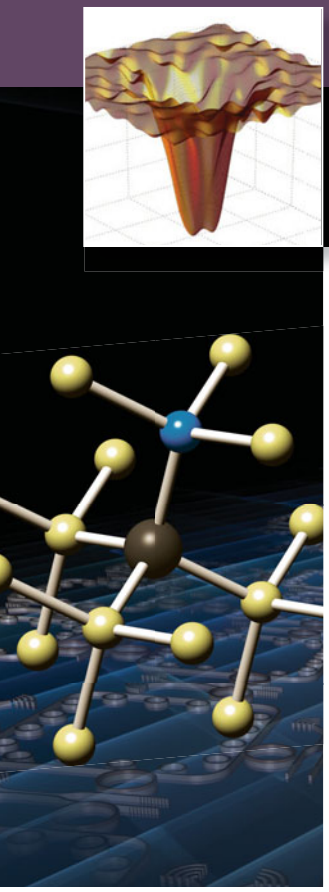


Nanoscale sensing and imaging in biology using the nitrogen-vacancy center in diamond

L.T. Hall, D.A. Simpson, and L.C.L. Hollenberg

The use of the nitrogen-vacancy (NV) center in diamond as a single spin sensor or magnetometer has attracted considerable interest in recent years because of its unique combination of sensitivity, nanoscale resolution, and room temperature operation. These properties, together with long-term photostability of the NV fluorescence and the inherent biocompatibility of diamond, make the NV system ideal for applications in biology. This article focuses on the role of the NV center in biological applications from optical tracking to nanoscale sensing.

Introduction

The nitrogen-vacancy (NV) center in diamond has emerged as an important system for quantum sensing applications. This atomic-level defect displays a remarkable range of properties, including sustained fluorescence,[1] long quantum coherence times under ambient conditions,[2] and demonstrated biocompatibility.[3–5] Nanoscale ambient magnetometry using single NV spins has been demonstrated experimentally in controlled environments[6–8] with reported AC sensitivities[2] of 4 nT $Hz^{-1/2}$. Wide-field imaging using NV emsembles[9] has recently demonstrated sensitivity[10] at 100 nT $Hz^{-1/2}$. By implementing dynamical decoupling control, it may be possible to extend the sensitivity even further (e.g., to the pT $Hz^{-1/2}$ level using the Uhrig scheme).[11] Optical absorption-based techniques at low temperatures (75 K) also show great promise with demonstrated sensitivities down to 7 nT $Hz^{-1/2}$.[12] For random magnetic field fluctuations in biological contexts, it has been proposed that probing the quantum decoherence time of the NV system *in situ* could enable direct noninvasive monitoring of processes at the nanoscale.[13,14]

In this article, we review some recent work on applications of NV magnetometry in biology, such as fluorescence tracking, noninvasive ion-channel detection, and neuronal network imaging, and discuss the opportunities and potential for nanoscale tracking, sensing, and imaging.

The NV center as a fluorescent biomarker *in vitro* and *in vivo*

Fluorescent nanoparticles have been lighting the way in biology for decades, providing great insight into the complex processes and mechanisms occurring at the intracellular level. Modern biomarkers exist in many forms, such as fluorescent proteins, organic dyes, quantum dots, and single molecules, and while these markers have been effective in illuminating biological processes, they often lack the desirable feature of photostability over arbitrarily long time scales. Over the past decade, there has been significant interest in the fluorescent properties offered by a new family of biomarkers in the form of optical defects in diamond. Color centers in diamond are photostable down to crystal sizes <10 nm,[15,16] and the chemically inert diamond matrix is optically transparent and exhibits low cytotoxicity.

The optical properties of the NV center in particular are well suited for biomarking applications, with convenient optical excitation from 514–560 nm, and emission in the near infrared (637–800 nm) away from most autofluorescent cell components such as flavins, nicotinamide adenine dinucleotides, collagens, and porphyrins. The luminescence from a single NV center is comparable to that observed from a single quantum dot,[17] and considering that a single nanodiamond (ND) on the order of 30 nm is capable of hosting multiple NV centers,

L.T. Hall, School of Physics, University of Melbourne, Australia; lthall@student.unimeb.edu.au
D.A. Simpson, School of Physics, University of Melbourne, Australia; simd@unimelb.edu.au
L.C.L. Hollenberg, School of Physics, University of Melbourne, Australia; lloydch@unimelb.edu.au
DOI: 10.1557/mrs.2013.24

© 2013 Materials Research Society
https://doi.org/10.1557/mrs.2013.24 Published online by Cambridge University Press

the brightness and stability of these diamonds become suited to single particle tracking (SPT) of NDs within cells[18,19] (see **Figure 1**).

