DOE BES Final Technical Report

DOE Award Number: DE-SC0006638
Institution: University of Pittsburgh
Street Address: 123 University Place, Pittsburgh, PA 15213-2303
Project Title: Quantum Control of Spins in Diamond for Nanoscale Magnetic Sensing and Imaging
Principal Investigator (PI): Gurudev Dutt
Email: gdutt@pitt.edu
Date of Report: October 25, 2017
Research Period Covered: July 14, 2011 – July 15, 2017 (with one year no-cost extension)
Program Manager: Jane Zhu

A Executive Summary

Our research activities during the grant period focused on the challenges of highly accurate and precise magnetometry and magnetic imaging using quantum spins inside diamond. Our work has resulted in 6 papers published in peer-reviewed journals, with two more currently under consideration by referees. We showed that through the use of novel phase estimation algorithms inspired by quantum information science we can carry out accurate and high dynamic range DC magnetometry as well as lock-in detection of oscillating (AC) magnetic fields. We investigated the geometric phase as a route to higher precision quantum information and magnetic sensing applications, and probed the experimental limits to the fidelity of such geometric phase gates. We also demonstrated that there is a spin dependent signal in the charge state flipping of the NV defect center in diamond, which could potentialy be useful for higher fidelity spin readout at room temperature. Some of these projects have now led to further investigation in our lab on multi-photon spectroscopy (manuscript in preparation), and plasmonic guiding of light in metal nanowires (manuscript available on arxiv). In addition, several invited talks were given by the PI, and conference presentations were given by the graduate students and postdocs. Below we report all of these.

B DOE-Supported Publications

1. N. M. Nusran, M. Ummal Momeen, M. V. Gurudev Dutt, "High-dynamic-range magnetometry with a single electronic spin in diamond", *Nature Nanotechnology* **7**, 109–113 (2012).

   Acknowledgment Excerpt: This work was supported by an NSF CAREER award (DMR-0847195), NSF PHY-100534, DOE Early Career (DE-SC0006638) and the Alfred P. Sloan Research Fellowship.
   We carried out the experiments for this paper on a room-temperature confocal microscope setup with integrated microwave excitation and magnetic field alignment, that was built to support research for the PI's NSF grants. In future, we plan a separate setup that will purely focus on the research that was proposed as part of this DOE award. Hence, we also acknowledge the support from NSF that was critical for making these experiments possible in our publication. Further, the technique that we have used for magnetometry here was originally conceived as part of the NSF proposal as a route to controlling and detecting nuclear spins in diamond.

2. N. M. Nusran, M. V. Gurudev Dutt, "A Dual-Channel Lock-in Magnetometer with a Single Spin in Diamond", Phys. Rev. B, **88**, 2201410R (2013)

   Acknowledgment Excerpt: This work was supported by an NSF CAREER award (DMR-0847195), NSF PHY-100534, DOE Early Career (DE-SC0006638) and the Alfred P. Sloan Research Fellowship.

DE-SC0006638 supported development of novel magnetometry technique which is the primary focus of this paper, key equipment such as Arbitrary Waveform Generator and high-fidelity AC amplifiers, key materials such as high-purity diamond samples, graduate student (N.M.N) and faculty (G. D.) effort. NSF DMR-0847195 (expiring 7/31/2014) supported development of a room-temperature confocal microscope setup with integrated microwave excitation and magnetic field alignment that was used in the experiments. NSF-PHY100534 (expired 6/30/2013) supported collaboration and graduate student exchange to learn nano-fabrication techniques. Alfred P. Sloan Fellowship awarded to faculty (G.D.) enabled collaboration and lesser teaching responsibilities which is gratefully acknowledged.

3. N. M. Nusran, M. V. Gurudev Dutt, "Optimizing phase estimation algorithms for diamond spin magnetometry", Phys. Rev. B. **90**, 024422 (2014)

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4. Kai Zhang, N. M. Nusran, B. R. Slezak, M. V. Gurudev Dutt, "Experimental limits on the fidelity of adiabatic geometric phase gates with a single solid-state spin qubit", *New Journal of Physics*, **18**, 0543029 (2016).

   Acknowledgment Excerpt: This work was supported by the DOE Office of Basic Energy Sciences (DE-SC 0006638) for development of geometric quantum control techniques, key equipment, materials and effort.

5. Peng Ji, M. V. Gurudev Dutt, "Charge state dynamics of the nitrogen vacancy center in diamond under 1064 nm laser excitation ", *Phys. Rev. B*, **94**, 024101 (2016).

   Acknowledgment Excerpt: This work was supported by the DOE Office of Basic Energy Sciences (DE-SC 0006638).

6. Jen-Feng Hsu, Peng Ji, Charles W. Lewandowski, Brian D'Urso, "Cooling the Motion of Diamond Nanocrystals in a Magneto-Gravitational Trap in High Vacuum ", *Scientific Reports*, **6**, 30125 (2016).

   Acknowledgment Excerpt: We thank M. V. Gurudev Dutt for invaluable discussions and for use of laboratory resources. This material is based upon work supported by the National Science Foundation under Grant No. 1540879. P.J. was supported in part by the DOE Office of Basic Energy Sciences (DE-SC 0006638).

C Invited talks by PI

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1. Enhancing magnetometry with single spins in diamond, NDNC 2014, Chicago IL, May 26th, 2014.
2. Enhancing magnetometry with single spins in diamond, Frontiers in Optics/Laser Science Conference 2013, Orlando FL, Oct. 6th, 2013.
3. Hybrid quantum devices with single spins in diamond, Workshop on Diamond – Spintronics, Photonics, and Bio-application, Hong Kong, April 27th - 29th, 2013. (invited but unable to present due to family reasons).
4. High dynamic range magnetometry with a single electronic spin in diamond, 21st International Laser Physics Workshop, Calgary Canada, July 23rd , 2012. (invited but unable to present due to health reasons).
5. High dynamic range magnetometry with a single electronic spin in diamond, Physics of Quantum Electronics Conference 2012, Snowbird UT, Jan 6th, 2012.

D People

Graduate Students:

1. Kai Zhang – 1/2 time (graduating Spring 2018)
2. Bradley Slezak - 1/2 time (graduating Spring 2018)
3. Peng Ji – 1/2 time (graduating Spring 2018)
4. Naufer Nusran - full time (obtained PhD)

Postdocs:

1. M. Ummal Momeen - 1/3 time