



Review

Twisted Bilayer Graphene at the Magic Angle: A Review of Highly Correlated Physics and Unconventional Superconductivity

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ABSTRACT

A novel platform for researching topological quantum phenomena, unusual superconductivity, and strongly coupled electron physics is Twisted Bilayer Graphene (TBG) at the “Magic Angle” ($\sim 1.05^\circ$). Two graphene layers are rotated to this exact angle to form a moiré superlattice, which produces flat electronic bands that significantly improve electron-electron interactions. This results in a rich phase diagram with non-Fermi liquid behaviour, correlated insulators, and superconductivity. This review covers the theoretical foundations, experimental results, and unanswered concerns about magic-angle TBG, including significant challenges like twist angle control, disorder effects, and the interaction of strain and electrical characteristics. Beyond basic research, TBG has great technological potential, with potential applications in neuromorphic devices, ultra-sensitive sensors, and quantum computing (e.g., topological qubits). This system provides a novel approach to comprehending high-temperature superconductivity and achieving next-generation quantum technologies by fusing insights from correlated physics with device engineering.

Keywords: Twisted Bilayer Graphene; Magic Angle; Superconductivity; Correlated Insulators; Moire Superlattice

1. Introduction

Due to its remarkable electrical properties, graphene's discovery in 2004 transformed condensed matter physics; at present, the absence of a natural bandgap restricts its applications in semiconductor devices. This basic limitation led to novel approaches for modifying the electrical structure of graphene, which ultimately resulted in the revolutionary discovery of twisted bilayer graphene (TBG). A moiré superlattice that radically changes the electrical behaviour of the system is produced when two graphene layers are rotated to a precise “magic angle” of roughly 1.05° , according to research conducted in 2018 by MIT researchers under the direction of Pablo Jarillo-Herrero [1]. In order to overcome the limits of monolayer graphene, this twist engineering creates flat electronic bands where strong electron correlations result in remarkable phenomena such as correlated insulating states and superconductivity.

The magic-angle TBG is a unique platform for investigating strongly correlated physics, replicating essential characteristics of high-temperature superconductors without the need for chemical

doping. Superconductivity, Mott-like insulators, and non-Fermi liquid behaviour are all included in the rich phase diagram made possible by the moiré-induced flat bands, which significantly improve electron-electron interactions and are adjustable by electrostatic gating [2]. In addition to having significant effects on basic physics, TBG's remarkable qualities have the potential to revolutionise quantum technology, such as topological quantum computers and extremely efficient electronic devices. Unprecedented insights into the interaction of band structure engineering, superconductivity, and correlation effects in two-dimensional materials are still being offered by this system.

The importance of magic-angle TBG's strength is its ability to replicate the physics of high-temperature superconductors while requiring no chemical doping and being solely controlled by electrostatic gating. The development of a moiré superlattice, which significantly changes the band structure and produces flat bands where electrons travel slowly and interact fiercely, controls the system's electrical characteristics. Superconductivity, Mott-like insulators, and odd metal behaviour are all encompassed in the rich