Investigations into particle/cell interactions and the internalization pathways of single NDs hosting NVs with human HeLa cells showed a relatively high co-localization of endosomes (intracellular vesicles) and agglomerated NDs (Figure 1c–d).[20,21] Although interestingly, transmission electron microscopy found that NDs less than 10 nm in size exhibit a low co-localization with the intracellular vesicles. This is an extremely promising result for the exploration of NDs as drug delivery vehicles, since it is common for nanoparticles to become trapped in endosomes, preventing them from delivering the attached drug, DNA, or protein. Faklaris and co-workers have also demonstrated improved image contrast of NDs in HeLa cells through time-gated detection of the NV center fluorescence.[20] In a separate study, Chang and co-workers demonstrated for the first time long-term SPT in all three dimensions in HeLa cells using the stable emission from NV.[19]

In vivo studies[4] of NDs containing NVs have been carried out in the model organism *Caenorhabditis elegans* nematode (roundworm) to explore the nano-biointeractions between the ND and organism (Figure 1e–f). NDs were introduced into wild-type *C. elegans* by either feeding them with a colloidal ND solution with multiple NV centers per particle or microinjecting the ND suspension into the gonads of the worms. The successful incorporation of NDs into the second generation of the organism showed that the entire embryonic development of the ND-containing embryos appeared to be normal.[4] The observation indicates that at this level, the NDs are biologically inert and do not cause any abnormality in cell division, differentiation, or morphogenesis during embryonic development. They also do not elicit any detectable stress response.

The NV as a bio-nanomagnetometer

The paramagnetic ground-state properties of the NV center in diamond provide a unique quantum sensing platform that ultimately might be used to probe the nanoscale intracellular

