ICFO Research Group Low Dimensional Quantum Materials

Magnetic Josephson Junctions and Superconducting Diodes in magic-angle twisted bilayer graphene

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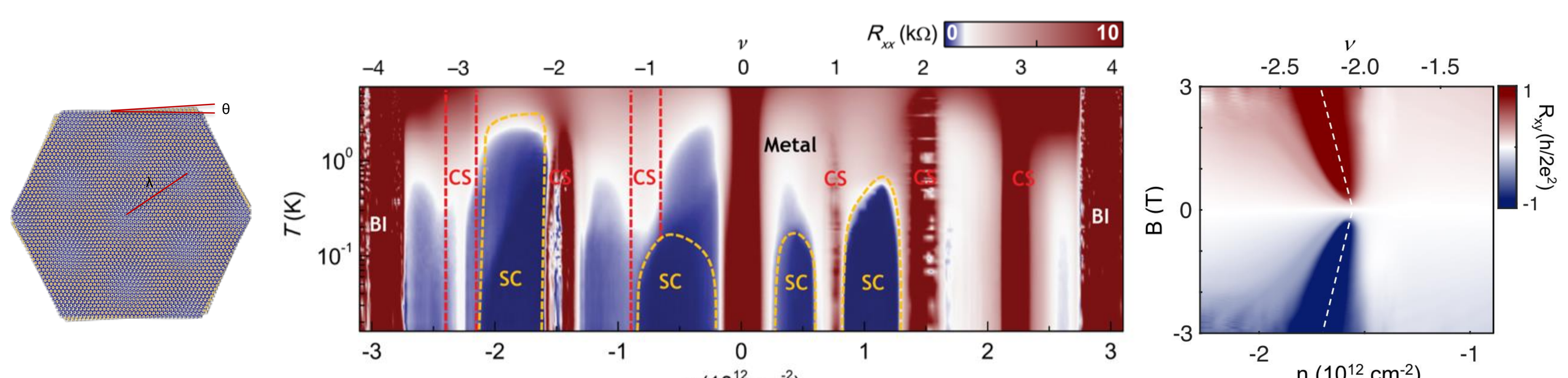
ABSTRACT

The simultaneous co-existence and gate-tuneability of the superconducting (SC), magnetic and topological states in magic-angle twisted bilayer graphene (MATBG) [1-3], allow for the creation of Josephson junctions (JJs) in a single device [4-6]. While magnetic and topological JJs enable applications in spintronics and lossless electronics, a major difficulty in their creation is to engineer ultra-clean interfaces between different materials. Here we report on the creation of a gate-defined, magnetic JJ in MATBG, where the weak link is gate-tuned close to the correlated state at a half-filling of the flat band $\nu=-2$. A highly unconventional Fraunhofer pattern emerges, which is asymmetric with respect to the current and magnetic field directions, and shows a pronounced magnetic hysteresis. We find that these features are explained by an orbital magnetic state with Chern number $C=-2$. Finally, we demonstrate how the switching of the supercurrent, induced in this state by magnetization, enables us to realize a programmable zero-field superconducting diode, which represents a major building block for a new generation of superconducting quantum electronics.

