Twisted Bilayer Graphene

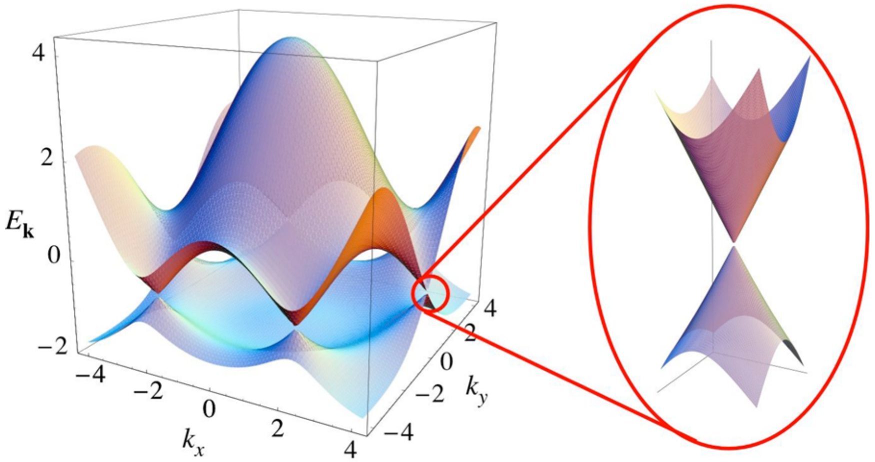
EXCITING ELECTRONIC PROPERTIES WITH AN ARTIFICIAL SUPERLATTICE

SKANDA RAO

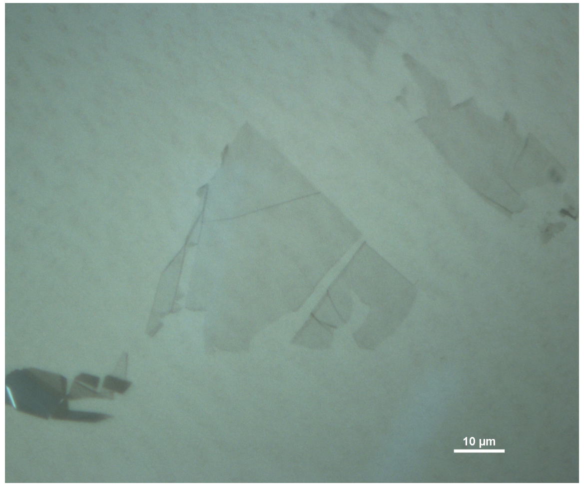
Outline

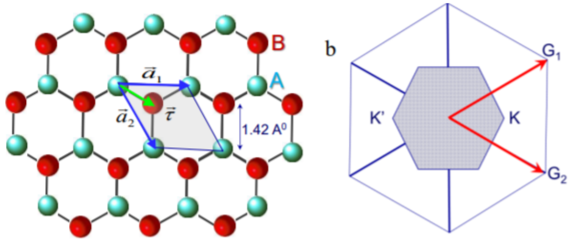
- Introduction to graphene/bilayer graphene
- Van Hove singularities in twisted bilayer graphene (TBG) and the flat band
- Emergence of correlated states in magic-angle twisted bilayer graphene (MATBG)
- Ongoing research and systems of interest

Meet graphene



Patrick Recher and Björn Trauzettel, University of Würzberg





E. Y. Andei et al, *Electronic Properties of Graphene*

- Hexagonal lattice of carbon atoms
  - Two triangular sublattices A and B

- Electronic dispersion relation produces two Dirac cones (K, K'), meaning near charge neutrality, electrons behave like massless Dirac fermions (no gap!)
  - Derived entirely from tight-binding approximation:

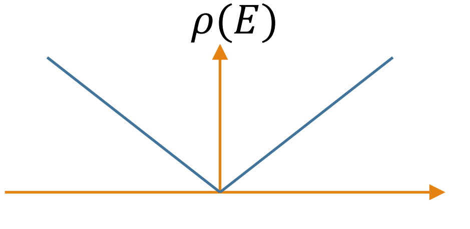
$$H = -t \sum_{|R\rangle} (|R\rangle\langle R+\tau| + |R\rangle\langle R-a_1+\tau| + |R\rangle\langle R-a_2+\tau| + h.c.)$$