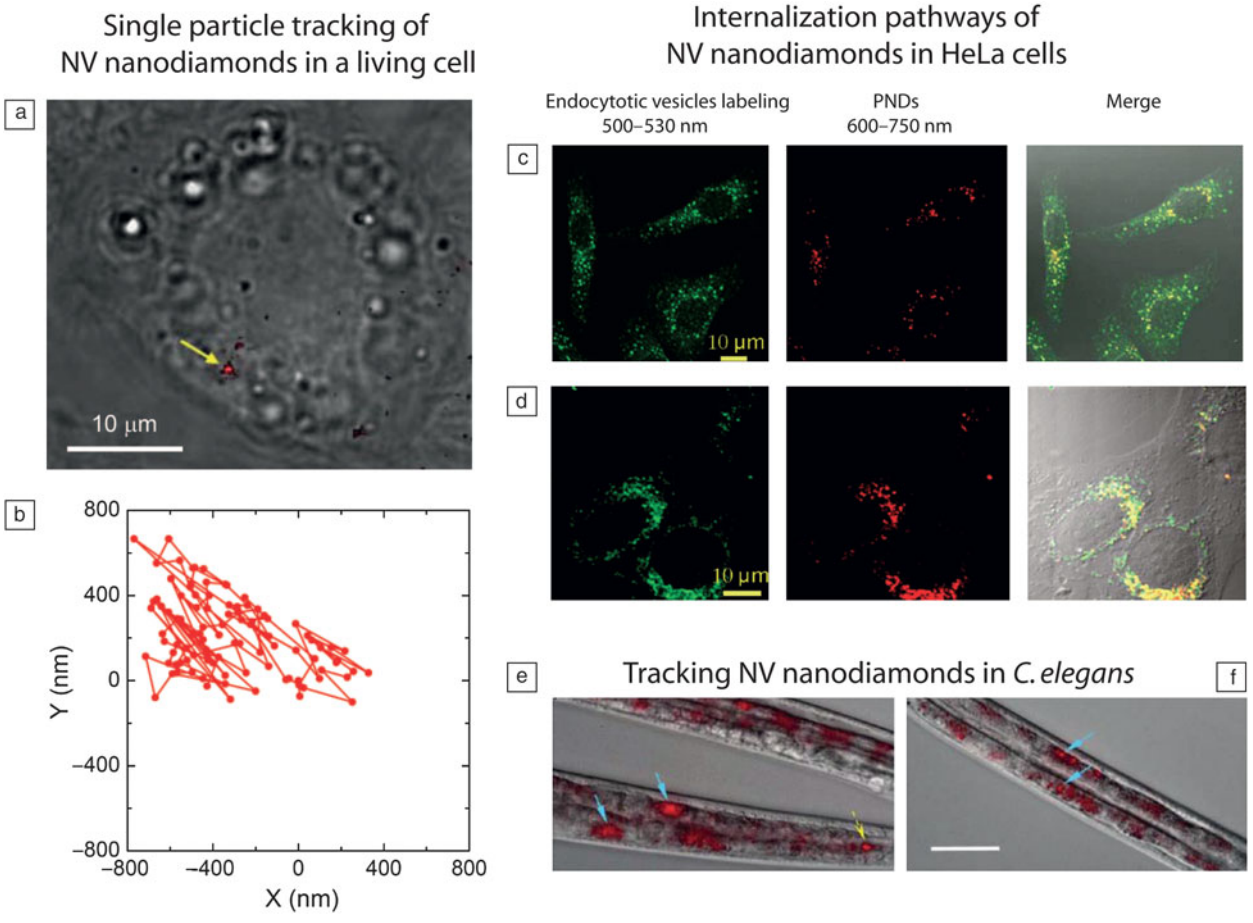


Figure 1. Examples of fluorescent tracking of nitrogen-vacancy (NV) centers in nanodiamonds (NDs). (a–b) 35 nm NV-NDs in a live HeLa cell and the corresponding trajectory of a single NV-ND, indicated by the yellow arrow. Reproduced, in part, with permission from Reference 4. (c–d) Co-localization studies of NDs with (c) early endosomes and (d) lysosomes. The NDs co-localized with endosomes or lysosomes appear in yellow in the merged fluorescence scans. Reproduced, in part, with permission from Reference 18. (e–f) *In vivo* tracking of NV-NDs in *C. elegans.* The images show worms fed with fluorescent NDs with either a (e) dextran-coating or a (f) bovine serum albumin-coating. Reproduced, in part, with permission from Reference 21. PNDs, photoluminescent nanodiamonds.

https://doi.org/10.1557/mrs.2013.24 Published online by Cambridge University Press

environment of cells. The ground-state manifold has spin sublevels ($m_s = 0, +1, -1$). The +1 and –1 states are degenerate in zero-field and are split from the 0 state by 2.87 GHz. An important property of the NV system is that under optical excitation, the spin levels are distinguishable by a difference in fluorescence, hence spin-state readout is achieved by purely optical means. Following the proposal of Chernobrod and Berman to use the optically detected magnetic resonance of a single spin as a nanoscale magnetometer,[22] proposals for DC and AC detection specifically using the NV center[23,24] were quickly followed by experimental demonstrations.[6,7,12] Generally, in these protocols, the phase accumulated by an NV spin in a magnetic field is converted to a population difference between the spin levels. Given that the population of the $m_s = 0$ state is proportional to the NV fluorescence under optical excitation, measurement of this fluorescence determines the phase accumulated and hence the magnetic field strength.

The sensitivity of the NV center as a magnetometer is primarily governed by the transverse spin relaxation time T_2 of the spin levels,[23–25] which can be measured by microwave-driven spin-echo sequences, and is relatively long even at room temperature. Type 1b diamond is typically T_2 times of ~15 μs,[26] however, t_2 = 1.8 ms has been demonstrated in isotopically engineered diamond. These times may be further extended using dynamical decoupling (see the article by Hong et al.),[11,27–29] hence multi-pulse magnetometry[11,24] offers increased sensitivity, as recently demonstrated experimentally.[28,30]

Many important biological and condensed matter systems exhibit non-sinusoidal fluctuating magnetic fields with extremely low or zero mean values, meaning that detection protocols based on the presumption of either DC or AC field dynamics will not be applicable. In Reference 13, the authors proposed using the change in decoherence (both T_1 and T_2 modes) of the NV as the primary sensing mechanism. By probing the decoherence rate of a spin qubit placed in a noisy environment, one can characterize the underlying fluctuation rates and root-mean-square field strengths that would be otherwise inaccessible.[14] A similar scheme for detecting spin noise using a modified control sequence was proposed in Reference 29. Related to this idea is the proposal to detect nuclear spin dimers through the modulation of the spin-echo envelope due to their mutual spin fluctuations.[32] These decoherence-based sensing methods may provide a useful addition to the toolbox of NV-based detection, particularly for random fields characteristic of certain biological processes. In the following, we outline two specific examples that have been proposed in this context—ion channel detection[33] and neuronal imaging.[34]

The importance of the cell membrane in biology as a critical regulator of life is reflected by the fact that the majority of drugs target membrane interactions.[35] Ion channels control the diffusion of ions across the cell membrane,[36] while ion pumps actively create and maintain the potential gradients across the membranes of living cells.[37] To monitor the effects of new drugs and drug delivery mechanisms, a wide-field ion channel monitoring capability is essential.[38] High-resolution recording of the ionic currents flowing through a cell's plasma membrane often employs invasive patch clamp techniques, in which a micropipette is attached to the membrane, that are difficult to scale-up. An interesting application of the NV therefore is as a noninvasive detector of ion-channel function.[34] The proposed scheme, shown in **Figure 2**, involves an NV center at the end of an AFM tip brought into close proximity to the ion channel. The conditions under which the quantum coherence of the NV center is sensitive to the flow of ions through the channel to

