Diamond Quantum Technologies

693. WE-Heraeus-Seminar

25 – 28 March 2019
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 693. WE-Heraeus-Seminar:

The WE-Heraeus seminar "Diamond Quantum Technologies" will summarize and discuss the state of the art in quantum devices made from diamond.

Diamond is a front-runner candidate for many applications in quantum sensing and quantum communication, mostly because it hosts NV color centers that can be operated as a quantum bit with very little technical effort under ambient conditions. The seminar will give an overview of the state of the art of this field, with a focus on applications in sensing and photonics as well as nanofabrication of diamond devices. It aims to bring together the numerous European groups that have entered this area of research in the past few years, and to give an introduction to junior researchers starting work in the field.

Scientific Organizers:

Dr. Elke Neu-Ruffing	Universität des Saarlandes, Saarbrücken, Germany E-mail: elkeneu@physik.uni-saarland.de
Dr. Friedemann Reinhard	TU München, Germany E-mail: friedemann@quantum-minigolf.org
Prof. Dr. Jörg Wrachtrup	Universität Stuttgart, Germany E-mail: wrachtrup@physik.uni-stuttgart.de

Program

Sunday, 24 March 2019

17:00 – 21:00	Registration	
from 18:30	*BUFFET SUPPER / Informal get together*	

Monday, 25 March 2019

07:30	*BREAKFAST*	
08:30 – 08:45	Friedemann Reinhard Elke Neu-Ruffing	**Opening and Welcome**
08:45 – 09:45	Nir Bar-Gill	**Enhanced polarization transfer and many-body dynamics in spin ensembles in diamond**
09:45 – 10:45	Emilie Bourgeois	**Photoelectric readout of NV center electron spin in diamond**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 12:15	Mark Newton	**Controlling and exploiting defects in diamond**
12:15	**Conference Photo** (in front of the Physikzentrum/Main entrance)	
12:30	*LUNCH*	

Program

Monday, 25 March 2019

14:00 – 15:00	Eilon Poem	**Experimental demonstration of quantum effects in microscopic heat engines made of nitrogen-vacancy centres in diamond**
15:00 – 16:00	Posters	
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:30	Posters	
17:30 – 18:30	Jan Meijer	**High lateral addressing of single qubits in diamond**
18:30 – 19:30	Lee Bassett	**Tailored spin-readout strategies for nitrogen-vacancy centers in diamond**

19:30 *HERAEUS DINNER at the Physikzentrum*
(cold & warm buffet, free beverages)

Program

Tuesday, 26 March 2019

07:00	*BREAKFAST*	
08:00 – 09:00	Dmitry Budker	**Some Recent Results on Sensing using NV centers in Diamond**
09:00 – 10:00	Thierry Debuisschert	**Applications of ensembles of NV centers**
10:00 – 10:30	*COFFEE BREAK*	
10:30 – 11:30	Fedor Jelezko	**Diamond spin qubits: quantum sensing and photoelectric readout**
11:30 – 12:30	Vincent Jacques	**Imaging exotic spin textures at the nanoscale with a spin spin microscope**
12:30	*LUNCH*	
14:00 – 15:00	Patrick Maletinsky	**Single spin magnetic sensing of mesoscopic condensed matter systems**
15:00 – 16:00	Jonathan Zopes	**Three-dimensional localization of nuclear spins in diamond**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 18:30	Tutorial (M. Plenio)	**Control Methods for Colour Centers in Diamond**
18:30	*DINNER*	

Program

Wednesday, 27 March 2019

07:00	*BREAKFAST*	
08:00 – 09:00	Romana Schirhagl	**Diamond magnetometry in a cell**
09:00 – 10:00	Anke Krüger	**Methods for the efficient surface functionalization of diamond for the control of electronic surface properties**
10:00 – 10:30	*COFFEE BREAK*	
10:30 – 11:30	Ulrik Lund Andersen	**Color centers coupled to photonic and plasmonic systems**
11:30 – 12:30	Helena Knowles	**Engineering interactions of spin ensembles in diamond for quantum metrology**
12:30	*LUNCH*	
14:00 – 15:00	Christoph Becher	**Spin properties and quantum control of group-IV vacancy centers in diamond**
15:00 – 16:00	David Hunger	**Towards a coherent spin-photon interface for NV centers in diamond**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:30	Anais Dréau	**Quantum frequency conversion of single photons from a nitrogen-vacancy center in diamond to telecommunication wavelengths**
17:30 – 18:30	Christopher Kay	**Room-Temperature, Continuous-wave Diamond Maser**
18:30 – 18:45	Friedemann Reinhard Elke Neu-Ruffing Jörg Wrachtrup	**Closing remarks and poster awards**
18:45	*DINNER*	

End of the seminar and Departure

Please note that there will be breakfast on Thursday morning 07:30 h for participants with an additional overnight.

Program

P01	Thomas Astner	**Solid-state electron spin lifetime limited by phononic vacuum modes**
P02	Hossein Babashah	**High Precision Optical Magnetometry Using NV Centers in CVD Diamond**
P03	Jonas Nils Becker	**Bending the Rules: Quantum effects in the operation of a microscopic heat engine in diamond**
P04	Juanita Bocquel	**Towards probing biological processes at the molecular level using single NV centers in diamonds**
P05	Mayeul Chipaux	**Ensembles of Nitrogen-Vacancy centers in practical industrial applications**
P06	Saddem Chouaieb	**Optimizing synthetic diamond samples for quantum sensing technologies by tuning the growth temperature**
P07	Pablo Cova Fariña	**Dynamical decoupling of Erbium spins in Yttrium Orthosilicate**
P08	Jéssica F. Da Silva Barbosa	**Towards detection of single spin in diamond via coupling with microwaves**
P09	Viraj Damle	**Comparing the effect of macro and micro environment on cellular FND uptake**
P10	Shane Eaton	**Laser inscription of nitrogen vacancy center ensembles within photonic circuits in diamond**
P11	Jonathan Finley	**Towards Fault Tolerant Quantum Communication using Diamond Quantum Photonic Devices**

P12	Johannes Görlitz	**Spectroscopic investigation of the neutral charge state of the tin-vacancy centre in diamond**
P13	Arne Götze	**Increasing the NV center incorporation during MECVD growth of homoepitaxial diamond**
P14	Jonas Gutsche	**Immersion of Nanodiamonds into three-dimensional direct-laser-written Waveguides**
P15	Galya Haim	**Sensing chiral-induced magnetization in an integrated Nitrogen-vacancy-based device**
P16	Swathi Hegde	**Efficient universal quantum gates via indirect control in diamond NV center**
P17	Dennis Herrmann	**Spectroscopy of the negatively charged tin-vacancy centre in diamond**
P18	Dominik Irber	**Towards single-shot readout of NV centers in diamond by low-temperature spin-to-charge conversion**
P19	Ottavia Jedrkiewicz	**Laser surface structuring of diamond for microfluidics and quantum sensing applications**
P20	Jan Jeske	**Progress and challenges of NV-doped diamond for ultrasensitive laser threshold magnetometry**
P21	Timo Joas	**Sensing Weak Microwave Signals by Quantum Control**
P22	Alastair Marshall	**Enhanced Dynamic Nuclear Polarisation with Quantum Optimal Control**

Posters

P23	Vardan Martikyan	**Optimal Control of Linear Systems-Application in Ion Cyclotron Resonance**
P24	Idan Meirzada	**Negative charge enhancement of near-surface nitrogen vacancy centers by multicolor excitation**
P25	Joseph Munns	**Towards mode manipulation for optimally interfacing disparate defect centres in diamond**
P26	Mackrine Nahra	**Single photon source in nanodiamonds for integrated quantum photonics**
P27	Richard Nelz	**Towards reliable, scalable scanning probe sensing using color centers in diamond**
P28	Martin Nicolle	**Enhanced light-matter interactions in ordered arrays of NV centres**
P29	Gregor Oelsner	**Modified Hanbury-Brown-Twiss Interferometer experiments on NV^0 and NV^- centers in diamond**
P30	Yori Ong	**Interaction of nanodiamonds with bacteria**
P31	Laura Orphal	**Reduction of spectral diffusion by applying a sequence of optical control pulses**
P32	Nimba Oshnik Pandey	**Optimal Control for Sensing With NV Centers in Diamond**
P33	Felipe Perona	**Detecting Hydroxyl Radical using NV centers in nanodiamonds in physiological conditions**
P34	Isabelle Philip	**Thermal imaging with NV centers in diamond**
P35	Markus Rademacher	**Towards laser refrigeration of NV centres on the nanoscale**

Posters

P36	Phila Rembold	**Optimal Manipulation of NV-Centers for Nuclear Polarisation**
P37	Yoav Romach	**Novel coupling scheme between distant Nitrogen-Vacancy centers through nano-fabricated superconducting structures**
P38	Tim Schröder	**Diamond nanostructures as spin-photon interfaces for controlled coupling of single defect centres to light**
P39	Marcel Schrodin	**Integrated opto-electronical setup for milli-Kelvin temperature experiments on vacancy centers in diamond**
P40	Vladyslav Shkolnykov	**Fast universal holonomic manipulation with the state of a two-qubit register**
P41	Jason Smith	**Engineering colour centres in diamond using laser-writing techniques**
P42	Kirill Streltsov	**Geometric Phase Magnetometry Beyond the Adiabatic Limit**
P43	Benedikt Tratzmiller	**Heisenberg-limited metrology with little entanglement**
P44	Luca Troise	**Sensing of magnetic field from *in-vivo* biological systems using diamond NV centers**
P45	Ronald Ulbricht	**Photo-Excitation Dynamics of the NV– Center in Diamond**
P46	Vadim Vorobyov	**Quantum sensor-processor system based on single NV center and ^{13}C nuclear spins**
P47	Kai Wagner	**Magnetic domain walls as controllable and non-volatile spin-wave nanochannels**

Posters

P48	Boris Yavkin	**Microwave-induced coherent population trapping in unknown defect in diamond**
P49	Jingfu Zhang	**Efficient indirect control of nuclear spins in diamond NV centers**
P50	Chen Zhang	**Diamond magnetometry with high DC field sensitivity for novel human machine interface applications**
P51	Huijie Zheng	**Microwave-free vector magnetometry using nitrogen-vacancy centers in diamond**

Abstracts of Lectures

(in chronological order)

Enhanced polarization transfer and many-body dynamics in spin ensembles in diamond

D. Farfurnik[1], Y. Hovav[2] and N. Bar-Gill[1,2]

[1]Racah Institute of Physics, Hebrew University of Jerusalem, Israel
[2] Dept. of Applied Physics, Hebrew University of Jerusalem, Israel

The study of open quantum systems, quantum thermodynamics and quantum many-body spin physics in realistic solid-state platforms, has been a long-standing goal in quantum and condensed-matter physics.
In this talk, I will describe our work on nuclear hyper-polarization, potentially relevant for enhanced MRI contrast, and research into open quantum systems and quantum thermodynamics [1]. I will then address the requirements for the study of quantum many-body spin physics using this platform, and demonstrate separate steps required to reach this goal, including TEM electron irradiation for improved N to NV conversion efficiencies, robust dynamical decoupling and simulations of noisy many-body spin systems [2-5].

[1] Y. Hovav, B. Naydenov, F. Jelezko and N. Bar-Gill, Phys. Rev. Lett. 120, 060405 (2018).
[2] D. Farfurnik et al., Appl. Phys. Lett. 111, 123101
[3] D. Farfurnik et al., Phys. Rev. B 92, 060301(R)
[4] D. Farfurnik et al., Phys. Rev. A 96, 013850
[5] D. Farfurnik, Y. Horowicz and N. Bar-Gill, Phys. Rev. A 98, 033409 (2018)

Photoelectric readout of NV center electron spin in diamond

E. Bourgeois[1,2], M. Gulka[1], J. Hruby[1] and M. Nesladek[1,2]

[1]IMOMEC division, IMEC, Diepenbeek, Belgium
[2] Institute for Materials Research (IMO), Hasselt University, Diepenbeek, Belgium

Applications of the negatively charged nitrogen-vacancy (NV^-) centre for quantum information processing and quantum sensing require the readout of NV^- spin state, usually done by optical detection of magnetic resonances (ODMR). We developed an alternative photoelectric method (PDMR) for the readout of NV spin state [1]. This technique presents advantages in terms of detection rate [2], compactness, spatial resolution and integration of qubits to electronic chips.

We present here the continuous wave [1] and pulsed [3] photoelectric readout of NV^- spins ensembles. We additionally report the downscaling of the PDMR method to a single NV^- center [4]. The photoelectric readout of a coherently driven single NV^- qubit was achieved (photoelectric detection of Rabi oscillations). This result constitutes an important step towards the development of electrically-read diamond chips for quantum computing and nanoscale quantum sensing.

The mechanism leading to magnetic resonances in the photocurrent induced by the two-photon ionization of NV^- under green illumination is described. Alternative dual-beam PDMR schemes (using a combination of green and blue or green and red illuminations) – developed to improve the PDMR performances in terms of detection rate [2] or contrast (limited by the background photocurrent resulting from ionization of defects other than NV centers in the diamond crystal) – are presented.

