‘Magic angle’ graphene

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PhD exams - 2022 spring session

Superconductors

- Superconductor: a material with 0 electrical resistance.

- Application in many fields that require powerful magnets:
  - MRI/NMR machines.
  - Mass spectrometers.
  - Particle accelerators.
  - Plasma confinement.

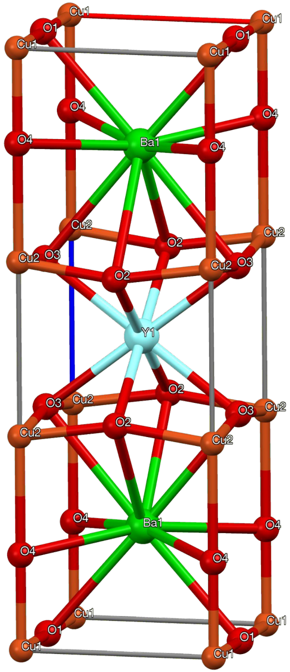
- Conventional superconductivity is explained by Bardeen–Cooper–Schrieffer theory:
  - The electron-lattice interactions produce Cooper pairs.
  - Then the Cooper pairs can form a Bose–Einstein condensate.

- Usually conventional superconductivity can be achieved only at low temperatures (few K).

- Conventional superconductor requires complex cryogenic apparatus.

High-temperature Superconductors

- Materials that behave as superconductors at temperatures above the boiling point of liquid nitrogen (77 K).
- Usually they are compounds of several elements:
    - Copper oxides (cuprates) like the Yttrium barium copper oxide.
    - Iron-pnictogen-based like the Potassium fluoride doped LaOFeAs.
- They do not conform to the conventional BCS theory (unconventional superconductors).
- Theoretically studying these superconductors is challenging.



$YBa_2Cu_3O_{7\text{-}\delta}$ unit cell

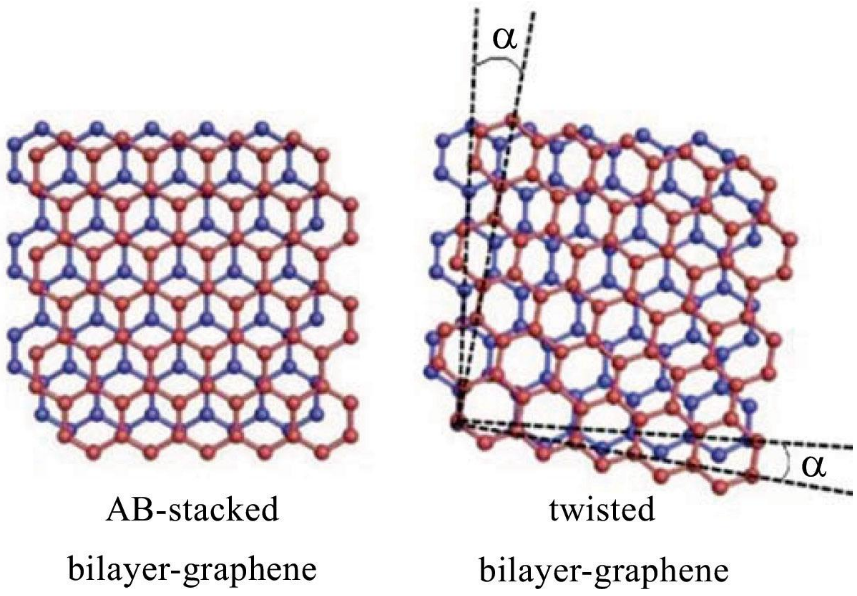
Superconductivity in bilayer graphene

- In 2018 was observed superconductivity in bilayer graphene with one layer twisted at an angle of ≈1.1°: twisted bilayer graphene (TBG)
- The critical temperature achieved is 1.7 K (lower than unconventional superconductors).
- However TBG has several features similar to that of cuprates:
    - Strong electron-electron coupling.
    - Structures in phase diagram, with Mott-like insulator behaviour.
- These features suggest that the TBG is an unconventional superconductors.
- TBG is relatively simple and the charge carrier density is tunable in situ.
    - Ideal testbed for unconventional superconductivity.

- I’ll show some resistance measurement of TBG and sample inspection with scanning tunneling microscopy.