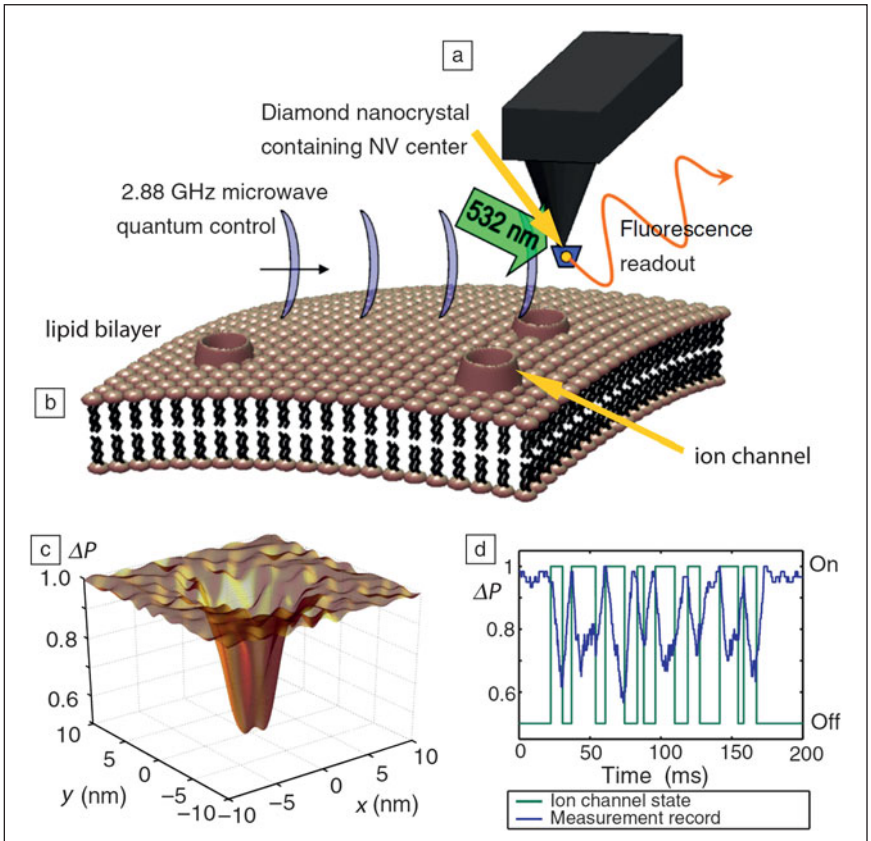


Figure 2. Quantum decoherence detection of ion channel operation using the nitrogen-vacancy (NV) system. (a) A single NV defect in a diamond nanocrystal is placed on an AFM tip. The nearby cell membrane is host to channels permitting the flow of ions through the membrane. (b) The ion motion with random nuclear spin orientations results in an effective fluctuating magnetic field at the NV position, which decoheres the quantum state of the NV system. (c) A planar *x*–*y* map of the decrease in fluorescence (ΔP) associated with the decoherence of the NV, which is most pronounced in regions close to the ion channel opening. (d) Monitoring changes in NV fluorescence ΔP also permits the temporal tracking of ion channel dynamics. Reproduced with permission from Reference 34. © 2010 National Academy of Sciences.

https://doi.org/10.1557/mrs.2013.24 Published online by Cambridge University Press

allow real-time detection of ion channel dynamics were determined theoretically.[34] Measuring the transverse spin relaxation time through a spin-echo sequence, the decrease in quantum coherence of the NV (seen as the reduction in fluorescence in Figure 2c–d) induced by the nuclear spins of the ion flux provides a potential monitoring capability for the ion channel system, despite the various background sources of magnetic noise.

It was shown that this decoherence-based detection method could resolve the spatial location of a given ion channel and/or temporally resolve a sequence of switch-on/switch-off events of an ion channel's operation.[34] With regard to scale-up to a wide-field imaging capability, a strategy using a thin sheet containing many NV centers in a bulk diamond probe[9] was considered. Such a detection mode has the potential to characterize ion channel action, and possibly other membrane proteins, over wide fields with important implications for molecular biology and drug discovery.

The NV center's ability to detect nanoscale magnetic fields under ambient conditions may open up new applications in neuroscience. Techniques based on electrical detection of neuronal activity are limited in the number of locations that can be recorded simultaneously at sufficiently high spatial and temporal resolution. The NV detection method described in Reference 33 is based on noninvasive magnetic field detection and is therefore fundamentally different to approaches based on detection of electric fields. Consequently, it does not suffer from associated drawbacks such as probe positioning with respect to the Debye length and ever-present background electrical noise sources. The setup consists of a wide-field NV imaging system where neurons can be grown directly on the diamond surface containing an ensemble of NV centers (**Figure 3**a).[39] The ensemble is sensitive to the magnetic fields arising from the transmembrane potentials generated by the neural activity at submillisecond time scales (Figure 3b).

The magnetic field of a physical neuron model (the hippocampal CA1 pyramidal neuron) has been simulated with reference to the NV detection scheme (Figure 3c–d).[33] The

