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Optimizing Diamond for Application to Laser Threshold Magnetometry

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14. ABSTRACT
This project was overall a great success. While a couple of the planned avenues of study were curtailed by COVID which resulted in the inability to travel to AFRL, two other studies resulted in some unexpected and highly significant results. The PIs discovered that contrary to expectations, a higher concentration of NV centers does not result in a high signal, but in fact lowers the output due to increased losses through quantum tunneling to the more prevalent neighboring centers. They have also produced the first stimulated emission from diamond emitters which, if experimentally optimized, may increase the sensitivity of these devices into the femtoTelsa range - something which will be a real game-changer if it can be exploited in a more applied setting.
Overall I would say this grant has been very fruitful and would be supportive of any future grant applications.

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Final Report for AOARD Grant FA2386-18-1-4056

"Laser Threshold Magnetometry with Diamond"

8/5/2022

Name of Principal Investigators (PI and Co-PIs): Andrew D Greentree, Brant C Gibson

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Abstract: This project was designed to explore the diamond properties necessary for the realization of magnetometry based on the laser threshold magnetometry approach. Specifically, we needed to understand the role of nitrogen in the photoionization, and hence quantum efficiency of nitrogen-vacancy centers, the optimal fabrication conditions for conversion of nitrogen to nitrogen-vacancy for laser applications, and the mechanisms of photoionization in such samples. We have explored the role of nitrogen concentration on the quantum efficiency of nitrogen-vacancy centers, finding that increasing nitrogen concentration leads to a *decrease* in quantum efficiency and even a decrease in *overall* fluorescence. This is despite the fact that nitrogen-vacancy concentration can be made to increase monotonically with increasing nitrogen concentration. We have continued progress on *in situ* annealing of diamond and the analysis of these samples. Lastly, we have begun the exploration of short-time dynamics in nitrogen-vacancy centers in diamond to understand photoionization processes.

Introduction: The specific aims of the research are:

- Create a range of homoepitaxial chemical vapor deposition single crystal diamond materials with varying nitrogen concentrations and defined nitrogen-vacancy alignment
- Optimize nitrogen to nitrogen-vacancy conversion using post-processing electron beam irradiation and annealing
- Characterize the samples in terms of residual nitrogen, background absorption, and stimulated emission
- Benchmark our results and make predictions relative to the state of the art in room-temperature magnetometry

The ultimate goal is to perform the necessary materials research to enable the creation of a laser threshold magnetometer based on nitrogen-vacancy color centers in diamond. This new class of magnetometer has the potential to achieve predicted

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sensitivities of fT/√Hz at room temperature and ambient magnetic fields and may find application for room temperature magneto-encephalography. Proof of concept experiments performed by the team has shown stimulated emission.

Simultaneously with our studies performed at RMIT University, we demonstrated magnetically-dependent laser operation in collaboration with our colleagues at the Fraunhofer IAF in Freiburg, Germany.[2] Using a macroscopic high-finesse laser cavity system containing an NV-rich diamond crystal, we demonstrated 64% signal power amplification by stimulated emission. Applying a magnetic field to the diamond, we show that the laser output dropped by 33%, more than double the contrast obtainable by conventional spontaneous emission techniques.

However, the optimization of the material is still necessary to further improve the finesse of the cavity and to achieve the sensitivity of fT/√Hz at room temperature.

Experiment: The diamond samples used in our experiments are a combination of commercially obtained samples and samples grown via chemical vapor deposition (CVD). All the commercial samples were high-pressure high-temperature (HPHT) diamonds bought from the companies ElementSix and Sumitomo. The CVD samples were grown from our collaborators at the Fraunhofer IAF (Jeske group, Freiburg, Germany). The samples are processed by implantation with our partners at QST (Ohshima group, Takasaki, Japan) and annealing. Local RMIT experiments use fluorescence and lifetime imaging via confocal microscopy, optically detected magnetic resonance, visible and infrared absorption spectroscopy, and ultrafast spectroscopy.

The ultrafast spectroscopy is also performed using apparatus at AFRL San Antonio by our research partner Dr Morgan Schmidt. Theoretical techniques include standard quantum optical and multi-level laser simulations.