Perturbation on H is the matrix elements connecting a point in the A sublattice to one of the three nearest neighbors of the B sublattice with interaction energy t

- States captured by pseudospin representation (Dirac-Weyl Hamiltonian)—superposition of Bloch waves in two sublattices

$$h_K = \hbar v_F \sigma \cdot p \qquad \begin{pmatrix} |k_A\rangle \\ |k_B\rangle \end{pmatrix}$$
$$h_{K'} = -\hbar v_F \sigma \cdot p$$

- Linear density of states—semimetal with easily tunable Fermi energy

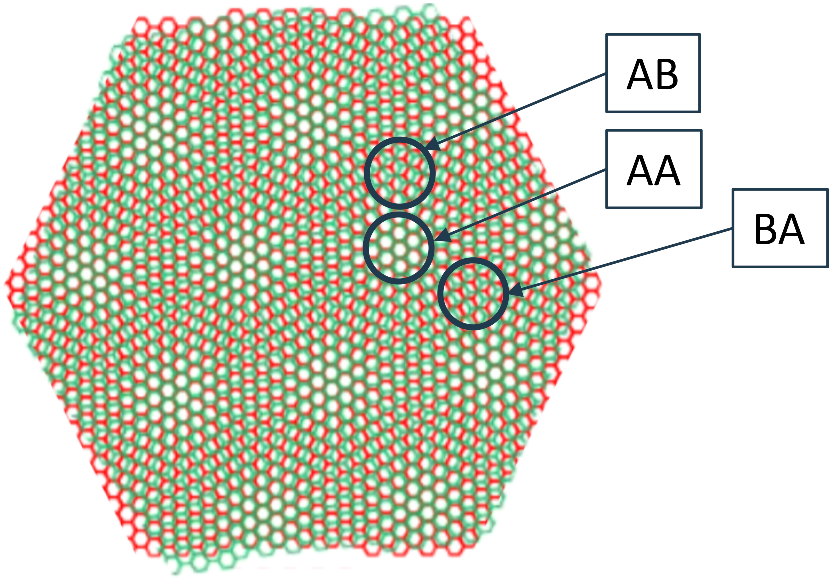