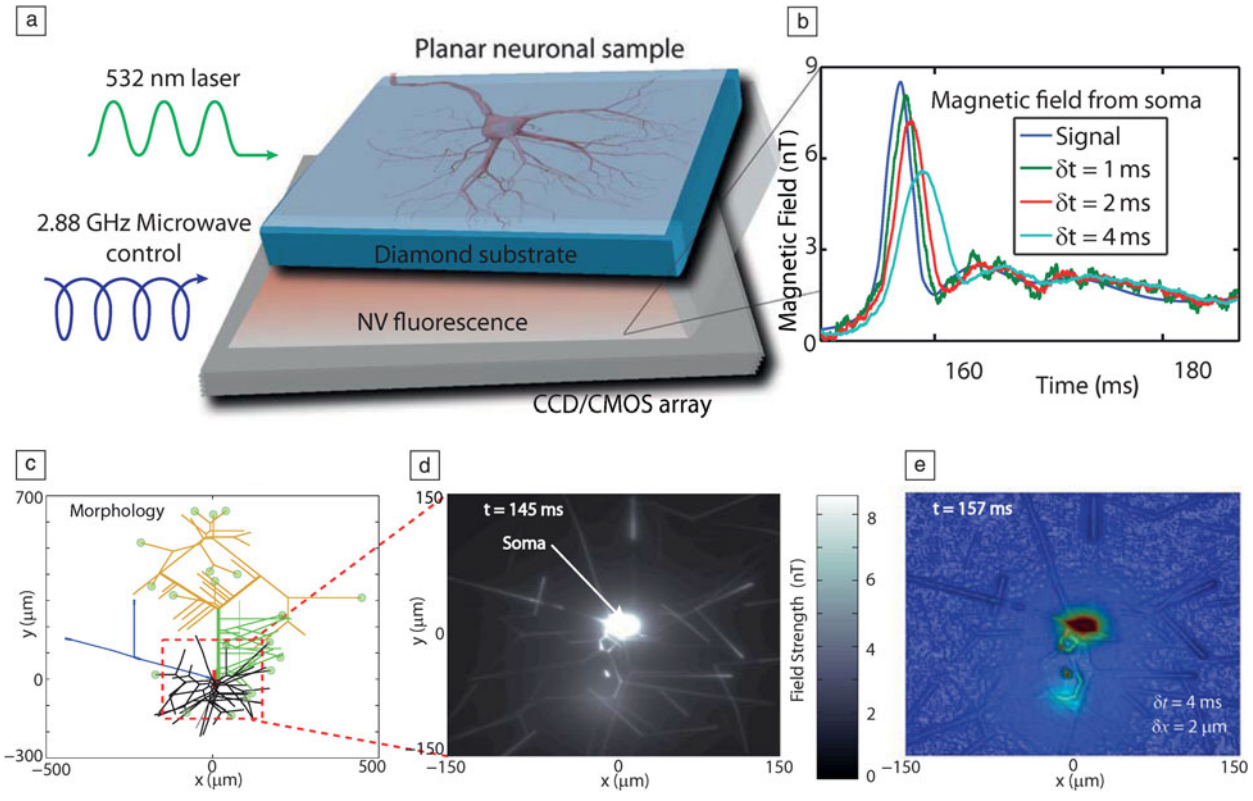


Figure 3. Schematic of a bulk-diamond nitrogen-vacancy (NV) neuronal detection system. (a) A neuronal system is grown directly on a single diamond crystal substrate with a near-surface layer of NV centers. The quantum state of the NVs is controlled via application of 2.88 GHz microwave radiation. Upon optical excitation at 532 nm, the NV centers' spin state, and hence ensemble coherence time in response to the neuron firing, may be measured (readout) by monitoring the intensity of the emitted red light using a charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) camera. (b) Simulated dynamic output from a single pixel corresponding to the neuronal magnetic field detected by the NV ensemble. (c) Morphology of a model neuron (Royeck–Wimmer model) and input excitation sites used in the simulations of the magnetic field generated as a function of time. (d) Magnetic field distribution at 100 nm standoff (i.e., NV layer position) showing a zoom of the central (somatic) activity and the reactionary dynamics in the dendritic region. (e) Simulation of the wide-field fluorescence (normalized) captured by the CCD system (where δx and δt are the spatial and temporal resolutions, respectively) corresponding to the magnetic field distribution in (d). Image reproduced, in part, with permission from Reference 33. © 2012 Nature Publishing Group.

https://doi.org/10.1557/mrs.2013.24 Published online by Cambridge University Press

scheme was shown to have the ability to capture the transmembrane potential activity in a series of near real-time images of the associated magnetic field, with spatial resolution at the level of the individual neural compartments (Figure 3e). Thus the wide-field NV imaging system has the potential to provide new insight into the key components of neuronal network activity at simultaneous micron and millisecond level resolution with the potential to scale-up to large network regions.

Quantum measurement and orientation tracking of fluorescent nanodiamonds inside living cells

The first proof-of-principle experiments toward using an NV center as a magnetometer in a biological system were carried out by tracking single-spin NV probes in living HeLa cells (**Figure 4**) and applying a resonant microwave field to monitor the quantum properties of the NV system over many hours.[40] Both Rabi (continuous microwave driving) and spin-echo measurements were made on two NV centers in distinct NDs over many hours, showing that the suite of quantum measurements required for magnetometry could be performed on biological systems without obvious degradation of the target. Given that the strain conditions in each ND are unique, the optically detected magnetic resonance (ODMR) spectra were shown to be a potential "barcode" identifier for the NDs of interest. Monitoring the Rabi period over the cell timeline (>10 hours) indicated that one ND was rotating while the other was relatively fixed in space (Figure 4b). Also, in a first attempt at decoherence sensing in this environment, the T_2 time of the NV centers was monitored, showing a change over the lifetime of the cell (Figure 4c). In a separate experiment, a NV-ND in a HeLa cell was tracked, and the ODMR spectrum was measured continuously (Figure 4d). From the change in Zeeman splitting, it was shown that the orientation of such a ND could be determined to within an accuracy of 1 degree in a fluorescence acquisition time of order of 100 ms.