BACKGROUND AND METHODS

❖ Strongly correlated states in MATBG



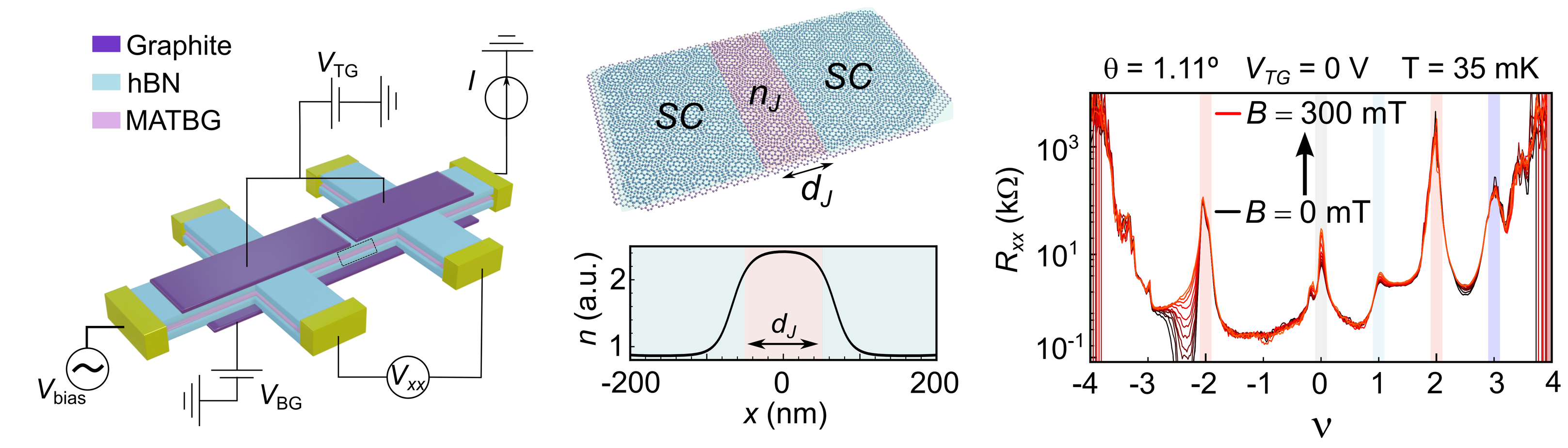
Moire pattern in tBG

Superconductors and correlated insulators

Chern Insulators and orbital magnets

- When two sheets of monolayer graphene are rotated by the magic angle $\theta_m \sim 1.1°$ and stacked together, a moiré superlattice with flat-bands emerges, hosting a variety of exotic states.