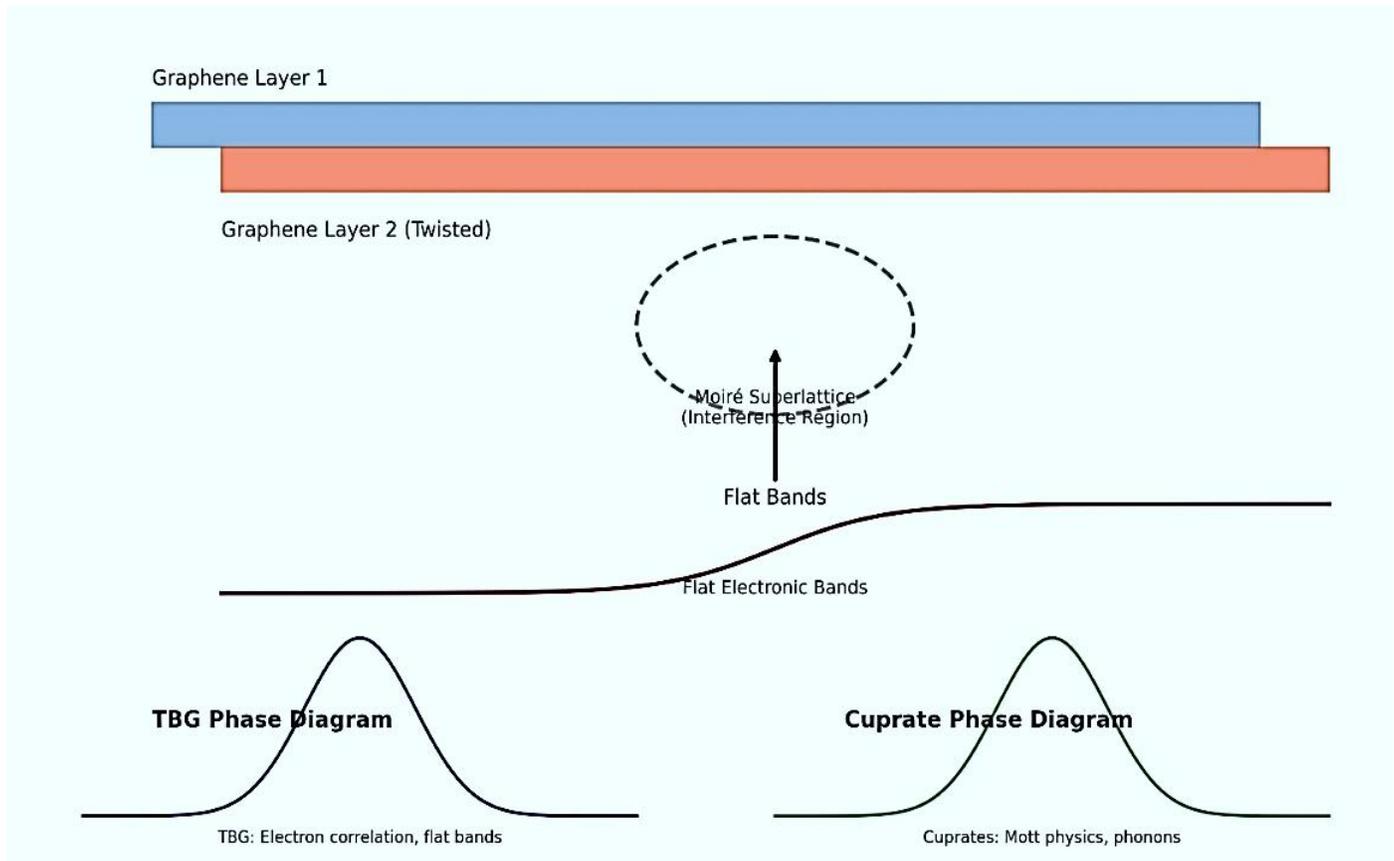


Figure 1: Moiré Superlattice and Flat Band Formation [5].

phase diagram that results from the enhancement of electron-electron correlations by these flat bands.

Beyond its basic scientific significance, TBG has potential applications in next-generation quantum technologies such as neuromorphic devices, topological quantum computing, and ultra-low-power electronics [2].

2. Theoretical Foundation

The creation of a moiré superlattice, which occurs when two graphene sheets are stacked with a slight rotational misalignment, is fundamental to the electrical behaviour of twisted bilayer graphene. The basic Dirac cone structure of graphene is altered by this moiré pattern's introduction of a long-range periodic potential, which causes flat bands to appear at specific "magic" twist angles. The first theoretical foundation for comprehending these effects was offered by the 2011 Bistritzer-MacDonald model, which predicted that the electrons' Fermi velocity would disappear and almost dispersionless bands would form at a twist angle of about 1.05° [3]. Because they enhance electron-electron interactions and allow for the formation of tightly correlated phases, these flat bands are essential [4].

