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The Dawn of Defects

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Traditionally, defects in semiconductors should be avoided. Multi billion dollar clean room facilities are aimed just at that – to keep the silicon wafers at an extreme purity for the semiconductor industry. Over the last two decades, however, defects and especially in wide bandgap materials, have found a new life. They are key components for quantum information and quantum photonic technologies as will be discussed below.

Realisation of quantum information processing and quantum photonic applications requires robust qubits. Controlled manipulation of the qubits is important, as well as its stability and the possibility to scale them up. Communications between qubits can be done via photons, and it is therefore desirable to have an interface between the qubit and the photon [1]. Traditionally, trapped ions considered amongst the best qubits with reliable optical pumping and readout [2]. However, despite decades of technological improvements into better and more efficient traps, as well as several startups, this technology is yet to be proven viable.

The motivation hence shifted a little, to find solid state sources that can host qubits. Non surprisingly efforts have been dedicated to study epitaxial quantum dots (QDs), mostly in the arsenide family. Those can be grown with high precision and high quality in large wafers, emit single photons on demand and be integrated with photonic cavities, resonators and waveguides. To date, QDs are still major driving force behind significant achievements in quantum photonics – namely quantum key distribution, entanglement, Bell states and other quantum effects [3]. Nevertheless, the dots suffer from ongoing spectrail diffusion, and have inherently low spin coherence times, which puts an upper limit on their use in practical quantum information applications.

Over the last two decades, defects in wide bandgap semiconductors are trailblazing a new era in the field of solid state quantum photonics. While defects in materials like diamond or Yttrium Aluminium Garnett (YAG) have bene studied for over 50 years, not many considered them important for quantum applications. This line of thought changed radically after the discovery of optically detected magnetic resonance (ODMR) from a nitrogen vacancy (NV) centre in diamond in 1997 [4]. Defects like the NV are considered an artificial atom, because their ground and excited state lie deep within the host matrix. The electron is localised at the defect, and the quantum properties are essentially similar to those of a trapped ion. Given that single NV centres can be engineered by ion implantation, one could easily create qubits on demand. Moreover, the option to couple the NV electron spin with some of the surrounding nuclear spins (i.e. 13C) essentially forms a fundamental node of a quantum network [5].

This situation seems ideal, and indeed, over the last 20 years the research into engineering NV centres with long coherence times skyrocketed. It also stimulated research into engineering and sculpting optical resonators from diamond, that were not really considered before [6]. But the most important paradigm shift came from the idea that defects are not always bad and can be leveraged to realise specific quantum tasks. Consequently, researchers now identified single defects (single photon sources)

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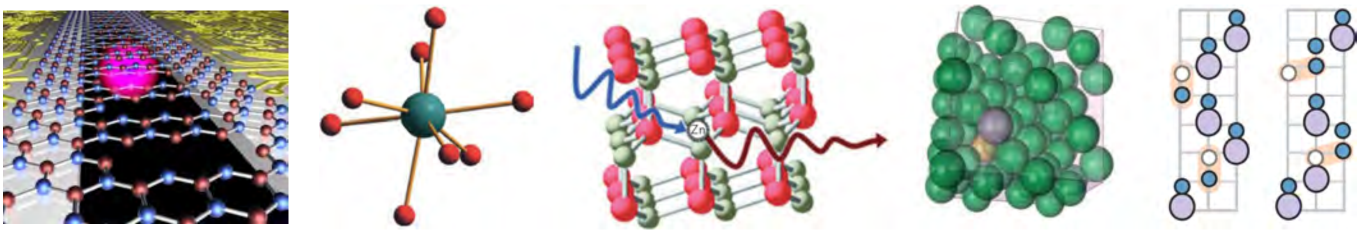
in silicon carbide, zinc oxide and even atomically thin wide bandgap materials such as hexagonal boron nitride (hBN) [7, 8] (see figure 1). Each system offcourse has its own advantages and disadvantages. For instance, silicon carbide can be grown to wafer scale, manufacturing is robust and nanoscale processing is truly established. However, the emitters are relatively dim and are still poorly understood. Diamond on the other hand is only available in small pieces, but material can now be grown isotopically pure, resulting in NV centers with long coherence times. Diamond can also host other impurities (e.g. silicon or germanium vacancies) that exhibit netter optical properties (e.g. narrow linediwths). hBN offers an entirely different set of properties. Being a 2D material, it can be exfoliated from commercial samples using a scotch tape technique, and it was shown to host some of the brightest emitters known to date. This is a great system for the novice PhD student that aims to begin studying single defects. On the other hand, it's a relatively new system and the origin of the defects in hBN is not understood yet.