Two layers of graphene with a relative twist angle

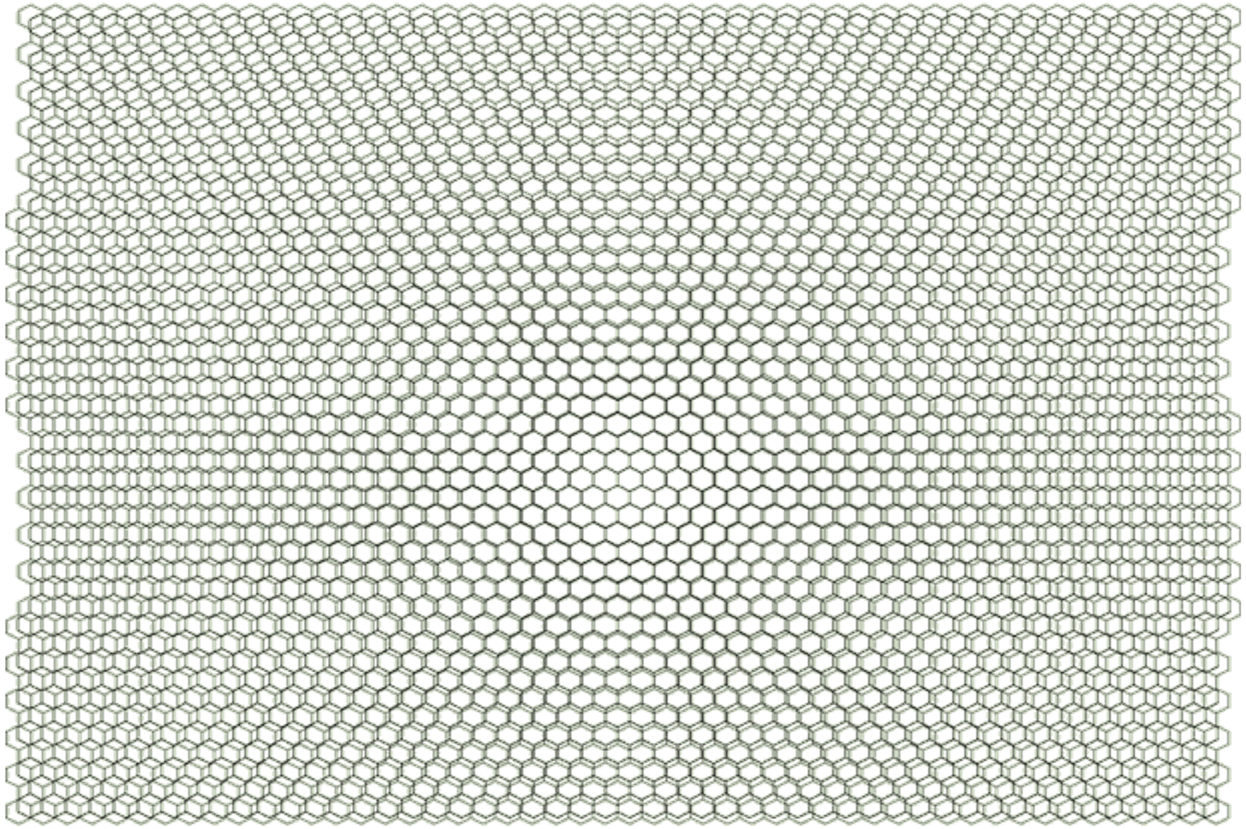
- Moire superlattice period determined by twist angle:

$$a_M = \frac{a}{2\sin\frac{\theta}{2}}$$

- Alternating areas of AA, AB, and BA alignment
  - AA: perfectly aligned
  - AB: A sublattice on top aligned with B sublattice in the bottom layer, B sublattice in top layer has no corresponding ion in bottom layer



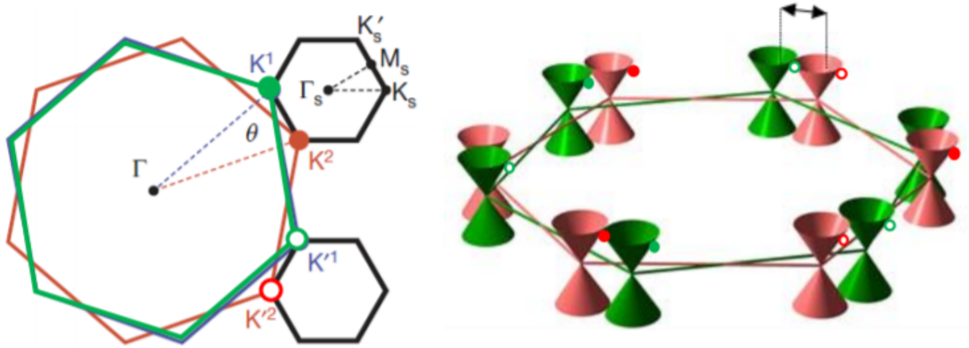
E. Y. Andei and A. MacDonald, *Graphene Bilayers with a Twist*