The existence of charge exchanges between NV centers and other defects in diamond influences the photoelectric readout. On most samples, application of a resonant microwave field induces a decrease in the photocurrent associated to ionization of NV^-. However, on a sample containing defects with low-energy (< 2 eV) ionization threshold, we observed positive magnetic resonances in the photocurrent. We show how these variations in the sign of photoelectrically detected resonances can be explained by the existence of charge transfers between NV and other defects.

References

[1] E. Bourgeois *et al.*, Nat. Commun. **6**, 9577 (2015)
[2] E. Bourgeois *et al.* Phys. Rev. B – RC **95**, 041402(R) (2017)
[3] M. Gulka *et al.* Phys. Rev. Applied **7**, 044032 (2017)
[4] P. Siyushev, *et al.,* Science - accepted (2019)

Controlling and exploiting defects in diamond

B. G. Breeze, E. Nako, B. L. Green, and M. E. Newton
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It is well known that the negatively-charged nitrogen-vacancy (NV^-) centre in diamond is established as a leading platform in solid state quantum applications, with potential technologies in sensing, computation and communication enabled by its long spin-coherence time, and the ability to optically initialise, manipulate and read out the spin state. However, NV's poor photonic properties (Debye-Waller factor ~0.04) have resulted in significant efforts on optical cavities to enhance its coherent emission, and search for alternate colour centres with comparable spin properties and superior optical properties. Currently, the vacancy-impurity family of defects is most promising, with major interest in group IV centres SiV^- [1,2], GeV^- [3] and SnV^- [4,5]. Of these, SiV^- is the most-studied, with $T_2 > 10$ ms and single-shot readout demonstrated at 100 mK. Nonetheless, the onerous experimental requirements and low quantum efficiency (~10% [6]) motivate further research on alternative centres. In this presentation, I will discuss recent work on the neutrally-charged silicon vacancy, SiV^0 [7,8] defect which has helped us understand the electronic structure and spin physics of this defect.

Full exploitation of their optical and spin properties necessitates that we control the position, orientation and environment of the chosen colour centre to optimise all of the desirable properties simultaneously, especially near the surface of the diamond. I will review our understanding of the production of intrinsic defect complexes and present new data on the production defect complexes by doping, electron irradiation, short pulse laser irradiation, ion implantation and annealing.

References

[1] J. N. Becker et al, Nat. Commun. **7**, 13512 (2016).
[2] B. Pingault, et al, Nat. Commun. **8**, 15579 (2017).
[3] S. Häußler et al, New J. Phys. **19**, 63036 (2017).
[4] T. Iwasaki et al, arXiv 1708.03576 (2017).
[5] S. Ditalia Tchernij et al, arXiv 1708.01467 (2017).
[6] A. Sipahigil et al, Science **354**, 847 (2016).
[7] B. L. Green et al, Phys. Rev. Lett. **119**, 96402 (2017).
[8] B. C. Rose et al, Science **361**, 60 (2018).

Experimental demonstration of quantum effects in microscopic heat engines made of nitrogen-vacancy centres in diamond

J. Klatzow[1], J. N. Becker[1], P. M. Ledingham[1], C. Weinzetl[1], K. T. Kaczmarek[1,2], D. J. Saunders[1], J. Nunn[3], I. A. Walmsley[1], R. Uzdin[4], and E. Poem[5]

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[2]Groupe de Physique Appliquée, Université de Genève, Genève, Switzerland
[3]Department of Physics, University of Bath, Bath, United Kingdom
[4]Fritz Haber Research Center for Molecular Dynamics, Hebrew University of Jerusalem, Jerusalem, Israel
[5]Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot, Israel

The ability of the internal states of a working fluid to be in a coherent superposition is one of the basic properties of a quantum heat engine. It was recently predicted [1] that in the regime of small engine-action, this ability can enable a quantum heat engine to produce more power than any equivalent classical heat engine. It was also predicted that in the same regime, the presence of such internal coherence causes different types of quantum heat engines to become thermodynamically equivalent. Here, we use an ensemble of nitrogen-vacancy centres in diamond for implementing two types of quantum heat engines, and experimentally demonstrate both effects. This constitutes the first experimental demonstration of quantum effects in heat machines.

References

[1] R. Uzdin, A. Levy, and R. Kosloff, Phys. Rev. X **5**, 031044 (2015).

High lateral addressing of single qubits in diamond

T. Lühmann, S. Pezzagna and Jan Meijer

Felix-Bloch Institute for solid state physics, University Leipzig

The key technology to fabricate and operate quantum systems in solids is the positioning and addressing of single atoms with high lateral resolution and convert the atom into a sutible charged color center. Whereas the manipulation of single atoms at the surface is possible since several years, the three dimensional addressing inside solids needs more effort. Especially counting of a single ion (so called deterministic implantation) is difficult. Several attempts are underway to meet this challenge. An image charge detection method is under development in Leipzig to achieve a fast and reliable signal. However, the technology to implant a single ion in a solid is only the first step. The activation of the implanted atom and the annealing of the surrounded defects is of similar importance. Indeed the defects themselves can help to understand these processes and optimize the defect engineering process. We will discuss new results based on doped diamonds.

Tailored spin-readout strategies for nitrogen-vacancy centers in diamond

Lee C. Bassett[1] and David A. Hopper[1,2]

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[2]Department of Physics & Astronomy, University of Pennsylvania, Philadelphia, PA, USA

Despite the technological maturity of nitrogen-vacancy (NV) centers in diamond as a platform for quantum technology, their performance in most applications is hindered by imperfect initialization and inefficient readout. The standard photoluminescence-based spin readout typically yields only a few hundredths of a photon on average, necessitating tens of thousands of repetitions to overcome shot noise in detecting the spin state. Recently, alternative readout strategies have been explored that leverage extra degrees of freedom such as the NV center's charge state or nearby nuclear spins [1]. However, these methods involve tradeoffs in experimental complexity and typically incur penalties in the required measurement time.

This talk will present a framework for optimizing the performance of these enhanced readout techniques by accounting for the additional experimental overhead. We will focus especially on spin-to-charge-conversion, which is an all-optical technique compatible with most quantum sensing schemes that can be applied to NV centers in bulk [2] or nanocrystalline diamond [3]. We will also discuss ongoing work that utilizes real-time signal processing and dynamical feedback control to improve the charge and spin initialization fidelity, as well as nanophotonic structures such as the diamond metalens [4] that can enable compact, high-performance, fiber-coupled quantum devices based on single NV-center spins.

References

[1] D. A. Hopper, H. J. Shulevitz, and L. C. Bassett, *Micromachines* **9**, 437 (2018)
[2] D. A. Hopper et al., *Phys. Rev. B* **94**, 241201(R) (2016).
[3] D. A. Hopper et al., *ACS Nano* **12**, 4678 (2018).
[4] R. R. Grote et al., arXiv:1711.00901 [physics.optics]

Some Recent Results on Sensing using NV centers in Diamond

D. Budker[1,2]

[1]Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany
[2]Department of Physics, University of California, Berkeley, USA

I will provide an overview of the recent activities of our group and collaborators [1,2] on magnetic sensing, including near-zero-field magnetometry with ensembles and single NV centers, microwave-free scalar and vector magnetometry, infrared-absorption based magnetometry, eddy-current imaging, and wide-field imaging of vortices in high-temperature superconductors.

References

[1] https://budker.uni-mainz.de/
[2] http://budker.berkeley.edu/

Applications of ensembles of NV centers

Ludovic Mayer[1], Loïc Toraille[2], Mayeul Chipaux[2], Simone Magaletti[1], Loïc Rondin[2], Jean-François Roch[2], Thierry Debuisschert[1]

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[2]Laboratoire Aimé Cotton, CNRS, Univ. Paris-Sud, ENS Cachan, Université Paris-Saclay, 91405 Orsay Cedex, France

The NV center in diamond is widely used as an atomic scale magnetic field sensor which is solid-state and works at room temperature under ambient conditions. We are developing several applications based on ensembles of NV centers in order to increase sensitivity and perform magnetic imaging.

A wide-field magnetic imager has been developed to reconstruct the vectorial structure of the magnetic field produced by a sample close to the surface of a CVD diamond hosting a thin layer of NV centers [1]. It has been used to image the magnetic fields generated by a mA range current in an integrated circuit structure with sub-micrometric resolution and then retrieve the current in the perspective of performing failure analysis of electronic circuits [2]. In biology, the mechanical manipulation of magnetic nanoparticles is a powerful approach to probing and actuating biological processes in living systems. Implementing this technique in high-throughput assays can be achieved using biocompatible micromagnet arrays. Such structures have been fully characterized combining the wide-field optical magnetometry technique with magneto-optic Kerr effect microscopy (Figure 1) [3].

We are currently developing a wide bandwidth instantaneous radio frequency spectrum analyzer. A magnetic field gradient applied on the crystal induces a Zeeman shift of the resonances and transforms the frequency information of an incoming microwave signal into spatial information, which allows for the instantaneous analysis in the entire frequency bandwidth (Figure 2) [4].

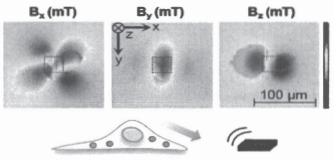

Figure 1

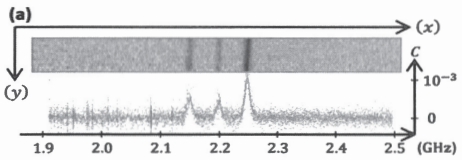

Figure 2

References

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Diamond spin qubits: quantum sensing and photoelectric readout

Fedor Jelezko[1]

[1]*Institute of Quantum Optics, Ulm University, German.*

A particularly interesting application of diamond based quantum sensing is the detection of nuclear magnetic resonance on nanometer scales, including the detection of individual nuclear spins or small ensembles of external nuclear spins. Single nitrogen vacancy (NV) color centers in diamond currently have sufficient sensitivity for detecting single external nuclear spins and resolve their position within a few angstroms. The ability to bring the sensor close to biomolecules by implantation of single NV centers and attachment of proteins to the surface of diamond enabled the first proof of principle demonstration of proteins labeled by paramagnetic markers and label-free detection of the signal from a single protein. Single-molecule nuclear magnetic resonance (NMR) experiments open the way towards unraveling dynamics and structure of single biomolecules. However, for that purpose, NV magnetometers must reach spectral resolutions comparable to that of conventional solution state NMR. New techniques for this purpose including technique that employs quantum entanglement will be discussed. Most of mentioned above results obtained so far with diamond centers are based on optical detection of single NV color centers. Recently it was shown that photoelectrical detection of NV centers base on spin selective photoionization can provide robust and efficient access to spin state of individual color center.

Imaging exotic spin textures at the nanoscale with a spin spin microscope

V. Jacques[1]

[1]*Laboratoire Charles Coulomb, Université de Montpellier and CNRS, 34095 Montpellier, France*

In this talk, I will show how scanning-NV magnetometry can be used as a powerful tool for exploring exotic spin textures in thin magnetic materials focusing on (i) domain walls and magnetic skyrmions in ultrathin ferromagnets [1-3] and (ii) cycloidal antiferromagnetic order in multiferroic materials [4].

References

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[2] Gross *et al.*, Phys. Rev. Materials **2**, 024406 (2018)
[3] Akhtar et al., arXiv :1812.05345
[4] Gross *et al.*, Nature **549**, 252 (2017)

Single spin magnetic sensing of mesoscopic condensed matter systems

P. Maletinsky[1]

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Electronic spins yield excellent quantum sensors [1], offering quantitative sensing [2] and nanoscale imaging [3] down to the level of single spins [4]. Over the last years, the Basel Quantum Sensing Group has developed all-diamond scanning probes [5,6], hosting individual Nitrogen-Vacancy (NV) centre electronic spins as nanoscale magnetometers, to address open problems in condensed matter physics. I will describe our recent advances in applying this novel and unique quantum-sensing technology to study nano-magnetism at room temperature as well as mesoscopic systems in cryogenic environments down to the millikelvin range.

Specifically, I will discuss applications of NV magnetometry in the emerging field of antiferromagnetic spintronics [7], where our quantum sensors can address thin-film antiferromagnets with unprecedented performance to reveal nanoscale domains [8,9] and non-trivial spin-textures [10]. The robustness of our scanning NV magnetometers further allows for their use under cryogenic conditions [11], where I will highlight recent advances in studying a novel class of two-dimensional magnetic materials in the atomic monolayer limit [12].

