Defects in solid materials remain a major focus of research because of potential applications in advanced technologies like quantum computers, sensors, or light sources. A particularly promising group of materials for these purposes are two-dimensional (2D) semiconductors, which may be split into extremely thin layers—just one atom thick—and can be stacked together to form more complex ”nano-LEGO” systems known as van der Waals heterostructures. One of these materials, hexagonal boron nitride (h-BN), has a layered crystal structure similar to graphene. It has a wide bangap of around 6 eV, which makes it suitable for producing deep ultraviolet (DUV) light. It can also contain various defects, such as the charged boron vacancies (Vb-), as well as single photon emitters (SPEs) that can emit one photon at a time. Importantly, h-BN can emit light from these defects even at room temperature, which is rare and very interesting for researchers.

When there are defects in the crystal structure, they can create extra energy levels within the bandgap. These levels can allow the material to emit light in specific ways. For example, the carbon dimer (C2)— a pair of carbon atoms in place of a neighboring boron-nitrogen pair — emits light at around 4.1 eV, while the Vb- defect can produce light in the visible range, strongly affected by its spin state. These defects can also respond to their surroundings, such as other nearby atoms or external magnetic fields. The carbon dimer, for instance, shows a shift in its main emission line (called the zero phonon line, or ZPL) of about 50 meV, depending on how the layers of the material are stacked.

The way layers are stacked in 2D materials plays a key role in a new and exciting research field called twistronics, which studies how twisting one layer slightly against another can change the material’s properties. This idea gained attention after surprising discoveries like unconventional superconductivity in twisted graphene and bright light emission from twisted layers of other 2D materials, called transition metal dichalcogenides (TMDs). Recently, researchers have started exploring similar effects in h-BN. A broad light emission seen in cathodoluminescence (CL) experiments may be caused by defects becoming brighter or by particles called excitons getting trapped - both effects likely triggered by tiny distortions in the crystal structure created by the twisting, known as the moiré potential.

In this project, we aim to study how twisting the layers in boron nitride affects single photon emitters and spin defects in layers grown using a method called Metalorganic Vapour Phase Epitaxy (MOVPE) at the Faculty of Physics. Unlike many other studies that use flakes peeled from commercially grown bulk crystals, which can vary a lot in quality and size, our approach allows us to precisely control the thickness, stacking type, and defect concentration of the crystals. This results in large, consistent layers up to 2 inches in diameter, making our samples great candidates for precise research and potential industry-scale applications.

Our plan includes detailed studies of the layers and the defects using various methods, such as optical, structural, and electrical measurements. These include Raman and photoluminescence (PL) spectroscopy, which study the interaction between light and matter, atomic force microscopy (AFM), and cathodoluminescence spectroscopy. We will also fabricate specially stacked structures with controlled twist angles. To do this, we will use both ”dry” and ”wet” methods (with and without the use of a liquid solvent) to separate the layers from the substrate wafer, and a custom-built setup that lets us carefully place and rotate the flakes. We also use a photolithography system that allows us to ”print” patterns on the target substrate to modify the structures, e.g. by adding electrical connections or applying local strain. Early results from our twisted boron nitride samples already show clear changes in CL emission around 4 eV depending on the twist angle, confirming the presence of a moiré effect similar to that seen in commercially grown bulk boron nitride.

The main goals of our project are the understanding of the twist angle effect on light emission from different defects and the improvement of growth techniques to better control these effects, as seen on the examples such as the C2 carbon dimer and the Vb- boron vacancy. While we already know that stacking type affects the carbon defect emission energy, much less is known about its impact on the Vb- defect. Finding out whether we can enhance or adjust the signals from these defects would be a major step toward creating large, high-quality layers for sensing applications.