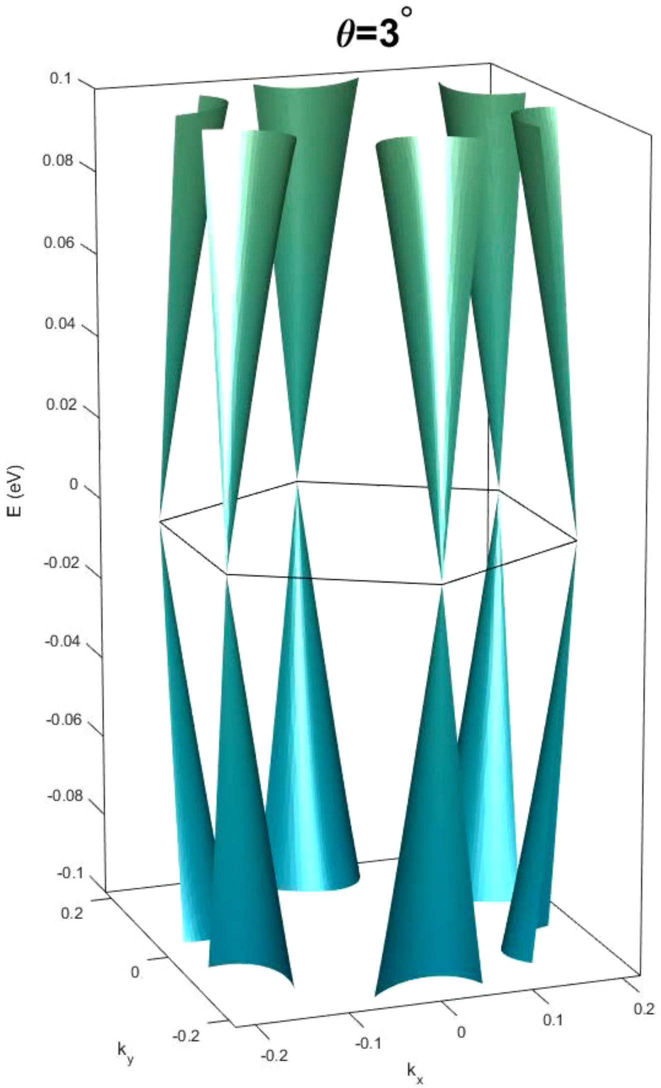
Brian LeRoy, University of Arizona

Hybridization

- Moire pattern in real space represents the development of a superlattice with a “mini-Brillouin zone”
- Hybridization of Dirac cones with Van Hove singularities at saddle points
  - Increasing pseudogap as angle decreases
- At $\theta \approx 1.05°$ (magic angle), the VHS collapses into two flat bands
  - 4-fold degeneracy per band: 2 valley + 2 spin



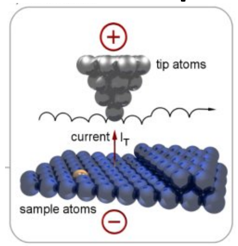
E. Y. Andei and A. MacDonald, *Graphene Bilayers with a Twist*

