REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)
30-10-2018

2. REPORT TYPE
Final Report

3. DATES COVERED (From - To)
13-Aug-2012 - 12-Aug-2016

4. TITLE AND SUBTITLE
Final Report: Nanometer-Scale Force-Detected Nuclear Magnetic Resonance Imaging

5a. CONTRACT NUMBER
W911NF-12-1-0341

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

University of Illinois - Urbana - Champaign
c/o Office of Sponsored Programs
1901 S. First Street, Suite A
Champaign, IL 61820 -7406

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
61668-MS.5

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Raffi Budakian
					19b. TELEPHONE NUMBER 519-888-4567

RPPR Final Report
as of 31-Oct-2018

Agency Code:

Proposal Number: 61668MS **Agreement Number: W911NF-12-1-0341**

INVESTIGATOR(S):

Name: Raffi Budakian
Email: rbudakian@uwaterloo.ca
Phone Number: 5198884567X31058
Principal: Y

Organization: **University of Illinois - Urbana - Champaign**
Address: c/o Office of Sponsored Programs, Champaign, IL 618207406
Country: USA
DUNS Number: 041544081 EIN: 376000511
Report Date: 12-Nov-2016 Date Received: 30-Oct-2018
Final Report for Period Beginning 13-Aug-2012 and Ending 12-Aug-2016
Title: Nanometer-Scale Force-Detected Nuclear Magnetic Resonance Imaging
Begin Performance Period: 13-Aug-2012 **End Performance Period:** 12-Aug-2016
Report Term: 0-Other
Submitted By: Raffi Budakian Email: rbudakian@uwaterloo.ca
Phone: (519) 888-4567X31058
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:** 2

Major Goals: The goal of the proposed research program is to develop fundamentally new approaches in force-detected magnetic resonance techniques and achieve nanometer-scale nuclear spin imaging. During the past several years, our group has pursued this goal using silicon nanowire (SiNW) resonators for force detection. The ultralow mechanical dissipation inherent in SiNW resonators is ideally suited for detecting sub-attonewton-scale forces. Recently, we have used radio frequency (RF) SiNW resonators to detect proton spins in polystyrene with a near thermally limited force sensitivity of 1.9 aN^2/Hz; this result represents a significant improvement in sensitivity over previous published MRFM data. To achieve this result, we developed a new spin detection protocol which uses time-dependent magnetic field gradients, generated by passing electric currents through a narrow metallic constriction, to achieve efficient coupling between nuclear spins and an RF mechanical resonator. The ability to generate time dependent field gradients opens the possibility for applying well-established Fourier encoding techniques for efficient MRFM imaging. The proposed work seeks to develop nanowire-based MRFM techniques and achieve nanometer-scale proton imaging by:

1. Achieving sub-attonewton force sensitivity using ultra-sensitive RF nanowire mechanical resonators.
2. Generating intense pulsed field gradients greater than 10^6 T/m on the nanometer scale.
3. Developing efficient spin imaging protocols using time-dependent and gradients, compatible with imaging statistical polarization.
4. Finding materials that optimize the force detection sensitivity of RF nanowire mechanical resonators.

Accomplishments: During the funding period of the grant, we succeeded in achieving several of the major goals of the proposal, namely (1) the ability to generate intense time dependent magnetic field gradients on the nanoscale, (2) the development of an efficient imaging protocol for encoding statistical polarization, and (3) the development of a robust fabrication process for mode engineering silicon nanowire (SiNW) mechanical resonators for use in magnetic resonance force microscopy experiments. By flowing current approaching 10^9 A/cm^2 through nanoscale constrictions patterned into silver films deposited on MgO, we could generate magnetic field gradients approaching 10^6 T/m. These large gradients in conjunction with the ultra-high force sensitivity of SiNW resonators allowed for high sensitivity spin detection. The large time-dependent magnetic field gradients, also allowed to to encode spatial location for high resolution imaging. We developed a new method of Fourier transform imaging capable of encoding the statistical polarization and applied this technique to image proton spins in a polystyrene sample attached to the tip of the SiNW resonator. Using the gradients generated by the constriction, we demonstrated two-dimensional Fourier transform imaging of proton spins with approximately 10-nm x 15-nm spatial resolution. The initial experiments with polystyrene represent a proof-of-concept of multi-dimensional imaging using the time-time-dependent fields produced by the constriction. Although we demonstrated imaging in two dimensions, the techniques presented here can be readily extended to three dimensions by fabricating gradient sources capable of applying gradients in all three directions.