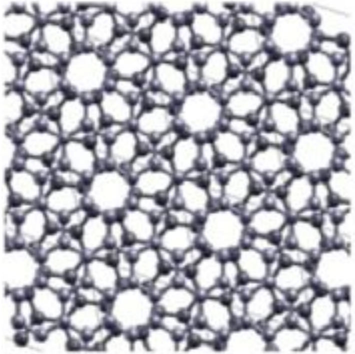
Twisted bilayer graphene

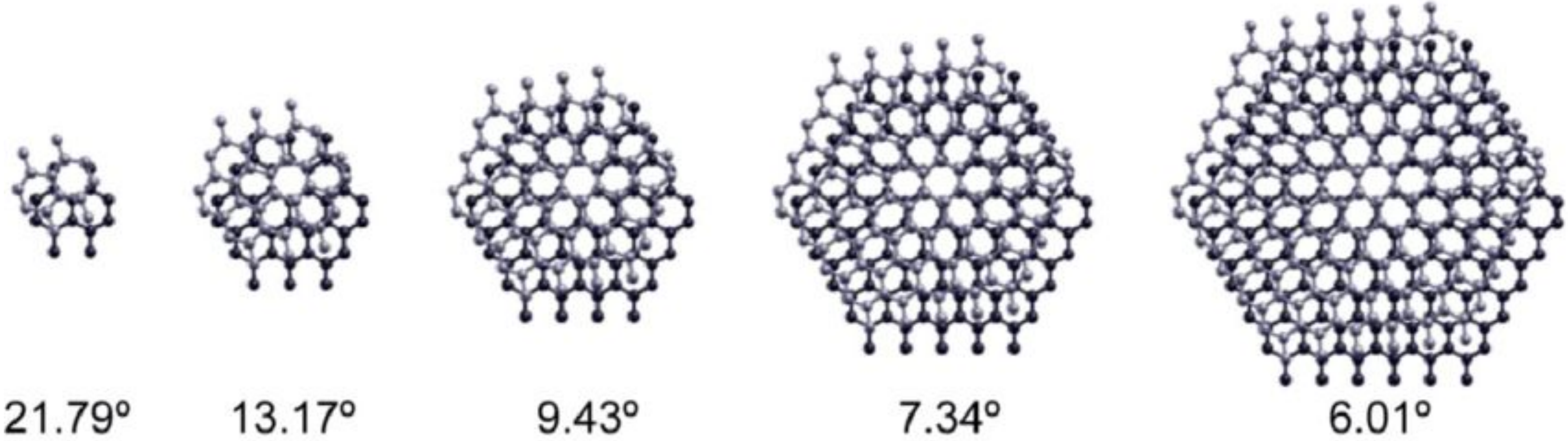
- Two aligned graphene sheets stack in a AB modular pattern.
- When twisted the pattern regularity is broken.



Twisted bilayer graphene

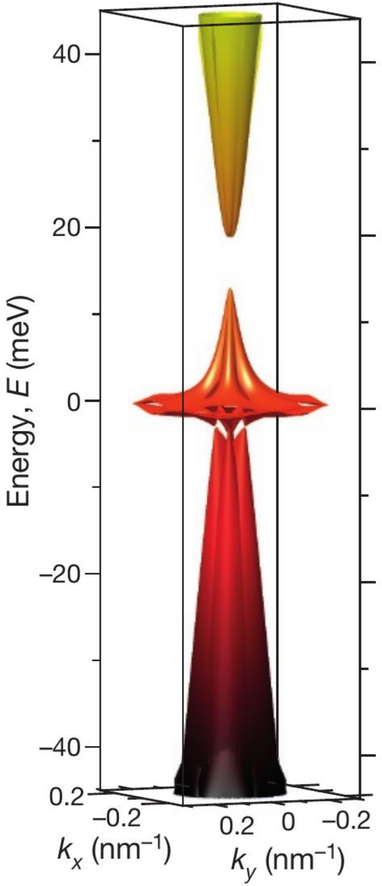
- Two aligned graphene sheets stack in a AB modular pattern.
- When twisted the pattern regularity is broken.
- The two-layer stack forms a more complex repeating structure (superlattice).
- The unit cell size increases when the rotation angle decreases.