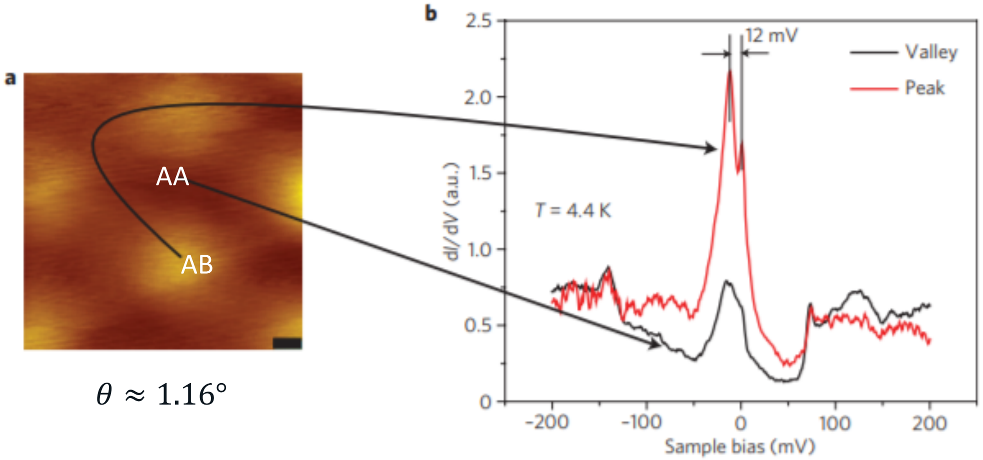


Y. Cao et al, *Unconventional superconductivity in magic-angle graphene superlattices*

Flat bands

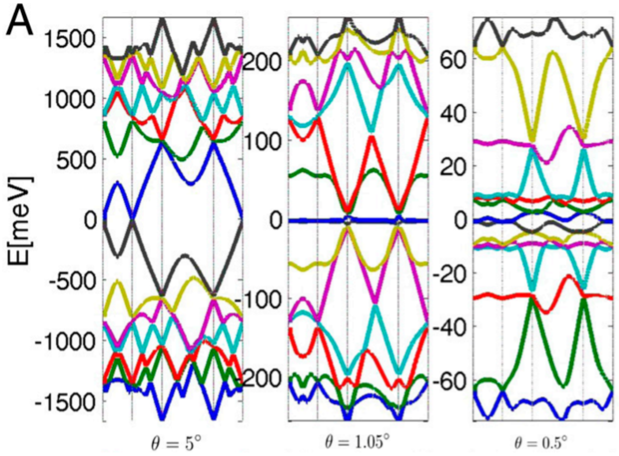
STS set-up



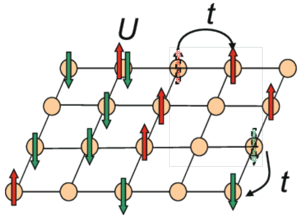


$\theta \approx 1.16°$

G. Li et al, *Observation of Van Hove singularities in twisted graphene layers*



R. Bistritzer and A. MacDonald, *Moire bands in twisted double-layer graphene*



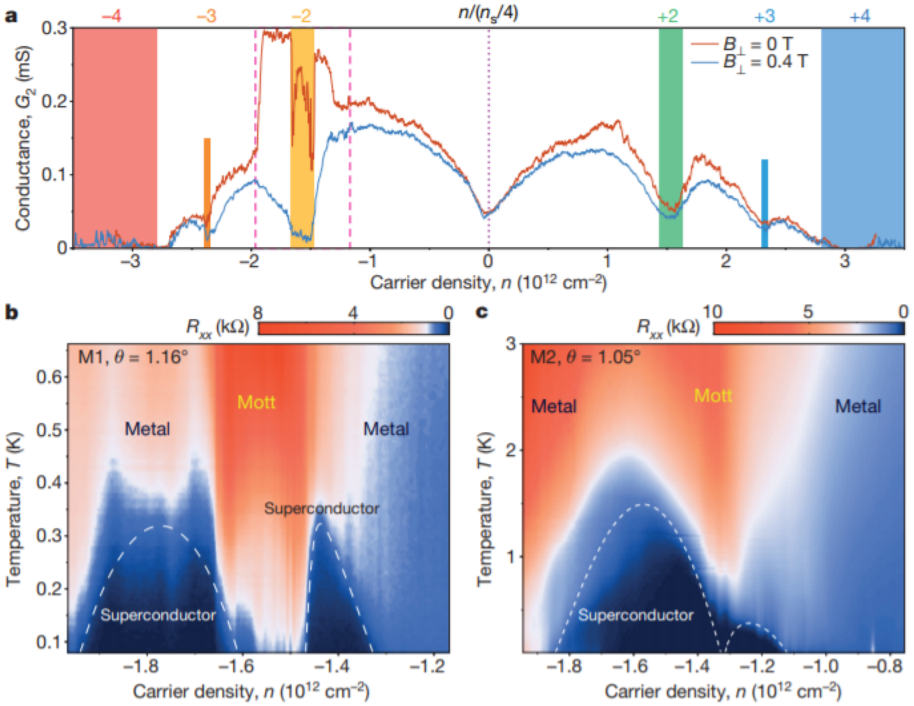
- Experimental verification of VHS at magic angle and theoretical prediction of flat Moire bands in 2010
  - Spatially electrons accumulate in AB regions
- Hubbard model: update on TBA

$$\hat{H} = -t\sum_{i,\sigma}\left(\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{i+1,\sigma} + \hat{c}^{\dagger}_{i+1,\sigma}\hat{c}_{i,\sigma}\right) + U\sum_{i}\hat{n}_{i\uparrow}\hat{n}_{i\downarrow}$$