References

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[3] L Rondin et al., Rep. Prog. Phys. **77** 056503 (2014)
[4] M. S. Grinolds et al., Nature Physics **9**, 215 (2013)
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Three-dimensional localization of nuclear spins in diamond

J. Zopes[1], K. Cujia[1], N. Hauff[1], K. Herb[1] and C. Degen[1]

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Nitrogen Vacancy (NV) centers in diamond are sensitive quantum sensors for local magnetic fields. In our group we use single NV centers to detect nuclear magnetic resonance (NMR) signals of small nuclear spin ensembles in its vicinity. Using high-resolution spectroscopy of the magnetic resonance signals, we aim to determine the location of individual nuclei via their spectroscopic signature. Here, the long-term goal is to image individual molecules that are attached to the diamond surface.

In this presentation, we will introduce spectroscopy techniques that enable the reconstruction of the full three-dimensional location of individual nuclei with high spatial resolution (below 0.5 Angstrom) by using the dipole field of the NV center as the imaging gradient. The imaging protocol requires active manipulation of the nuclei, which we realize with micro coils that generate strong and high-bandwidth radio-frequency pulses.

High-precision localization critically depends on the accurate, in-situ calibration of the field vector and temporal shape of the radio-frequency pulses. In this context we will also present our recent results to directly, that is reconstruction-free, detect magnetic fields in the time-domain with both high field and time resolution using the NV center.

References

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Control Methods for Colour Centers in Diamond

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The robust and efficient control of colour centers in diamond by means of microwave fields is essential for the implementation of a broad range of applications ranging from quantum information processing on nuclear spins and quantum repeaters to nuclear spin polarisation. In this talk I will present methods to achieve robust control and/or energy efficient control using continuous wave [1,6] and pulsed protocols [2,3,4,5].

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Diamond magnetometry in a cell

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The aim of my group is to apply diamond magnetometry to biomedical applications. Most interesting to us is the measurement of free radicals inside cells. Since these are generated deeply inside the cell, it is necessary to use nanodiamonds. These diamonds can be ingested by the cell[1]. Once the diamonds are inside the cell it is important to bring them to the region of interest. Here my team has mainly investigated targeting specific cell-membrane structures as well as nuclear and mitochondria targeting[2]. While nuclear and cell membrane targeting is straight-forward to analyze, mitochondria are more challenging with that respect. Here I will present our first successful targeting results and discuss how we obtain them as well as the first magnetometry data we have collected.

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Methods for the efficient surface functionalisation of diamond for the control of electronic surface properties

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The surface chemistry of diamond plays a crucial role for the electronic properties of the material, i.e. the electron affinity of the surface[1] or the control of charge states of lattice defects[2] such as the NV or SiV centre.

Namely, the establishment of electron withdrawing or electron donating surface termination or functionalisation exerts such influence that for lattice defects in close vicinity to the surface, the negative charge state – a prerequisite for quantum applications of NV centres – can be either stabilised or adversely affected. Therefore, the generation of homogeneous and stable surface terminations with suitable atoms or groups is of great importance for the fabrication of diamond based quantum devices.

Here we report on the efficient surface termination of different diamond materials using a novel wet-chemical fluorination method as well as the treatment with ozone at low temperatures in comparison to other oxidation methods. These novel treatments lead to highly functionalised surfaces with groups that enable the stabilisation of negative charge states of lattice defects.

Advanced characterisation using solid-state NMR techniques as well as wet-chemical methods such as Boehm titration have been used to analyse the functionalised materials both qualitatively as well as quantitatively.

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Color centers coupled to photonic and plasmonic systems

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Color centers in diamond represent one of the leading platforms for realizing quantum technologies such as quantum computing, communication and sensing. However, on the road to fault-tolerant computation, high-fidelity communication and high-sensitivity sensing, there are numerous bumps that must be overcome. This includes, e.g., fast and efficient spin read-out at room-temperature and efficient generation of indistinguishable photons.

Here I report on our investigations of spin read-out of a single Nitrogen-Vacancy center embedded in a plasmonic system, and our recent results on increasing photon emission from a single Germanium-Vacancy center using a micro-cavity.

Engineering interactions of spin ensembles in diamond for quantum metrology

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Spins in solid state systems can be powerful nanoscale sensors for electric and magnetic fields. Enhancing their performance promises to open new avenues for the detection of single electronic and nuclear spins, revealing intricacies of quantum-mechanical phenomena in the few-spin regime at the nanometer scale.

A natural approach to improving sensitivity is to make use of a large number of spins, which together form the sensor. The challenge then becomes tailoring spin-spin interactions to either generate entangled states that offer enhanced sensitivity, or to allow for independent, unperturbed evolution of a parallelized system comprised of a large spin ensemble. In this talk, I will present both enhanced sensing approaches realized in two different diamond-based systems.

First, a small cluster of electronic spins in a diamond nanocrystal is used to generate an entangled state of one nitrogen-vacancy (NV) centre and one nitrogen spin. We use this state to detect an external magnetic field and observe a double-frequency component in the interferometer signal, corresponding to the contribution of two electronic spins, in contrast to the NV spin only. Conversely, this platform can also be used to generate states which are less sensitive to noise in their environment, allowing for operation in both a 'phase amplifier' and 'phase attenuator' mode.

Second, using a dense ensemble of NV centres in diamond, we experimentally demonstrate fault-tolerant decoupling of spin-spin interactions, achieving a five-fold enhancement of spin coherence time. This is made possible by a novel dynamical decoupling sequence that simultaneously suppresses disorder, interactions, and imperfections in controls. We utilize the extended coherence time to demonstrate an increase in magnetic field sensitivity of 30% compared to conventional sensing protocols such as the XY8 sequence. These results demonstrate a significant enhancement by breaking the interaction limit, and reveal the potential of tailored control in complex, interacting ensembles.

Spin properties and quantum control of group-IV vacancy centers in diamond

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Color centers in diamond, i.e. atomic-scale, optically active defects in the diamond lattice, have received large recent attention as versatile tools for solid-state-based quantum technologies ranging from quantum information processing to quantum-enhanced sensing and metrology. They provide individually addressable spins with very long coherence times, narrow optical spectra and bright single-photon emission. However, identifying a spin impurity which combines all of these favorable properties still remains a challenge.

We will present the example of the Silicon vacancy (SiV) center which allows for optical addressing [1] and ultrafast all-optical coherent manipulation [2,3] of its orbital and spin states. However, this color center reaches long spin coherence times only in the limit of very low temperatures (<100mK) due to phonon-induced decoherence processes [3,4]. A potential resort are vacancy defects with a heavier group-IV impurity atom, such as GeV, SnV and PbV centers, featuring a larger ground state splitting and thus less susceptibility against phonon-induced decoherence. Here, we will report on spectroscopy of SnV centers [5,6] with a ground state splitting larger by a factor of 20 as compared to the SiV center, potentially enabling long spin coherence times even at liquid He temperatures. For the SnV center the two charge states, SnV^- and SnV^0, are investigated where both show promising optical properties.

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Towards a coherent spin-photon interface for NV centers in diamond

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NV centers in diamond offer long-lived spin coherence that can be mapped to indistinguishable photons to provide spin-photon entanglement. The weak (~3%) branching ratio into the coherent zero-phonon line (ZPL) however strongly limits the efficiency of the spin-photon interface. To increase the efficiency as required e.g. for large distance quantum networks, the ZPL of the NV center can be coupled to an optical microcavity and strongly enhanced by the Purcell effect. Therefore, we use a fiber-based microcavity, which combines a small mode volume (few λ^3) with a high quality factor (~10^5) and full tunability. As a first step, we perform experiments on the cavity enhancement of the fluorescence of NV centers [1] and SiV centers [2] in nanodiamonds at ambient conditions.

For operation of a spin-photon interface, the optical coherence of the photons is of key importance, and it remains an important task to achieve Fourier-limited emission in cavity-compatible diamond structures [3]. We report on the current status of our work to couple high-quality NV centers in a diamond membrane with the goal to achieve an extraction efficiency of indistinguishable ZPL photons of up to 80%.

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Quantum frequency conversion of single photons from a nitrogen-vacancy center in diamond to telecommunication wavelengths

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The demonstration of an inter-metropolitan quantum network is currently a great challenge for quantum communications [1]. This architecture relies on connecting many optically active qubit-hosting nodes, separated by dozens or hundreds of kilometres, while keeping a high inter-node entanglement rate [2]. Nitrogen-vacancy (NV) defect in diamond stands out as a promising platform for realizing such networks due to its multi-qubit character combined with a solid-state spin-photon interface. First steps in the creation of these networks have already been demonstrated with the recent realization of a km-scale entanglement between two distant NV centres [3]. Nevertheless, the wavelength of the NV centre zero-phonon line (ZPL) photons (637 nm) used in the remote entanglement protocol [4] exhibit high photon loss during propagation in the optical fibres, which currently prevents the application of these defects for inter-metropolitan quantum connections.

Here, we will present the first telecom conversion of single photons emitted by an individual NV defect in diamond. By means of the non-linear process of difference frequency generation, NV center ZPL spin-selective photons are down-converted to the target wavelength of 1588 nm in the L-telecom band, corresponding to the range of minimal loss in optical fibres. This one-step frequency conversion reaches a maximal efficiency of 17%, along with a signal-to-noise ratio of ~7, limited by detector dark counts and pump-induced noise, and preserves the single photon light statistics. This result constitutes the first step towards the realization of telecom photon-spin interface based on NV centers in diamond in the prospect of implementing future quantum communication networks.

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Room-Temperature, Continuous-wave Diamond Maser

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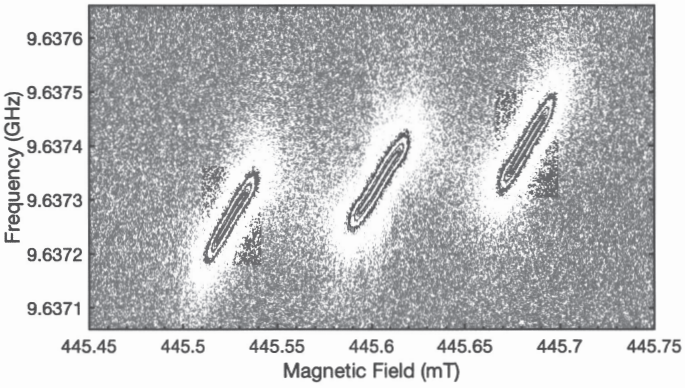
One of the main uses of masers is for deep space communication, due to their ability to function as extremely low noise amplifiers. However, most masers work under inconvenient conditions, such as low temperatures, that require cryogenic temperatures to decrease relaxation.

In this talk, I will describe how we designed and built a continuous-wave, solid-state maser operating at room temperature [1]. We employed NV- centers in diamond which have a S = 1 ground state (D ~2.87 GHz), a 532 nm laser to polarize the electron spins, a sapphire resonator (v ~ 9.6 GHz, Q ~ 30,000) providing a high Purcell factor and an external magnetic field to tune the resonance via the Zeeman interaction.

The figure shows how the microwave output depends on the applied external magnetic field. The three lines are due to the hyperfine coupling to the ^{14}N nucleus.



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Abstracts of Posters

(in alphabetical order)

Solid-state electron spin lifetime limited by phononic vacuum modes

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The negatively charged nitrogen-vacancy (NV) center in diamond has attracted significant attention for possible applications in quantum information tasks. It possesses long lifetimes (T1) and spin-phase coherence times (T2) even at room temperature. In hybrid architectures robust coupling between remote ensembles demonstrated that these spin species may open the opportunity for solid-state quantum information transfer [1]. To exploit all features of this spin system, sound knowledge of spin-environment interaction is necessary.

In the solid state environment, the most fundamental process by which an excited spin ensemble transfers energy to the surrounding is governed by longitudinal relaxation processes. These processes are usually driven by spin-phonon interaction. Here we show a method to study the longitudinal spin-lattice relaxation of large ensembles of NV spins in diamond in the low temperature limit where quantum effects become relevant. Our experiment is based on a cavity quantum electrodynamics framework, where we use a novel 3D lumped element resonator [2]. The spin ensemble is in the strong coupling regime and in the experiment we measure the spin-lattice relaxation below the single phonon limit. There quantum fluctuations become important and provide the ultimate upper bound for T1 [4]. Remarkably, we find that the low phononic density of states at the NV transition frequency enables the spin polarization to survive over macroscopic timescales of up to 8h [3].

We additionally present a theoretical model that describes the direct spin phonon coupling mechanism and calculate the relaxation rate ab initio based on density functional theory (DFT).

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High Precision Optical Magnetometry Using NV Centers in CVD Diamond

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Quantum sensing is poised to revolutionize the future of sensing platforms. We want to contribute to this revolution by developing a very compact and highly sensitive magnetometer operating at room temperature, based on Nitrogen-Vacancy center spins in diamond. The high sensitivity offers potential to do nanoscale protein sensing and the compact size makes the sensor applicable for small mobile platforms [1]. To achieve these goals, we will work in collaboration with the company LakeDiamond to establish in-situ nitrogen doping of CVD diamond during the growth, so that the resulting NV centers have long coherence times [2]. Moreover, we will explore growth along different crystal orientations in order to obtain self-aligned NV centers along a particular axis.

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Bending the Rules: Quantum effects in the operation of a microscopic heat engine in diamond.

