

Optoelectronic Probes of Out-of-Equilibrium Criticalities in Tunable Graphene Moiré Superlattices

Riccardo Bertini¹

Xiueqiao Wang², Sergey Slizovskiy³, Julien Barrier¹, Zhiren Zheng², Krystian Nowakowski¹, Pablo Jarillo-Herrero², Roshan Krishna Kumar¹, Vladimir Fal'ko³, Frank H.L. Koppens^{1,4}

¹ ICFO – Institut de Ciències Fòniques, Castelldefels (Barcelona), Spain

² Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA

³ Department of Physics and Astronomy, The University of Manchester, Manchester, UK

⁴ ICREA - Institutio Catalana de Recerca i Estudis Avancats, Barcelona, Spain

Contact email: riccardo.bertini@icfo.eu

Abstract

2D moiré crystals have opened a new era in quantum materials, offering a tunable platform to engineer novel electronic properties. Thanks to their narrow bands, they provide a unique system to explore the nonlinear and out-of-equilibrium physics of electrons under high electric fields. As the DC bias current increases, graphene superlattices show a drastic change in transport properties, marked by a peak in differential resistivity at a critical current [1]. This out-of-equilibrium criticality is believed to mark a transition from a Fermi-liquid to an electron-hole plasma, and has proven extreme sensitivity to light, enabling broadband single-photon detection [2]. Yet, the microscopic nature of this transition and its interaction with light is still unknown.

We investigate this regime in Bernal bilayer graphene aligned to hBN, whose bandstructure can be modified with external electric fields. By measuring changes in the critical current, we demonstrate the sensitivity of nonlinear transport to variations in moiré bands and its ability to probe their bandwidth. Using scanning photocurrent microscopy, we reveal field-induced domains hosting the observed nonlinearities and provide new

insight into the origin of the criticality. Our results establish the high-bias regime as a new probe of moiré minibands and as a platform to exploit the physics of nonequilibrium electrons for novel optoelectronic applications.

References

- [1] Berdyugin A. I. *et al. Science* **375**, (2022).
- [2] Nowakowski K. *et al. Science* **389**, (2025).

Figures

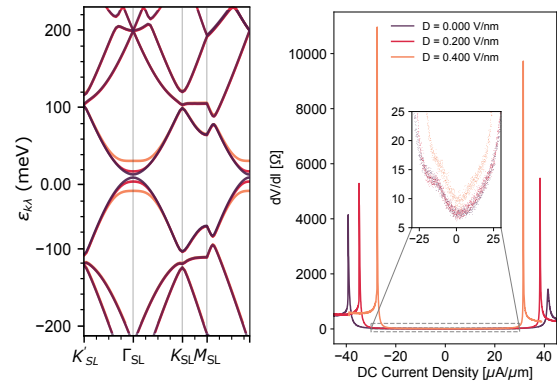


Figure 1: Left: Band structure of the BLG/hBN superlattice at $D = 0, 0.2$, and 0.4 V/nm. Right: Differential resistivity vs. bias current density, with a sharp peak marking the critical current; curves correspond to the same displacement fields as in the left panel.

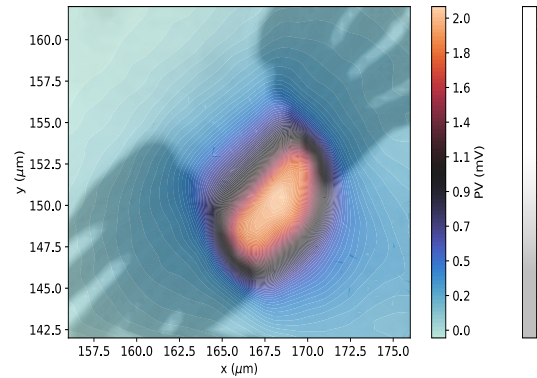


Figure 2: Photovoltage map at the critical condition (coloured) and device outline (grayscale).