- Flat band width $w \ll U$
  - High U/t
  - Electron-electron interactions dominate→correlated electronic states

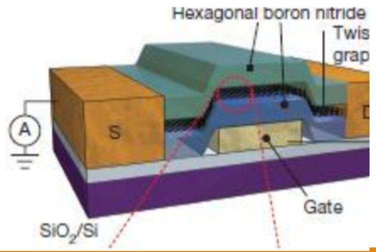
Potentially a better understanding of correlated electronic states

Correlated states



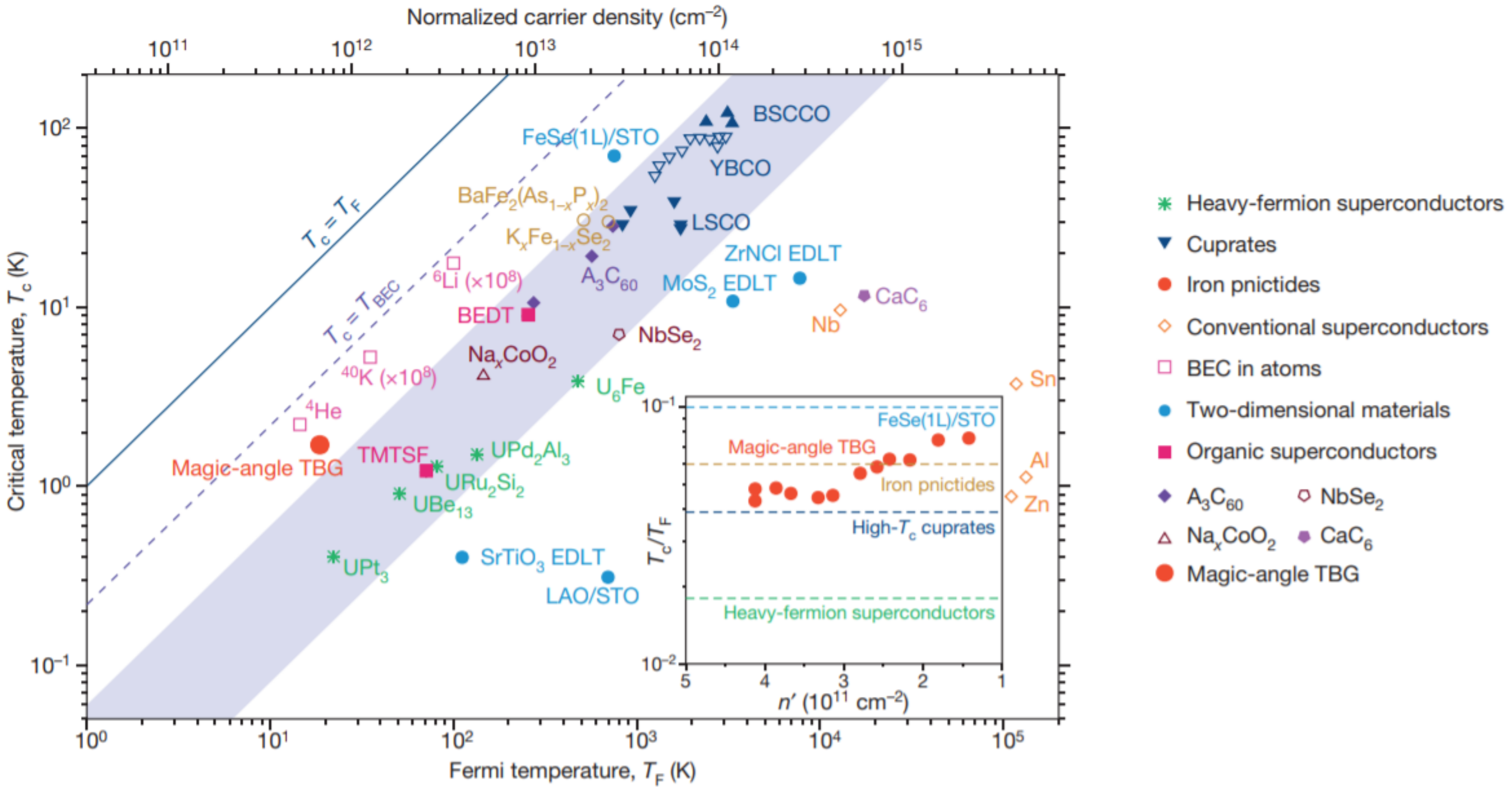
Y. Cao et al, *Unconventional superconductivity in magic-angle graphene superlattices*