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A classical heat engine that extracts work from thermal sources and which does not include coherence amongst its microscopic degrees of freedom is a fundamental concept of classical thermodynamics. In contrast, the internal states of a quantum heat engine (QHE) can exist in a coherent superposition of energy levels and a question of interest for such a QHE is whether it can exhibit thermodynamic behavior fundamentally different to that allowed in a classical engine. QHEs have recently been implemented using for example trapped ions [1]. However, experiments so far have not shown any non-classical features in their thermodynamic quantities. While the efficiency of a QHE is still bound by the Carnot limit, recent theoretical predictions show that coherence can boost its power output above the classically allowed limit for an engine using the same thermal resources [2]. Moreover, the presence of coherence was predicted to result in the equivalence of different QHE types in the limit of weak driving and short cycle duration.

Here, we test both predictions experimentally by implementing a QHE using NV^- centres in diamond inside a magnetic field of 0.2T at room temperature, with a microwave drive serving as a work reservoir [3]. We show that thermal Markovian dynamics, equivalent to coupling the ground states to hot and cold thermal baths, can be emulated utilizing off-resonant optical pumping and intersystem crossing. With this system, we break the upper output power bound of the equivalent incoherent classical engine by 2.4σ. Moreover, by either interlacing thermal action and coupling to the work reservoir or by switching both on simultaneously and continuously, we implement a two-stroke and a continuous QHE and show their predicted equivalence for a weak drive. This work constitutes the very first observation of quantum thermodynamic signatures in QHEs and will enable the study of signatures based on other quantum agents such as entanglement as well as their role for enhanced work extraction from QHEs as it is for example relevant to understand photosynthetic complexes or developing novel energy storage solutions.

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Towards probing biological processes at the molecular level using single NV centers in diamond

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Biological systems host a large variety of complex physico-chemical processes. Identifying and understanding biological processes at the molecular level is essential, yet difficult to achieve. The strict requirements for handling biological systems without altering their function, makes their manipulation and the probing of their charge and spin properties at the nanoscale particularly challenging.

We are currently working on using a single negatively charged nitrogen-vacancy (NV) center in diamond as a sensor to achieve this goal. This project builds on our recent achievements to create a highly sensitive and local quantum probe using the spin states of a NV center in diamond, either as a two- or a three-level quantum system (2-LS / 3-LS) [1,2]. Both the environmental noise and the driving noise were reduced by using a continuous dynamical decoupling scheme in the 2-LS [1] and a combined on- and off-resonant driving scheme in the 3-LS [2]. By extending the coherence time of the NV center towards the lifetime limit of the system, we achieved a high sensitivity to signals at various frequencies.

In this contribution, we present our current efforts to establish a biocompatible platform for single NV based quantum-sensing experiments to probe single molecules in conditions similar to their natural environment. We combine an inverted confocal microscope and positioners with nanometer precision. Interactions between biomolecules of interest, such as radicals, will take place on a functionalized surface placed in the sensing range of the NV center using the nano-positioners. Different approaches for the preparation of such surfaces are explored with the biochemists expressing and purifying these biomolecules. With this experimental approach, we aim to observe the dynamics of physico-chemical processes at the nanoscale and thereby give new insights into the molecular mechanisms behind biological functions.

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Ensembles of Nitrogen-Vacancy centers in practical industrial applications

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As heavily discussed during this workshop, the Nitrogen-Vacancy center gathers fantastic experimental advantages. It possesses state of the art room temperature coherence properties, works with microwave and visible light and its holding crystal lattice, the diamond, allows to manipulate it under various extreme conditions such as high temperature, high pressure[1], or in a biological environment[2]. This not only supports cutting-edge quantum physics experiments, but gives significant credits to practical applications.

Implanted into a two-dimensional layer close to the surface of a bulk diamond and put under wide field photoluminescence microscope, NV centers' spin dependent photoluminescence makes it possible to reconstruct, at once, the 3D components of the magnetic field generated by a sample of interests with an optical diffraction limited resolution [3]. In the case where the magnetic field is caused by a current, the inversion of the Biot-Savart law allows to cartography its passes in the sample [4].

My goal will be to present concrete applications of commercial interest of these principles. Depending on our latest actualities I will talk about high pressure high temperature superconductors [5], Paleomagnetism or electronic transport properties in two-dimensional materials.

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Optimizing synthetic diamond samples for quantum sensing technologies by tuning the growth temperature

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During the last decade, performance improvements on NV-based quantum technologies have been closely linked to the design of innovative diamond samples hosting NV defects with optimized properties. In most diamond samples, NV defects are oriented with equal probability along the four equivalent 111 crystal directions. Such a statistical distribution leads to a decreased sensitivity of sensing protocols relying on ensemble of NV defects, since only a quarter of NV spins are efficiently contributing to the detected signal[1,2]. An intuitive candidate towards achieving preferential orientation is the (111) oriented diamond, but its poor crystalline quality [3] doesn't promote it to be used in devices. In this work we use instead the (113) oriented substrates in which not only high crystalline quality is preserved but also significant alignment along the (111) direction[4].
We first demonstrate the effect of temperature variation during (CVD) growth over the orientation of NV centers created on a (113)-oriented substrate. We then succeed in obtaining preferential alignment along (111)-direction by decreasing the growth temperature. Taking advantage of the temperature dependent incorporation of NV centers during growth we succeed in engineering dense and preferentially aligned thin layers. The measured spin coherence time of these ensembles $T2 = 232 \pm 6\ \mu s$ is similar to values usually obtained on conventional (100) crystals [5]. These results prove that CVD growth temperature is a parameter that can be used as a degree of freedom to engineer optimized diamond samples for quantum sensing applications.

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Dynamical decoupling of Erbium spins in Yttrium Orthosilicate

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Rare-earth doped crystals have attracted considerable attention for applications in quantum information processing as they can exhibit exceptional coherence in both their spin and optical transitions. In the context of fiber-based quantum networks, Erbium is of special relevance as it offers a transition at a telecom wavelength. However, Erbium spins are very sensitive to interactions with each other and with their environment due to their large effective g-factor. This dramatically reduces their spin coherence times. We plan to overcome this challenge by dynamical decoupling using microwave-pulses at frequencies around 3 GHz, building on techniques that have been pioneered with NV centers. We will present simulations and the current status of an experiment that aims at achieving long coherence times of the electronic spins in Erbium-doped Yttrium Orthosilicate. In addition, we will discuss the prospects of extending the developed techniques to other Erbium-doped materials, including Yttrium Orthovanadate and diamond.

Towards detection of single spin in diamond via coupling with microwaves

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Our project aims at detecting a single spin using magnetic resonance techniques by coupling it to a high quality factor superconducting resonator. The electron spins of choice are shallow (15 nm) implanted single Nitrogen-vacancy (NV) centers in an ultrapure isotopically-enriched C12 diamond layer. After characterization at room temperature using a confocal microscopy, an Aluminium microwave resonator is fabricated on top with a nanometric constriction (width 40 nm) carefully aligned to a pre-selected NV center. The constriction enhances the magnetic field generated by the microwave frequency current, and therefore allows to increase the spin-resonator coupling strength to a range of 1 to 5 kHz [1] . Microwave-only measurements in a dilution refrigerator at 20mK should then allow to observe a spin-echo signal from a single spin.

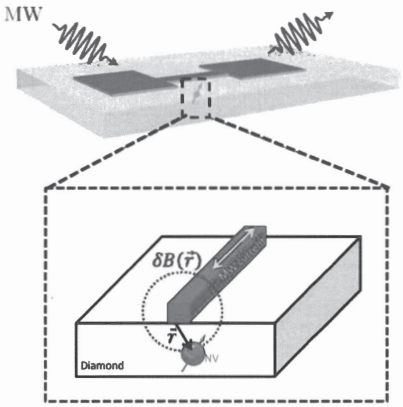

Figure 1. Sketch of our method

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Comparing the effect of macro and micro environment on cellular FND uptake

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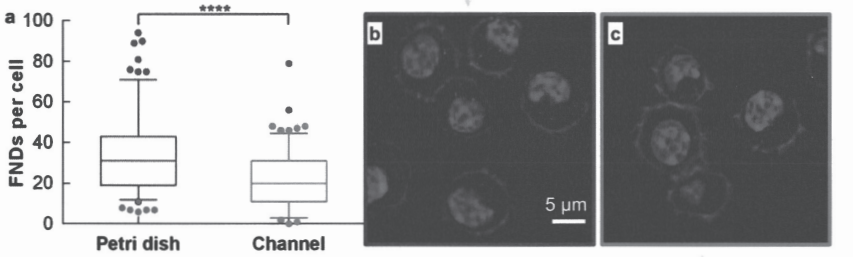
The potential of diamond magnetometry in detecting cellular free radicals has recently been identified [1,2]. This method primarily depends on the fluorescent nanodiamond (FND) uptake by cells. It uniquely allows us to conduct free radical measurements under physiologically relevant flow conditions in a microfluidic device in real time with nanoscale resolution. Although the microenvironment is well known to influence cellular metabolism and growth [3], its effect on the FND uptake in cells is not yet investigated. Specifically, it is not clear if FND uptake is enhanced or suppressed in the microenvironment compared to the macroenvironment. To this end, we compared the FND uptake in J774 murine macrophages cultured in a petri dish and a commercially available microfluidic device. Both systems have a similar cover glass bottom. Equal number of cells were seeded in both the devices followed by diamond incubation. Cells were then fixed, stained, imaged and analyzed. Figure below shows our primary results. We found that, FND uptake (shown by red spots in b & c) in cells cultured in a petri dish is significantly higher than that in a microfluidic device. To further investigate the underlying cause for this difference, we explored the effect of several parameters such as gas exchange, amount of food, size of microfluidic chip on the uptake efficiency. Based on our primary results we conclude that, extracellular gas environment and pH that are known to govern the endocytosis also alters the FND uptake. Maintaining the optimal cellular gas environment results in similar uptake efficiency in the micro and macro environment.



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Laser inscription of nitrogen vacancy center ensembles within photonic circuits in diamond

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A photonics platform in diamond would be useful for NV-based magnetometry and quantum computing [1], in which nitrogen vacancy (NV) centers are optically linked for long-range quantum entanglement due to the integration and stability provided by monolithic optical waveguides. We applied femtosecond laser inscription to form buried 3D optical waveguides in diamond (Fig. 1(a)). We show the formation of single, high quality NV centers on demand in ultrapure diamond using a single pulse from a femtosecond laser. With these building blocks in place, we fabricated an integrated quantum photonic circuit consisting of a single NV placed deterministically within an optical waveguide [2]. The single NV was excited and its emission collected by the optical interconnect, allowing easy interfacing to standard optical fibers (Fig. 1(b)). In addition, we demonstrate the laser writing of a high concentration of NV centers which show great promise for electric field sensing with record high sensitivity.

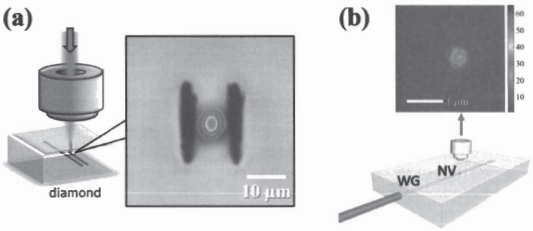

Fig. 1. Femtosecond laser written (a) buried waveguide and (b) integrated quantum device of NV addressed by waveguide (WG).

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Towards Fault Tolerant Quantum Communication using Diamond Quantum Photonic Devices

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Recently, completely new approaches have been proposed for quantum communication without quantum memories. These are measurement-based approaches that use multiphoton states, so-called photonic cluster states [1-3]. The multi-dimensional entanglement between photons in such states results in an inherent insensitivity to photonic losses: If an initial measurement fails, further measurements can be performed, significantly increasing the probability of success. In addition, since all photonic Bell-state measurements are local this eliminates the need for traditional communication between the parties and therefore the generation of entanglement at higher rates.

The goal of this research project is the realization of novel platforms for quantum communication based on novel efficient spin-photon interfaces in diamond. We aim to exploit SiV, GeV and PbV in diamond [4-6] and establish new methods for the fabrication of high-quality nanophotonic structures [7]. In contrast to the NV center, that has been well studied, such color centres promise to combine excellent photonic properties with excellent spin properties paving the way to expand quantum nanophotonics to the diamond platform [7]. Nanofabrication of photonic nanostructures will make it possible to tailor the light-matter interaction and to develop devices for spin-photon entanglement at the highest rate and quality.

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Spectroscopic investigation of the neutral charge state of the tin-vacancy centre in diamond

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Recent experiments have proven colour centres in diamond to be highly suitable for application in quantum information processing and electrical as well as magnetic field sensing, in particular the well studied nitrogen vacancy centre (NV). Nevertheless there is an ongoing effort to overcome the limitations of the NV centre which are the low photon emission into the zero phonon line and the high spectral diffusion while maintaining its excellent coherence times at room temperature. One promising candidate to achieve this aim is the neutral tin vacancy centre (SnV(0)) due to its theoretically proposed inversion symmetry, high Debye-Waller factor and long coherence times. We here provide first experimental evidence of the SnV(0) including the charge transition from the negative to the neutral charge state as well as room temperature and cryogenic spectra.

