

Exploring the Role of Magic Angle Graphene Superconductivity in Advancing Quantum Computing

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Abstract. Magic-angle twisted bilayer graphene (MATBG) has emerged as a highly tunable platform for studying strongly correlated electronic phenomena, including unconventional superconductivity. This material exhibits flat electronic bands at specific “magic” twist angles, leading to enhanced electron-electron interactions and a rich phase diagram featuring insulating and superconducting states. This review explores the structural and electronic properties of MATBG, superconducting mechanisms, and potential applications in quantum computing. We discuss how its gate-tunable superconductivity and high level of material purity may help mitigate decoherence in superconducting qubits. Comparisons with other superconductors highlight its unique position in the Uemura plot, aligning with unconventional high-temperature superconductors. Despite limitations such as low critical temperatures, MATBG offers promising pathways toward advanced quantum electronic devices.

Keywords: twisted bilayer graphene, superconductivity, flat bands, quantum computing, Josephson junctions.

1. Introduction

Graphene, composed of single-layer carbon atoms arranged in a hexagonal pattern, exhibits exceptional electrical and thermal conductivities [1]. The discovery of magic-angle twisted bilayer graphene (MATBG) refers to a special configuration where two graphene layers are stacked at a precise angle, exhibiting unusual electrical properties such as superconductivity and correlated insulating states [1-2]. The moiré superlattice that arises from twisted bilayer graphene leads to flat electronic bands, strong Coulomb repulsion, and tunability of electric fields [3]. This review aims to synthesize the current understanding of MATBG, from its fundamental structure and electronic properties to its emergent superconducting behavior. It further explores the critical application of this material in quantum computing, particularly in the development of superconducting qubits. Among many applications of MATBG, superconductivity is crucial for quantum computing, notably in the development of superconducting qubits. Superconducting circuits enable quantum states to last longer, and Josephson junctions serve as a vital platform for qubits. The primary challenge in quantum computing, decoherence, is mitigated by zero dissipation, which reduces noise. Unlike some conventional superconductors, MATBG’s flat electronic bands strengthen electron correlations, and its superconductivity can be turned on or off through electrostatic doping or by adjusting the twist angle.

2. Structure and Properties of Twisted Bilayer Graphene

2.1 Discovery and Special Properties

Graphene, a single layer of carbon atoms in a hexagonal lattice, is renowned for its exceptional electrical and mechanical properties, arising from its sp^2 hybridized structure and delocalized π -electron system [1]. It is the fundamental building block for other carbon allotropes [4-5]. While isolating single-layer graphene in 2004 was a landmark achievement [6-7], stacking these layers introduces new physics. When two graphene sheets are overlaid with a small rotational misalignment, a long-period moiré pattern emerges.

This moiré superlattice dominates the electronic properties of this twisted bilayer graphene (TBG). The key theoretical framework for understanding TBG is the Bistritzer-MacDonald continuum model [8,11-12]. This model combines the Dirac Hamiltonian for each isolated layer with an interlayer tunneling term, revealing that the electron velocity depends critically on the twist angle. The Fermi velocity drops to nearly zero at a specific "magic angle" of approximately 1.1° [3,8]. This creates flat electronic bands where electrons become highly localized, quenching their kinetic energy and dramatically enhancing the effects of electron-electron correlations. This foundational structure sets the stage for the unconventional superconducting states observed in MATBG.

A long-periodic moiré pattern occurs when two graphene sheets twisted by a specific angle emerge from a large-scale interference pattern. At a tiny, twisted angle, whether the periodic superlattice is commensurate or incommensurate is not essential, because the spatial period of the moiré pattern is significantly larger than the atomic lattice constant, leading to common periodicity [8]. The electronics of TBG were first addressed by Rafi Bistritzer and Allan MacDonald in 2011, and they developed the continuum model now known as the Bistritzer-MacDonald model [8,11-12]. The stacking arrangement determines the low-energy electronic properties of bilayer graphene. As mentioned above, epitaxial graphene synthesised on SiC substrates frequently exhibits a high prevalence of small twist angles. For any twisted angle, this model combines the well-known Dirac Hamiltonian for each isolated graphene layer with a tunnelling term that captures the electron hopping between the two layers. The key insight that makes this model tractable is the recognition that the interlayer tunnelling amplitude is a smooth function of position; its Fourier components decay rapidly for large momentum transfers. This allows the model to consider only the three most critical tunnelling processes connecting a Dirac point in one layer to its three equivalent points in the other. Consequently, the Hamiltonian becomes periodic with the moiré pattern, which can be applied to Broch's theorem [8,11-12]. Hence, reveals that the Dirac velocity oscillates with the angle, dropping to zero at a specific "magic angle" that produces a high density of states and enhanced counterflow conductivity. While we can explain the first magic angle, the explanation of the pattern of subsequent angles and the complete flattening of the band at around 1.05 degrees remains unresolved [11]. Future work must address multilayer stacks and the significant role of electron-electron interactions, which can lead to correlated states such as superconductivity.