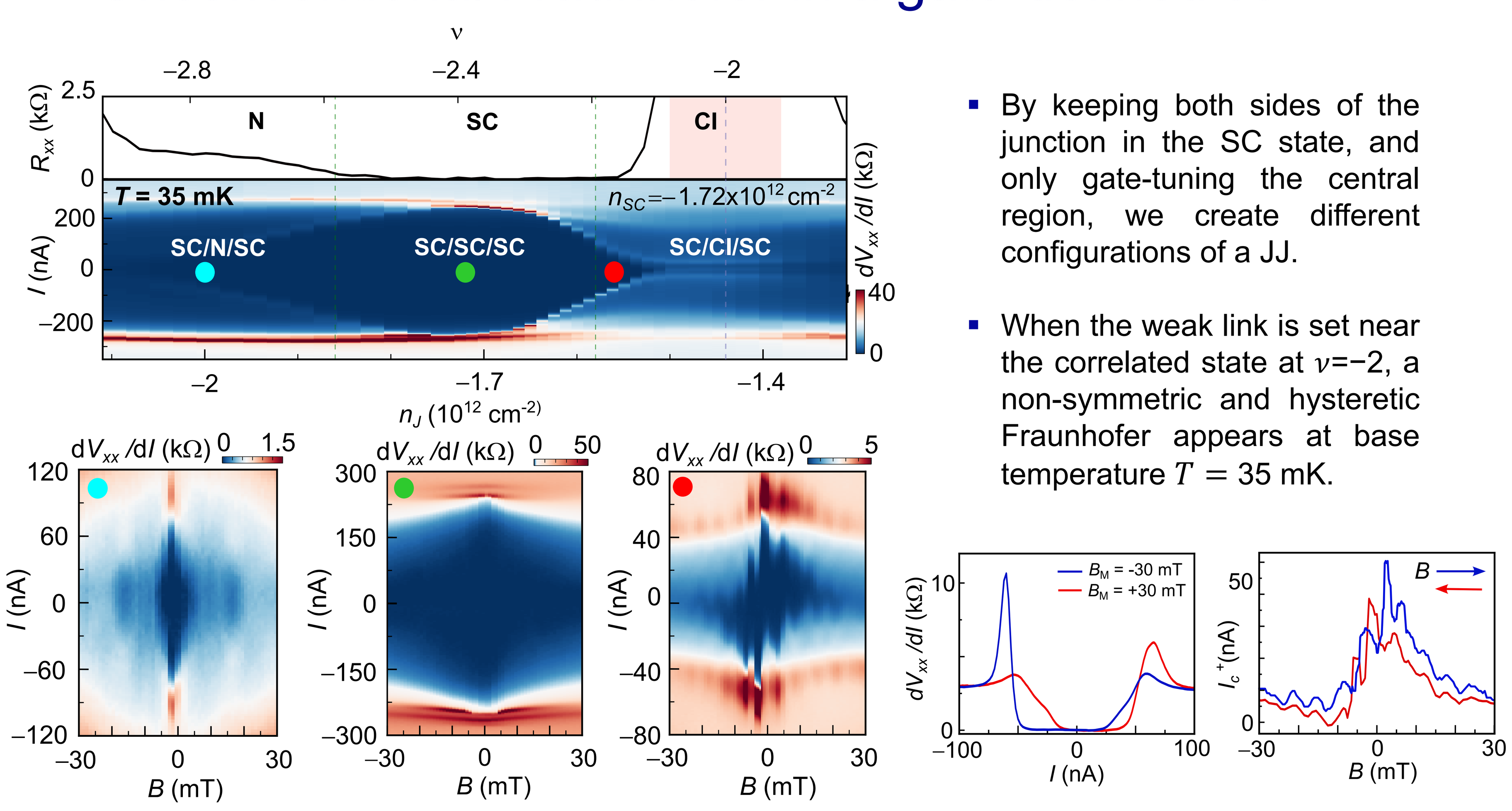
❖ Device structure



- The gate-tunability of MATBG and our three-gated geometry allows to create junctions made of the same material, thus with ultra-clean interfaces. This enables us to probe the correlated states of our device in a narrow region $d_J \sim 100$ nm with a JJ.