Results and discussion: Our results focus on the effect of single nitrogen defects on the photo-physical properties of the nitrogen-vacancy (NV) center in diamond. The single nitrogen defect is of particular interest since it is the precursor defect that allows the creation of NV centers in diamond. We studied diamond crystals fabricated and processed using different methods and compared them using microscopy techniques. Our results focused on four properties of the NV centers:

1. Emission intensity and fluorescence spectrum. Our studies show that the emission intensity has a non-trivial dependence on the density of single nitrogen defects. Higher nitrogen densities contribute to the creation of a larger number of negatively-charged NV centers (which should lead to stronger overall emission) while also reducing the fluorescence quantum yield of each NV center (weaker emission per NV center).
2. Quantum yield and transition rates. We demonstrated that the nitrogen defects allow the tunnelling of electrons from the NV center to its closest nitrogen donor [1]. This tunnelling effect introduces an additional non-radiative pathway that reduces the fluorescence quantum yield of the NV center. As a consequence, we predict the laser-threshold of diamond crystals with a high density of nitrogen defect will be higher than for samples with lower nitrogen

concentration and therefore such samples are less effective for magnetometry applications.

3. Magnetic field sensing. We characterized the magnetic field sensitivity of the different diamond crystals using optically detected magnetic resonance (ODMR) combined with a lock-in amplified detection scheme. We concluded that nitrogen defects decrease the sensitivity to magnetic fields by both increasing the width of the magnetic resonance (as previously known in literature) and decreasing the emission contrast.
4. Fast dynamics of the NV center excited states. In collaboration with Dr Morgan Schmidt from the AFRL in San Antonio, Texas, we studied the time dynamics of the NV center using a pulse-probe system. We observed a fast change of charge state within the first 300 fs from the excitation pulse. Unfortunately, the COVID-19 lockdowns prevented deeper investigations.

Emission intensity and fluorescence quantum yield

Although it is self-evident that the NV fluorescence must be related to the number of NV centers, which is in turn dependent on the number of nitrogen atoms in the diamond lattice; the actual relationship between NV fluorescence yield and nitrogen concentration was unknown and dependent on non-trivial interactions. Our work [1] has allowed a breakthrough in the understanding of NV fluorescence, which is critical in the development of NV-based laser threshold magnetometry systems.

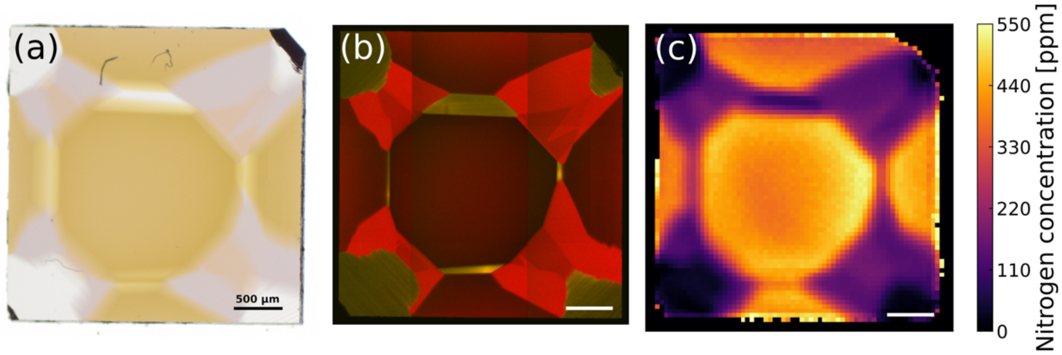

Figure 1: (a) Brightfield transmission micrograph of a 3 × 3 × 0.3 mm HPHT diamond sample, irradiated and annealed to create NV centers. (b) Emission intensity map collected using a confocal microscope using an excitation wavelength of 478 nm. The fluorescence is separated into a red channel (emission between 650 nm and 750 nm) and a green channel (emission between 550 nm and 600 nm). (c) Nitrogen concentration map collected using Fourier-Transform Infrared (FTIR) spectroscopy. The scale bar is 500 µm for all three images.

Figure 1 shows an example of how the diamond's properties change across different growth sectors, which originate from the HPHT synthesis process. Each sector incorporates additional lattice defects, such as the single substitutional nitrogen, at different rates and concentrations. different. Figure 1(c) shows the distribution of nitrogen defects across the same diamond crystals. We identified three main regimes corresponding to low, medium, and high nitrogen concentrations, ranging from less than 10 ppm to more than 500 ppm. The same areas are reflected in Figures 1(a) and 1(b) which show, respectively, the absorption of white light passing through the diamond sample and the fluorescence of the NV centers.

