Boron nitride tunnelling heterostructures: an innovative platform for optoelectronics

Two-dimensional (2D) materials have recently attracted significant interest due to their intriguing properties, which arise from the fact that these materials are only one atom (or a few atoms) thick. This ultimate limit of thickness gives rise to a plethora of interesting physical phenomena, initially studied in the prototype 2D material, graphene. Researchers quickly realized that graphene was not the only 2D material, and soon many different materials were experimentally studied. These materials can have very different properties, ranging from metallic or semiconducting to insulating. Another very important aspect inherently connected to 2D materials is their strong anisotropy, with strong covalent bonds in-plane and weak (van der Waals) interactions out-of-plane. This property eliminates the need for lattice matching between different materials, allowing arbitrary 2D materials to be stacked on top of each other to build so-called van der Waals (vdW) heterostructures. The large and steadily growing library of 2D materials can thus be used to fabricate new structures that combine different properties, leading to a new class of devices.

In this project, we plan to use graphene and combine it with hexagonal boron nitride (h-BN), which is a 2D insulator. Hexagonal boron nitride (h-BN) is one of the primary building blocks for many vdW heterostructures, commonly serving as a dielectric spacer or an encapsulating layer. However, in addition to these important and widely employed applications, it has been largely overlooked that h-BN itself can also function as an active element in such heterostructures. Recently, electroluminescence (EL) from graphene/h-BN/graphene tunnelling heterostructures was reported, enabled by direct charge carrier injection into the conduction and valence bands of h-BN. This new paradigm of quantum transfer of charge carriers directly into a 2D insulator without the need for doping has enabled the observation of electrically driven emission (EL) in the deep UV range (DUV). For this technologically important spectral range (e.g., for disinfection and sterilization), no efficient solid-state light sources are currently available. The observation of EL without doping opens up an entirely new field of study, circumventing the challenges of effectively doping wide-bandgap semiconductors - one of the major technological barriers hindering the development of DUV sources based on other material systems. In addition to band-edge emission, EL from point defects and color centers at around 300 nm, 436 nm, and in the range of 500-600 nm was observed in tunnelling heterostructures based of h-BN, demonstrating that EL from h-BN can span a wide range of energies. This mid-gap, visible spectral range is particularly significant, as optically pumped single-photon emission has been observed for several of these defect-related emission bands, generating considerable interest in h-BN for quantum information applications.

We plan to establish a research team that will focus on vdW tunnelling heterostructures with BN as the active element. This topic began to be explored only a few years ago, and in this proposal, we introduce a further innovative aspect: the use of epitaxially grown BN for such heterostructures. To achieve this, we will employ metal-organic vapor phase epitaxy (MOVPE) on 2-inch sapphire substrates. The MOVPE growth of BN was implemented at the Faculty of Physics, University of Warsaw over a decade ago, enabling the fabrication of high-quality layers. Unlike the commonly employed scotch tape mechanical exfoliation of flakes of 2D materials, this method allows us to fabricate large-area BN, where we can not only control the thickness but also fine-tune the growth process to manipulate impurity density (e.g., carbon-related defects), polytypic composition, and doping.

One of the important goals of the project is to manipulate the carbon impurity concentration to demonstrate electrically driven single-photon emission in h-BN. This objective will be pursued in collaboration with the National University of Singapore (NUS). In addition to EL studies, new device schemes will be developed, for example based on piezoelectric, non-centrosymmetric polytypes of BN, which is currently becoming a hot research topic.

The proposed project will focus on both the fundamental processes occurring in the fabricated tunnelling heterostructures and the technical aspects related to the growth of BN by MOVPE and perspective device fabrication. Given that MOVPE is a well-established industrial growth method, the results obtained from this proposal could significantly impact the transition from prototype devices to scalable innovative optoelectronic applications.