Twisted bilayer graphene

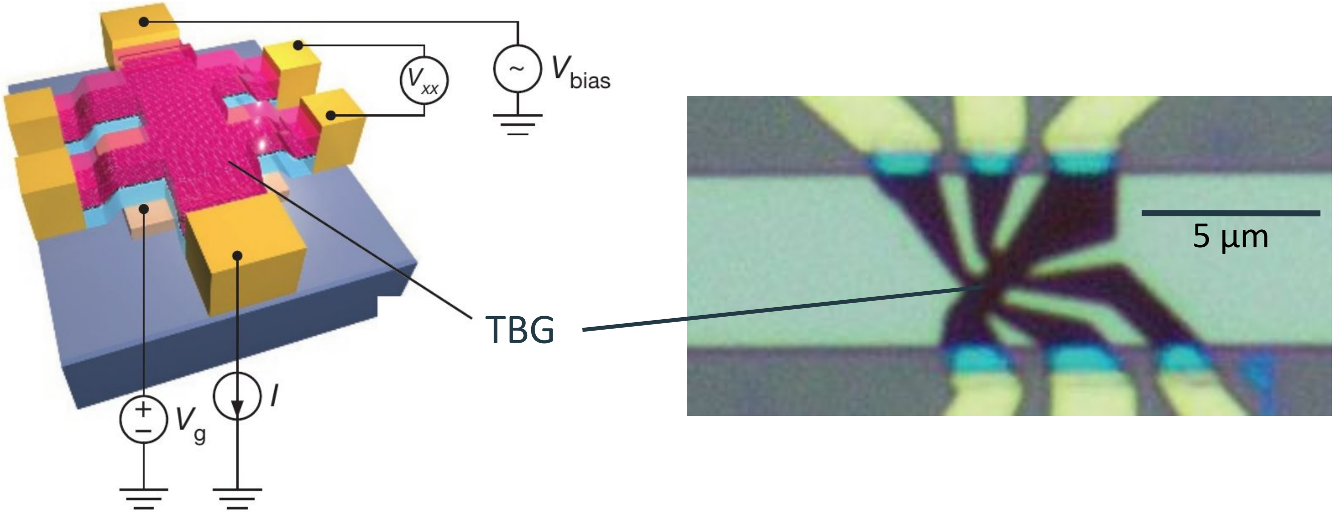
- The superlattice potential folds the band structure, modifying the Fermi velocity.
- At 1.1°, the first ‘magic angle’, the Fermi velocity drops to zero.
- The energy bands near charge neutrality become flat
  → ‘magic angle’ TBG acts as an Mott-like insulator Half-filling of these bands.
- The phase diagram of ‘magic angle’ TBG consists of correlated insulator phases and superconducting phases, which can be realized via continuous tuning of temperature, magnetic field and carrier density.



Band energy E of TBG at θ = 1.05°.
https://doi.org/10.1038/nature26160

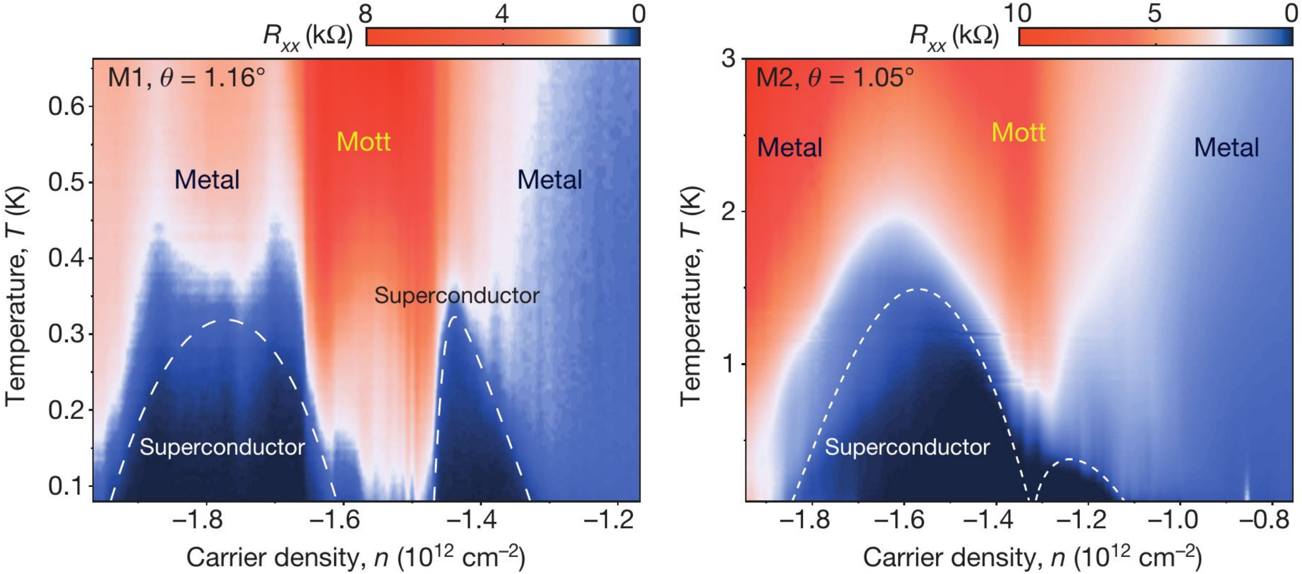
TBG device

- TBG device is etched into a ‘Hall’ bar.
- Resistance R_{xx} is measured as V_{xx} / I .
- Carrier density n is tuned by regulating the voltage to the back gate V_g (no need of chemical doping).
  - This allows to fine study conductance and resistance as a function of n.



Resistance vs temperature

- Superconducting domes on each side of the half-filling correlated insulating state.
- This is a behaviour similar to cuprate one.