The diamond crystal shown in Figure 1 is only one of the samples included in our published results. The large variation in nitrogen concentration and fluorescence across the sample is a consequence of sectoring, which is a property of high-pressure high temperature (HPHT) diamonds. This sectoring leads to strong variation in the diamond properties within a single crystal. This limits the utility of such commercial diamonds for laser applications. We added seven more diamond samples to our study, to demonstrate that our observations were not unique to one sample. The samples are described in detail in Ref. [1].

The main conclusion of our work demonstrates that in the diamond crystal there is a tunnelling interaction between the NV centers and their closest single nitrogen defect. The tunnelling happens from the NV center excited state and results in a relaxation pathway that does not involve the emission of a photon. The fluorescence quantum yield, defined as the ratio between the number of emitted photons over the number of photons absorbed, decreases as the density of nitrogen defects increases and the tunnelling interaction becomes more likely.

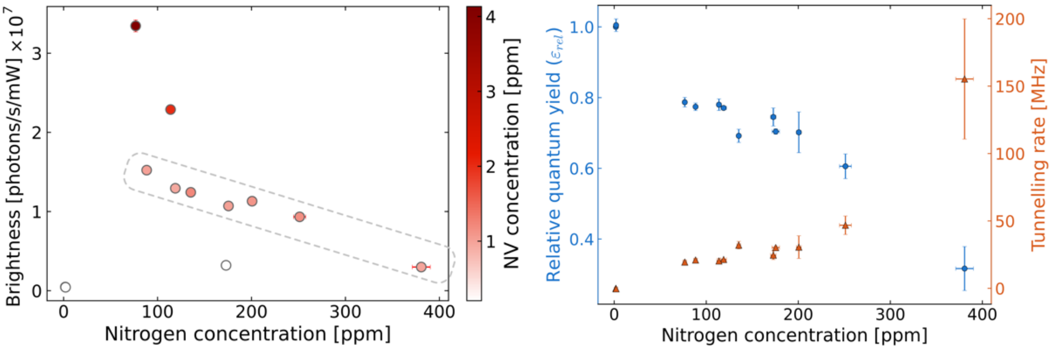

Figure 2: Emission properties of NV centers from different diamond sectors as a function of nitrogen concentration. (Left) The brightness of each sample depends on both the NV concentration (colorscale) and the nitrogen concentration (x-axis). As the NV concentration increases (darker circles) the brightness increases due to the larger number of emitters. However, the dashed area highlights samples with comparable density of NV centers and shows how their brightness decreases with increasing nitrogen concentration. (Right) Relative quantum yield (blue circles) and corresponding tunnelling rate (orange triangles) as a function of nitrogen concentration. The tunnelling rate is shown to increase with the increasing density of nitrogen defects as they get closer – on average – to the NV centers and therefore making the tunnelling interaction more frequent. Since the tunnelling does not involve the emission of photons, as the tunnelling rate increases the relative quantum yield decreases – with increasing nitrogen concentration. Reproduced from [1].

Figure 2 shows the effect of nitrogen concentration on the brightness, the tunnelling rate, and the relative quantum yield of the NV centers. When the density of nitrogen defects increases the average distance between an NV center and its closest nitrogen defect decreases. As a consequence, the rate of electron tunnelling between the excited NV center and the closest nitrogen defect increase, as shown by the dataset in Figure 2(right). The increase of the not-radiative tunnelling rate as a process for the NV center relaxation decreases its fluorescence quantum yield and hence the overall emission intensity (or brightness) of the sample. It is important to note that while the brightness can be recovered by increasing the density of NV centers (as shown by the darker points in Figure 2(left)), the relative quantum yield of each NV center only depends

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on the nitrogen concentration.

As a direct consequence of this study, we predict that the reported tunnelling rate will directly oppose the stimulated emission of the NV centers, therefore compromising the effectiveness of laser threshold magnetometry in diamond samples with high nitrogen concentration.

Our results show that material research should focus on high-efficiency conversion of nitrogen to negatively charged NV, rather than simply high NV concentration. This particular topic was the focus of a Ph.D. candidate in the group of our collaborators at Fraunhofer IAF, Freiburg, Germany. A detailed study of CVD-grown diamond samples with varying densities of nitrogen defects and different electron irradiation parameters – to explore different densities of NV centers – was recently published.[3, 4] The publication included data collected during this project by Dr Marco Capelli, due to the close connection between the two studies. Our involvement resulted in the co-authorship of the papers and the acknowledgement of the AOARD funding.