When two graphene sheets are rotated relative to one another at a tiny twist angle, a moiré superlattice is formed in twisted bilayer graphene (TBG), as shown in Figure 1. The electronic band structure is considerably modified by the superlattice periodicity that results from the ensuing moiré interference pattern. The system displays flat electronic bands within the described "magic angle" ($\sim 1.1^\circ$), where kinetic energy is suppressed and electron-electron correlations are strengthened.

A comparison of the superconducting phase diagrams of cuprate high-temperature superconductors and TBG, as discussed in Table 1. As a function of carrier concentration, both show a distinc-

tive dome-shaped superconducting phase, indicating the existence of strong correlation physics [5].

2.1. Schematic Diagram

The system behaves like other correlated materials, including heavy fermion compounds and high-temperature cuprate superconductors, in this domain. For example, the system becomes a correlated insulator, similar to a Mott insulator, at half-filling, when the number of electrons in the moiré unit cell equals the number of possible states. The strong Coulomb repulsion between electrons, which stops them from flowing freely, is what causes this insulating state. Superconductivity emerges when the system is slightly doped away from half-filling, indicating a delicate balance between coherence and localisation. With continuous discussions over the exact mechanisms underlying superconductivity in TBG, the interaction between these phases has emerged as a central area of theoretical investigation. While some theories propose solely electrical causes, others relate it to phonon-mediated pairing, such as excitonic effects [6].

3. Experimental Breakthrough

By observing a superconducting transition at temperatures below 1.7 Kelvin, the Jarillo-Herrero group reported the experimental discovery of superconductivity in magic-angle TBG in 2018, as demonstrated in Table 1. Because it showed that superconductivity might develop in a system devoid of the strong electron-phonon interaction commonly associated with normal superconductors, this discovery was very remarkable. Rather, the hallmark of unconventional superconductivity, strong electron correlations, seems to be the driving force behind the superconductivity in TBG. Its potential as a flexible platform for researching quantum phase transitions was further demonstrated by the capacity to shift the system be-



Table 1:
Moiré Superlattice and Flat Band Formation [5].

Year	Milestone/Event	Twist Angle (°)	Critical Temperature (Tc)	Doping Level / Filling Factor	Key Observation
2018	Discovery of superconductivity in magic-angle TBG	~1.1° (magic angle)	~1.7 K	±2 electrons per moiré unit cell	Superconductivity adjacent to a correlated insulating state
2018	Observation of a correlated insulating state	~1.1°	N/A	Half-filling (±2)	Mott-like insulating behavior
2019	Enhancement of Tc via pressure tuning	~1.1°	Up to 3.5 K	±2	Tc increased under hydrostatic pressure
2020	Nematic order and symmetry breaking observed	~1.1°	~1.5 K	Near half-filling	Broken rotational symmetry detected
2021	Identification of "strange metal" or "odd metal" behavior	~1.1°	—	Near charge neutrality to ±2	Linear-in-T resistivity over a wide temperature range
2022	Tunable moiré heterostructures (twist angle/strain control)	Various	~1–5 K	Broad range	Broader tunability of correlated phases
2023	Superconductivity in twisted trilayer graphene (TTG)	~1.5° TTG	~3 K	Similar fillings	Shows superconductivity beyond bilayer systems

tween insulating and superconducting states using an external electric field [6].

Even more complex physics has been discovered in TBG through subsequent research, such as odd metal behaviour with linear-in-temperature resistivity, a hint of non-Fermi liquid physics. This behaviour, in which the system hovers close to a phase transition at absolute zero temperature, is frequently linked to quantum criticality. Comparison between conventional and odd metals has been described (in Table 2) to showcase the need to explain both of them. Recent developments have broadened the focus of TBG studies to encompass twisted multilayer structures with novel associated phases and increased superconducting transition temperatures, including trilayer graphene [7].

The phase diagram of TBG has also been further enhanced by the discovery of topological states, such as quantum Hall effects, by the use of magnetic fields. These findings have solidified TBG as a model system for investigating the relationship among superconductivity, topology, and correlation [8].