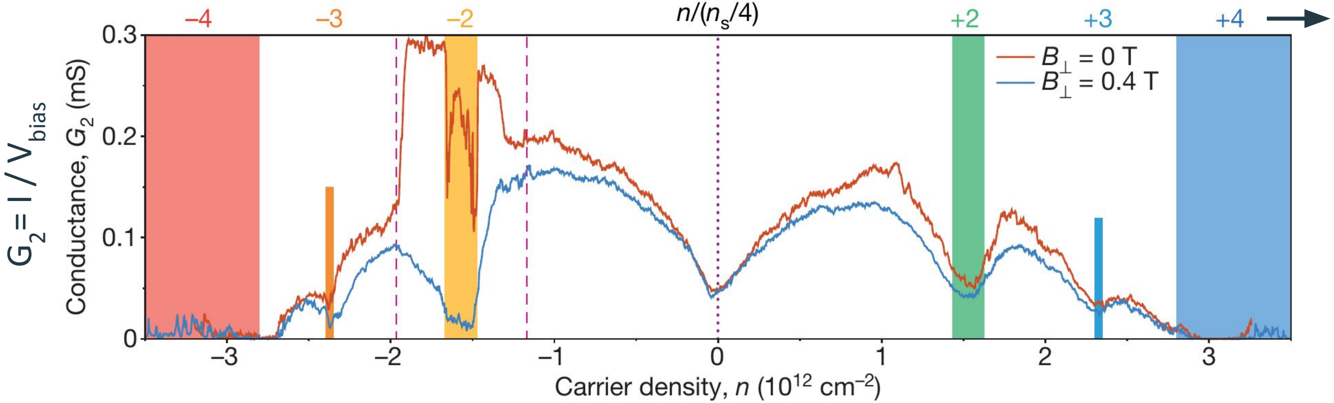
Resistance as a function of carrier density and temperature. https://doi.org/10.1038/nature26160

Conductance vs carrier density

- V shape at charge neutrality point.
- Insulator at $\pm 3.2 \times 10^{12}$ cm^{-2} (n_s) due to single-particle bandgaps.
- Minima at ±2 and ±3 electrons per unit cell due to competition between the Coulomb energy and the reduced kinetic energy.
- Perpendicular magnetic field suppresses superconductivity.

half-filling

charge neutrality

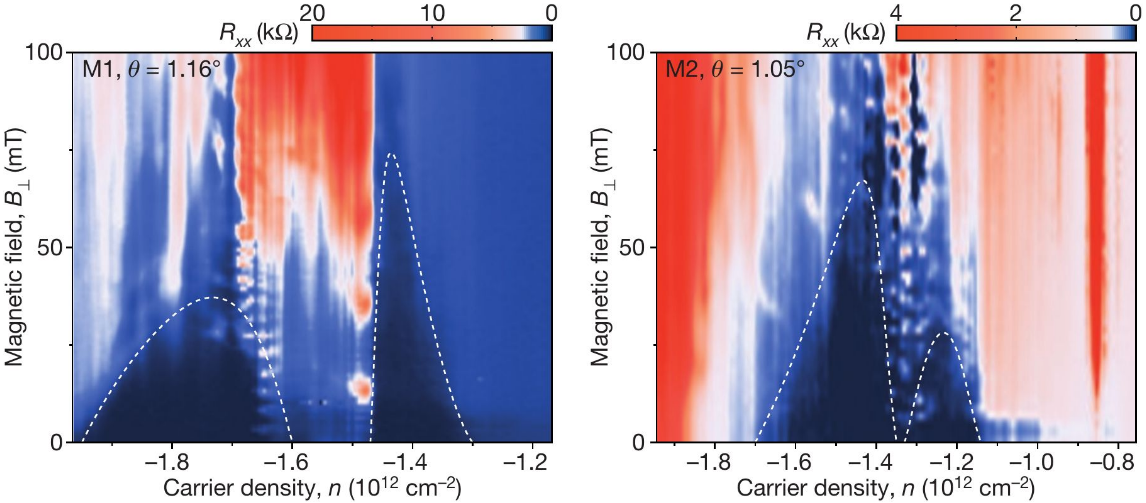


→ electrons in each unit cell

Conductance as a function of carrier density. T = 70 mK; V_{bias} = 10 µV. https://doi.org/10.1038/nature26160

