



ENSEMBLE MAGNETOMETRY WITH NITROGEN-VACANCY CENTERS IN DIAMOND

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REGENTS OF THE UNIVERSITY OF CALIFORNIA

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Final Report

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Final report by the UCB/UCLA team for the DARPA/AFOSR QUASAR project

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January 12, 2018

During the final stage of the project, including a six-month NCE, we continued the work started during the project and were able to bring a number of activities to successful conclusion, publishing a number of papers describing our results. Please note that a “tail” of publications based on the work either started or conducted under QUASAR is continuing after the end of funding.

Publications. Recently, the following papers were published with acknowledgement of the QUASAR support:

UCB/UCLA joint papers:

- Jeson Chen, Sean Lourette, Kristine Rezai, Tobias Hoelzer, Michael Lake, Milos Nesladek, Louis-S. Bouchard, Philip Hemmer, and Dmitry Budker, Optical quenching and recovery of photoconductivity in single-crystal diamond, [Applied Physics Letters](#) **110**, 011108 (2017), [arXiv:1607.08354](#)
- Waxman A, Schlussek H, Groswasser D, Acosta VM, Bouchard LS, Budker D, Folman R, Diamond magnetometry of superconducting thin films, *Phys. Rev. B* **89**, 054509 (2014)

UCB papers (since 2016 only):

- D. Farfurnik, A. Jarmola, D. Budker, and N. Bar-Gill, Optimizing spin ensemble-based AC magnetometry using dynamical decoupling at low temperatures, [J. Opt.](#) **20**, 024008 (2018), [arXiv:1709.03368](#)
- Georgios Chatzidrosos, Arne Wickenbrock, Lykourgos Bougas, Nathan Leefer, Teng Wu, Kasper Jensen, Yannick Dumeige, and Dmitry Budker, Miniature cavity-enhanced diamond magnetometer, [Phys. Rev. Applied](#) **8**, 044019 (2017), [arXiv:1706.02201](#)
- Huijie Zheng, Georgios Chatzidrosos, Arne Wickenbrock, Lykourgos Bougas, Reinis Lazda, Andris Berzins, Florian Helmuth Gahbauer, Marcis Auzinsh, Ruvim Ferber, and Dmitry Budker, Level anti-crossing magnetometry with color centers in diamond, [Proc. SPIE](#) 10119, Slow Light, Fast Light, and Opto-Atomic Precision Metrology X, 101190X (20 February 2017); doi: [10.1117/12.2261160](#), [arXiv:1701.06838](#)
- A. Jarmola, Z. Bodrog, P. Kehayias, M. Markham, J. Hall, D. J. Twitchen, V. M. Acosta, A. Gali, and D. Budker, Optically Detected Magnetic Resonances of Nitrogen-Vacancy Ensembles in ¹³C Enriched Diamond, [Phys. Rev. B](#) **94**, 094108, (2016), [arXiv:1608.08706](#)
- Arne Wickenbrock, Huijie Zheng, Lykourgos Bougas, Nathan Leefer, Samer Afach, Andrey Jarmola, Victor M. Acosta, and Dmitry Budker, Microwave-free magnetometry with nitrogen-vacancy centers in diamond, [Appl. Phys. Lett.](#) **109**, 053505 (2016), [arXiv:1606.03070](#)
- K. Jensen, P. Kehayias, and D. Budker, Magnetometry with Nitrogen-Vacancy Centers in Diamond, in [High Sensitivity Magnetometers](#), ed. by A. Grosz, M. J. Haji-Sheikh, and S. C. Mukhopadhyay, Springer, 2016.

- D. Farfurnik, A. Jarmola, L. M. Pham, Z. H. Wang, V. V. Dobrovitski, R. L. Walsworth, D. Budker, and N. Bar-Gill, Improving the coherence properties of solid-state spin ensembles via optimized dynamical decoupling, [Proc. SPIE](#) 9900, Quantum Optics, 99000N (April 29, 2016); doi:10.1117/12.2227479
- M. Mrozek, A. Wojciechowski, D.S. Rudnicki, J. Zachorowski, P. Kehayias, D. Budker, and W. Gawlik, Coherent population oscillations with nitrogen-vacancy color centers in diamond, [Phys. Rev. B](#) **94**(3) (2016), [arXiv:1512.03996](#)
- L. T. Hall, P. Kehayias, D. A. Simpson, A. Jarmola, A. Stacey, D. Budker, and L. C. L. Hollenberg, Electron Spin Resonance Spectroscopy via Relaxation of Solid-State Spin Probes at the Nanoscale, [Nature Communications](#) **7**, Article number: 10211 doi:10.1038/ncomms10211 (2016), [arXiv:1503.00830](#)

UCLA papers:

- Lake M, Bouchard LS, Targeted nanodiamonds for identification of subcellular protein assemblies in mammalian cells, PLOS ONE 12, e0179295 (2017)
- Youssef K, Jarenwattananon NN, Bouchard LS, Feature-preserving noise removal, IEEE Trans. Med. Imag. 34, 1822-1829 (2015)
- Koumoulis D, Morris GD, He L, Kou X, King D, Wang D, Hossain MD, Wang KL, Fiete GA, Kanatzidis MG, Bouchard LS, Nanoscale β -nuclear magnetic resonance depth imaging of topological insulators, Proc. Natl. Acad. Sci. USA 112, E3645-E3650 (2015)

A highlight. One of the major goals of our team for the QUASAR project was the development of a sensitive broad-band optical-cavity-enhanced ensemble magnetometer. We have recently reported such a magnetometer with a unique set of parameters in: Georgios Chatzidrosos, Arne Wickenbrock, Lykourgos Bougas, Nathan Leefer, Teng Wu, Kasper Jensen, Yannick Dumeige, and Dmitry Budker, Miniature cavity-enhanced diamond magnetometer, [Phys. Rev. Applied](#) **8**, 044019 (2017), [arXiv:1706.02201](#).

Transitions. The QUASAR project supported training of a number of post-doc students of all levels and has resulted in multiple collaborations within and outside of QUASAR. As an example, a QUASAR PhD student Pauli Kehayias, upon graduating from Berkeley, moved to the group of Ron Walsworth at Harvard Smithsonian to become one of the lead post-docs there. QUASAR also stimulated the founding of a start-up, ODMR Technologies, Inc. that has been in business for over two years, securing multiple STTR and SBIR grants from NSF and NIH. One such project resulted in a recent high-impact result reported in:

- P. Kehayias, A. Jarmola, N. Mosavian, I. Fescenko, F. M. Benito, A. Laraoui, J. Smits, L. Bougas, D. Budker, A. Neumann, S. R. J. Brueck, and V. M. Acosta, Solution nuclear magnetic resonance spectroscopy on a nanostructured diamond chip, [Nature Communications](#) **8**, Article number: 188 (2017), doi:10.1038/s41467-017-00266-4, [arXiv:1701.01401](#) .

Patents.

- [US Patent 9689679](#) - Gyroscopes Based On Nitrogen-Vacancy Centers In Diamond. Inventors: Dmitry Budker, Micah Ledbetter, Kasper Jensen, and Andrey Jarmola.
- US Patent Application no. 14/971,775 (Filed: Dec. 16, 2015). Title: “Feature-preserving image noise removal for arbitrary noise distribution”. Inventors: Youssef K, Bouchard LS.