3.1. Summary of Differences

Twisted bilayer graphene (TBG) exhibited linear-in-T resistivity over a broad temperature range close to specific doping levels in the 2018–2021 studies, lacking a discernible superconducting dome, depicted in Figure 2. This is an excellent option for investigating non-Fermi liquid physics since it is anomalous and represents a breakdown of quasiparticle-based transport [9].

Table 2:
Summary of Differences Between Conventional and Odd Metals [9].

Feature	Fermi Liquid	Odd/Strange Metal
Resistivity vs Temperature	$\rho(T) \sim T^2$	$\rho(T) \sim T$
Dominant scattering	Electron-electron	Unknown, likely critical or collective
Quasiparticles	Long-lived	Not well-defined
Underlying theory	Landau-Fermi liquid theory	No complete theory yet
Typical materials	Simple metals	Cuprates, TBG, heavy fermions

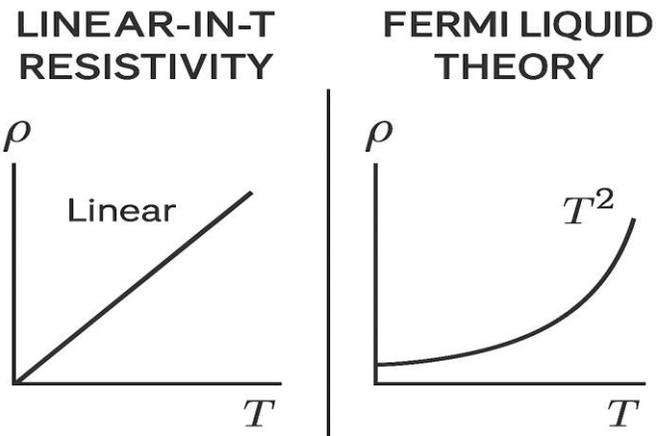


Figure 2: The Graphical Demonstration between Fermi Liquid and Linear-IN-T-Resistivity [10].

4. Mechanism of Superconductivity

There is still much disagreement on the genesis of Superconductivity in magic-angle TBG. The superconductivity of TBG may result from solely electronic causes, in contrast to ordinary superconductors, where pairing is mediated by lattice vibrations (phonons). One theory is that spin fluctuations serve as the glue that holds electrons together in Cooper pairs because they are fueled by strong electron correlations. In this case, TBG would be categorised with high-temperature cuprate superconductors, where spin fluctuations are believed to be important. Excitonic pairing, in which electron-hole interactions stabilise the superconducting state, is the subject of another proposal [11].

4.1. Introduction to Valley Degrees of Freedom

- The valley index is an additional quantum number that electrons in materials like graphene possess.
- The Brillouin zone of graphene has two inequivalent Dirac cones at locations designated K and K'.
- These provide an additional degree of freedom, much like spin, and function similarly to pseudospins or valleys.



- Thus, an electron's characteristics include its valley (K or K') as well as its momentum and spin.

4.2. Intervalley Coherence

A quantum superposition between states in the K and K' valleys is known as Intervalley Coherence (IVC), as described by the equation (1) below:

$$|\Psi\rangle = \alpha |K\rangle + \beta |K'\rangle \quad (1)$$

New coherent states can be created when electrons interact or pair across troughs. This is comparable to spin-singlet creation or exciton condensation, but it occurs between valleys. It can result in time-reversal symmetry breakage, nematicity, or new superconducting order parameters [10].

The moiré superlattice itself may be essential for promoting superconductivity. Pairing instabilities are more likely when the moiré lattice increases the density of states close to the Fermi level by generating a periodic potential with a large unit cell. Additionally, the superlattice can encourage intervalley coherence, which produces exotic superconducting order parameters by pairing electrons from various momentum-space valleys. Recent studies have pointed to spin-triplet pairing, which would distinguish TBG from conventional s-wave superconductors and align it with other unconventional systems like strontium ruthenate [11]. Higher-quality samples with less disorder, theoretical modelling, and sophisticated spectroscopic techniques will all be needed to answer these problems [11].