Increasing the NV center incorporation during MECVD growth of homoepitaxial diamond

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Since the unique spin properties of the nitrogen-vacancy (NV) center in diamond generate more and more attention in the fields of quantum sensing, quantum information and quantum computing [1], there is a large demand for highly controllable, repeatable and reliable incorporation of NV centers in CVD grown diamond.

Even though post-growth nitrogen implantation allows the controlled generation of thin and shallow layers of NV centers in CVD diamond, radiation induced lattice defects may degrade the coherence time of the NV centers [2] and thus their usefulness. The addition of nitrogen to the gas phase during CVD growth allows a direct incorporation of nitrogen into the diamond lattice. Post-growth annealing in combination with electron irradiation can be used to increase the generation of NV centers.

A high yield, in-situ generation of NV centers without the necessity of post-growth irradiation processes would be desirable, requiring an optimization of the CVD growth conditions. Lobaev et. al. investigated temperature and pressure dependence of nitrogen incorporation [3, 4], with secondary ion mass spectrometry as the primary analytical method. Using photoluminescence (PL), post treatment-free NV center generation was verified on a reference sample only. Tallaire et. al. [5] used different growth conditions (pressure p and temperature T) to create thin and well-defined layers with NV centers, with the drawback of a reactor inherent codependency of p and T.

In this work, an independent analysis of the effects of the gas pressure and the substrate temperature on NV center incorporation during MECVD will be presented. A dedicated substrate heater is used to control the sample temperature independently from the power density of the plasma. PL measurements are used to determine the NV center concentration in the diamond layers, with supplementary analysis of the nitrogen incorporation using SIMS. This allows for a separation of pressure- and temperature dependent effects on NV center incorporation during MECVD growth and paves the way for an optimization strategy for high yield, high quality in-situ generation of NV centers.

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Immersion of Nanodiamonds into three-dimensional direct-laser-written Waveguides

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Waveguide-coupled sensors have several applications such as magnetometry, electrometry or thermometry, harnessing the resolution of nano-sized probes as well as tight light control in macroscopic waveguide networks.

We present our approach to incorporate nanodiamonds into direct-laser-written (DLW) three-dimensional photonic structures. The nanodiamonds house ensembles of 10^3 nitrogen vacancy (NV) centers, acting as probes that can be read-out optically. Guided by the waveguide structure, detection of the optical signal from the nanodiamond does not require direct optical access. In fact, the waveguides written feature extended planar sections laid onto the substrate as well as three-dimensional structures. The latter enables simultaneous addressing and imaging of waveguide inputs and outputs through the glass substrate using a single microscope objective [1].

The NV center offers an accurately controllable spin in a solid-state system, serving as a sensitive probe of, e.g., magnetic fields. Additionally these defect centers are photostable and compatible with the DLW process. We show optically detected magnetic resonance spectra together with Rabi oscillations on an effective two-level system in waveguide-embedded nanodiamonds. We compare their performance with free-space emission and complement our experimental studies by numerical simulations [2].

This approach opens the way for on-chip three-dimensional structures for optically integrated spin-based sensing.

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Sensing chiral-induced magnetization in an integrated Nitrogen-Vacancy-based device

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Nitrogen-Vacancy (NV) centers in diamond, exhibiting unique optical and quantum spin properties, can be used as sensitive magnetometers with high spatial resolution, specifically in integrated solid-state devices [1].

In recent years, there has been increasing interest in using chiral molecules as spin filters and effective nano-magnets [2], in the context of various applications, e.g. spintronics, magnetic memories and quantum information processing. However, the exact nature and mechanisms underlying these effects are still unknown.

In this work we fabricated an integrated device, comprising of an NV-containing diamond substrate as a sensitive, localized magnetic sensor, together with a thin ferro magnetic layered topped by spatially structured chiral molecule domains. We are employing the NV sensors for studying the properties of the magnetized layer, characterizing domain size and dynamics, magnetization diffusion and magnetic field decay. This unique, local and sensitive approach could lead to new insights on chiral-induced proximity effects, advancing the state-of-the-art in understanding the physics of these phenomena, and opening new possibilities for integrated spintronics and quantum information devices.

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Efficient universal quantum gates via indirect control in diamond NV center

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Over the recent years, hybrid quantum registers, such as electron and nuclear spin systems, have emerged as promising hardware for implementing quantum information and computing. Nevertheless, the coherent control of such systems still sees challenges. Upon suitable unitary operations, the lower gyromagnetic ratios of the nuclear spins render them to respond slowly with a time scale much larger than the coherence time of the electron spin. To exploit the system advantages, we utilize an indirect control scheme that involves control fields only on the electron spin along with free evolutions under the hyperfine couplings. Here we realize a universal set of quantum gates via indirect control that form the basic building blocks of any quantum algorithm. We demonstrate high fidelity operations on nuclear spins: single qubit Hadamard gate and a two qubit controlled-NOT gate with a low number of control operations on the electron spin. The experiments are carried out on a single NV center in diamond coupled to a ^{13}C nuclear spin at room temperature. In implementing the gates, we chose a specific ^{13}C spin with hyperfine couplings of three orders of magnitude weaker than the first shell ^{13}C spin. Such spins are present in abundance and efficient control of such spins may pave the way to scalable quantum computing via indirect control.

References

Manuscript in preparation.

Spectroscopy of the negatively charged tin-vacancy centre in diamond

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Colour centres in diamond are promising candidates for quantum information processing applications. The well studied colour centres the nitrogen-vacancy centre exhibits milliseconds coherence times for the electron spin at room temperature. On the other hand the silicon-vacancy (SiV) centre shows superior optical properties including negligible spectral diffusion and high photon emission rates into its zero phonon line. The negatively charged tin-vacancy (SnV(-)) centre is a potential candidate in order to combine the favourable features of those colour centres. In comparison to the SiV centre it exhibits a roughly 20 times larger fine structure ground state splitting and is thereby potentially suitable to suppress phonon mediated decoherence processes already at liquid helium temperatures. We here present spectroscopical investigations on SnV(-) centres determining the lifetime and polarization as well as the temperature dependence of linewidth and line shifts. Furthermore, a precise determination of Debye-Waller factor and single photon emission properties are presented, enabling further investigations of spin coherence times assessing the suitability of the SnV(-) centre as spin qubit.

Towards single-shot readout of NV centers in diamond by low-temperature spin-to-charge conversion

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We present our recent progress in implementing an improved readout scheme for the nitrogen-vacancy (NV) center's spin-state combining resonant excitation at low temperature with spin-to-charge conversion. Resonant excitation exploits that the optical excitation spectrum at low temperature has sufficiently narrow linewidths[1,2] to selectively address the spin-sublevels. In combination with a second laser pulse, a spin-to-charge conversion[3,4] protocol can be implemented, where the NV center is spin-selectively excited and converted to different charge-states. These are more stable than the initial spin-state and can currently be read-out with near single-shot fidelity.

Compared to the state-of-the-art readout[5], this work promises to accelerate readout by a factor of up to 100. Besides, laser power in the optical regime can be reduced by orders of magnitude. This reduces the risk of photodamage for future sensing experiments with biological samples.

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Laser surface structuring of diamond for microfluidics and quantum sensing applications

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Quantum sensors based on the spin-dependent photoluminescence of nitrogen-vacancy (NV) centers in diamond offer great potential to achieve single-molecule detection with atomic resolution at room temperature [1]. Integrated diamond photonics would thus be beneficial for optical magnetometry, due to the enhanced interaction provided by waveguides. In fact, femtosecond laser inscription in diamond has recently been applied to form buried 3D optical waveguides in diamond, together with the formation of single high quality NV centers deterministically placed within the waveguides [2]. Diamond is also compelling for microfluidics and biosensing applications due to its outstanding biocompatibility, with sensing functionality provided by NV centers. Therefore the possibility to integrate in a diamond platform

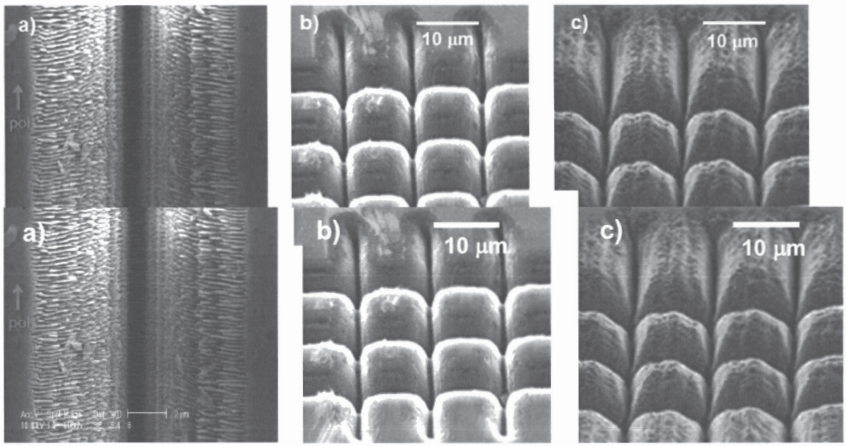

Fig. 1: Examples of surface microchannel (a) and pillar-like microstructures (b,c) obtained on synthetic diamond with different laser beam parameters.

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Progress and challenges of NV-doped diamond for ultrasensitive laser threshold magnetometry

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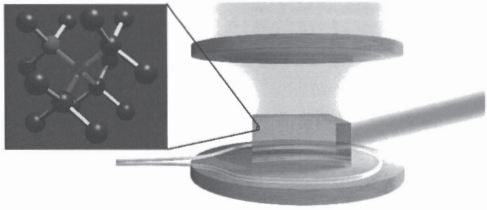
Nitrogen-vacancy centres in diamond are being widely employed to measure magnetic fields. We performed theoretical calculations showing that the precision of NV magnetometry can be vastly improved by using diamond material with high NV densities as a laser medium and making use of the intrinsic amplification and high collection efficiency of a laser system. In this way quantum-limited sensitivities could become competitive with ultra-sensitive SQUID sensors.



Motivated by this result we investigated experimentally the properties of stimulated emission of NV centre ensembles in diamond. Combining green (532nm) pump light with red (~700nm) stimulating light, we measured spontaneous and stimulated emission and characterised the occurrence of induced absorption channels.

Placing NV diamonds in optical cavities we measured an amplification of red light transmitted through the cavity, when a green pump laser was added, by a factor of 3. We furthermore identified material properties and improvement challenges and strategies for CVD growth of diamond tailored to the realisation of an NV centre laser and laser threshold magnetometry.

Sensing Weak Microwave Signals by Quantum Control

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Solid state qubits, such as the Nitrogen-Vacancy (NV) center in diamond, are attractive sensors for nanoscale magnetic and electric fields, owing to their atomically small size. A major key to their success have been dynamical decoupling protocols (DD), which enhance sensitivity to weak AC signals such as the field of nuclear spins from a single protein. However, those methods are currently limited to signal frequencies up to several MHz.

Here we harness a quantum-optical effect, the Mollow triplet splitting of a strongly driven two-level system, to overcome this limitation. We microscopically understand this effect as a pulsed DD protocol and find that it enables sensitive detection of fields close to the driven transition. To this end, we create a pair of photon-dressed qubit states which support a new transition with narrow linewidth. Generally, our scheme is applicable to any qubit but we consider sensitive detection of signals close to the NV's transition frequency (≈ 2 GHz). As a result, we demonstrate slow Rabi oscillations with a period up to $\Omega_{Rabi}^{-1} \sim T_2$ driven by a weak signal field. The corresponding sensitivity could enable various applications. Specifically, we consider single microwave photon detection, as well as fundamental research on spin-phonon coupling.

Enhanced Dynamic Nuclear Polarisation with Quantum Optimal Control

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The application of dynamic nuclear polarisation (DNP) techniques to systems with quantum defects is a promising way of achieving high levels of polarisation. The nitrogen vacancy centre (NV) in diamond is an excellent candidate as its state can be manipulated with a microwave pulse. While polarisation sequences have been designed to be robust, this is often at the expense of their efficiency. To achieve maximal polarisation transfer in as short a time as possible other techniques must be applied. We chose to apply quantum optimal control algorithms to shape the microwave pulses. A set of constraints that closely mimic our experimental setup were chosen to ensure that the shaped pulses remain realistic. Here, we hope to demonstrate pulses that have an increased robustness to errors while maintaining a high level of efficiency. In future, we hope to use these to achieve high levels of polarisation in diamond.

