

Extended Citation:

Professor Steven Praver is Australia's foremost authority on the Physics of diamond and related materials and has brought Australian physics to the forefront in their study and application. For the past two decades he has established a record of innovation and leadership in the field through successful research programs, the creation of world-class infrastructure at the University of Melbourne, authorship of authoritative book chapters and review articles and over 170 articles in internationally refereed journals which have received over 2400 citations. He has shown great leadership as the inaugural director of the Melbourne node of the special research centre for Quantum Computer Technology (now an ARC Centre of Excellence) and as director of the Melbourne Node of the NANO (Nanostructural Analysis Network Organization) MNRF.

In particular he has been pivotal in elucidating the fundamental nature of the interaction of energetic ion beams with diamond and related materials. Based on this fundamental understanding he has demonstrated that practical quantum devices can be fabricated from diamond. He is widely recognized as a world leader in the push to see the immense potential of diamond realized for quantum information processing.

Diamond is a material which exhibits extraordinary hardness and optical transparency, as well as the highest thermal conductivity and electron and hole mobility. Less well known are the extraordinary quantum properties of the optical centres in diamond. These are, in fact, the only photostable single-photon sources at room temperature reported so far **in any material**. In particular, the nitrogen-vacancy (NV) centre, displays a range of remarkable quantum properties, (including remarkably long spin coherence times at room temperature) which are exactly those required to build single photon sources and qubits for quantum computation. Because of the 'optical handle' for spin readout, diamond is extremely attractive for the fabrication of few (10-50) qubit quantum information processing devices.

Praver's recent work has had a major impact in showing how diamond devices can be engineered to take advantage of these properties. For example, in his recent paper in Nature [1], he showed, in collaboration with Wrachtrup's group in Stuttgart, how it is possible to couple coherently single spins in diamond at room temperature. Prof John Morton (University of Oxford), describes the impact of this result as having '*...thrust it [diamond], towards the very forefront of the candidates for solid state quantum computing*'.¹ He concludes; '*...if, and when, a scalable controlled entanglement is demonstrated, this NV approach [in diamond] will really have won its spurs and other candidates currently dominating the field may suddenly find themselves outclassed*'. In order to effect strong coupling, close proximity of two spins is required, but large distances from other spins are needed to avoid deleterious decoherence. Praver's crucial contribution to this work was the recognition that these two conflicting requirements can be reconciled by implanting molecular nitrogen (as opposed to atomic nitrogen) to create the optically detectable spin centres with very close spacing (<3nm) in a controlled fashion. The samples were prepared in Praver's lab, and then the measurements were performed with the Stuttgart group.

In a second tour de force Praver demonstrated [2] how one can sculpt mirrors, waveguides and cavities into single crystal diamond. The very properties that make diamond so attractive, also make it very hard to process by standard techniques. Praver showed how photonic devices can be fabricated in single crystal diamond using an ingenious combination of implantation, focused ion beam milling and electrochemical etching. Most recently, he has shown the ability to carve out *single crystal* structures in diamond which are only 200nm thick, a feat never before accomplished in diamond. This is an important breakthrough because structures of this dimension are required in order to create efficient single mode optical waveguides and cavities.

Thus the impact of Praver's work is that he has shown how diamond can be engineered into quantum devices by exquisite control of (i) the position and properties of the NV centres as qubits and (ii) the engineering of cavities, waveguides, mirrors and other optical components to capture,

¹ J. Morton, Nature Physics, 2, 265, (2006)

transport and manipulate the quantum state of the qubits. Evidence of the impact of these new methodologies is evidenced by the invitations that Prawer has received to collaborate with leading research groups around the world. Of particular note are the strategic linkages with Hewlett Packard in the USA who have joined with Prawer in a bid to construct a massively parallel defect tolerant quantum computer and the successful bid to the European Union Sixth framework for a proposal for engineered quantum information in nanostructured diamond. The importance of these linkages has been recognized by the financial support of the Australian Government for these international programs which exceeds \$1M. Most recently, Prawer hosted an international workshop in Melbourne at which leading luminaries from around the world, including collaborators from Oxford University, Harvard University and Hewlett-Packard reported on the staggering progress in diamond based quantum memories and devices. Prawer's pivotal role in these linkages is his group's expertise in diamond ion implantation and processing, the provision of engineered diamond samples and the drive and motivation to set the agenda for the future of quantum information processing in diamond.

