



Congratulations to New ICFO PhD Graduate

Dr. Jaime Diez Merida graduated with a thesis entitled 'Probing Magic-Angle Twisted Bilayer Graphene with Monolithic Gate-Defined Josephson Junctions'

May 23, 2024

We congratulate Dr. Jaime Diez Merida who defended his thesis today in ICFO's Auditorium. Dr. Jaime Diez Merida obtained his MSc in Nanotechnology at the University of Twente in the Netherlands. He joined the Low-dimensional quantum materials research group at ICFO led by Prof. Dr. Dmitri K. Efetov as a PhD student.

Dr Diez Merida's thesis entitled 'Probing Magic-Angle Twisted Bilayer Graphene with Monolithic Gate-Defined Josephson Junctions' was supervised by Prof. Dr. Dmitri K. Efetov and by ICREA Prof. Dr. Maciej Lewenstein.

ABSTRACT:

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In 2018, following a theoretical prediction from 2011, it was found that stacking two layers of

graphene with a relative twist angle of 1.1° between them leads to multiple new properties. At this so-called magic angle, the electronic band structure of the material reconstructs creating a narrow flat band at the Fermi level. The formation of a flat band enhances electron-electron interactions, resulting in the emergence of states of matter not present in the original graphene layers, including correlated insulators, superconductivity, ferromagnetism and non-trivial topological states. The understanding of the origin of these correlated states could help unravel the physics of highly correlated flat band systems which could potentially provide key technological developments.

The main objective of this thesis is to study magic-angle twisted bilayer graphene (MATBG) by creating monolithic gate-defined Josephson junctions. By exploiting the rich phase space of the material, we can create a Josephson junction by independently tuning the superconductor and the weak link state. Studying the Josephson effect is a first step toward understanding fundamental properties of a superconductor, such as its order parameter.

First, we have optimized the fabrication of these gate-defined junctions made of all van der Waals materials. We have made double-graphite-gated hBN encapsulated MATBG device where the top gate is split into two parts via nanolithography techniques. This configuration allows to independently control the three regions of the Josephson junction (superconductor, weak-link and superconductor). Then, we have studied the gate-defined Josephson junctions via low-temperature transport measurements. After demonstrating the Josephson effect in the fabricated devices, we focus on the behavior of one of these junctions in great detail.

In particular, we have observed an unconventional behavior when the weak link of the junction is set close to the correlated insulator at half-filling of the hole-side flatband. We have observed a phase shifted Fraunhofer pattern with a pronounced magnetic hysteresis characteristic of magnetic Josephson junctions. To understand the origin of the signals, we have performed a critical current distribution Fourier analysis as well as a tight binding calculation of a MATBG Josephson junction. Our theoretical calculations with a valley polarized state as the weak link can explain the key signatures observed in the experiment. Lastly, the combination of magnetization and its current-induced magnetization switching has allowed us to realize a programmable zero-field superconducting diode.

Finally, we have shown the flexibility of these devices by studying a MATBG p-n junction under light illumination. We have studied the relaxation dynamics of hot electrons using time and frequency-resolved photovoltage measurements. The measurements have revealed an ultrafast cooling in MATBG compared to Bernal-bilayer from room temperature down to 5 K. The enhanced cooling in MATBG can be explained by the presence of the moiré pattern and the corresponding mini-Brillouin zone.

In summary, we have demonstrated that by integrating various MATBG states within a single device, we can gain a deeper insight into the system's properties and can engineer innovative, complex hybrid structures, such as magnetic Josephson junctions and

superconducting diodes

Thesis Committee:

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