4.3. Summary

Electrons exist in valley states (K, K') in addition to spin states in systems such as twisted bilayer graphene. Exotic superconducting states can result from superpositions formed by these valleys. In contrast to what occurs in typical (phonon-driven) superconductors, this opens the door to unusual pairing mechanisms, some of which display topological features or break symmetries [12].

5. Critical Perspectives in Twisted Bilayer Graphene Research

Recent developments in the study of twisted bilayer graphene (TBG) have uncovered a number of surprising occurrences that challenge generally held assumptions and pave the way for further investigation. Scientists have found additional magic angles at 0.5° and 1.8° that show separate superconducting and associated insulating states, in addition to the well-studied first magic angle of roughly 1.1°.

5.1. Introduction to Higher Magic Angles

Superconductivity in TBG is not restricted to the original "magic angle" (~1.05°), as shown in Figure 3, according to recent research. At 0.5° and 1.8°, further magic angles show:

- Differential superconducting domes at varying doping concentrations
- SC re-emerging after suppression in re-entrant superconductivity
- Comparable to cuprate phase diagrams are competing charge orders [13].

5.2. Phase Diagram of Multi-Dome Superconductivity

The phase diagrams of these higher-order angles show (in Figure 3) re-entrant superconductivity with many superconducting domes, indicating a more intricate quantum phase environment than was previously thought. The finding of conflicting charge orders that seem to be entangled with superconductivity and show remark-

able similarities to the phase diagrams of high-temperature cuprate superconductors is very noteworthy. However, there is currently a substantial knowledge gap in the field, as there is no complete theoretical framework to explain why some higher-order angles exhibit improved superconducting transition temperatures while others do not [14].

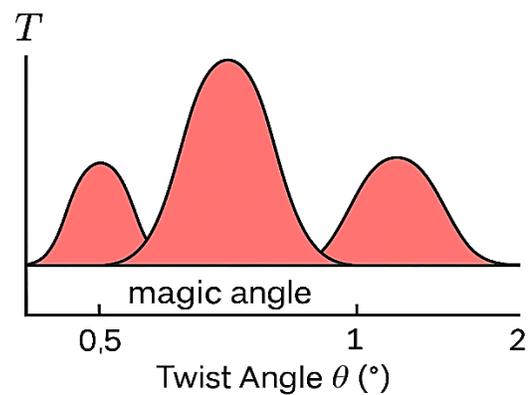


Figure 3: Phase Diagram Illustration of Multi-Dome Superconductivity [13].

5.3. Experimental Validation of Photo-Induced Superconductivity

Photo-Induced Superconductivity: Experiments demonstrate that ultrafast laser pulses, with durations on the order of ~100 femtoseconds, can profoundly modify the electronic properties of TBG. These pulses have been shown to temporarily increase the superconducting critical temperature (T_c) by as much as 50%, enabling transient access to enhanced superconducting phases not achievable under equilibrium conditions. Additionally, the intense photoexcitation can melt charge orders that otherwise compete with superconductivity, thereby unmasking the underlying superconducting state. Beyond these effects, ultrafast excitation generates highly non-thermal distributions of electrons, driving the system into nonequilibrium regimes where novel electronic behaviours and transient phases may emerge.

- **Proposed Mechanisms:** Experiments have further shown that photons can stimulate electrons to form ideal pairing states, leading to a selective population of specific electronic bands that favour superconductivity. In addition, the excitation of coherent phonons enhances electron-phonon coupling through dynamic lattice modulation, which can further stabilise superconducting and other correlated phases.
- **Engineering Floquets:** Experiments and theoretical studies have also demonstrated that time-periodic drives can create virtual flat bands, which effectively reshape the electronic structure and enhance correlation effects beyond what is possible in static conditions [15].

5.4. Equilibrium and Non-Equilibrium Approach

Recent developments in spin-orbit engineering have given TBG research fascinating new avenues for investigation. Scientists have successfully produced artificial Rashba effects that produce spin-split bands by intercalating heavy atoms like tungsten between graphene layers. The possibility of achieving topological superconductivity in TBG systems has increased as a result of this research. Results from hybrid structures that combine TBG with transition-metal dichalcogenides have been especially encouraging, exhibiting improved spin-valley locking effects. These developments do, however, provide a unique set of difficulties since the spin-orbit coupling that is introduced frequently clashes with the correlation



effects that are already there, leading to phase diagrams that are more complicated and challenging to understand. Because of its intricacy, more advanced theoretical instruments are required to handle the interactions between these different quantum processes [16].