Potential applications include, not only quantum information processors, but also highly non-linear optical devices for noise reduction in optical communications systems, and Q switched devices for transform limited single photon sources. Such devices are the building blocks for photonic based computing with light instead of electrons. Ultimately, such devices are necessary to drive ever higher levels of integration, eventually leading to a "Moore's Law" for optical information technology.

The devices that Prawer and his group are building also include an optical fibre based single photon source that is a critical component in secure communication systems which has attracted very considerable funding from the State Government and industry. Together with Shane Huntington, he established Quantum Communications Victoria², which is dedicated to prototyping quantum devices based on diamond for quantum key distribution.

It is particularly impressive to witness the progression from a fundamental understanding of the physics of diamond to the fabrication of practical quantum devices that are in turn designed to be able to realize quantum information processing.

Further details of Prawer's scientific contribution are provided below, together with selected references.

² See www.qcvictoria.com

Ion Beam Modification of Diamond and Carbon.

Praver and his group have been pivotal in elucidating the physics of the interaction of ion beams with diamond. These studies are of both fundamental and applied significance. The fundamental interest arises because (i) diamond is metastable with respect to graphite and these studies form a fascinating insight into the relaxation of a metastable insulating phase (diamond) to the stable conducting one (graphite) and (ii) point defects in diamond form a model system simple enough to be directly compared to computer simulations. The applied interest arises because removal of these defects is a necessary condition for the use of diamond as a semiconductor and potential quantum device. A series of seminal publications [3,4,5] throughout the 1990s (undertaken in collaboration with colleagues at the Technion) has made a major contribution to our understanding of the way in which defects are formed in diamond upon the passage of an ion and their method of removal.

This fundamental understanding of defects and their removal allowed the implementation of a scheme for the production of very high mobility buried doped layers in diamond [6] and indeed the role of defects in compensating boron doped diamond is now quite well understood. The understanding of the implantation process provides the basis for the nanofabrication tool-kit developed by Praver and his team which lies at the core of strategies for the construction of quantum devices in diamond. In particular the lift-off technique for the fabrication of waveguides, mirrors and cavities [2], depends crucially on the understanding of the ion beam induced diamond to graphite conversion.

Raman Microscopy of Diamond and Carbon Films

Praver and his group have been at the forefront of the development of advanced methods to characterize diamond and diamond-like carbon films, in particular providing clarity and insight into the use of Raman spectroscopy for the analysis of carbons. Diamond Like Amorphous Carbon films (DLC) and tetrahedral amorphous carbon films (TAC) have attracted considerable scientific and technological interest because of their unique combination of properties, viz., extreme hardness, optical transparency, high electrical resistivity and chemical inertness. DLC films are extensively used today as coatings on hard drives and TAC films are being pressed into service as ultra-thin, ultrahard films that will enable the magnetic head to come even closer to the disk surface, thus allowing greater storage densities. There is therefore a pressing need for cheap, non-destructive methods for the characterization of such films.

In a seminal paper [7], Praver showed how it was possible to extract an estimate of the crucially important diamond-like to graphite-like bonding (i.e. sp^3/sp^2) ratio using a simple fitting procedure of the Raman spectra for amorphous carbon films. The paper concluded that ... "the data presented may serve as a reference for diamond-like carbon characterization". Indeed so! This paper has been cited over 215 times. The work that followed showed what the Raman spectrum should be like for a pure sp^3 bonded carbon material, (if such a material can ever be made) and reported the difficulty to obtain Raman spectrum of 5nm diamond nanoclusters [8].

Praver has also used Raman Spectroscopy in a most creative manner to elucidate the nature of point defects in diamond and their annealing behaviour [9]. By using molecular dynamics simulations Praver, in collaboration with workers from the Technion, [10] provided an unambiguous identification of the signature of the most basic of defects in diamond (i.e. vacancies and interstitials).

Production of Quantum Dots of NanoDiamond.

An impressive aspect of Praver's recent work [11] is the demonstration that carbon implanted directly into fused silica can be turned directly into diamond. His team demonstrated for the first time that diamond is the stable form of carbon provided that the crystallite size is sufficiently small (less than 7nm). This is a remarkable finding because graphite, not diamond, is the stable form of carbon at room temperature and pressure, but the finding does accord with predictions from molecular dynamics that small diamond clusters are more stable than graphite clusters. Praver's work is the first to demonstrate this experimentally. The simplicity of the technique is noteworthy and since it uses an ion irradiation technique lays the groundwork for the production of arrays of diamond quantum dots.