So why don't we have a solid state quantum processor just yet? Having a solid state environment means that a lot of unwanted interactions are present – strain fields and unwanted impurities in the proximity of the defects cause unwanted stark shifts and blinking. Surfaces are also a poorly understood phenomenon that often hinders the qubit performance. Emitters embedded in a solid state matrix means that light extraction is an issue and most systems should have basic structures like solid immersion lenses to increase the collection efficiency. Finally, there is always a trade-off between the best qubit in terms of coherence times (e.g. NV centre in diamond or di vacancy in Silicon carbide that have relatively long coherence times) vs brightness/photons emitted into zero phonon line, and the ultimate system is yet to be fully exploited.

So where to next? As the number of groups exploring solid state quantum emitters steadily growing, the community in large focuses on defects tailored to specific applications. For example, it is clear that quantum sensing and magnetometry is a field where the NV centre will have its highest impact. Consequently, there is a push to engineer NV centres with long coherence times at the tips of diamond cantilevers or near surfaces. The brightness of defects in hBN motivates better studies to understand their atomic structure and engineer them on demand for applications in quantum communications. Defects in silicon carbide are amenable to controlled electrical excitation, and given the large area wafers available, research into integrated photonics with silicon carbide is booming. Researchers are also revisiting the rare earth systems (e.g. YAG). Rare earth ions have long coherence times and are great candidates for quantum memories, but their long fluorescence lifetime means that isolation on a single (quantum) level is still challenging. Hence many attempt coupling them to plasmonic or photonic resonators to shorten the lifetime and achieve single photon emission.

It is hard to predict which system, if at all, will make it at the end. But it is the journey that is most important. Over the last decade we learnt to harness defects to our advantage: use them as sensors and feed the information back to characterise the host material – for instance. Sources become more brighter and more stable and new protocols for spin manipulations are constantly implemented. Many components for an integrated quantum photonic chip are already in place. It is clear that in the years to come we will be able to better control the impurities in host matrixes and deterministic engineering in every system will be possible. As access to materials becomes increasingly easier, defects in solid become naturally a platform of choice to explore more sophisticated and advanced quantum effects.



Examples of the most commonly studied defects in solid studied for quantum information. Left to right: Hexagonal boron nitride; Yttrium aluminium garnet; Zinc Oxide; Diamond; and Silicon carbide.

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Igor Aharonovich completed his undergraduate and masters studies in the Technion – Israel Institute of Technology, studying the growth of semiconductor nanowires (supervisor Prof Yeshayahu Lifshitz). He then moved to Australia to pursue his PhD in the University of Melbourne (supervisor Prof Steven Prawer). During his PhD, Igor discovered a new class of ultra bright emitter in diamond. After graduation, he moved to Harvard for two years of postdoctoral research in the group of Prof Evelyn Hu, where he broadened his research into nanofabrication of photonic devices from diamond and gallium nitride. He returned to Australia in 2013 to start his own group at the University of Technology Sydney. Igors' passion was always exploring defects in solid, and his initial works as a group leader focused on studying quantum emitters in diamond, silicon carbide and zinc oxide. In 2016 his group discovered the first quantum emitter in hBN and since then it is a major focus of his research. Igor is particularly proud of the multicultural group, with members from Australia, Korea, Iran, Russia, Vietnam, China, Italy, Poland, USA, Czech republic and Austria.