Magnetic field sensitivity

We further investigated the magnetic field sensitivity in a few areas of diamond crystals with varying nitrogen concentrations. The known effect of nitrogen defects on the NV center sensitivity is the broadening of its resonant transitions. Single nitrogen defects in the diamond lattice have unpaired electrons that contribute to the spin noise in the crystal. Any background spin noise contributes by degrading the spin properties of the NV centers themselves and broadening the resonant frequency transitions, decreasing the overall sensitivity to small changes in magnetic fields.
However, in our study, we observed the additional effect caused by the electron tunnelling to the closest nitrogen defect.

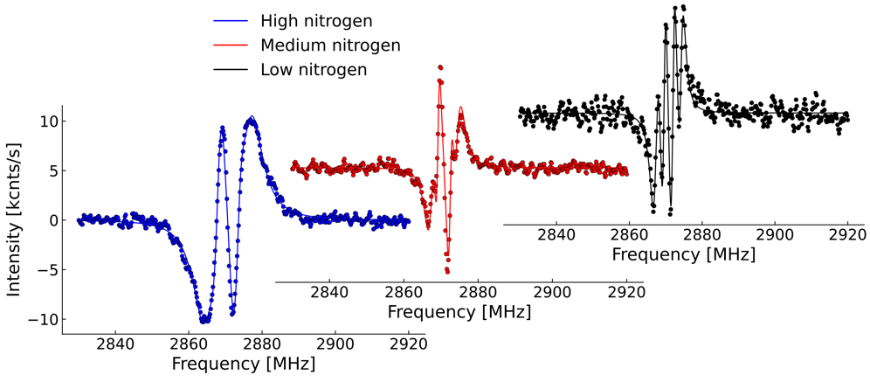

Figure 3: Optically detected magnetic resonance (ODMR) combined with lock-in detection of diamond samples containing different densities of nitrogen defects. The ODMR technique identifies the resonant frequencies of the NV center by applying a microwave field of tunable frequency and recording the change in emission intensity from the NV center. Lock-in amplification detection is performed by frequency-modulation (FM) of the main microwave frequency. The lock-in amplification filters the emission signal not oscillating with the period of the FM microwave, therefore, isolating and enhancing the signal detected from the NV center. However, at high nitrogen concentration (blue data) the spin noise blurs the fine details of the NV center resonant transitions. Decreasing the nitrogen concentration below 10 ppm (right-most black data) the finer structure of the NV center becomes measurable and the contrast between high-low emission intensity becomes sharper.

The optically detected magnetic resonance (ODMR) technique is the most common experiment performed to characterize the magnetic field sensitivity of the NV center. The NV centers reach high magnetic field sensitivities when they have strong emission intensity (high signal-to-noise ratio), sharp resonant transitions and high contrast between the emission intensity in and out of resonance. We mentioned in the previous paragraph the known effect of nitrogen defects on the width of the resonance. Figure 3 shows such an effect in three different diamond crystals. The spin noise caused by the nitrogen defects broadens the resonant transitions. The broader features in the ODMR spectrum result in a slower response of signal intensity after the application of magnetic field. Decreasing the nitrogen concentration below 10 ppm sharpens the slope at which the fluorescence signal changes and corresponds to a more sensitive measurement of the magnetic field.

In addition, in our results, we observed a reduction in signal-to-noise ratio with increasing nitrogen concentrations and a reduction of contrast around the resonances. The reduction in signal-to-noise ratio is connected to the decrease in overall emission intensity discussed in the previous section. In the diamond sample with high nitrogen concentration (more than 400 ppm), the electron tunnelling between the NV center and its closest nitrogen defect decreases the total fluorescence signal emitted by the NV center.

Magnetic field-sensitive stimulated emission

Parallel to our studies at RMIT University, Melbourne, we strongly collaborated with our colleagues at the Fraunhofer IAF, Freiburg, Germany on the topic of laser threshold magnetometry. This collaboration led to the first example of magnetic field-dependent laser output from an NV-diamond cavity system.[2] We published the results in Science Advances and the funding of the AOARD program was acknowledged in the manuscript.