Resistance vs magnetic field

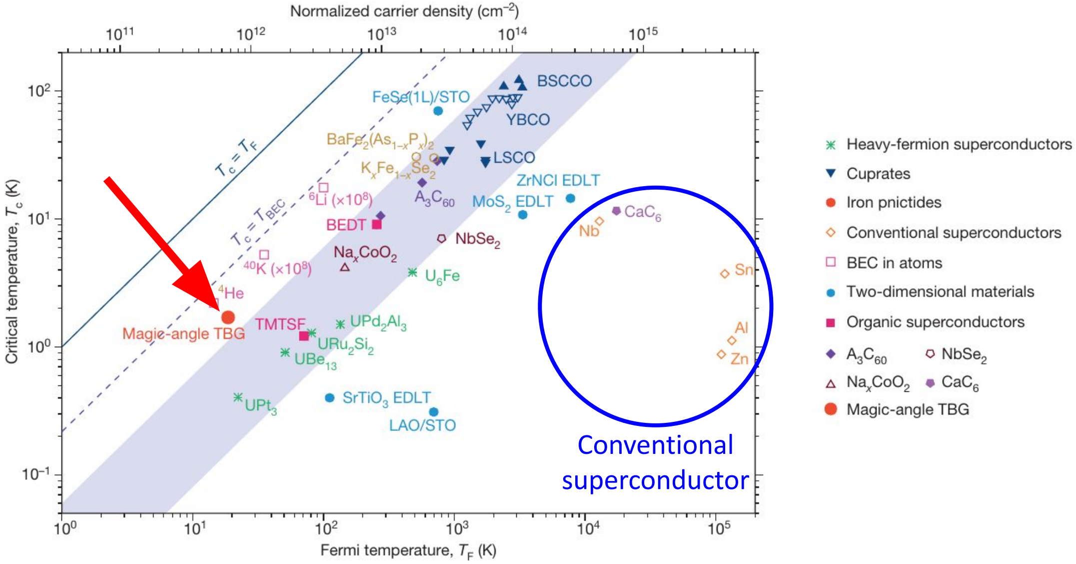
- Superconducting domes on each side of the half-filling correlated insulating state with a perpendicular magnetic field.
- The critical temperature dependence from magnetic field is well described by conventional theory but not for in-plane magnetic field.



Resistance as a function of carrier density and perpendicular magnetic field. T = 70 mK. https://doi.org/10.1038/nature26160

Comparison to other superconductor

- The extremely small carrier density of ‘Magic angle’ TBG suggests strong interaction between electron.
- Also the ratio T_c / T_F is similar and sometimes higher than other unconventional superconductors.
- That classify the ‘Magic angle’ TBG as unconventional superconductor.

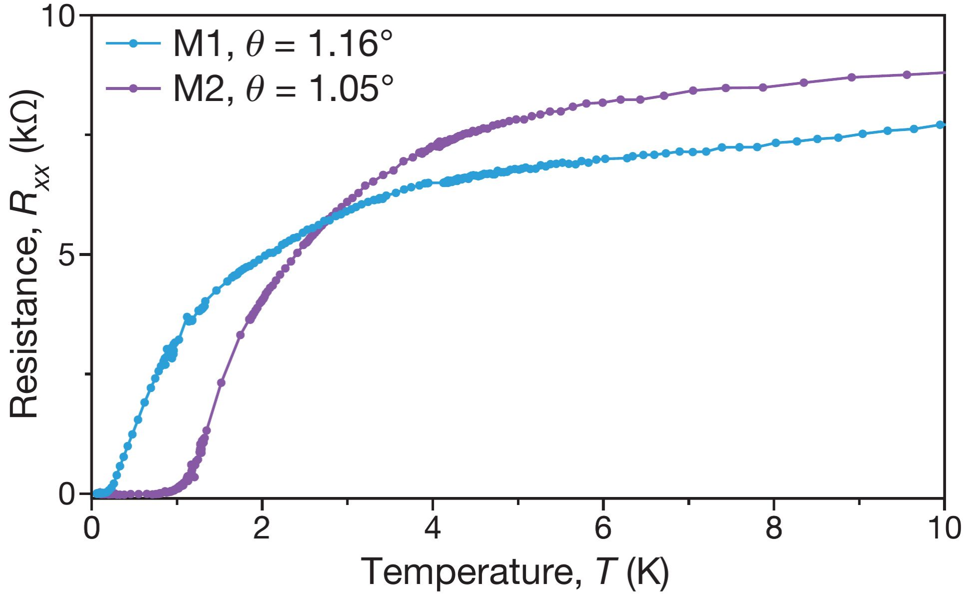


Conventional superconductor

https://doi.org/10.1038/nature26160

Twist angle

- The twist angle has a great impact on the behaviour of TBG.
- We need a way to measure the twist angle in TBG.



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Scanning tunneling microscopy (STM)

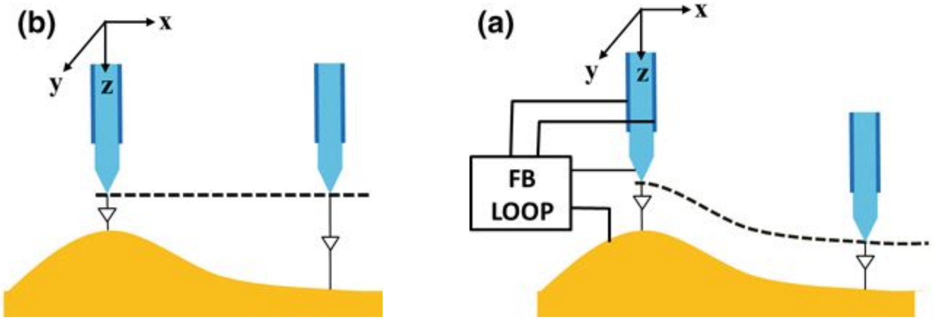
- STM is a powerful means to study the surface atomic structure and electronic structure.
- Based on quantum tunneling.
- When a conducting tip is brought very near to the surface, a bias applied between the two allows electrons to tunnel through the vacuum between them.
- The tunneling current is a function of bias (V), tip-sample distance (S) and the local density of states (Φ) of the sample and tip.