The theoretical basis of implementing these approaches involves carefully tuning the drive parameters, such as using frequencies in the terahertz range (1–10 meV) and employing circularly polarised light to break time-reversal symmetry, while maintaining intensities below the damage threshold for graphene (approximately 1 MW/cm²). Expected outcomes include the emergence of artificial flat bands even at non-magic twist angles, the opening of topological gaps in the electronic spectrum, and an enhancement of spin-orbit interactions. However, integrating these techniques into functional devices presents several challenges, including the design of photonic cavities capable of providing continuous illumination, efficient dissipation of heat within confined structures, and achieving precise state selectivity through tailored pulse shaping.

Through periodic driving, Floquet engineering enables non-equilibrium tuning of quantum systems, as explained in Table 3. This method could:

- Generate superconducting phases driven by light
- Improve existing pairing mechanisms or perhaps make them available.
- Enable future quantum devices to have switchable, controllable quantum states [17].

The study of non-equilibrium events in TBG has produced unexpected findings that may have technological ramifications [18]. Photo-induced superconductivity, in which precisely calibrated laser pulses can momentarily increase superconducting transition temperatures by as much as 50%, has been established using ultrafast spectroscopic tests. The use of Floquet engineering, in which time-periodic drives might theoretically produce artificial flat bands even at non-magic angles, is another exciting avenue. These effects serve as a crucial proof of concept for non-equilibrium control of quantum materials, even though they only last for picosecond durations at the moment. These results imply that additional routes to reaching and stabilising desired quantum states that are unavailable through static techniques may be provided by dynamic manipulation of TBG systems.

Long-held beliefs regarding the dominating physics in TBG systems are being called into question by an increasing amount of high-resolution scanning tunnelling microscopy data. According to new data, strain solitons that drastically alter the electrical band structure are produced when graphene layers are reconstructed at the atomic scale at modest twist angles. Unexpected quantum phases seem to be hosted by inevitable local angle fluctuations on the order of 0.05°, even in meticulously manufactured "perfect" systems [18]. These findings have raised important questions concerning whether atomic-scale features are more important than previously thought or whether moiré effects alone can account for TBG's complex phenomenology. The conventional moiré band models that have influenced a large portion of the field's theoretical work up to this point may need to be modified in light of this new viewpoint [19].

Although there is still much excitement surrounding the possible uses of TBG in quantum technologies, a more sophisticated comprehension of real-world limitations is starting to take shape. There are still several obstacles in the way of creating practical devices, especially when it comes to qubit coherence times, which are now restricted to nanoseconds due to charge noise. Another significant challenge with TBG-based systems is their scalability, since no method now in use can consistently align hundreds of moiré devices on a single chip with the necessary sub-0.01° precision.

These drawbacks imply that hybrid strategies that integrate TBG with more established silicon-based platforms would be necessary for near-term commercial applications. As the discipline develops, this reality check emphasises how crucial it is to strike a balance between basic research and real-world engineering requirements.

5.5. Summary

According to the current status of TBG research, three paradigm shifts are required in order to influence the future direction of the discipline. First, disorder must be viewed as a potential design characteristic that can be tailored to stabilise desired quantum states, rather than as an inevitable annoyance. Second, dynamic control strategies that take advantage of non-equilibrium phenomena should be included in the emphasis on static systems. Third, more integrated methods that integrate TBG with other functional elements in photonic, spin, and three-dimensional architectures must replace the isolation of TBG systems in research settings.

The importance of mechanical characteristics and strain solitons in quantum transport, the thermodynamic features of TBG that seem to defy traditional constraints, and the creation of standardised metrology for twist angle calibration are some important areas that are still poorly understood. As the subject develops, scientists must balance the exquisite simplicity of moiré physics with the growing understanding that the secrets of TBG may lie in atomic-scale intricacies [20].