2.2 Twisted Bilayer Graphene Superconductivity

2.2.1 Flattened Bands

The moiré pattern acts as a superlattice potential, modifying the electronic structure and creating a "mini Brillouin zone" [3]. At this magic angle, the Fermi velocity of the electrons drops to nearly zero [3]. This results in bands that are "flat" in momentum space, meaning electrons have a huge effective mass and are highly localised with zero bandwidth. The wave functions of the flat band can also be constructed analytically. They are built from ratios of theta functions, reminiscent of the wave functions for electrons in the lowest Landau level in the quantum Hall effect on a torus [3,8]. The zero-mode wave function at the K point in the Brillouin zone develops a zero at the real-space location of the BA-stacked regions. This zero perfectly cancels a pole in the theta function construction, creating a valid, non-singular wave function for every momentum k at the same energy. The first magic angle is predicted and observed to be approximately 1.1 degrees [3,8].

2.2.2 Strong Electron-electron Interactions

In most materials, including single-layer graphene, electrons have high kinetic energy, often overshadowing the Coulomb repulsion energy between electrons. This system is well-described as a "Fermi liquid" where electrons behave as independent, weakly interacting particles. As we mentioned earlier, the bands become flat at the magic angle. The kinetic energy of electrons is dramatically reduced, and the Coulomb repulsion energy between electrons becomes the dominant energy scale in the system. This leads to a vast, peaked density of states, meaning many electronic states are crammed into a tiny energy window. Independent electrons can no longer describe the system; instead, it

becomes strongly correlated. Despite the Mott-like insulating state caused by this many-body gap, unconventional superconductivity upon doping is also raised [3,13]. When the system is electrostatically doped away from the insulating state, it does not simply become a metal but transitions to a new state. The paper presents several key pieces of evidence pointing to a correlation-driven origin. The superconducting domes emerge directly next to a correlation-driven Mott insulating state. This intimate connection suggests that the same strong electron interactions that localise electrons to create the insulator are also responsible for pairing them to form the superconductor upon doping.

Additionally, quantum oscillation measurements reveal that the charge carriers responsible for superconductivity form small Fermi pockets with a large effective mass. The area of these pockets corresponds not to the total carrier density (n), but to a shifted density $n' = |n| - n_s/2$, where n_s is the density of the correlated insulator [3]. This indicates that the parent state is the insulator, and doping adds new mobile quasiparticles into the system, a phenomenon also observed in underdoped cuprates. Furthermore, when plotted on a graph of critical temperature (T_c) versus Fermi temperature (T_F), magic-angle TBG falls among the strongest-coupled superconductors known, alongside cuprates and iron-based superconductors. The ratio T_c / T_F is very high (~ 0.1), indicating that the pairing energy scale is a significant fraction of the Fermi energy, which is impossible in weak-coupling BCS theory [3]. The coherence length is also remarkably short, on the same order as the average distance between electrons. This suggests the system is near the crossover between BCS superconductivity and Bose-Einstein condensation (BEC) of pre-formed pairs. In conclusion, the magic-angle of twisted bilayer graphene establishes TBG as a “model quantum material” where the strength of correlations can be finely tuned with a gate voltage, providing a new and powerful avenue for understanding the long-standing mystery of high-temperature superconductivity.

3. Quantum Computing

Quantum computation is a revolutionary paradigm that harnesses the principles of quantum mechanics to process information. It began with centralised mainframe computing, dominated by companies like IBM, which provided massive processing power to large organisations. We now operate in the mobile and cloud computing era, where companies like Apple and Google put computers in everyone's pocket. At the same time, the digital world's infrastructure runs on remote data centres operated by Amazon Web Services, Microsoft Azure, and Google Cloud. The current frontier is defined by artificial intelligence and big data, with companies like NVIDIA providing the hardware for complex AI models. A new quantum computing paradigm is emerging, pursued by players like IBM and Google, promising to solve problems beyond the reach of classical computers [15-16].