In this study, we built a macroscopic external cavity system that reached a high finesse F > 1000. The system was configured with a 532 nm pump laser to excite the NV centers and seeded at 710 nm with a narrow bandwidth laser. In the middle of the cavity, we used an HPHT diamond with a high density of NV centers and low absorption. We simultaneously monitored the transmitted and reflected stimulated emission signal as well as the spontaneous emission from the side of the diamond sample.

The stimulated amplification was strongly dependent on both the pump and seed laser power. Optimizing the parameter space to achieve the largest amplitude of the fundamental cavity mode, we observed a maximum of 64% amplification between 1-2 W of pump power and < 0.2 W of seed power.

We then tested the effect of a magnetic field on the output amplitude. Using a permanent magnet reach > 100 mT, we observed a drop of almost 33% compared to the amplitude without the magnetic field. We compared the result from the cavity with the impact of the same magnetic field on the spontaneous emission of the NV center, conventionally used for magnetometry. The spontaneous emission contrast was only 15%, less than half the result we reached with the cavity. This result is extremely significant from multiple perspectives. Firstly, it is the first demonstration of magnetic field-dependent stimulated emission. Secondly, it demonstrates the advantage of the laser-threshold approach by showing a stronger contrast under an external magnetic field when measuring the stimulated emission compared to the spontaneous emission of the NV center. With further optimization and a lock-in system able to remove the baseline output from the seed laser, we can reach the 100% contrast predicted by the theory.

Finally, we added a microwave antenna to the system and performed ODMR measurements to estimate the magnetic field sensitivity of the system. The cavity system improved all the ODMR parameters of interest: stronger contrast, narrower width and stronger absolute intensity – when combining the transmitted and reflected stimulated emission. The sensitivity we measured went from 276 pT/√Hz using the spontaneous emission to 29 pT/√Hz using the stimulated emission.

Time-resolved dynamics of the NV center

Our results about tunnelling rates and not-radiative transitions show how important it is to have a better understanding of the intrinsic photo-dynamics of the NV center. However, measuring the transition dynamics at timescales below the nanosecond is difficult and requires advanced instrumentation.

Via our collaboration with Dr Morgan Schmidt at the AFRL in San Antonio, Texas, we studied the time-resolved dynamics of the NV fluorescence and observed a strong change in the absorption features of the NV center. Our absorption measurement – reported in Figure 4 – shows a switch from the neutral charge state to the negative charge state occurring before 400 fs from the laser excitation pulse. We can identify both charge states from the respective zero-phonon lines at 575 nm (NV^0) and 638 nm (NV^-).

The femtosecond pulse-probe system combines two sources of light: a femtosecond laser pulse which brings the NV center to its excited state; and a pulse of white light that is used to measure the absorption spectrum of the diamond crystal. The interval between the two sources of light is precisely controlled to investigate the change in absorption behavior with femtosecond accuracy.

Common absorption techniques measure the absorption features of a material in its equilibrium state. Instead, the pulse-probe technique shows the evolution of the NV center in diamond immediately following the perturbation induced by the excitation laser and it helps us understand the transition pathways that occur.

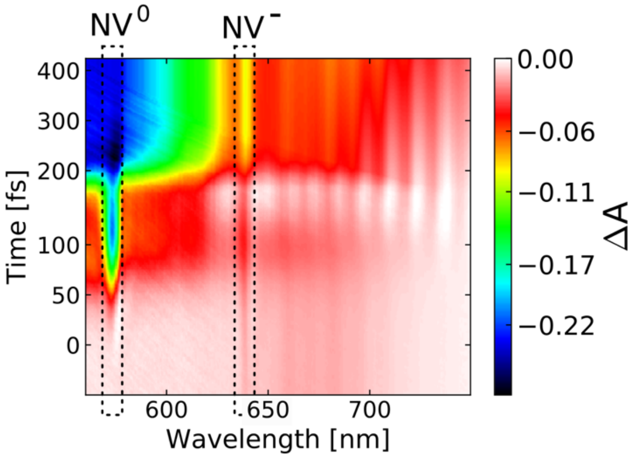

Figure 4: Transient absorption graph measured using a femtosecond pulse-probe system. A 532 nm excitation pulse is followed by a pulse of white light at time t (on the y-axis). The color scale shows the change in absorption (ΔA) between the white light transmittance through the sample without the 532 nm pulse and the transmittance signal at a time t after the excitation pulse. The dashed boxes indicate the peak position of the characteristic nitrogen-vacancy center charge states: NV^0 at 575 nm and NV^- at 638 nm.