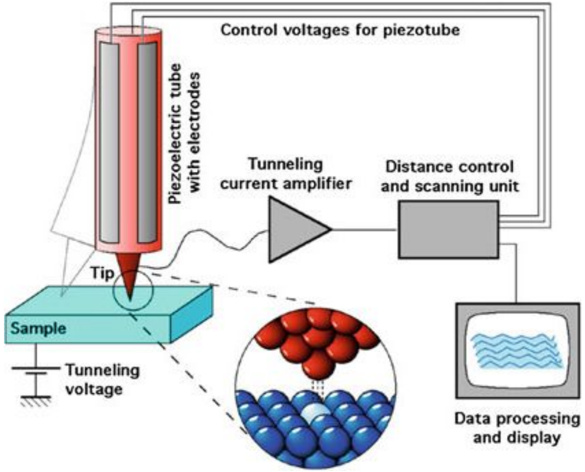
- 0.02 nm lateral resolution.
- 0.01 nm depth resolution.
- Can produce a 3D profile of a surface.
- The tip can manipulate the surface.

Scanning tunneling microscopy (STM)

The main components of STM are

- The scanning tip.
- Coarse sample-to-tip control to move the tip close to the sample.
- The vibration isolation system to produce clean measure and avoid crash (tip-sample separation 0.4-0.7 nm).
- 3D piezoelectric scanner to move precisely the tip.
- Control electronics.

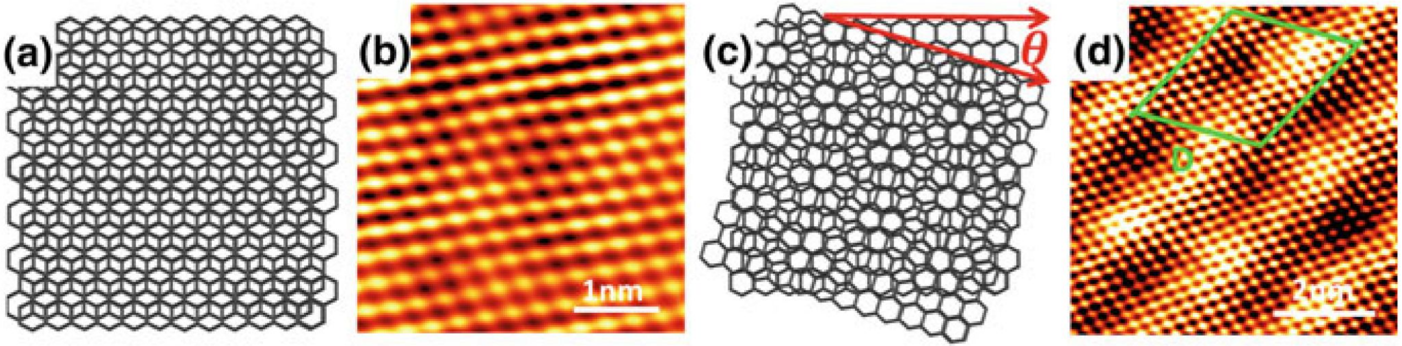




STM can work at constant-height mode and constant-current mode

STM of bilayer graphene

- As anticipated both aligned and twisted bilayer graphene presents modular pattern.
- STM image of AB-stacking bilayer graphene shows hexagonal close-packed structure.
- Twisted stacking shows moiré patterns.