Table 3:
Comparison of Equilibrium Vs. Non-Equilibrium Approaches [21]

Feature	Static TBG	Floquet-Engineered TBG
Band structure	Fixed by θ	Dynamically tunable
Tc limit	~3 K	Potentially higher
Stability	Permanent	Requires continuous drive
Topology	Intrinsic	On-demand

6. Challenges and Solutions

Even while our understanding of Twisted Bilayer Graphene (TBG) has advanced significantly, there are still a number of important issues. These challenges fall into three primary categories:

6.1. Fabrication Challenges

The twist angle between layers has a remarkable impact on TBG's electrical characteristics. Reproducible device fabrication is a significant challenge since even small deviations (~0.1°) from the magic angle (~1.05°) can significantly change the behaviour of the system. At scale, existing methods like the "tear-and-stack" method are unable to provide the necessary precision. Furthermore, after production, external variables like substrate interactions and temperature fluctuations may cause unforeseen changes. Although they have not yet completely solved these obstacles, emerging techniques like as strain engineering and alignment, helped by scanning probes, show promise.

6.2. Theoretical Uncertainties

There is still much discussion about the microscopic processes underlying TBG's unusual phases, as shown in Table 4. The superconducting order parameter remains contentious, with conflicting evidence suggesting s-wave, d-wave, or even p-wave pairing symmetry [21]. Similarly, the extent to which superconductivity and correlated insulating states are driven by electron-phonon coupling, spin fluctuations, and Coulomb repulsion remains unclear. The



Table 4:
Moiré Superlattice and Flat Band Formation [5].

Pairing Symmetry	Gap Structure	Time-Reversal Symmetry	Orbital Angular Momentum	Candidate Mechanism	Observed In
s-wave	Isotropic	Preserved	0	Phonon-mediated	Conventional superconductors (e.g., Nb)
d-wave	Nodes	Preserved	2	Spin fluctuations	High-Tc cuprates
p-wave	Chiral or helical	Broken or preserved	1	Triplet pairing, spin-orbit	Sr ₂ RuO ₄ (possible), topological SCs
s± (sign-changing s-wave)	Isotropic but sign-changing	Preserved	0	Interband scattering (e.g., spin fluctuations)	Fe-based superconductors
Intervalley s-wave	Isotropic or anisotropic	Preserved or broken	0	Intervalley phonons or Coulomb	Twisted bilayer graphene (TBG)
Chiral d+id / p+ip	Gapped, complex	Broken	±2 / ±1	Intervalley coherence, topology	TBG, Moiré materials (proposed)

linear-in-temperature resistivity observed in the strange metal phase further hints at an underlying quantum critical point, although its origin is still unknown. Overall, the inherent complexity of strongly coupled moiré systems makes them exceptionally challenging to model, necessitating sophisticated computational and analytical approaches that contribute to this persistent uncertainty [21].

6.3. Material Imperfections

Intrinsic and extrinsic disorders significantly affect real-world TBG devices. Strain inhomogeneity, arising from local lattice deformations, induces electronic inhomogeneity by disrupting the moiré potential. Impurities and defects, including adsorbates, vacancies, and ripples, act as scattering centres that obscure the underlying physics. The substrate also plays a crucial role, as dielectric screening from surrounding materials such as hBN unpredictably alters the strength of interactions. Even “high-quality” devices exhibit nanoscale variations in twist angle and strain, as revealed by recent scanning tunnelling microscopy studies, complicating the interpretation of bulk measurements. Regarding superconductivity and topology, the superconducting phase of TBG may be stabilised through topological effects. Majorana zero modes (MZMs), which are robust non-Abelian quasiparticles appearing at edges or vortices in topological superconductors, have been theoretically predicted to emerge in TBG due to proximity-induced spin-orbit coupling, offering a potential pathway to fault-tolerant quantum computing [21]. In addition, helical edge states, akin to those in quantum spin Hall insulators, could enhance Cooper pair coherence and suppress dissipation, while topological protection from edge states may localise detrimental scattering processes and help preserve the superconducting phase. These theories are supported by experimental observations such as quantised conductance in magnetic fields and anomalous edge currents, though direct evidence of topological superconductivity, for example, via Josephson interferometry, remains elusive [22].