3.1 Qubits to Entangled Qubits

Unlike classical computers, which use bits (0s and 1s), quantum computers utilise quantum bits, or qubits, focusing on superconducting qubits [17]. Qubit's power comes from two key phenomena: superposition and entanglement. Both states' superposition allows a quantum computer to perform many calculations in parallel. Furthermore, quantum operations are performed using quantum logic gates. In the standard quantum circuit model of computation, these gates are the fundamental building blocks. Each gate performs a specific operation on a few qubits, similar to how classical logic gates form the basis of conventional digital circuits. Under this operation, qubits can become entangled, so that the state of one instantly influences the state of another, regardless of distance. This creates robust correlations that are impossible for classical systems to achieve. This is a mathematical feature of the Schrödinger equation, which governs quantum systems. The equation's linear nature means that any sum of its possible solutions also constitutes a correct solution [18-19].

3.2 Coherence and Decoherence of Quantum Computing

However, their quantum state is easily disrupted by environmental “noise,” such as temperature changes or vibrations, a phenomenon known as decoherence. They must often be isolated and kept at temperatures near zero to combat decoherence. The decoherence in a superconducting quantum bit circuit is called the qubit, which combines a split Cooper pair box with a hysteretic Josephson junction. The performance of these qubits is measured by their coherence times. The current superconducting qubits have achieved times of 100 microseconds, demonstrating the concepts of quantum error correction. The main factors limiting coherence are dielectric loss, external couplings, and flux noise. [19].

The loss of quantum coherence is the major obstacle for quantum computing, as it limits the number of operations that can be performed error-free. Microscopic two-level state (TLS) defects in amorphous materials primarily cause decoherence, resulting in energy relaxation and dephasing. These defects cause energy relaxation by providing dissipation channels through resonant dipole interactions with the qubit’s electric field. Additionally, TLS defects cause dephasing through low-frequency $1/f$ noise in control parameters such as Josephson energy, gate charge, and phase. Critical current noise (Josephson energy) stems from TLS modulating the junction barrier’s transmissivity. Charge noise (gate charge) results from fluctuating trapped charges in insulators, while flux noise (phase) is attributed to unpaired surface spins on superconducting films. These fluctuations shift the qubit frequency unpredictably, resulting in a loss of phase coherence. In summary, decoherence in superconducting qubits is predominantly material-limited. Coherence times require improving materials quality to suppress dissipation and noise [20-21].

3.3 Josephson junction and effect

A Josephson junction is a nonlinear, non-dissipative circuit element formed by two superconducting electrodes separated by a fragile insulating barrier. Two key equations classically describe its behaviour, the current-phase relation and the voltage-phase relation. The key consequence of these equations is that the junction acts as a nonlinear inductor, and the inductance depends on the phase difference across the junction. This nonlinearity is its most critical property for quantum bits, or qubits. Energy conservation means the energy stored in the intersection is a purely reactive, non-dissipative element essential for maintaining quantum coherence.

The primary use of the Josephson junction in quantum computing is to create the nonlinearity necessary to form an effective two-level quantum system from an electric circuit. The problem with linear elements is that a simple LC circuit made from a linear inductor and a capacitor is a harmonic oscillator. Its energy levels are evenly spaced. This degeneracy makes it impossible to address only the two lowest states without exciting higher ones, disrupting the qubit operation. The Josephson junction’s nonlinear inductance breaks this degeneracy, making the energy-level spacings anharmonic.

There are three basic ways to harness this nonlinearity, resulting in three distinct types of qubits. Firstly, a phase qubit uses a single current-biased Josephson junction, which is biased close to its critical current, where the nonlinearity is most substantial. Secondly, the charge qubit uses the Josephson junction’s capacitance and the Coulomb blockade effect to create nonlinearity in the charge degree of freedom. Lastly, a flux qubit uses a junction embedded in a superconducting loop; the loop inductance and the junction’s negative inductance are tuned to cancel each other out, creating a quartic potential. There are also some refinements with increased coherence times, such as the transmon qubit and fluxonium qubit [22-26].