DOI: 10.1007/978-981-10-5181-4_3

AB-stacking

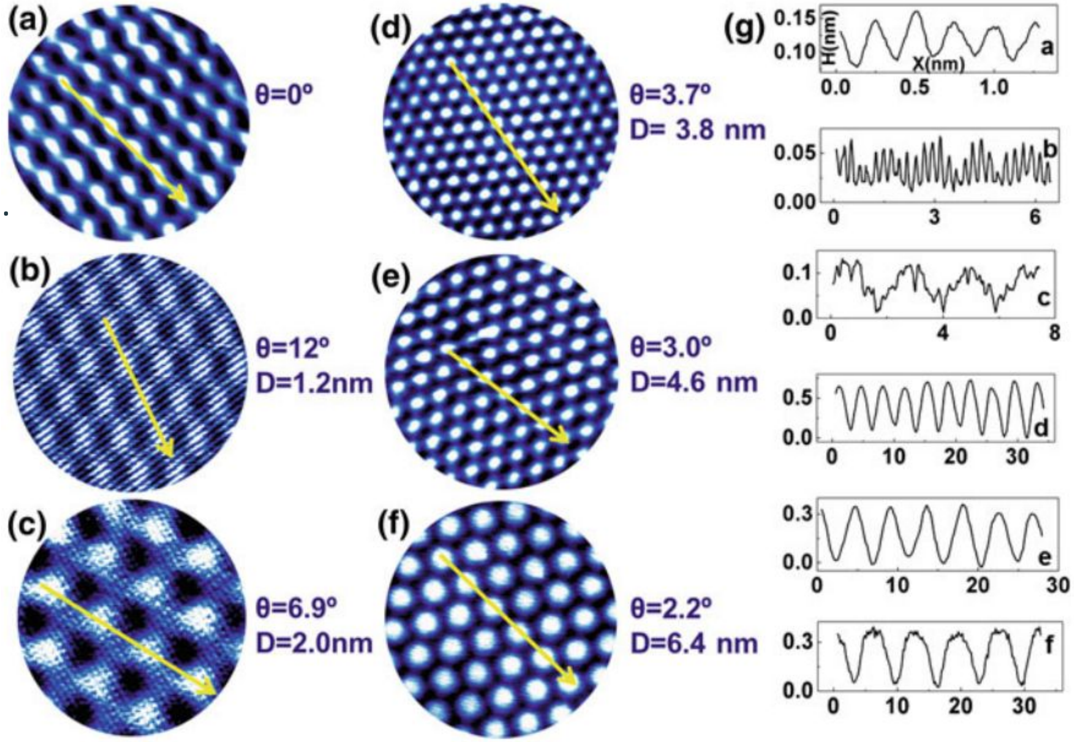
Twisted stacking

- Moiré pattern period (*D*) and the twisted angle (*θ*) are binded by the equation (*d* = 0.246 nm lattice constant of graphene)

$$D = \frac{d}{2\,sin\left(\frac{\theta}{2}\right)}$$

STM of bilayer graphene

- So STM allows to characterize bilayer graphene quite easily.
- Twist angles can span from 1° to 12° on bilayer graphene on rhodium (Rh) foil (b-f).
- On this substrate there is no prefered twist angle.
- Figure g shows the pattern periodicy.
- The atomic structure is visible only if D < 3 nm.



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Bilayer graphene domains inspection

- The graphene synthesized on the Rh substrate follows the mechanism of segregation growth.
- Obtain large-scale singlecrystalline graphene domains is difficult.
- STM can inspect graphene searching for domains boundary.

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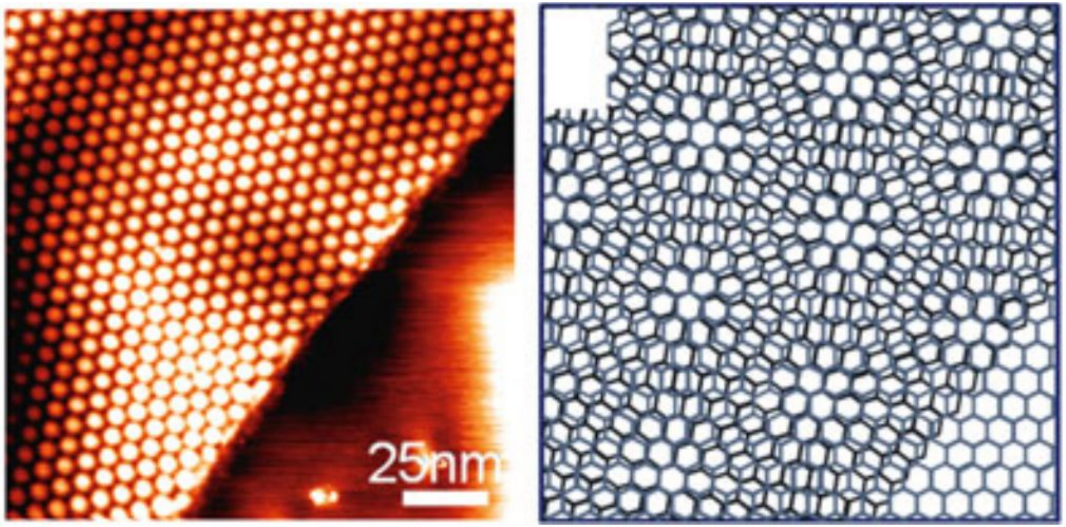