6.4. Solutions and Insights

To overcome all of these challenges, advances in fabrication techniques are essential, including improved strain management and atomic-precision alignment, along with the development of non-perturbative theoretical tools capable of addressing the strong correlations inherent in TBG. Additionally, phase-sensitive probes

will be crucial for distinguishing between topological signatures and the symmetries of the superconducting order parameter. By addressing these obstacles, TBG research holds the promise of achieving unprecedented control over correlated quantum matter, thereby bridging the gap between fundamental studies and practical applications [23].

7. Application and Future Perspectives

Twisted Bilayer Graphene (TBG) at the magic angle has transformative promise in both basic research and quantum technologies, owing to its unique features as an incredibly tunable substrate for correlated physics.

7.1. Quantum Technologies

Fault-tolerant qubits based on Majorana zero modes, exotic quasiparticles that arise at the borders of topological superconductors and are naturally shielded from local noise, may be made possible by TBG's topological superconductivity. They're perfect for quantum computing because of this. Furthermore, TBG's electrostatically adjustable insulator-superconductor transitions resemble neural plasticity, indicating potential uses in neuromorphic computing with extremely low power requirements. TBG is a promising material for quantum sensors, such as single-electron transistors and nanoscale magnetometers, due to its extraordinary sensitivity to external fields [23].

7.2. Unresolved Challenges

Despite quick advancements, major challenges still exist:

- **Material control:** The ability to fabricate devices with exact twist angles and negligible disorder in an accurate way.
- **Mechanistic comprehension:** Demonstrating the characteristics of superconductivity (such as s-wave versus d-wave pairing) and how topology interacts with it.
- **Scalability:** For real-world applications, combining device-level capabilities with atomic-scale phenomena.

7.3. Moving Beyond Room-Temperature Superconductivity

A route to higher transition temperatures (T_c) is suggested by the identification of strain-tunable phases and larger magic angles (e.g., 0.5°, 1.8°). According to theoretical proposals, distinctive



pairing may be stabilised by heterostructures that combine TBG with effective spin-orbit materials. It may be possible to artificially produce and maintain high-T_c states using non-equilibrium techniques, e.g., Floquet engineering.

Beyond superconductivity, TBG offers a variety of experimental opportunities for exceptional quantum phases, such as quantum spin liquids and Wigner crystals, which have the potential to revolutionise our knowledge of strongly correlated matter [24].

From a practical standpoint, the technological promise of TBG-based materials is immense. Their compatibility with existing 2D heterostructure platforms and the potential to switch superconductivity dynamically using light or gating hold implications for quantum computing, reconfigurable electronics, and energy-efficient switching devices.

7.4. Future Perspectives

Future research must bridge atomic-scale insights with device-scale engineering, uniting fundamental discoveries in moiré quantum matter with scalable, robust technologies for the next generation of quantum materials [8],[9],[10],[11].

8. Conclusion

One of the most intriguing platforms in contemporary condensed matter physics is magic-angle twisted bilayer graphene, which provides previously unheard-of insights into strongly coupled electron systems and unusual superconductivity. In addition to offering a highly adjustable experimental system for verifying theoretical predictions, its discovery has helped to bridge the gap between other domains, including topological quantum matter and high-temperature superconductivity. Even if disorder and sample variability present difficulties, continuous improvements in manufacturing methods and theoretical knowledge keep expanding the realm of what TBG may achieve.

The possible uses of TBG, ranging from energy-efficient electronics to quantum computing, are becoming more apparent as research advances. In order to unlock additional functions, future research will probably concentrate on improving control over twist angles, investigating multilayer systems, and combining TBG with other quantum materials.

TBG has already had a significant impact on our knowledge of quantum materials, solidifying its position as a pillar of 21st-century physics regardless of whether it eventually results in useful room-temperature superconductors.

Declaration

Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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