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Optimal Control of Linear Systems-Application in Ion Cyclotron Resonance

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Optimal Control Theory (OCT) is a powerful technique which is widely used in different fields of physics and engineering [1,2]. In this study, we address a new application of OCT in Ion Cyclotron Resonance [3,4]. This mass spectrometry technique is made of two experimental phases namely the excitation phase and the detection one, in which ions are subjected to electric and magnetic fields. In the excitation process, the goal of the control is to be robust with respect to the Larmor frequency of the ions of the cell [5,6]. The second objective of the control pulse is to maximize the detection efficiency and thus the sensitivity of the measurement process. Adiabatic pulses are commonly used to realize these tasks. Applying Pontryagin Maximum Principle, we show how to derive optimal fields in this setting. We point out the advantages and the flexibility of optimal fields, which can account for experimental imperfections and constraints. A comparison with adiabatic pulses is made.

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Negative charge enhancement of near-surface nitrogen vacancy centers by multicolor excitation

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Nitrogen-Vacancy (NV) centers in diamond have been identified over the past few years as promising systems for a variety of applications, ranging from quantum information science to magnetic sensing. This relies on the unique optical and spin properties of the negatively charged NV. Many of these applications require shallow NV centers, i.e. NVs that are close (a few nm) to the diamond surface. In recent years there has been increasing interest in understanding the spin and charge dynamics of NV centers under various illumination conditions, specifically under infra-red (IR) excitation, which has been demonstrated to have significant impact on the NV centers' emission and charge state. Nevertheless, a full understanding of all experimental data is still lacking, with further complications arising from potential differences between the photo-dynamics of bulk and shallow NVs. Here we suggest a generalized quantitative model for NV center spin and charge state dynamics under both green and IR excitation. We experimentally extract the relevant transition rates, providing a comprehensive model which reconciles all existing experimental results in the literature, except for high non-linear regimes. Moreover, we identify key differences between the photo-dynamics of bulk and shallow NVs, and use them to significantly enhance the initialization fidelity of shallow NVs to the useful negatively-charged state [1].

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Towards mode manipulation for optimally interfacing disparate defect centres in diamond

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Practical architectures for quantum communication and information processing will most likely rely on hybrid networks drawing upon the strengths of disparate physical quantum systems [1]. Interfacing stationary quantum states, based on particular disparate systems, with optical states directly imposes requirements on the spectral/temporal properties of the photons. Therefore, in order to build up a larger scale quantum network by concatenating processes in hybrid systems, a key requirement is the ability to coherently transform the photon in frequency and time to interact efficiently with the disparate nodes of the network.

One physical system is a Raman-based quantum memory (QM) which can be realised in, e.g., phonons in diamond [2] or spin ensembles in warm alkali vapour [3]. Such a QM implements a time non-stationary interaction between a single optical signal mode and an atomic excitation in the storage medium, mediated by a Raman transition control pulse. This scheme enables the storage of a chosen mode, and the on-demand retrieval of the signal. Such a scheme also enables frequency, bandwidth, and temporal-mode conversion between the stored- and retrieved-mode by appropriately tuning the control field between the storage and retrieval interactions [4], and can facilitate the coherent mode conversion required for interfacing multiple disparate physical systems.

An experimental tomography of the process underlying the storage interaction in a Raman QM in warm caesium vapor for different control pulses has previously been performed [5]. This enables one to determine the optimal control pulse needed to selectively address a chosen optical signal mode.

Here we investigate how these methods could enable the optimal interfacing via photons between dissimilar diamond quantum emitters by manipulating the spectral/temporal profile of generated photons.

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Single photon source in nanodiamonds for integrated quantum photonics

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The negatively charged silicon-vacancy (SiV-) centers in diamonds have emerged as a very promising candidate for quantum emitters (QE) due to their narrow emission line. Modifying the emission properties and enhancing the interaction strength of such QE coupled to nanophotonic structures, based on dielectric waveguides, is a challenge for integrated quantum photonics.
This work aims to study and compare physical properties of nanodiamonds NDs and optical properties of SiV centers in NDs prepared under the same HPHT conditions [1] but treated by two different methods (vacuum treatment and hydrogen-treatment) and its coupling with an ion exchange waveguide IEW in glass. We present the effect of growth temperature, Si:C ratio , and treatment methods on the morphology, crystallinity of nanodiamonds and on the optical properties of SiV in NDs (Photoluminescence spectra at room and cryogenic temperature).

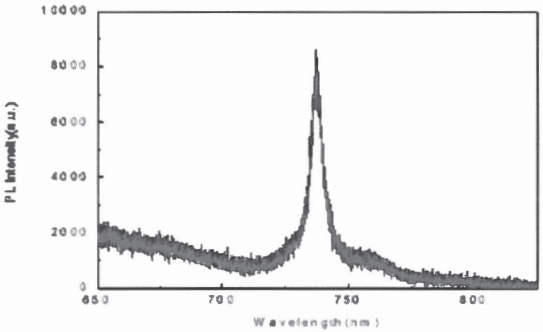

Fig.1: PL spectra of SiV centers in nanodiamonds exhibiting a narrow emission line at room temperature

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Towards reliable, scalable scanning probe sensing using color centers in diamond

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The negatively charged nitrogen vacancy (NV) color center in diamond is a bright, photo-stable dipole emitter [1]. Due to its optically addressable spin states it is used for e.g. electrical and magnetic field sensing applications. In recent years, shallowly implanted NV centers in nanopillars have been introduced as scanning probes for high resolution imaging [2]. We aim to apply these probes to life science applications. However, these applications currently suffer from an insufficient control of the surface termination of the devices leading to a potentially unstable charge state of the color center as well as a poor fabrication yield. We here show routes to overcome these issues. We discuss charge state stabilization of shallow NV centers via different surface treatments and show upscaling capabilities of the nanofabrication by using novel diamond material [3] and we introduce sensing applications relevant for life sciences.

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Enhanced light-matter interactions in ordered arrays of NV centres

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Atomic ensembles are a promising candidate for the implementation of efficient and controlled light-matter interactions, such as optical quantum memories or deterministic two-photon gates. Unfortunately, the performance of many protocols employing disordered ensembles in the solid state is limited by inhomogeneous broadening, a common consequence of increasing the density of emitters.

In ordered atomic arrays, interference of fields rescattered by atoms in the ensemble can occur. These collective effects drastically alter the optical properties of the ensemble and for example, in the case of a 1D chain in a waveguide, lead to a drastic increase in optical depth.

As a first step towards realizing solid-state devices that utilize these effects, we here theoretically investigate an enhanced light-matter interface using an array of negatively-charged nitrogen-vacancy (NV) centres in diamond coupled to a square waveguide. We report enhanced absorption compared to independent spontaneous emission. Furthermore, the influence of disorder in the array has been studied, suggesting that suitable chains of NVs can be created using state-of-the art laser-writing techniques [2]. Along with the applications mentioned above, we here study another interesting use case of these phenomena which is the enhancement of infrared-absorption in chains of NVs, enabling magnetometry protocols employing the singlet transition [3], potentially leading to more compact device designs which do not require additional cavities or multipass cells.

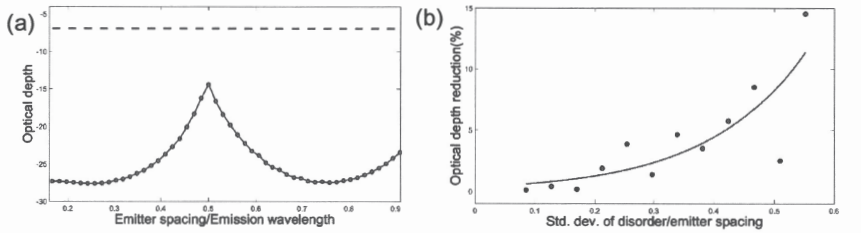

Fig.1 (a) Optical depth values with (solid line, dots) and without (dashed line) collective effects as a function of the normalized lattice period. (b) Optical depth reduction for increasing disorder.

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Modified Hanbury-Brown-Twiss Interferometer experiments on NV^0 and NV^- centers in diamond

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The master thesis will be examines the transition rates between different states (NV^0, NV^-) of a single NV center in diamond in dependence of outer influences and excitation laser wavelength and intensity. Nitrogen implementations deep into the diamond are found in negative state, more get to surface the NV centers likelier transform into neutral charging state. Hydrogen terminated diamond or diamond surface contact with air suppress negative charge state. Also adsorbates at surface, like acceptors for electrons reducing density of free charge carriers. To suppress that behavior, oxygen terminated diamond can be used. On the other hand, higher density of NV centers increases probability of finding a negative charge state in the near of the surface. Due the ionization and recombination processes, the ratio of negative to neutral charged NV centers will be changed by varying of the excitation wavelength and the power of the laser. Time dependent characterization possibilities of the charge state of a single NV center helps for estimation more complex experiments. Therefore a microscope and Hanbury-Brown-Twiss interferometer based measurement set-up was established together with controlling software. Also NV centers of standard NV doped diamonds (Element Six, Type Ib, IIa) was localized and identified by microwave frequency sweeping and anti-bunching test (see Fig.1). More accurate measuring of bunching effect in dependence on the excitation laser intensity [1] should be done. In the future the Hanbury-Brown-Twiss Interferometer will be modified in such a way, that switching between NV^0 and NV^- charged state should influence the correlation function. It would be possible to estimate the ionization rate for the concrete diamond and concrete experiment parameters.

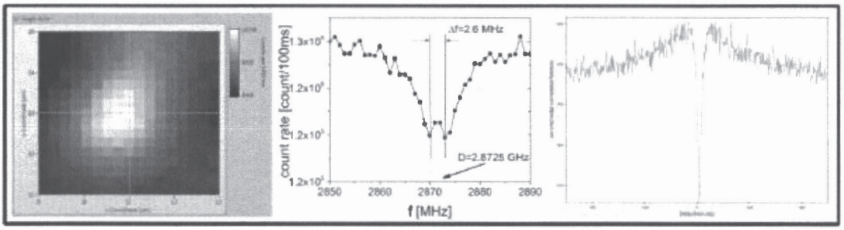

Fig.1: left: detection of NV center in diamond by measuring fluorescence intensity in xy-scan, **middle:** identification as NV center by microwave frequency sweep, **right:** identification of a single NV center by measuring anti-buncing effect in correlation function

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Interaction of nanodiamonds with bacteria

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Nanocarbons come in many forms and among their applications is the engineering of biocompatible and antibacterial materials. Studies have shown that diamond nanoparticles might have the interesting combination of both properties: they are highly biocompatible, while surprisingly reducing bacterial viability or growth at the same time. In this paper, we consider the interaction of milled HPHT nanodiamonds with bacteria. These nanoparticles are capable of hosting nitrogen-vacancy (NV) centers, which provide stable fluorescence with potential use in sensing applications. An initial study was performed to assess the interaction of partially oxidized monocrystalline nanodiamonds with Gram positive S. aureus ATCC 12600 and Gram negative E. coli ATCC 8739. It was shown that for S. aureus ATCC 12600, the presence of these nanodiamonds leads to a sharp reduction of colony forming ability under optimal conditions. A different effect was observed on Gram negative E. coli ATCC 8739, where no significant adverse effects of ND presence was observed. The mode of interaction was further studied by electron microscopy and confocal microscopy. The effects of NDs on S. aureus viability were found to depend on many factors, including the concentration and size of nanoparticles, the suspension medium and incubation time.

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Reduction of spectral diffusion by applying a sequence of optical control pulses

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Lifetime limited emission linewidths are a fundamental requirement for the generation of coherent photons, which are crucial for efficient entanglement of stationary qubits in quantum information systems.

Particularly for the nitrogen-vacancy centre (NV) in diamond, natural linewidths (~13 MHz) are challenging to achieve. To date, only NVs in bulk have shown nearly lifetime limited linewidths [1], while NVs in nanostructures with linewidth down to 400 MHz have been demonstrated [2] and nanodiamonds show even broader linewidths in the range of hundreds of GHz [3]. In addition to homogeneous broadening, especially, spectral diffusion, i.e., the change of optical transition frequency over time, caused by a fluctuation of the electrostatic environment, leads to an inhomogeneous broadening of the zero-phonon emission line (ZPL).

For the application of diamond nanostructures, for example, as spin–photon interfaces, spectral diffusion needs to be supressed. While work is done on optimizing nanofabrication methods, active control schemes are an interesting alternative. One way are active feedback schemes, where the emission frequency is adjusted by the DC Stark effect through external electric fields [4]. This method is comparably slow and requires the detection of single photons as a "reference" signal making the scheme inefficient. Recently, pulsed coherent control was proposed for the reduction of spectral diffusion [5]. This approach relies on the fact that the frequency of an emitted photon is determined by the average rate of phase accumulation between the states of a solid-state emitter over the spontaneous emission time. Applying a sequence of optical pulses to the emitter modifies the phase between the involved states and consequently the emission spectrum. An average spectral detuning due to spectral diffusion is expected to be cancelled over the spontaneous emission time by the use of several π-pulses, each changing the sign of the detuning. In this way the ZPL can be stabilized at a chosen frequency given by the carrier frequency of the pulses. Here, we present our work towards experimentally implementing the protocol for reducing spectral diffusion of the ZPL of NV defect centres by applying a sequence of optical control pulses.