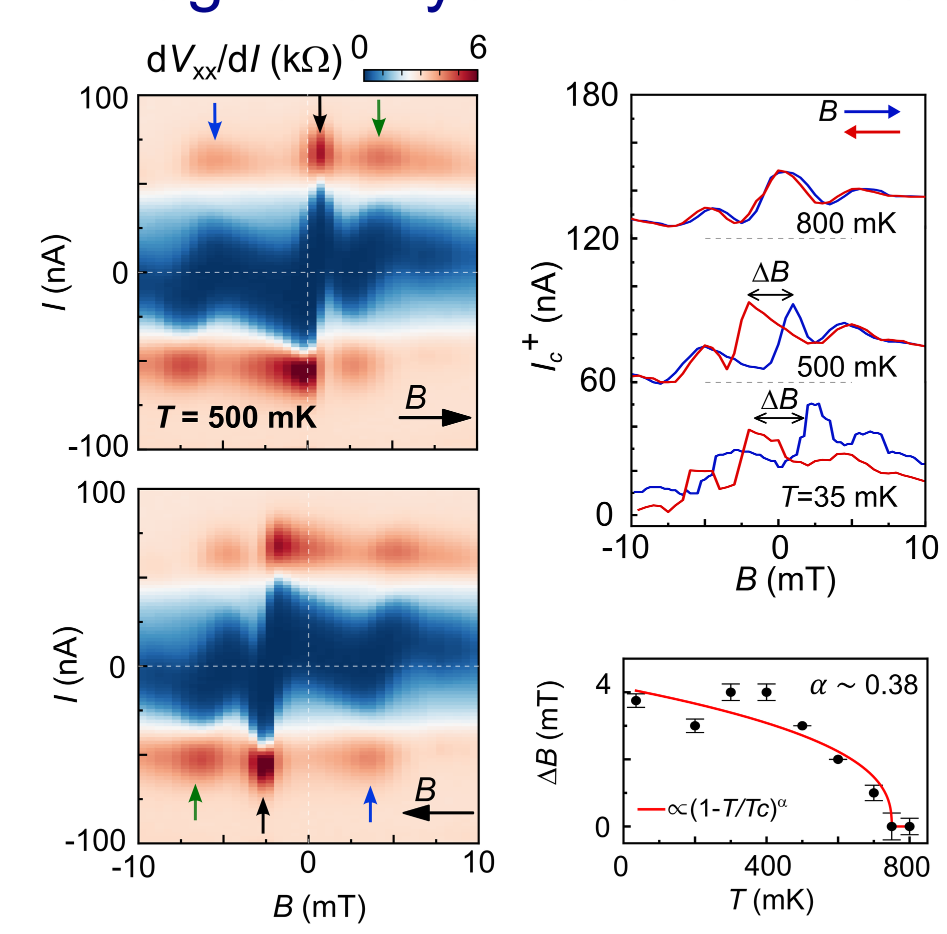
RESULTS

❖ Unconventional Fraunhofer in a gate-defined JJ



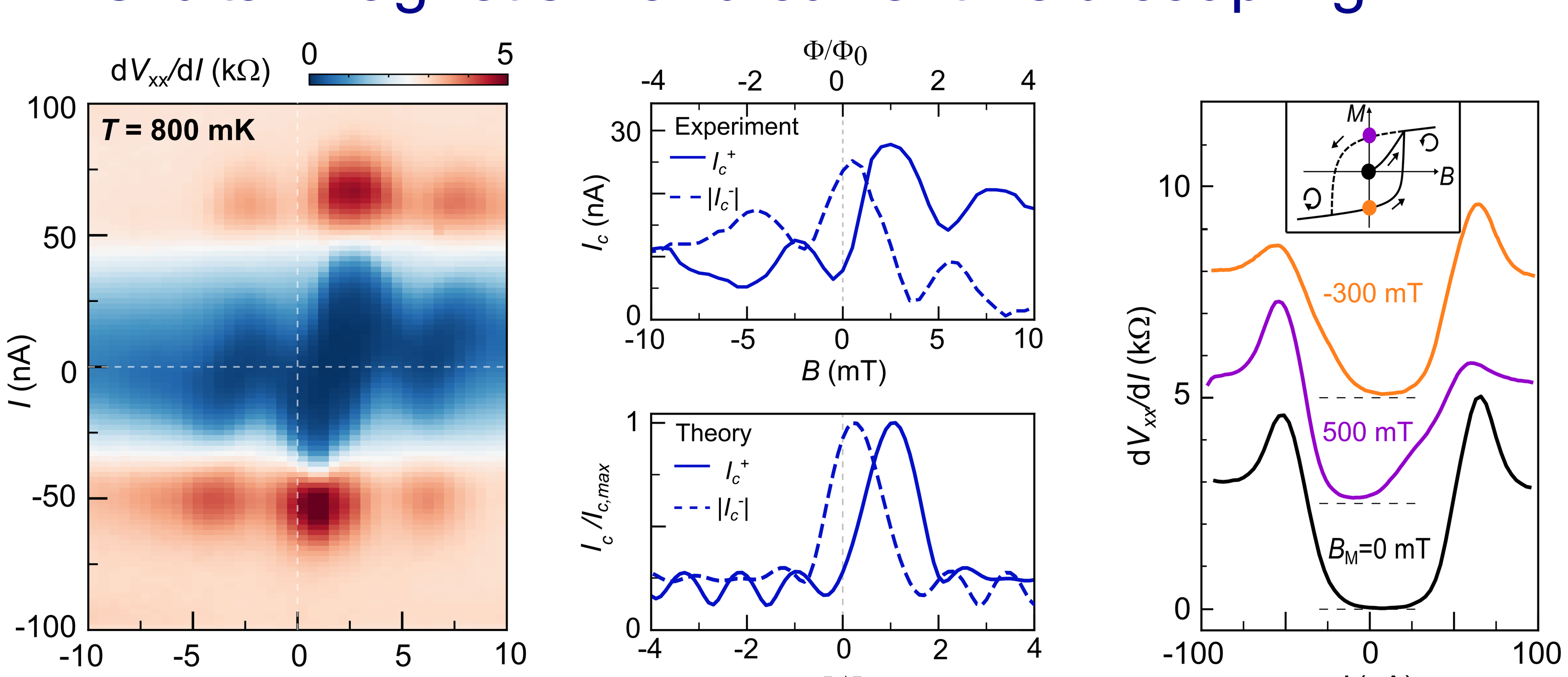
- By keeping both sides of the junction in the SC state, and only gate-tuning the central region, we create different configurations of a JJ.
- When the weak link is set near the correlated state at $\nu=-2$, a non-symmetric and hysteretic Fraunhofer appears at base temperature $T = 35$ mK.