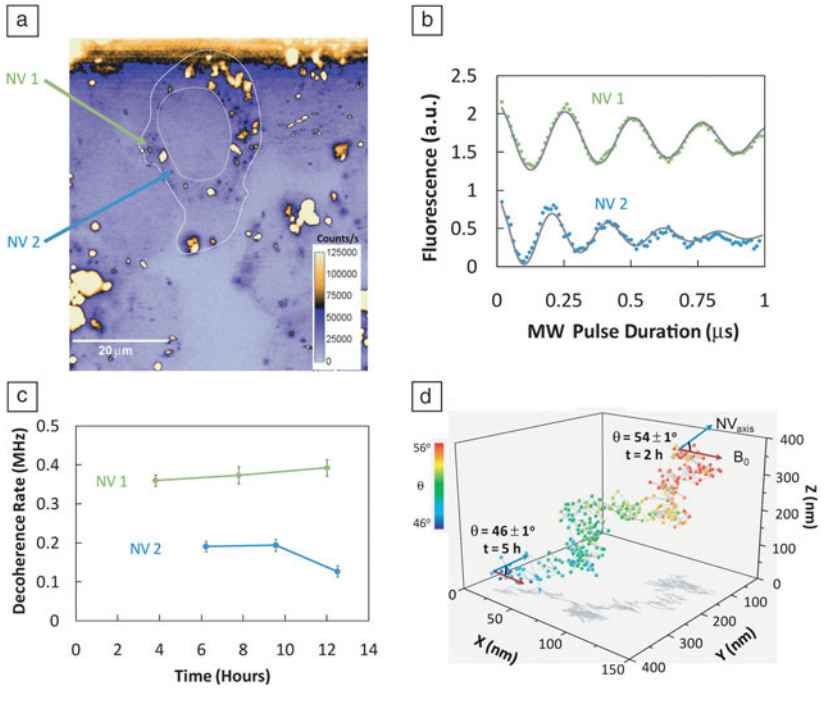


Figure 4. Quantum measurement of nitrogen-vacancy (NV) spin probes in a living cell. (a) Confocal image of a HeLa cell (outlined) with two identified NV centers in distinct nanodiamonds. (b) Typical Rabi measurement on each NV center showing quantum coherent oscillations. (c) Progression of the spin-echo dephasing rate of each center as a function of the cell timeline. (d) Combined tracking/orientation data obtained from continuous monitoring of the fluorescence and optically detected magnetic resonance spectrum of a NV-nanodiamond in a HeLa cell over several hours. Reproduced with permission from Reference 40. © 2011 Nature Publishing Group.

Conclusion

Recent progress on both theoretical and experimental fronts indicates that the nitrogen-vacancy (NV) system has a fortuitous convergence of physical properties that make it ideal for biological imaging and detection applications. The first experiments in NV nanobiomagnetometry demonstrate that the combination of high precision fluorescence tracking and quantum measurement is compatible with cell viability, and that quantum coherence is maintained within the complex electromagnetic intracellular environment. These results indicate that an NV probe, either used in a passive decoherence-sensing mode or in conjunction with magnetic resonance protocols, could provide valuable new information about the dynamics of the probe's motion and its surroundings within a living cell. In addition, the diamond surface lends itself to a range of functionalization possibilities.[41] As such, it may soon be possible to employ NV centers to measure specific fundamental subcellular properties and processes, a few examples of which have been outlined here.

References

1. A. Gruber, A. Dräbenstedt, C. Tietz, L. Fleury, J. Wrachtrup, C. Von Borczyskowski, *Science* **276**, 2012 (1997).
2. G. Balasubramanian, P. Neumann, D. Twitchen, M. Markham, R. Kolesov, N. Mizuochi, J. Isoya, J. Achard, J. Beck, J. Tissler, V. Jacques, P.R. Hemmer, F. Jelezko, J. Wrachtrup, *Nat. Mater.* **8**, 383 (2009).
3. V. Vaijayanthimala, Y.K. Tzeng, H.C. Chang, C.L. Li, *Nanotechnology* **20**, 425103 (2009).
4. N. Mohan, C.-S. Chen, H.-H. Hsieh, Y.-C. Wu, H.-C. Chang, *Nano Lett.* **10**, 3692 (2010).
5. C.-Y. Fang, V. Vaijayanthimala, C.-A. Cheng, S.-H. Yeh, C.-F. Chang, C.-L. Li, H.-C. Chang, *Small* **7**, 3363 (2011).
6. G. Balasubramanian, I.Y. Chan, R. Kolesov, M. Al-Hmoud, J. Tisler, C. Shin, C. Kim, A. Wojcik, P.R. Hemmer, A. Krueger, T. Hanke, A. Leitenstorfer, R. Bratschitsch, F. Jelezko, J. Wrachtrup, *Nature* **455**, 648 (2008).
7. J.R. Maze, P.L. Stanwix, J.S. Hodges, S. Hong, J.M. Taylor, P. Cappellaro, L. Jiang, M.V.G. Dutt, E. Togan, A.S. Zibrov, A. Yacoby, R.L. Walsworth, M.D. Lukin, *Nature* **455**, 644 (2008).
8. R.S. Schoenfeld, W. Harneit, *Phys. Rev. Lett.* **106**, 030802 (2011).
9. S. Steinert, F. Dolde, P. Neumann, A. Aird, B. Naydenov, G. Balasubramanian, F. Jelezko, J. Wrachtrup, *Rev. Sci. Instrum.* **81**, 043705 (2010).