3.4 In comparison to other superconductors

The key comparison is made using the Uemura plot, a fundamental diagram in superconductivity. The Uemura plot charts a superconductor’s critical temperature against its Fermi temperature, which measures the energy of the highest occupied electron state. Compared to conventional superconductors, Bose-Einstein condensate superconductors have a ratio of critical temperature and

Fermi temperature between 0.01 and 0.05, sharing the same ratio band. MATBG behaves like a canonical unconventional superconductor regarding energy scales, falling into the same category as heavy fermions and cuprates.

Another comparison is made between deduced parameters from MATBG and the universal weak-coupling limits of BCS theory, classifying the unconventional feature of superconductivity in MATBG as consistent with its position on the Uemura plot.

Additionally, the pairing symmetry is compared to confirm the unconventional superconductivity of MATBG. As a result, the superconductivity of MATBG can be turned on or off and tuned with a gate voltage to control superconducting devices. Furthermore, MATBG, a pure carbon lattice with no random chemical dopants, represents an extremely clean and ordered system. A cleaner system could have fewer parasitic TLS and defects that cause energy relaxation and dephasing. This could lead to longer intrinsic coherence times for any qubit built from this material [27-28].

4. Potential and limitations

The new finding is that MATBG is not an isolated phenomenon. Superconductivity is observed in magic-angle twisted trilayer, four-layer, and five-layer graphene. This establishes alternating twist multilayer graphene as a robust family of moire superconductors, suggesting a common underlying mechanism rooted in the unique flat bands they all share. The yield of superconducting devices was higher for MAT4G, MAT5G, and MAT6G than for MATBG. This is because larger magic angles make these structures less susceptible to mechanical relaxation during fabrication, producing more reproducible and robust devices.

Despite its robustness, the fundamental limitation is that the critical temperature remains low, requiring temperatures of dilution refrigerators. The mechanism behind superconductivity remains unresolved. For example, the Pauli limit violation in $N > 2$ systems suggests non-singlet pairing. Still, it's unclear if MATBG is also non-singlet, with its response masked by the orbital effect [29].

5. Conclusion

In conclusion, discovering unconventional superconductivity in MATBG is an inevitable consequence of producing few-layer graphene. By analysing the nature of superconductivity, the concept of flat bands with strong electron-electron interaction emerges, providing insight into manipulating the magic angle to enhance superconductivity performance. The significance of superconductors is emphasized by introducing the evolution of quantum computation with superconducting qubits. Josephson junctions of various types are utilised to improve superconductivity in quantum computing. Meanwhile, the decoherence of quantum computation is the problem that obstructs the efficiency of calculation and operation. A comparison of unconventional superconductivity in MATBG and conventional superconductors is made to conclude that the improvement in superconductor quality contributes to the development of quantum computation. Although the research on the MATBG is not comprehensive, there is great potential for discovering new physics and enabling entirely new concepts in quantum electronics.

References

- [1] Castro Neto, A. H., Guinea, F., Peres, N. M., Novoselov, K. S., & Geim, A. K. (2009). The electronic properties of graphene. *Reviews of modern physics*, 81(1), 109-162.
- [2] Fang, T., Wang, X., & Liu, J. (2025). Design of coupled magic-angle graphene/single-layer graphene surface-incident 2D photonic modulators. *Following Materials*, 8, 100740.
- [3] Cao, Y., Fatemi, V., Fang, S., Watanabe, K., Taniguchi, T., Kaxiras, E., & Jarillo-Herrero, P. (2018). Unconventional superconductivity in magic-angle graphene superlattices. *Nature*, 556(7699), 43-50.
- [4] Hirsch, A. (2010). The era of carbon allotropes. *Nature Materials*, 9(11), 868-871.