Transport set-up



- Experimental realization in 2018
  - Tuning between insulating, metallic, and superconducting phase with carrier density n and temperature T
  - Insulating near integer fillings, like with Landau levels
  - Different behaviors in samples with different twist angles near magic angle
- Competitions of phases: insulating (*not necessarily* Mott-insulating), superconducting, charge density wave, nematic
- Experimental challenges of transport:
  - Difficulty controlling twist angle due to twist inhomogeneities (disorder through inhomogenous strain) and sample-to-sample lattice relaxation effects modifying the single particle dispersion relation
  - May not be a superconducting path between leads

Superconducting properties

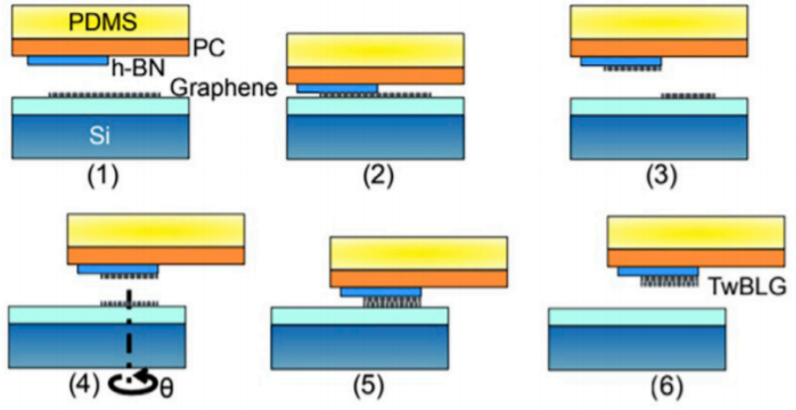


- Unusually high $\frac{T_c}{T_F}$ ratio compared to other superconductors
  - Strong interactions more characteristic of e-e correlations than e-ph correlations in conventional BCS superconductors

Current research

- Broken symmetries induced in experimental set up with hexagonal boron nitride
  - Can address with other 2D insulators that interact less with graphene
  - Intentional symmetry breaking with applied B
- Pressure to increase inter-layer coupling
- "Twistronics"
  - Higher twist angles for more stability
  - Twisted trilayer graphene (Pablo, 2021)
  - Twisted transition metal dichalcogenides
    - Twisted WSe_2 (Pasupathy, 2020)
- New superlattice structures
  - Strain superlattices

Tear and stack method:



Zhuxing Sun and Yun Hang Hu, *How Magical is Magic-Angle Graphene*

Questions?

THANK YOU FOR LISTENING

2D Materials

- 1966: David Mermin and Herbert Wagner showed that long-range fluctuations could be created with little energy cost in materials with $d \leq 2$ using the propagator for scalar fields
  - Used by many to suggest that 2D materials were impossible to realize due to thermal and quantum fluctuations
- Theoretical work on graphene in the 20^{th} century mainly as a model and to understand graphite as layers of graphene
- Discovery of graphene in 2004 by Andre Geim's group though "micromechanical cleavage"