https://doi.org/10.1557/mrs.2013.24 Published online by Cambridge University Press

10. L.M. Pham, D.L. Sage, P.L. Stanwix, T.K. Yeung, D. Glenn, A. Trifonov, P. Cappellaro, P.R. Hemmer, M.D. Lukin, H. Park, A. Yacoby, R.L. Walsworth, *New J. Phys.* **13**, 045021 (2011).
11. L.T. Hall, C.D. Hill, J.H. Cole, L.C.L. Hollenberg, *Phys. Rev. B* **82**, 045208 (2010).
12. V.M. Acosta, E. Bauch, A. Jarmola, L.J. Zipp, M.P. Ledbetter, D. Budker, *Appl. Phys. Lett.* **97**, 174104 (2010).
13. J.H. Cole, L.C.L. Hollenberg, *Nanotechnology* **20**, 10 (2009).
14. L.T. Hall, J.H. Cole, C.D. Hill, L.C.L. Hollenberg, *Phys. Rev. Lett.* **103**, 220802 (2009).
15. C. Bradac, T. Gaebel, N. Naidoo, M.J. Sellars, J. Twamley, L.J. Brown, A.S. Barnard, T. Plakhotnik, A.V. Zvyagin, J.R. Rabeau, *Nat. Nano* **5**, 345 (2010).
16. J. Tisler, G. Balasubramanian, B. Naydenov, R. Kolesov, B. Grotz, R. Reuter, J.P. Boudou, P.A. Curmi, M. Sennour, A. Thorel, M. Borsch, K. Aulenbacher, R. Erdmann, P.R. Hemmer, F. Jelezko, J. Wrachtrup, *ACS Nano* **3**, 1959 (2009).
17. O. Faklaris, D. Garrot, V. Joshi, J.P. Boudou, T. Sauvage, P.A. Curmi, F. Treussart, *J. Eur. Opt. Soc. Rapid Public.* **4**, 09032 (2009).
18. C.C. Fu, H.Y. Lee, K. Chen, T.S. Lim, H.Y. Wu, P.K. Lin, P.K. Wei, P.H. Tsao, H.C. Chang, W. Fann, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 727 (2007).
19. Y.R. Chang, H.Y. Lee, K. Chen, C.C. Chang, D.S. Tsai, C.C. Fu, T.S. Lim, Y.K. Tzeng, C.Y. Fang, C.C. Han, H.C. Chang, W. Fann, *Nat. Nano* **3**, 284 (2008).
20. O. Faklaris, D. Garrot, V. Joshi, F. Druon, J.P. Boudou, T. Sauvage, P. Georges, P.A. Curmi, F. Treussart, *Small* **4**, 2236 (2008).
21. O. Faklaris, V. Joshi, T. Irinopoulou, P. Tauc, M. Sennour, H. Girard, C. Gesset, J.C. Arnault, A. Thorel, J.P. Boudou, P.A. Curmi, F. Treussart, *ACS Nano* **3**, 3955 (2009).
22. B.M. Chernobrod, G.P. Berman, *J. Appl. Phys.* **97**, 3 (2005).
23. C.L. Degen, *Appl. Phys. Lett.* **92**, 243111 (2008).
24. J.M. Taylor, P. Cappellaro, L. Childress, L. Jiang, D. Budker, P.R. Hemmer, A. Yacoby, R. Walsworth, M.D. Lukin, *Nat. Phys.* **4**, 810 (2008).
25. D. Budker, M. Romalis, *Nat. Phys.* **3**, 227 (2007).
26. J.R. Rabeau, A. Stacey, A. Rabeau, S. Prawer, F. Jelezko, I. Mirza, J. Wrachtrup, *Nano Lett.* **7**, 3433 (2007).
27. G. de Lange, Z.H. Wang, D. Ristè, V.V. Dobrovitski, R. Hanson, *Science* **330**, 60 (2010).
28. B. Naydenov, F. Dolde, L.T. Hall, C. Shin, H. Fedder, L.C.L. Hollenberg, F. Jelezko, J. Wrachtrup, *Phys. Rev. B* **83**, 081201 (2011).
29. C.A. Ryan, J.S. Hodges, D.G. Cory, *Phys. Rev. Lett.* **105**, 200402 (2010).
30. G. de Lange, D. Ristè, V.V. Dobrovitski, R. Hanson, *Phys. Rev. Lett.* **106**, 080802 (2011).
31. C.A. Meriles, L. Jiang, G. Goldstein, J.S. Hodges, J. Maze, M.D. Lukin, P. Cappellaro, *J. Chem. Phys.* **133**, 124105 (2010).
32. N. Zhao, J.-L. Hu, S.-W. Ho, J.T.K. Wan, R.B. Liu, *Nat. Nano* **6**, 242 (2011).
33. L.T. Hall, G.C.G. Beart, E.A. Thomas, D.A. Simpson, L.P. McGuinness, J.H. Cole, J.H. Manton, R.E. Scholten, F. Jelezko, J. Wrachtrup, S. Petrou, L.C.L. Hollenberg, *Sci. Rep.* 2 (2012).
34. L.T. Hall, C.D. Hill, J.H. Cole, B. Städler, F. Caruso, P. Mulvaney, J. Wrachtrup, L.C.L. Hollenberg, *Proc. Natl. Acad. Sci.* **107**, 18777 (2010).
35. E. Reimhult, K. Kumar, *Trends Biotechnol.* **26**, 82 (2008).
36. T. Ide, Y. Takeuchi, T. Aoki, T. Yanagida, *Jpn. J. Physiol.* **52**, 429 (2002).
37. G. Baaken, M. Sondermann, C. Schlemmer, J. Ruhe, J.C. Behrends, *Lab Chip* **8**, 938 (2008).
38. K. Lundstrom, *Cell. Mol. Life Sci.* **63**, 2597 (2006).
39. C.G. Specht, O.A. Williams, R.B. Jackman, R. Schoepfer, *Biomaterials* **25**, 4073 (2004).
40. L.P. McGuinness, Y. Yan, A. Stacey, D.A. Simpson, L.T. Hall, D. Maclaurin, S. Prawer, P. Mulvaney, J. Wrachtrup, F. Caruso, R.E. Scholten, L.C.L. Hollenberg, *Nat. Nano* **6**, 358 (2011).
41. T. Meinhardt, D. Lang, H. Dill, A. Krueger, *Adv. Funct. Mater.* **21**, 494 (2011). □