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Optimal Control for Sensing With NV Centers in Diamond.

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Quantum optimal control theory has been traditionally utilized in atomic/molecular physics and NMR to overcome various limitations posed by the experimental conditions and the scientific equipment [1]. In this work we aim to develop and test nano-photonic diamond scanning probe structures containing Nitrogen Vacancy centers and implement optimal control fields to improve the sensitivity and robustness of our sensing protocols.

NV centers in diamond are extensively studied and tested as sensors due to their high spin coherence times. Their electronic spin states can be effectively read out due to the spin-dependent fluorescence, even for single NV sites. Using atomic scale single-spin sensors in a scanning probe based geometry enables sensing and imaging with maximum spatial resolution; in principle up to order of magnitude of 10 nm[2]. Optimal spin properties of NV centers as well as efficient fluorescence collection can be obtained with single NVs embedded in single-crystal diamond scanning probes. We aim to develop control functions using quantum optimal control algorithms and implement them to enhance the full imaging capability, and to achieve desired robustness against control field amplitude variations and detuning. We plan to test optimization approaches for spin manipulation followed by first proof of principle experiments on optimized sensing.

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Detecting Hydroxyl Radical using NV centers in nanodiamonds in physiological conditions

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The hydroxyl radical (*OH) is a highly reactive molecule produced naturally inside the cell. One mechanism that produces hydroxyl radicals is the decomposition of hydrogen peroxide (H_2O_2), catalyzed by ferrous iron, to one hydroxide ion and one hydroxyl radical[1]. The excess of *OH has been related to several diseases triggered by oxidative alterations of important components of the cell, such as DNA and proteins[2]. Although there are chemical indicators for *OH available commercially, they lack the ability to measure at high spatial and temporal resolution. Those two characteristics are crucial to study the processes behind the production and effects of the hydroxyl radical inside the cell. For example, the damage produced by the radical can have more or less harmful effects depending on the location where it is produced and the distance that it diffuses. On the other hand, the high reactivity of this radical makes monitoring its concentration at real time impossible with traditional markers. Diamond Magnetometry stands on a promising position because it allows the sensing of magnetic species at a subcellular scale and at a real-time sampling rate[3].

In this work, we present the results of the first attempts to detect the elusive hydroxyl radical in physiological conditions. In the experiments, to create hydroxyls radicals we have reproduced the Fenton reaction occurring in the cell. This reaction increases the complexity of the detection, because the presence of iron in the sample interfers with the signals emitted by the radical, but reproduce more accurately the situation we expect to find inside the cell.

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Thermal imaging with NV centers in diamond

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Recently, electronic spins associated to NV centers in diamond revealed attractive nanothermometers. The electronic spin resonance indeed depends on the temperature due to thermal expansion and vibronic interactions in the diamond lattice. This feature has already been exploited for thermal sensing at nanoscale, revealing sensitivities down to $mK/Hz^{1/2}$ in bulk diamond and 100 $mK/Hz^{1/2}$ in nanodiamonds [1]. Various practical sensing configurations for thermal imaging are currently envisioned depending on the sensor geometry and are here investigated: (i) wide-field or confocal imaging with bulk diamond or (ii) confocal imaging with nanodiamonds. Our experiments corroborated by numerical simulations demonstrate the strong assets of the nanodiamond-based configuration compared to bulk diamond geometry.

In order to push the sensor's sensitivity, one recently-implemented strategy builds on a hybrid architecture, exploiting a conversion of temperature variations on magnetic field variations. It takes advantage of the high sensitivity of the electronic spin to magnetic fields (down to $nT/Hz^{1/2}$) and the efficient transduction of temperature changes on magnetic field provided by ferromagnetic or ferrimagnetic coatings attached or deposited on the nanodiamond hosting the probing spin [2]. Such hybrid strategy promises to reach sensitivities down to sub-$mK//Hz^{1/2}$.

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Towards laser refrigeration of NV centres on the nanoscale

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Nitrogen vacancy (NV) centres in nano-diamonds are of considerable interest for exploring macroscopic quantum mechanics via a type of Ramsey interferometry utilising the single electron spin of the embedded NV [1]. While this idea is attractive, as it does not require strong centre-of-mass cooling, a central issue in its experimental realization is internal heating of the diamond due to the absorbed 532nm light that is used for spin polarisation. This problem intensifies when one tries to levitate the nano-diamond using optical fields, since the thermal interaction with the environment is reduced to the black body radiation of the nanoparticle.

A promising route to combat the deleterious effects of heating is the use of a laser-refrigeration via a nanocrystat [2] attached to the NV centre. So far, levitated rare-earth metal doped crystals on the nanoscale have shown to exhibit comparable cooling rates to bulk solid-state material refrigeration [3] where heat transfer from the crystal to the environment occurs by fluorescence without physical contact.

We report on progress towards laser refrigeration coupled with centre-of-mass cooling of nanocrystals. Laser refrigeration of levitated Yb3+:YLF nanocrystals to 130 K has been demonstrated, while simultaneously using the optical trapping field to align the crystal to maximise cooling. In addition, we will include our more recent results on single colloidally grown Yb3+:YLF nanocrystals and the prospects for cooling NV nanodiamond.

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Optimal Manipulation of NV-Centers for Nuclear Polarisation

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NV centers bear potential to be at the basis of a range of quantum applications. Even at room temperature and ambient conditions, their spin can be optically initialised almost perfectly. This property makes them a promising candidate to polarise other materials. Hence, applications range from hyperpolarised nanodiamonds, used as contrast agents in MRI, to nanoscale NMR spectroscopy of liquids. Different schemes have been developed to realise such polarisation transfer. Our work is concerned specifically with the optimisation of PulsePol [1], a sequence that is characterised by its speed and robustness against detuning and amplitude errors. We have identified an optimisation strategy, taking into account the quantum mechanical background and the experimental limitations using the dressed Chopped RAndom Basis algorithm (dCRAB) [2]. Furthermore, we have implemented the optimal control algorithm into the software suite RedCRAB (Remote dCRAB) which allows any user to remotely connect their simulation or experiment. This tool opens the doors for future closed loop optimisation, which promises to yield even better results. So far, our optimal control strategies have improved the pulse sequence significantly for a confocal setup, while also limiting the pulse bandwidth. Preliminary results show an increase of our figure of merit by 81%, which translates to a 30% increase in peak polarisation and improved robustness.

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Novel coupling scheme between distant Nitrogen-Vacancy centers through nano-fabricated superconducting structures

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We propose to extend NV-NV dipolar coupling to much longer distances by introducing a superconducting structure nearby the NV spins. In this work we examine a "dog-bone" shaped hole in a thin superconducting material [Fig.1 (a),(b)]. This structure should trap the magnetic flux inside the holes through the Meissner effect, and naively, transfer the flux between the two loops of the structure. By placing the structure such that the two holes are directly above NVs, we can expect an increase of the NV-NV dipolar interaction. Thus paving the way to scalable networks [Fig.1 (c)].

A numerical semi-classical magneto-static approach was taken, with the NVs treated as static magnetic dipoles positioned beneath a superconducting layer with a "dog-bone" structure. The simulation results are shown in [Fig.1 (d)]. The figure shows the current using a stream function, with the current flowing on the contour lines. Notice that the structure was not explicitly marked in the figure, the black "dog-bone" outline is a contour line resulting in currents that flow around the structure. As can be seen in the figure, only a small part of the current circulates around the entire structure. We next use these currents and calculate the magnetic fields and the expected dipolar interaction for different structure lengths. Normally, the NV dipolar interaction scales as r^{-3}, where r is the NV-NV distance, but with the structure this scaling becomes $\approx r^{-\frac{3}{2}}$ [Fig.1 (e)]. As such, the coupling is substantially improved and the relative gain in the interaction increases with r.

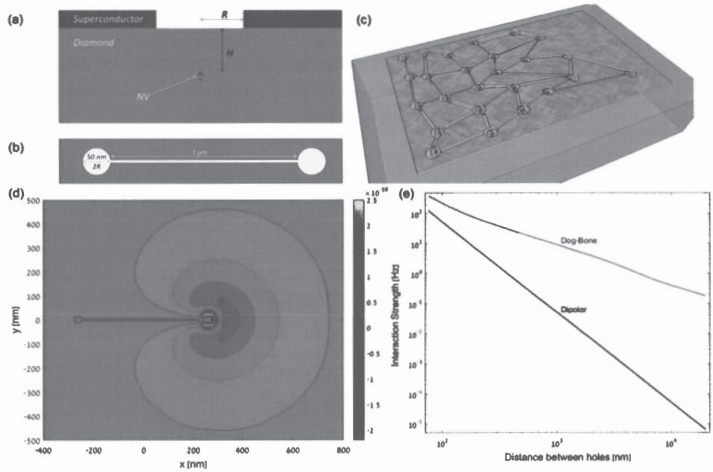

Fig. 1. (a) Side and (b) top view of the suggested structure, typical sizes marked. (c) A possible implementation of many such structures coupling multiple NVs. (d) The current stream function arising from a single NV under one of the holes (center of figure) in the structure. The Current flows on the contour lines, units are in Ampere. (e) The NV-NV dipolar interaction strength as a function of the distance between the NVs with the structure (red) and without (blue).

We are in the process of fabricating such "dog-bone" structures in order to perform experiments.

Diamond nanostructures as spin-photon interfaces for controlled coupling of single defect centres to light

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A central aim of quantum information processing is the efficient entanglement of multiple stationary quantum memories via photons to realize scalable quantum networks. Recently, quantum entanglement was demonstrated between two individual nitrogen-vacancy (NV) electron spins with rates slightly higher than the decoherence rates of the entangled NV spins [1]. The further improvement of these entanglement rates and scaling to networks with more than two nodes requires spin-photon interfaces based on optical resonators and efficient collection strategies. Nanophotonic devices can provide such functionalities.

Here, we present our previous and present work on fabricating and implementing nanophotonic devices in diamond for interfacing single spin defects with light. We describe NV–nanophotonic systems in the strong Purcell regime [2] with optical cavity quality factors approaching 14,000 [3] and electron spin coherence times exceeding 1.7 ms [4], a scalable method to create spin–cavity systems via implantation of nitrogen [5], and how nanophotonic devices can be used to shape the emission properties of spin defects to overcome their intrinsic optical inefficiencies, and can provide extremely high photon extraction efficiencies [6,7]—an important step towards improved entanglement rates. Hybrid diamond–semiconductor on-chip networks are used for the integration of multiple functional NV–nanostructure systems [8] and highly-efficient coupling to fibres is demonstrated [9]. Towards multi-qubit quantum registers, we demonstrate how three quantum memories within ~150 nm^3 can be simultaneously coherently controlled and read-out resonantly [10]. For the generation of coherent optical photons [11], we exploit novel group-IV diamond defect centres coupled to optical nanocavities. Finally, we give an update on our most recent work on coherent optical control and nanophotonic integration.

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Integrated opto-electronical setup for milli-Kelvin temperature experiments on vacancy centers in diamond

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Vacancy centers in diamond are emerging as powerful quantum elements for various technologies, such as sensing, computing, and communication. Their single emitter quality and distinguished electronic and nuclear spin properties make them a remarkable tool for many quantum technological applications both at room and cryogenic temperatures.

We are developing a cryogenic setup for addressing the vacancy centers both optically and electromagnetically at mK temperatures, allowing fundamental investigations and an integration of the emitters into molecular quantum devices. The optical setup is a fiber-based scanning confocal microscope implemented in a table-top dilution refrigerator with 20 mK base-temperature. An elaborated wiring allows the operation of dedicated dc- and rf-equipment at low temperatures, including filters, coils, and micro-fabricated devices. Special care is taken to eliminate thermal leakage and to minimize mechanical vibrations present close to the sample.

Fast universal holonomic manipulation with the state of a two-qubit register

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We present a scheme that allows to perfrom a universal set of geometric gates on a two qubit register, formed by a carbon-13 nuclear spin coupled to the electron spin of a nitrogen-vacancy center in diamond. Our scheme does not require application of radio frequency pulses. Such a scheme that relies on microwave tones only should allow to perform any gate on the submicrosecond timescale.

Engineering colour centres in diamond using laser-writing techniques.

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The engineering of colour centres in diamond is one of the key challenges in the realisation of diamond quantum technologies. In recent years there have been many advances in the controlled positioning of NV centres in diamond using ion implantation and electron beam irradiation methods, but questions remain as to whether these techniques can be translated to the scalable manufacturing of devices or to realise advanced quantum technologies, where factors such as the yield of useable colour centres become important. Recently, laser processing was shown to be an effective way of writing lattice vacancies into diamond with minimal residual damage such that binding with substitutional nitrogen impurities already present in the lattice yielded high quality single NV centres [1,2]. However the 'global' thermal anneal used to facilitate the random diffusion of vacancies and subsequent NV centre creation meant that the number of NV centres produced per site was nevertheless determined by Poisson statistics such that the maximum probability of creating a single NV centre at a given site was 37%, and that the positioning accuracy of the resultant NV centres was limited to a few hundred nanometers by the vacancy diffusion length.

