



Congratulations to New ICFO PhD Graduate

Dr. Krystian Nowakowski graduated with a thesis entitled *½*Graphene-based Moire superlattices under opto-electronic spotlight: Bloch oscillations, single photon detection, and polarization-resolved photocurrents*½*

December 11, 2024

We congratulate Dr. Krystian Nowakowski who defended his thesis this morning in ICFO's Elements Room.

Dr. Nowakowski obtained his MSc in Nanotechnology at the University of Twente, in the Netherlands, before joining the Quantum Nano-Optoelectronics research group led by ICREA professor at ICFO Dr. Frank Koppens. His thesis titled *½*Graphene-based Moire superlattices under opto-electronic spotlight: Bloch oscillations, single photon detection, and polarization-resolved photocurrents*½* was supervised by Prof. Frank Kop

ABSTRACT:

In the last two decades, two-dimensional (2D) materials have captivated the scientific community thanks to their surprising characteristics and technological potential. Significant advancements in the understanding of their properties have opened up promises of applications in the electronics, photonics, sensing, and energy sectors.

One of the most unprecedented prospects is the ability to freely combine various 2D materials into heterostructures. The 2D layers can be twisted with respect to each other, enabling a novel tuning mechanism in the solid-state physics toolbox. Introducing a few-degree angle between the layers can create a superlattice structure because of the moiré effect, allowing one to tune the material band structure. Graphene-based moiré superlattices have become a focal point of research in recent years, facilitating the design of many exotic phenomena and effectively bridging the fields of strongly correlated electrons, 2D materials, and topological physics. Optical measurements of these materials were non-existent at the inception of this thesis, prompting the investigation presented herein.

In the first part of this thesis, the initial goal was to understand the photoresponse mechanisms of these materials using optoelectronic techniques in the mid-IR wavelength range. Our study reveals a nontrivial polarization-dependent photocurrent response in graphene-based materials. This response can significantly affect the measured signals and exhibit complex spatial patterns. A novel approach was developed to extract spatial maps of polarization-dependent components.

One potential responsible mechanism is the bulk photovoltaic effect (BPVE) response. BPVEs are second-order photocurrent generation mechanisms that are intricately connected to the quantum geometric tensor, reflecting the phase of the electron wavefunctions and distance between quantum states. Measuring BPVEs can provide insights into the underlying quantum nature of electronic states in moiré materials. We discuss the role of BPVEs in our results and their potential artifacts that can mimic it as well as the methodology and insights that are fundamental for discerning these different contributions.

In the second part of this thesis, we report the discovery of negative differential conductance (NDC) in the high-bias regime in bilayer graphene aligned with hexagonal boron nitride. The NDC probably arises from Bloch oscillation-like mechanisms enabled by a folded band structure of the moiré superlattice. From the NDC we engineer a bi-stable state and demonstrate its sensitivity to single photons. This moiré single photon detector (MSPD) can operate at wavelengths from 675 nm to 11.3 μm (and beyond) and up to temperatures of 20 K, a combination that remains elusive in the single-photon detector field. The design is compact, CMOS-compatible, and array-integrable, presenting exciting opportunities for upscaling.

This is the first observation of Bloch oscillations in a 2D system, enabling the entire arsenal of highly versatile experimental methods suited to these material platforms. We introduce spatially resolved photocurrent measurements as a pioneering technique for visualizing the Bloch oscillation regions. This advancement could lead to new high-frequency electronic

and optoelectronic applications in addition to single-photon detection

This thesis lays the groundwork for further exploration of BPVE effects and high-bias phenomena in moiré superlattices and promising breakthroughs in Bloch oscillations, 2D optoelectronics, and photodetector technologies. These findings significantly advance our understanding of both the applied and fundamental physics in these systems, while also introducing crucial methodological innovations for future research in optoelectronics and photodetection

Thesis Committee:

Dr. Klaas-Jan Tielrooij, Applied Physics and Science Education, Eindhoven University of Technology

Prof. Dr. Carmen Rubio-Verdu, ICFO

Prof. Dr. Marco Polini, Physics Department, University of Pisa