https://doi.org/10.1557/mrs.2013.24 Published online by Cambridge University Press

WASHINGTON, DC

ICNS-10

10th International Conference on Nitride Semiconductors 2013

CALL FOR PAPERS

CONFERENCE ORGANIZER

JAIME A. FREITAS, JR.
Naval Research Laboratory

CHRISTIAN M. WETZEL
Rensselaer Polytechnic Institute

HONORARY CHAIR

ASIF KHAN
University of South Carolina

IMPORTANT DATES

Abstract Submission Ends
April 16, 2013

Preregistration Opens
Late April, 2013

Preresistration Ends
Early August, 2013

10th International Conference on Nitride Semiconductors | August 25-30, 2013
Gaylord National Hotel and Convention Center—Washington, D.C.

Join us for the 10th International Conference on Nitride Semiconductors 2013 (ICNS-10). Hosted in historic Washington, D.C., the conference will present high-impact scientific and technological advances in materials and devices based on group-III nitride semiconductors. The conference will feature plenary sessions, parallel topical sessions, poster sessions and an industrial exhibition. Mark your calendars today and plan to attend ICNS-10!

Scientific Program

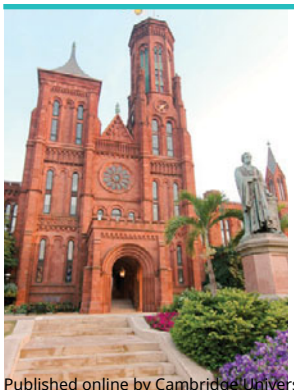
The six-day conference will concentrate on the following topical categories:

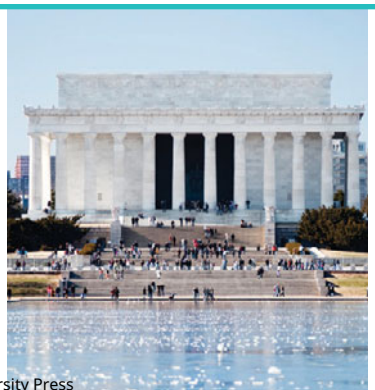
- Bulk Crystal Growth
- Epitaxial Growth
- Optical and Electronic Properties
- Processing and Fabrication
- Defect Characterization and Engineering
- Structural Analysis
- Theory and Simulation
- Nanostructures
- Light Emitting Devices
- Electron Transport Devices
- Photovoltaics and Energy Harvesting
- New Materials and New Device Concepts

Conference Venue

ICNS-10 will be held at the beautiful National Harbor, located on the banks of the Potomac River. This unique, ever expanding complex, offers something interesting and different for everyone in the family. Featuring numerous shopping, dining and entertainment venues, the waterfront community brings the finest options from land or water. Just minutes from the harbor, find one of the world's cultural, government and historic epicenters—Washington, D.C. The architecture, monuments, museums and cultural diversity add up to one ideal conference and vacation destination.

For the most up-to-date information, **visit www.ICNS10.org** or the Conference website, **www.mrs.org/ICNS-10.**







https://doi.org/10.1557/mrs.2013.24 Published online by Cambridge University Press