mechanical exfoliation.

Dry Transfer Using Viscoelastic Stamping

- Monolayers are highly sensitive $\Rightarrow$ wet mechanical transfer (having a liquid contact) are not suitable
- Using a viscoelastic stamp, preserving the properties of the transferred materials.
- Detach the stamp, release the flakes to the acceptor surface

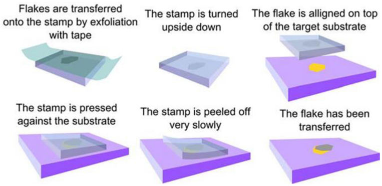


Figure: Transfer by viscoelastic stamping.

Rotational Alignment

- hBN is already picked up, lying on the stamp
- Press down the stamp, and let hBN pick up half of the monolayer crystal
- Rotate the stamp with a specific angle
- Press down the stamp, and pick up another half of the monolayer crystal
- A deterministic control of the twist angle since the crystal's orientation is known absolutely

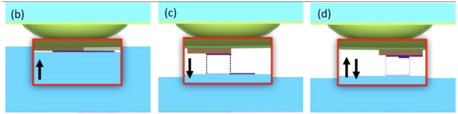


Figure: Rotational alignment of the monolayer flakes

AFM Cleaning the Surfaces and Interfaces

- Interlayer coupling are mitigated due to the dirt (like bubbles) trapped between layers, during the transfer process
- Using an atomic force microscope (AFM) to clean: applying a normal load and push the dirt away

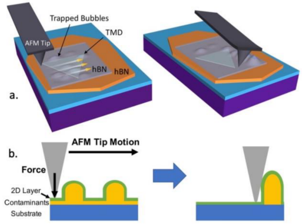


Figure: AFM removing the dirt between layers.

Electron Beam Lithography (EBL)

- EBL: Use electron beam to draw shape on electron-sensitive film (called resist)
- High resolution

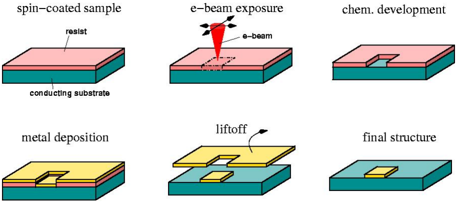


Figure: Process of EBL.