Here we will discuss latest developments in the use of laser processing to not only create but also to diffuse vacancies in place of a thermal anneal, providing site-specific control of NV centre formation [3]. When combined with online fluorescence feedback to allow active control of the process we achieve near-deterministic writing of NV centres with an accuracy of around 50 nm in the image plane (figure 1).

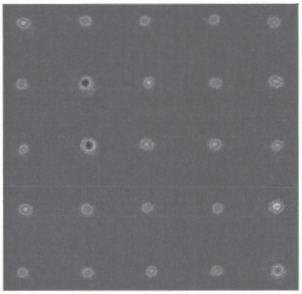

Figure 1: Fluorescence image of a 2-μm pitch laser-written array in which 24 out of the 25 sites are occupied by a single NV centre.

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Geometric Phase Magnetometry Beyond the Adiabatic Limit

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We present a protocol for sensing static magnetic fields based on the non-adiabatic geometric phase. Due to an unwrapping of the 2π phase ambiguity the protocol works with a higher range of field-amplitudes as compared to a Ramsey scheme while at the same time achieving a higher sensitivity. Our scheme is not constrained by an adiabaticity requirement and therefore goes beyond current proposals for magnetometry via Berry's phase. We propose an experimental implementation of the protocol with NV centers.

Heisenberg-limited metrology with little entanglement

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The derivation of bounds on metrology typically assume access to full control over all involved particles. Here we relax this assumption and study metrological performance in scenarios where only limited control is available. As an example, we consider the measurement of a static magnetic field when a fully controlled quantum sensor is supplemented by number of particles over which only global control is possible. Even in the case that the quantum sensor is subject to significant noise, by adopting a protocol that maps the magnetic field to a precession frequency first, it becomes possible to achieve transient super-Heisenberg scaling and an uncertainty that can approach that of the scenario with full control to within a constant factor. Remarkably, in this protocol an initial product state is used and entanglement is not used as a resource. Applications to hybrid quantum sensor and the detection of weakly coupled nuclear spins are discussed.

Sensing of magnetic field from *in-vivo* biological systems using diamond NV centers

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Nitrogen-vacancy (NV) color centers in diamond are atomic-scale defects that enable high-resolution quantum sensing and imaging of magnetic field via the process of optically detected magnetic resonance (OMDR). ODMR has the potential to reach sub-picotesla[1] sensitivity with high spatial resolution. Diamond magnetometry is highly applicable to biological systems requiring close sensor proximity under ambient conditions. Here we present an example of such magnetometry measurements taken *in-vivo* on frog (*rana esculenta*) sciatic nerve in our inverted microscope setup. We use a defect ensemble in a ^{12}C-enriched, CVD-overgrown diamond with high defect density from proton irradiation, yielding sub-nanotesla sensitivity with bandwidth >1KHz. This has allowed us to directly measure the magnetic field arising from nerve action potential when stimulated by an external current pulse. Although not limited to biological samples, we show that our setup is highly suitable for non-invasive biological sensing, allowing a sample to remain in solution in a custom-built holder and permitting measurements for extended periods (hours). This can be achieved without laser-induced damage and with high thermal stability[2].

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Photo-Excitation Dynamics of the NV⁻ Center in Diamond

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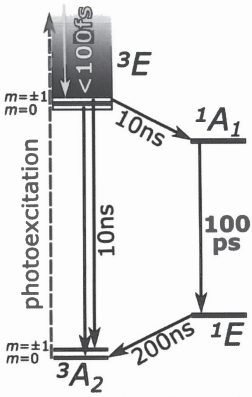
The negatively-charged nitrogen-vacancy defect (NV^-) features an interesting combination of spin and optical properties that lead to remarkable properties that can potentially be exploited in applications such as solid-state qubits, highly sensitive electric and magnetic field probes and single-photon emitters.

Within the diamond bad gap, the main NV^- center electronic levels are the spin triplet $^3A_2$ electronic ground state and doubly degenerate ^3E excited state, which are separated by an energy of ~1.95 eV. Vibronic coupling to localized vibrational modes gives rise to a broad (~300meV) phonon sideband in the optical absorption and fluorescence spectrum. Furthermore, the ^3E excited state is subject to a Jahn-Teller (JT) distortion that lifts its double orbital degeneracy and creates a conical intersection (CI) between both orbitals. Two more spin singlet states ($^1A_1$ and ^1E) are present that are essential for enabling optical readout of the $^3A_2$ spin projection state m and establishing its spin polarization through a series of electronic transitions, as shown in the Figure.



We apply optical transient absorption spectroscopy to study the dynamics of the NV^- defect after photoexcitation by probing the transient dynamics of its optical spectrum with femtosecond time resolution. Our measurements probe hitherto unresolvable dynamics and permit determining the timescales of two relaxation channels. We measure the vibrational relaxation in the phonon sideband of ^3E to occur within less than 100 fs [1], two orders of magnitude faster than previous 2D coherent spectroscopy experiments have found [2]. The electronic relaxation $^1A_1 \rightarrow {}^1E$ between the two singlet states, which occurs predominantly non-radiatively, is measured to be 100 ps [3].

We also report on time-domain measurements of the electronic dephasing between the two orbitals in the ^3E excited state where we find biphasic decoherence dynamics [4]. Backed up by ab-initio molecular dynamics simulations we find the dephasing to be due to non-adiabatic transitions between the two electronic orbitals that are facilitated by the presence of the CI and phonon-induced dephasing.

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Quantum sensor-processor system based on single NV center and ^{13}C nuclear spins.

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With current advances in technology the control over individual quantum systems has become possible including individual cold atoms, ions and molecules, superconducting qubits and quantum dots and solid-state spin defect. This paves the way towards sensing and measurements on quantum level as well as quantum information processing and quantum simulation. The nitrogen-vacancy (NV) center in diamond as a solid-state system gained much interest thanks to its unique combination of spin and optical properties, allowing for the optical initialization and readout of the electron spin state and the ability to coherently manipulate it with resonant microwave excitation. The electron spin resonance frequency is shifted by various external fields, including magnetic and electrical fields. Precision sensing of nuclear spins with a chemical resolution [1] and [2] was shown recently with the potential to perform single molecule or single cell spectroscopy. This task remains challenging due to difficulties with low sensing sensitivity and dynamic range, as well as fast diffusion in the target media. However, various pathways were proposed to overcome these challenges, one of them is to increase the performance of the quantum sensor by using the quantum coprocessor formed by ancilla nuclear spins. The NV center can not only act as a sensor to interact with external measured quantities but also with individual nearby nuclear spins. These nuclear spins include the intrinsic ^{14}N nuclear spin but also ^{13}C nuclear spins which are at proximal sites of the NV center and thus interact strongly with it. In this work we show how quantum algorithms can be efficiently used to improve the performance of the quantum NV electron spin sensor, in particular to increase its dynamic range and the amount of sensing information obtained by it per time. We show its performance in quantum phase estimation measurement involving a sensing phase with subsequent application of the quantum Fourier transformation to the quantum register. Thereby, we perform efficient readout of multiple acquired phases of the sensor in one run of the sensing sequence.

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Magnetic domain walls as controllable and non-volatile spin-wave nanochannels

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Utilizing spin waves as information carriers in wave-based logic architectures is a promising approach to extend conventional charge-based circuitry by additional functionalities as well as to reduce energy consumption connected to Joule heating [1,2]. For the realization of complex devices with high integration densities, efficient and flexible means have to be established to guide spin waves on the nanometer scale. Magnetic domain walls are highly versatile and reconfigurable, rendering them ideal candidates for spin-wave channels that confine the information transport to nm-wide conduits [3-5]. Using μBLS, we investigate spin waves that are guided along Néel walls in microstructured thin-film elements made of Py and Fe and support our findings by micromagnetic simulations [6]. Additionally, we present first experimental observations of spin-wave transport along interconnected Néel walls in flux closure domain structures as well as along walls that suddenly change their direction at the edge of the microstructure. The NV spin system will be an ideal and unique tool for real-space studies of magnons, since it forms a sensitive, nanoscale magnetometer, which readily offers sensing bandwidths in the GHz range. These versatile sensors, operating under ambient conditions, probe both the static and dynamic magnetic stray fields emerging from magnons as well as the domain walls with high spatial resolution [8]. Hence, the aim is to employ nitrogen vacancy centers in diamond to shed light on this novel type of spin-wave modes confined via magnetic textures on the nanoscale and their use in quantum sensing technologies.

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Microwave-induced coherent population trapping in unknown defect in diamond

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Solid-state point defects with optically addressable spin state present an interest for quantum technology [1]. In this work a previously unknown centers have been observed in IIa natural diamond by photoluminescence spectrum with zero-phonon line at 446 nm and studied by ODMR technique at room temperature. In addition coherence population trapping of electron spin have been demonstrated. To address each center individually a home-built microscope with confocal detection volume of 0.6 μm^3 has been utilized. The concentration of defects is estimated to be around $3*10^9$ cm^{-3}. A preliminary model for defect is S = 1 metastable level in between ground and excited S = 0 levels. Zero-field ODMR spectra of a triplet state are characterized by two pronounced lines at approximately 2270 MHz and 500 MHz with substantial – up to 10 MHz – difference from center to center with positive contrast up to 50 percent. Under moderate magnetic field of few hundred gauss, ODMR lines are shifted depending on the orientation of defect along the external magnetic field and broadened considerably. Additional NV^- confocal detection path was implemented to align the direction of external magnetic field and corresponding ODMR spectra were measured to calibrate strength of this field.

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Efficient indirect control of nuclear spins in diamond NV centers

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(Dated: November 23, 2018)

Hybrid quantum registers, such as electron-nuclear spins of nitrogen vacancy (NV) center in diamond [1], consist of different types of qubits. They offer a range of advantages as well as challenges. The main challenge is that some types of qubits react only slowly to external control fields, thus considerably slowing down the information processing operations. Here, we propose and demonstrate an indirect control scheme that allows us to control the nuclear spins of an NV center indirectly, by control operations applied to the electron spin, combined with free precession under the anisotropic hyperfine interaction [2]. The scheme provides universal control and we present two typical applications: polarizing the nuclear spin and measuring nuclear spin free induction decay signal, both without applying radio-frequency pulses. Our elementary unitary operations consist of only 2 - 3 rectangular microwave pulses separated by delays, thus greatly reducing the control cost. This scheme is versatile as it can be implemented over a wide range of magnetic field strengths and at any temperature.

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Diamond magnetometry with high DC field sensitivity for novel human machine interface applications

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Negatively charged nitrogen vacancy (NV^-) center ensembles in diamond has demonstrated a great potential with achieving a subpicotesla magnetic field sensitivity [1], which makes it a competitive candidate for magnetoencephalography (MEG) based human machine interface applications. In order to take full advantages of the diamond magnetometer, the DC field sensitivity need to be further improved for such applications. In this work, ^{13}C purified diamonds with high quality NV^- center ensembles in concentration of 0.9 ppm were used, demonstrating a ~80 kHz optically detected magnetic resonance (ODMR) linewidth. Several techniques are proposed to push the noise floor approaching the limit. (i) Balanced detection is well maintained with the optical reference arm being closed-up so that the common mode noises are perfectly suppressed; (ii) high frequency laser modulation is applied for phase sensitive detection of the evanescent fluorescence signal in pulsed measurement scheme, in order to avoid 1/f noises from the photodiodes; (iii) Hahn-echo measurement scheme is applied to achieve a DC gradient field sensing with the diamond vibrating along its 111 direction. A high depth resolution can be achieved using one diamond with the relevant coherence time being extended from T_2^* to T_2. With these techniques, diamond magnetometers can get both a high field sensitivity and depth resolution to acquire MEG signals for HMI applications.

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Microwave-free vector magnetometry using nitrogen-vacancy centers in diamond

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We demonstrate a microwave-free magnetometer that simultaneously measures all Cartesian components of a magnetic field using nitrogen-vacancy (NV) ensembles in a single-crystal diamond. In particular, we present a magnetometer based on the photoluminescence (PL) feature of the level anti-crossing in the triplet ground state at 102.4 mT, capable of vector sensing of the magnetic field. This solid-state system enables simultaneous readouts of each Cartesian component free from heading errors [1].

Vector capability of a previously demonstrated microwave-free magnetometer [2] is achieved by low frequency modulation of the transverse field and subsequent demodulation of the magnetic-resonance frequency. This sensor exhibits a demonstrated axial and transverse noise floor of ≈300 pT/√Hz and 850 pT/√, respectively. We like to point out that this technique is also applicable to single NV center magnetometer.

The proposed and demonstrated solid-state microwave-free magnetometer with high resolution and high sensitivity that can work under ambient conditions. Removing the requirement for microwaves while maintaining measurement sensitivity represents a significant step towards the development of robust, non-invasive and miniaturized magnetic field sensors.

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