Coexistence of monolayer and bilayer graphene on Rh substrates.
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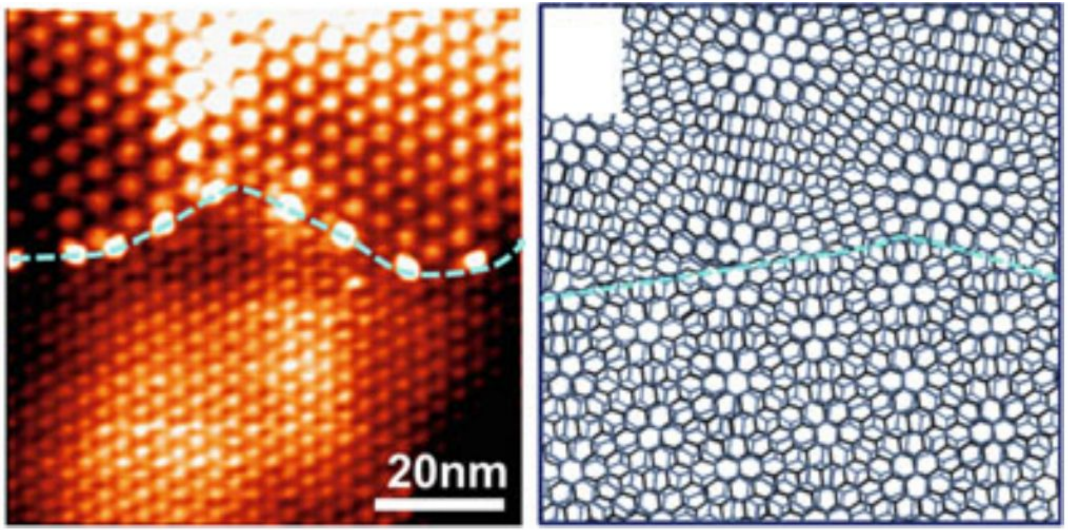


Different angle linking of twisted bilayer graphene on Rh substrates.

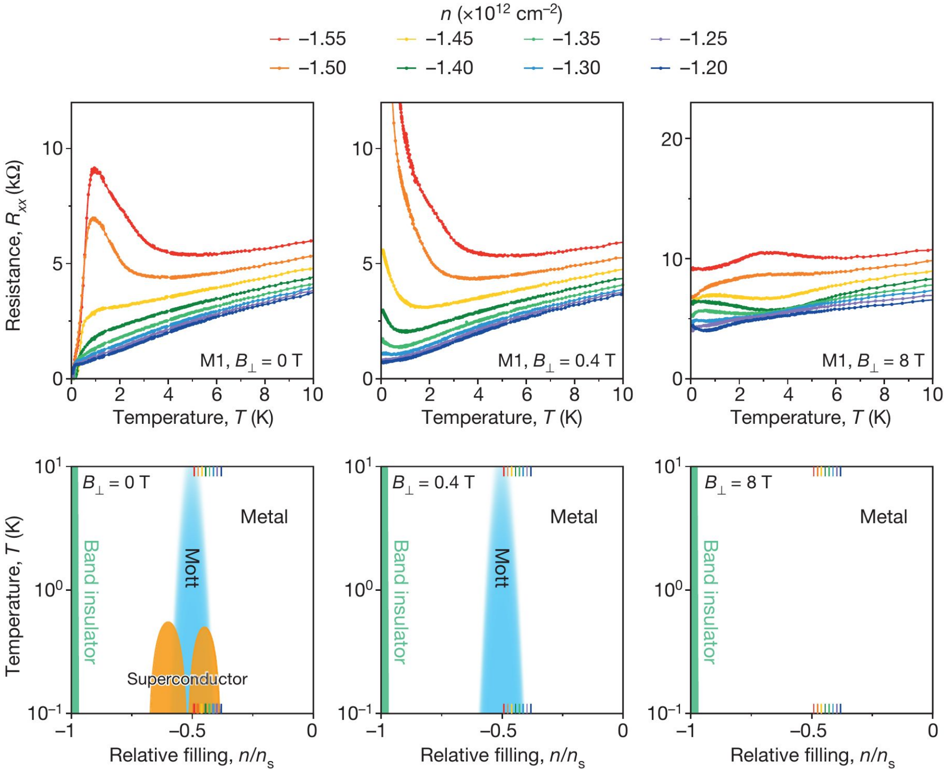
DOI:10.1007/978-981-10-5181-4_3

Summary

- Theoretically studying unconventional superconductors is challenging.
- Twisted bilayer graphene is a simple tunable material that represents a good testbed for superconductivity.
- It share some features with unconventional superconductors opening the possibility to study unconventional superconductors theoretically.
- Scanning tunneling microscopy allows to measure accurately the twist angle between the two layers.
- Scanning tunneling microscopy can also highlight disuniformity on TBG introduced by the synthesis process.

Backup

Temperature–density phase diagrams



Temperature–density phase diagrams of ‘magic angle’ TBG at different magnetic fields. https://doi.org/10.1038/nature26160