Building devices in magic angle graphene

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Many electronic devices derive their functionality from interfaces where the electric properties of a material change abruptly. Typically, such interfaces require a sharp change in the atomic composition, while avoiding ionic migrations and maintaining lattice-matching in order to reduce the scattering of charge carriers. It is often difficult to reconcile these requirements. One solution is to use the recently discovered twisted bilayer graphene that can host a variety of electronic ground states without having to change its atomic composition. When two graphene sheets are stacked with their lattices misaligned by roughly 1.1°, the result is a material that can be a conductor, an insulator, a superconductor or even a ferromagnet, depending on the external electric field and the induced charge doping [1-3]. Writing in Nature Nanotechnology, Daniel Rodan-Legrain and co-workers [4] and Folkert de Vries and co-workers [5] independently report electronic devices that rely on interfacing these different electronic states on a sub-micrometer length scale. Specifically, Josephson junctions and quantum-dot constrictions are made entirely within the graphene bilayer using nearby gate electrodes to change the local charge density. The borders between different electronic states are determined purely via electrostatic fields rather than by interfacing dissimilar materials, suggesting a natural path to avoid edge disorder. Moreover, it is possible in principle to switch between different device types while using a fixed set of gate electrodes.

Biasing a narrow gate electrode in a parallel plate capacitor geometry is a standard method to modify the resistance of a 2D conductor. Such field-effect control is at the heart of modern electronics. Practically, the impact of electrostatic gating on uniform systems with electronic bands that are nearly full or empty is restricted. To occupy or drain an entire electronic band, one has to add or remove an electron per a few atoms as dictated by the periodic unit cell of the crystal. However, field-effect transistors may tune the local charge density only by one electron per about 1000 atoms, limited by the breakdown field of dielectric substance between the electrodes. A key difference in super-lattice structures such as magic-angle graphene is the large area of the moiré unit that includes about 10000 atoms, much larger than the underlying unit cell of conventional graphene. The induced mini-bands hold one electron per moiré unit cell. Standard field-effect control is then sufficient to add or remove several electrons per super-cell and completely alter the mini-band occupancy and its corresponding electronic order.

To create devices within the magic angle graphene, the authors designed electrodes above and below the layers and used them to induce the desired pattern of ground states by controlling the local charge doping. By inducing superconducting regions separated by a short, non-superconducting weak link, the two research groups were able to create planar Josephson junctions via purely electrostatic interfaces [4,5]. Josephson junctions linking superconducting reservoirs with different phases are the basis for technologies such as SQUID magnetometers, superconducting digital electronics, Josephson voltage standards and superconducting qubits. They can also couple voltage to microwaves via the AC Josephson effect, a behaviour de Vries and co-workers confirmed in the magic angle junctions. The researchers exposed the device to a microwave excitation and observed fixed voltage Shapiro steps in the voltage–current characteristic as the signature of the microwave photon absorption [5].

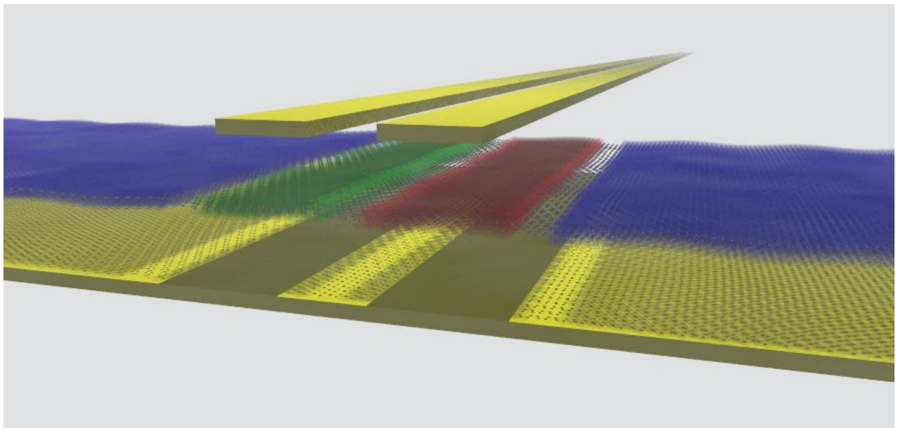

Figure 1: cartoon of a device made in magic-angle twisted bilayer graphene. Gate electrodes (yellow) above and below the graphene sheets induce different electronic ground states in the graphene. The ground states can be conducting, insulating, superconducting or ferromagnetic depending on the voltage applied to the electrodes.

Working with a slightly different pattern of electrodes, Rodan-Legrain and co-workers [4] also connected a conducting region of magic angle graphene to a superconducting region via a tunnel barrier. With this arrangement, they were able to perform spectroscopy of the states in the superconducting region by measuring the flow of unpaired electrons across the tunnel barrier. Their results confirm the presence of an energy gap in the superconducting state, but cannot unveil the superconductor pairing symmetry yet. The origin and nature of superconductivity in magic angle graphene remains an open question and this experiment shows that improvements to the technique could help answer it.

Beyond superconducting devices, Rodan-Legrain and co-workers also created a single-electron transistor in magic angle graphene [4]. They separated a conducting island from adjacent conducting regions by short insulating barriers. At very low temperature, the island was small enough and the tunnel barriers sufficiently opaque to make the number of electrons on the island fluctuate by less than one on average. Under these conditions current flows through the island one electron at a time and can be switched on and off by varying the potential of the island. Single electron transistors and their smaller counterparts, quantum dots, are sensitive probes of the local electronic states in a material. If smaller islands containing only a few electrons can be made, they could be a useful tool for studying the electronic ground states of magic angle graphene.

The demonstration of multiple electronic components within such a versatile material is very enticing. One can now couple different ground states for new fundamental insights and for useful devices, all without any interface in material composition where some strain and disorder are unavoidable and deteriorate electron transmission. One challenge however is the twist angle uniformity at different sections of the structure. The misaligned bilayer is not inherently stable and it is hard to keep the twist angle constant over long distances. The components made by Rodan-Legrain and co-workers and de Vries and co-workers show that the magic angle graphene can be sufficiently uniform over distances around one micron. More complex circuits and scale-up will be possible if this size can be increased. Nonetheless, the individual components already demonstrated offer potential benefits. In his Nobel lecture, Herbert Kroemer noted that often "the interface is the device" [6]. With magic angle graphene, it is possible to access a broad range of interfaces in a single material to build a device using purely electrostatic control.

The authors declare no competing interests.

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