Diamond quantum devices:

It has recently become clear that diamond offers truly unique opportunities for practical quantum devices. It is the only solid state system in which single spin read out can be routinely achieved at room temperature. The fundamental ion implantation work described above is the basis for the toolkit necessary for the fabrication of practical quantum devices such as single photon sources for secure communications, room temperature read-out for spintronics, and platforms for the fabrication of device capable of exploring the entanglement in the solid state for quantum computing applications.

(i) D3.1 Single photon sources and quantum communication

Secure data transfer has long been a key requirement of governments and corporations – for defense, intelligence agencies, the finance industry, any business seeking to protect its competitive advantages, and any citizen concerned with privacy in electronic dealings. Quantum communication and data transfer is set to revolutionize communications in the business world. Quantum communication systems use a deep understanding of quantum mechanics to create communication systems with a security that is impossible to compromise *in principle*. The first commercial quantum communication systems are now available and a quantum-based network has already been installed in the Boston district. Although clearly in its infancy, these systems will become increasingly common, and will ultimately be a requirement for many commercial and military data transfer systems.

A critical component for secure quantum communications systems is that the information be encrypted one photon at a time. The laws of quantum mechanics dictate, through rather subtle reasoning, that any attempt to detect the information carried by this single quantum can be sensed and as a consequence the sender and receiver are alerted to an eavesdropper attempting to compromise the security of the communication. The key point here is that a source is required that is known to have produced one and only one photon per pulse i.e. a single photon source (SPS). Current systems often use highly attenuated laser beams (with on average 0.1 photons or fewer per pulse). In order to remain secure (i.e. no pulse should contain more than one photon), the attenuation is so high that the data transmission rate becomes vanishingly small, particularly over large distances. Hence there is a need for an efficient, high-power, robust, reliable device that can produce single photons *on demand*. A particular optical centre in diamond (the 'N-V' centre), because of its high quantum efficiency and stability, is extremely well suited for immediate application as a high brightness, room temperature, robust single photon source (SPS) for secure quantum encryption. N-V centers in diamond have already been demonstrated to be efficient sources of single photons and quantum key distribution has been demonstrated in free space¹. However, light from an N-V centre is emitted isotropically, making it difficult to collect the light efficiently, and expensive collection optics are required. More efficient optical coupling is a major objective facing researchers in the realization and implementation of single photon sources in the laboratory and for commercial applications

Dr James Rabeau, working under Praver's supervision, demonstrated that single nanocrystals of N doped diamond could be grown on cleaved fibres [12], thus showing that a fibre based single photon source could be fabricated with immediate application in secure communications. Together with Dr. Shane Huntington, Praver has established Quantum Communications Victoria, a joint

venture to develop this fibre based single photon source to prototype stage. The initiative is supported by a \$3.3M STI grant from the Victorian State Government as well as leading industry partners. This is one of the very few examples of a program to manufacture *in Australia* an actual quantum device destined for the commercial market. Furthermore, the idea of depositing nanoparticles on fibre tips, opens the possibility for practical, room-temperature, spin read-out.

(ii) *Diamond Photonics*

Embedding nanoparticles into fibre based systems is but the first step to exploiting the quantum properties of diamond. The next step involves coupling the N-V centre output into a cavity mode which would enhance many-fold the sensitivity of each embedded centre by trapping the photon to be emitted and/or detected. Once again, based on his profound understanding of the interaction of ion beams with diamond, Prawer has shown that it is feasible to create an all diamond quantum photonic platform. In a recently accepted paper in the high impact journal 'Advanced Materials', [2] his team demonstrated for the first time the fabrication and operation of a multimode waveguide hewn from single crystal diamond together with integrated output mirrors. This, together with the direct implantation of N atoms into diamond to form quantum bits, provide the necessary toolkit for the realization of a quantum computer in diamond.

(iii) *Creation of qubits in diamond*

Ion implantation offers the possibility for the direct placement of NV centres in diamond with nm precision. Recent publications by Prawer and his collaborators [14] demonstrate an unprecedented level of control of this process. For example, by using ^{15}N implantation [13] it is possible to distinguish between NV created by the implanted ion and that created by the combination of vacancies with native N, and thus directly measure the yield of NV centres per incident N atom. Dimer N_2 implantation provides control of the NV-N spacing down to a few nm [1]. Other demonstrations, undertaken in collaboration with the Stuttgart, Hewlett Packard and Oxford groups, include electrical Stark shift tuning of single NV defect centres and electromagnetically induced transparency of a single NV centre [15,16]. Collectively these demonstrations provide all the necessary single qubit operations required for the fabrication of complex photonic structures that will take full advantage of the unique quantum properties of diamond.

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