The two main challenges to achieving higher spatial resolution is extending the spin coherence times, and achieving higher detection signal-to-noise ratio. Future work will focus on developing the capability to apply high-resolution magnetic resonance techniques, such as dynamical decoupling, to enhance spin coherence times. In addition, we will explore dynamic nuclear polarization as a means to significantly increase the spin signal.

In 2014, I have begun construction of labs at the Institute for Quantum Computing at the University of Waterloo in Canada. These labs will be dedicated to developing the nanowire-based MRFM platform. In particular, we are constructing an ultra-high vacuum CVD system for growing high quality SiNW resonators for MRFM and a dedicated 300-mK MRFM apparatus for dynamics nuclear polarization experiments and single-electron spin imaging.

Training Opportunities: During the 3-year funding period, the following students received training:

John Nichol (PhD received in 2013) — John developed the silicon nanowire based magnetic resonance force microscopy (MRFM) platform. John received extensive training in magnetic resonance spectroscopy, scanning probe microscopy, low temperature techniques, and ultra-sensitive force detection. John was the lead student on this project; he was the first author on 4 papers. For his development of nanowire-MRFM spin detection techniques, John was an invited speaker at the American Physical Society March Meeting, and Nano-MRI conference—an international conference that hosts world-renowned researchers in the field of nanoscale spin detection. John received the prestigious John Bardeen Award from the Department of Physics at the University of Illinois for his outstanding graduate work in Condensed Matter Physics. This award is given to one outstanding student each year. John is currently a postdoc with Amir Yacoby at Harvard, working on spin qubits.

2. William (Bill) Rose (PhD student) — Bill joined the group in 2014 to extend the nanowire-based MRFM measurements to include high resolution magnetic spectroscopy. Bill is focusing on using optimal control theory techniques to implement high-fidelity quantum control of nuclear spins in nanoscale ensembles. This capability will be essential to being able to implement high-resolution NMR techniques, such as dynamical decoupling pulse sequences, in our nano-MRI setting. As discussed in the Accomplishments section, such techniques will be essential to extending spin coherence times, allowing us to significantly enhance the spatial resolution MRI imaging.

3. Angela Chen (MSc student) — Angela was the nano fabrication expert in my group, in charge of fabricating the current focusing field gradient sources for the MRI measurements. Angela received extensive training in nano-fabrication techniques, including optical and e-beam lithography and epitaxial growth of metal films on insulators. In addition Angela learned many advanced characterization techniques including electron microscopy, atomic force microscopy, X-ray diffraction, and EDX.

4. William (Will) McFaul (MSc student) — Will was involved with the project for two year. His main contribution was to design and construct a free space interferometer for displacement detection of silicon nanowire mechanical resonators. Will successfully constructed an high-sensitivity interferometer, capable of working at low light level, and able to sense the SiNW motion at the theoretical shot-noise limit of the interferometer. In conducting this work, Will gained valuable experience in optics, high precision current measurements, and finite-element simulation. Will also took part in the nano-fabrication efforts in mode shaping of the SiNW resonators.

Results Dissemination: In 2015, I organized the 5th nanoMRI conference at the University of Waterloo, bringing together over 30 invited speakers and 60 graduate students and postdocs working in the areas of nanoscale spin detection, quantum sensing, and nano-mechanics. Our results were prominently featured at both the 4th nanoMRI conference in 2012 and the 5th nanoMRI conferences. In addition, the results obtained during this funding period were presented in numerous department seminars, colloquia and workshops, both in North America and in Europe.

While at the University of Illinois, I sponsored two REU undergraduate students during Summer 2012 and 2013. The students participating in the program came from smaller Physics Departments, and did not have access to significant research opportunities. Each student worked closely with me and my students to gain valuable lab experience. Projects included construction and testing of high frequency mixer circuitry for frequency demodulation, and other RF circuitry for NMR experiments.

Honors and Awards: 2015 WIN/IQC Endowed Chair in Superconductivity
2013 John Bardeen Faculty Scholar

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: John Nichol
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: William Rose
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Angela Chen
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: William McFaul
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

DISSERTATIONS:

RPPR Final Report
as of 31-Oct-2018

Publication Type: Thesis or Dissertation
Institution:
Date Received: 20-Aug-2013 Completion Date:
Title: Nanoscale magnetic resonance imaging using silicon nanowire oscillators
Authors:
Acknowledged Federal Support:

Nothing to report in the uploaded pdf (see accomplishments)