- [5] Tiwari, S. K., Kumar, V., Huczko, A., Oraon, R., Adhikari, A. D., & Nayak, G. C. (2016). Magical allotropes of carbon: prospects and applications. *Critical Reviews in Solid State and Materials Sciences*, 41(4), 257-317.
- [6] Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D. E., Zhang, Y., Dubonos, S. V., ... & Firsov, A. A. (2004). Electric field effect in atomically thin carbon films. *science*, 306(5696), 666-669.
- [7] Geim, A. K., & Novoselov, K. S. (2007). The rise of graphene. *Nature Materials*, 6(3), 183-191.
- [8] Tarnopolsky, G., Kruchkov, A. J., & Vishwanath, A. (2019). Origin of magic angles in twisted bilayer graphene. *Physical Review Letters*, 122(10), 106405.
- [9] Varchon, F., Feng, R., Hass, J., Li, X., Nguyen, B. N., Naud, C., ... & Magaud, L. (2007). Electronic structure of epitaxial graphene layers on SiC: effect of the substrate. *Physical Review Letters*, 99(12), 126805.
- [10] Mishra, N., Boeckl, J., Motta, N., & Iacopi, F. (2016). Graphene growth on silicon carbide: A review. *physica status solidi (a)*, 213(9), 2277-2289.
- [11] Bistritzer, R., & MacDonald, A. H. (2011). Moiré bands in twisted double-layer graphene. *Proceedings of the National Academy of Sciences*, 108(30), 12233-12237.
- [12] Watson, A. B., Kong, T., MacDonald, A. H., & Luskin, M. (2023). Bistritzer–MacDonald dynamics in twisted bilayer graphene. *Journal of Mathematical Physics*, 64(3).
- [13] Sun, Z., & Hu, Y. H. (2020). How magical is magic-angle graphene?. *Matter*, 2(5), 1106-1114.
- [14] Kotov, V. N., Uchoa, B., Pereira, V. M., Guinea, F., & Castro Neto, A. H. (2012). Electron-electron interactions in graphene: Current status and perspectives. *Reviews of modern physics*, 84(3), 1067-1125.
- [15] Hidary, J. D. (2021). A brief history of quantum computing. In *Quantum Computing: An Applied Approach* (pp. 15-21). Cham: Springer International Publishing.
- [16] Hassija, V., Chamola, V., Saxena, V., Chanana, V., Parashari, P., Mumtaz, S., & Guizani, M. (2020). Present landscape of quantum computing. *IET Quantum Communication*, 1(2), 42-48.
- [17] Zohuri, B. (2020). What is quantum computing and how it works. *Journal of Material Sciences & Manufacturing Research*, 3, 3-5.
- [18] Bravyi, S., Dial, O., Gambetta, J. M., Gil, D., & Nazario, Z. (2022). The future of quantum computing with superconducting qubits. *Journal of Applied Physics*, 132(16).
- [19] Gambetta, J. M., Chow, J. M., & Steffen, M. (2017). Building logical qubits in a superconducting quantum computing system. *npj quantum information*, 3(1), 2.
- [20] McDermott, R. (2009). Materials origins of decoherence in superconducting qubits. *IEEE Transactions on Applied Superconductivity*, 19(1), 2-13.
- [21] Ithier, G., Collin, E., Joyez, P., Meeson, P. J., Vion, D., Esteve, D., ... & Schön, G. (2005). Decoherence in a superconducting quantum bit circuit. *Physical Review B—Condensed Matter and Materials Physics*, 72(13), 134519.
- [22] Martinis, J. M. (2004). Superconducting qubits and the physics of Josephson junctions. In *Les Houches* (Vol. 79, pp. 487-520). Elsevier.
- [23] Averin, D. V. (2000). Quantum computing and quantum measurement with mesoscopic Josephson junctions. *Fortschritte der Physik: Progress of Physics*, 48(9-11), 1055-1074.
- [24] Golubov, A. A., Kupriyanov, M. Y., & Il'ichev, E. (2004). The current-phase relation in Josephson junctions. *Reviews of modern physics*, 76(2), 411.
- [25] Makhlin, Y., Schön, G., & Shnirman, A. (2001). Quantum-state engineering with Josephson-junction devices. *Reviews of modern physics*, 73(2), 357.
- [26] Kockum, A. F., & Nori, F. (2019). Quantum bits with Josephson junctions. In *Fundamentals and Frontiers of the Josephson Effect* (pp. 703-741). Cham: Springer International Publishing.
- [27] Talantsev, E. F., Mataire, R. C., & Crump, W. P. (2020). Classifying superconductivity in Moiré graphene superlattices. *Scientific reports*, 10(1), 212.
- [28] Oh, M., Nuckolls, K. P., Wong, D., Lee, R. L., Liu, X., Watanabe, K., ... & Yazdani, A. (2021). Evidence for unconventional superconductivity in twisted bilayer graphene. *Nature*, 600(7888), 240-245.

- [29] Park, J. M., Cao, Y., Xia, L. Q., Sun, S., Watanabe, K., Taniguchi, T., & Jarillo-Herrero, P. (2022). Robust superconductivity in the magic-angle multilayer graphene family. *Nature Materials*, 21(8), 877-883.