Figure 4 shows our results while investigating an ensemble of NV centers in a diamond crystal with approximately 100 ppm of nitrogen defects (medium density, according to the classification used in previous sections). Figure 4 demonstrates that most of the dynamic occurs within the first hundreds of femtoseconds after the excitation pulse.

We observe an initial strong absorption from the neutrally-charged NV center (NV^0) which is then converted into the most common negatively-charged NV center (NV^-). We initially associated the presence of a strong NV^0 absorption with the electron tunnelling to neighboring nitrogen defects as observed in the previous experiments. However, further measurements with different diamond samples will be required to confirm our hypothesis. Unfortunately, the Covid-19 pandemic and associated lockdowns prevented us from performing more experiments on the pulse-probe system.

The short time scales are necessary to understand in better detail both the electron tunnelling to the neighboring nitrogen defects and the absorption features from the nitrogen-vacancy excited state. Both behaviors have a major impact on the lasing threshold of the NV center in diamond.

Additional contributions

The impact of COVID-19 on our research program has been severe. We had previously identified milestones to be completed with our partners in the ARFL (Dr Morgan Schmidt and Dr Luke Bissell). However, a combination of travel restrictions and reduced occupancy at our laboratories (minimizing the total amount of time that could be used to perform experiments at RMIT University), has meant that our progress has been less than originally anticipated. Accordingly, we have performed more theoretical and modelling work, and some of this is discussed below.

Synergistic research activities with our Australian Defence Science and Technology Group funded project on diamond in fiber for magnetometry meant that Dr Marco Capelli was able to apply his expertise in diamond magnetometry to enhance sensitivity calculations for a modelling paper on diamond in fiber magnetometry. Accordingly, his involvement and AOARD funding was acknowledged in the published paper by Li et al., "Preferential coupling of diamond NV centres in step-index fibres".[5]

List of Publications and any Significant Collaborations that resulted from your AOARD supported project: In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:

a) papers published in peer-reviewed journals,

[1] Marco Capelli, Lukas Lindner, Tingpeng Luo, Jan Jeske, Hiroshi Abe, Shinobu Onoda, Takeshi Ohshima, Brett Johnson, David A Simpson, Alastair Stacey, Philipp Reineck, Brant C Gibson, and Andrew D Greentree, "Proximal nitrogen reduces the fluorescence quantum yield of nitrogen-vacancy centres in diamond", New J. Phys., 24(3), 033053 (2022)

[2] Felix A Hahl, Lukas Lindner, Xavier Vidal, Tingpeng Luo, Takeshi Ohshima, Shinobu Onoda, Shuya Ishii, Alexander M Zaitsev, Marco Capelli, Brant C Gibson, Andrew D Greentree, and Jan Jeske, "Magnetic-field-dependent stimulated emission from nitrogen-vacancy centers in diamond", Science Advances, 8, eabn7192 (2022)

[3] Tingpeng Luo, Lukas Lindner, James Langer, Volker Cimalla, Xavier Vidal, Felix Hahl, Christian Schreyvogel, Shinobu Onoda, Shuya Ishii, Takeshi Ohshima, Di Wang, David A Simpson, Brett C Johnson, Marco Capelli, Remi Blinder, and Jan Jeske, "Creation of nitrogen-vacancy centers in chemical vapor deposition diamond for sensing applications", New J. Phys., 24(3), 033030, (2022)

[4] Tingpeng Luo, Lukas Lindner, Remi Blinder, Marco Capelli, James Langer, Volker Cimalla, Felix Hahl, Xavier Vidal, and Jan Jeske, "Rapid determination of single substitutional nitrogen Ns0 concentration in diamond from UV-Vis spectroscopy", Appl. Phys. Lett., 121, 064002 (2022)

[5] Shuo Li, Dongbi Bai, Marco Capelli, Qiang Sun, Shahraam Afshar V., David A Simpson, Scott Foster, Heike Ebendorff-Heidepriem, Brant C Gibson, and Andrew D Greentree, "Preferential coupling of diamond NV centres in step-index fibres" Optics Express, 29 (10), 14425 (2021)

b) papers published in peer-reviewed conference proceedings,

[6] Marco Capelli, Hiroshi Abe, Takeshi Ohshima, Brett C. Johnson, David A. Simpson, Jan Jeske, Andrew D. Greentree, Philipp Reineck, and Brant C. Gibson, "The effect of nitrogen concentration on quantum sensing with nitrogen-vacancy centre", Proc. SPIE 11202, Biophotonics Australasia 2019, 112021O (2019)