❖ Magnetic hysteresis in the Josephson Effect



- At lower temperatures, hysteretic phase jumps appear when sweeping the field in opposite directions. The magnetizing field is much lower than at 800 mK.
- This hysteresis can be explained by a further spin polarization of the state near $\nu=-2$, with a Curie temperature $T_c \sim 750$ mK.
- Orbital magnetism is still present. The combination of both effects leads to an inversion of the field and current, as shown by the colour arrows.

❖ Orbital magnetism and current-field coupling

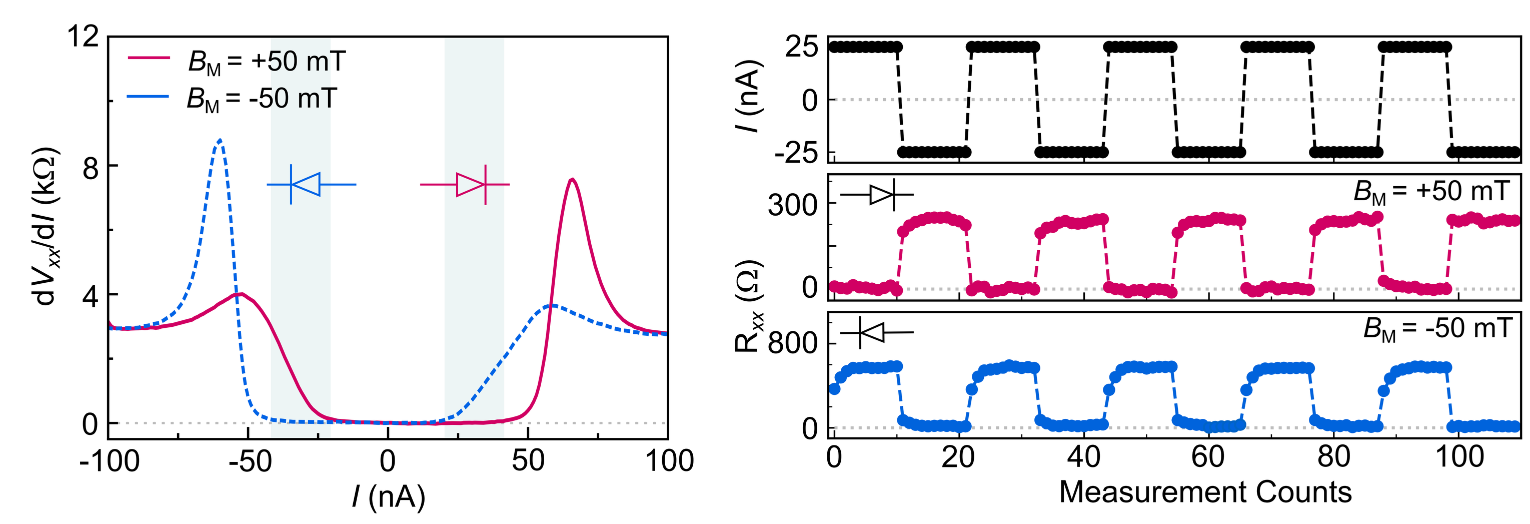


Non-symmetric Fraunhofer pattern with respect to the current and field. Time-reversal symmetry is broken and therefore the relation $I_c^+(B^+) = |I_c^-(B^+)|$ is not satisfied.

Our data is reproduced by simulations of a JJ with an orbital magnetic state with Chern number $C=-2$ set as the weak link. The current induces orbital magnetism.

By pre-magnetizing the sample at $\sim \pm 300$ mT, the dV/dI curve becomes asymmetric at zero field. The current direction is thus affected by the field.

❖ Superconducting diode



- The non-reciprocal transport caused by the current-field coupling enables us to realize a programmable, zero-field superconducting diode. By applying a DC current in opposite directions, we can measure a rectifying behaviour in the sample, which can be switched by previously magnetizing the device at positive or negative low fields.

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