[7] Z. Al-Baiaty, F. Hahl, S. Nair, L. Rogers, B. Gibson, R. Mildren, T. Volz, J. Jeske, and A Greentree, "Nitrogen vacancy centres in diamond for laser threshold

magnetometry", Proc. SPIE 11202 Biophotonics Australasia 2019, 112020S (2019)

c) papers published in non-peer-reviewed journals and conference proceedings,
None

d) conference presentations without papers,
Marco Capelli, Hiroshi Abe, Takeshi Ohshima, Brett C. Johnson, David A. Simpson, Jan Jeske, Andrew D. Greentree, Philipp Reineck, Brant C. Gibson, "How the density of nitrogen defects impacts nanoscale sensing applications with nitrogen-vacancy centres" Poster presentation, International Conference on Nanoscience and Nanotechnology (ICONN) 2020 (Brisbane, February 2020)

Marco Capelli, Hiroshi Abe, Takeshi Ohshima, Brett C. Johnson, David A. Simpson, Tingpeng Luo, Jan Jeske, Andrew D. Greentree, Philipp Reineck, Brant C. Gibson, "Nitrogen impurities reduce the quantum yield of nitrogen-vacancy centres in diamond" Oral presentation, New Diamond and Nano Carbons (NDNC) 2020-2021, (Remote, June 2021)

e) manuscripts submitted but not yet published, and
None

f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

2018 (24 August) – Brant visited Dr Luke Bissell at Wright-Patterson AFB AFRL/RX (with AFOSR Window on Science funding) to discuss the initial stages of the collaborative AOARD grant FA2386-18-1-4056 - 'Laser Threshold Magnetometry with Diamond'. He also met with Dr Mike Slocum, Dr Mike Page and Dr Joshua Kennedy and had some detailed discussions regarding diamond material properties for magnetometry and hybrid nanodiamond integration applications. Brant also met with the Director of the Airman Systems Directorate, Dr Kevin Geiss during his visit to Wright-Patterson AFB. They discussed the human performance research activities that are being undertaken within the CNBP. He also discussed collaborations with Dr Morgan Schmidt (AFRL, 711th Human Performance Wing, Radio Frequency Bioeffects Branch) who was visiting Australia and our group at RMIT University on a 'Window on the World' Application.

2018 (19 Oct) - Brant Gibson met with Lt Col Briana Singleton near the AOARD offices in Tokyo to discuss the Laser Threshold Magnotometry project and other collaboration opportunities with Japanese researchers.

2019 (30 Jan) - Andrew Greentree met with Lt Col Briana Singleton at the AOARD offices in Tokyo to discuss the Laser Threshold Magnotometry project and other opportunities.

2019 (6th Dec – 8th Dec) Dr Morgan Schmidt visited RMIT University for meetings, discussions, and experimental collaboration

Unfortunately, due to COVID-19 travel restrictions, further travelling interactions with the AFRL have been impossible. However, research generated through this program has informed our successful grants:

D. Simpson, B. Gibson, A. Greentree, L. Hall and L. Hollenberg, Quantum diamond
magnetometers for subterranean magnetic anomaly detection (MAD), Army Quantum Technology Challenge 2021 & Army Quantum Technology Exploration
Day 2021 (AQTED21), Project funding AUD$50,000 (USD$40,000).

D. Simpson, A. Stacey, L. Hollenberg, L. Hall, B. Gibson, A. Greentree, S. Foster,
"Air Force Office of Scientific Research - International Quantum U Tech Accelerator- FA9550-19-S-0003 - Towards sub-picotesla quantum diamond magnetometers for defense, Project funding USD$75,000 (~AUD$100,00).

Additionally, our publication in Science Advances [2] received extensive media coverage. The main media release was "Discovery could inspire new way to detect brain abnormalities" from RMIT University (June 2022) found at the following link: [https://www.rmit.edu.au/news/all-news/2022/june/magnetic]

Among the media coverage, some highlights include journal articles published in the Daily Mail (UK), Times Now (India), and Science Daily (US) as well as more specific outlets like ITwire (Australia) and GoPhotonics (US).