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14. ABSTRACT
This is a final report for the STIC Grant "Development of a System of Nonlocally Interconnected Spin Quibits for Quantum Computation", supporting research by Charles Marcus (PI), Mikhail Lukin, and Amir Yacoby at Harvard University.

15. SUBJECT TERMS
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Report Title

Final Report on "STIC: Development of a System of Nonlocally Interconnected Spin Quibits for Quantum Computation"

ABSTRACT

This is a final report for the STIC Grant "Development of a System of Nonlocally Interconnected Spin Quibits for Quantum Computation", supporting research by Charles Marcus (PI), Mikhail Lukin, and Amir Yacoby at Harvard University.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
2012/09/04 1	8	J.R. Petta, A.C. Johnson, J.M. Taylor, E.A. Laird, A. Yacoby, M.D. Lukin, C.M. Marcus, M.P. Hanson, A.C. Gossard. Preparing, manipulating, and measuring quantum states on a chip, Physica E: Low-dimensional Systems and Nanostructures, (12 2006): 251. doi: 10.1016/j.physe.2006.08.020
2012/09/04 0	2	J. Taylor, W. Dür, P. Zoller, A. Yacoby, C. Marcus, M. Lukin. Solid-State Circuit for Spin Entanglement Generation and Purification, Physical Review Letters, (06 2005): 236803. doi: 10.1103/PhysRevLett.94.236803
2012/09/04 0	3	J. R. Petta. Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots, Science, (09 2005): 2180. doi: 10.1126/science.1116955
2012/09/04 0	1	J. R. Petta, J. M. Taylor, A. Yacoby, M. D. Lukin, C. M. Marcus, A. C. Johnson, M. P. Hanson, A. C. Gossard. Triplet–singlet spin relaxation via nuclei in a double quantum dot, Nature, (06 2005): 1. doi: 10.1038/nature03815
2012/09/04 0	16	C. Barthel, D. Reilly, C. Marcus, M. Hanson, A. Gossard. Rapid Single-Shot Measurement of a Singlet-Triplet Qubit, Physical Review Letters, (10 2009): 160503. doi: 10.1103/PhysRevLett.103.160503
2012/09/04 0	15	D. J. Reilly, J. M. Taylor, J. R. Petta, C. M. Marcus, M. P. Hanson, A. C. Gossard. Suppressing Spin Qubit Dephasing by Nuclear State Preparation, Science, (08 2008): 817. doi: 10.1126/science.1159221
2012/09/04 0	5	H.-A. Engel, W. Dür, A. Yacoby, C. M. Marcus, P. Zoller, M. D. Lukin, J. M. Taylor. Fault-tolerant architecture for quantum computation using electrically controlled semiconductor spins, Nature Physics, (12 2005): 177. doi: 10.1038/nphys174
2012/09/04 0	7	E. Laird, J. Petta, A. Johnson, C. Marcus, A. Yacoby, M. Hanson, A. Gossard. Effect of Exchange Interaction on Spin Dephasing in a Double Quantum Dot, Physical Review Letters, (07 2006): 0. doi: 10.1103/PhysRevLett.97.056801
2012/09/04 0	9	J. Taylor, J. Petta, A. Johnson, A. Yacoby, C. Marcus, M. Lukin. Relaxation, dephasing, and quantum control of electron spins in double quantum dots, Physical Review B, (07 2007): 35315. doi: 10.1103/PhysRevB.76.035315
2012/09/04 0	17	D. J. Reilly, J. M. Taylor, J. R. Petta, C. M. Marcus, M. P. Hanson, A. C. Gossard. Exchange Control of Nuclear Spin Diffusion in a Double Quantum Dot, Physical Review Letters, (06 2010): 236802. doi: 10.1103/PhysRevLett.104.236802
2012/09/03 1	10	J. Petta, J. Taylor, A. Johnson, A. Yacoby, M. Lukin, C. Marcus, M. Hanson, A. Gossard. Dynamic Nuclear Polarization with Single Electron Spins, Physical Review Letters, (02 2008): 67601. doi: 10.1103/PhysRevLett.100.067601

TOTAL: 11

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
2012/09/09 2	19	D. E. Chang, A. S. Sørensen, P. R. Hemmer, M. D. Lukin. Quantum Optics with Surface Plasmons, Physical Review Letters (06 2005)
2012/09/09 2	18	L. Jiang, J. M. Taylor, N. Khaneja , M. D. Lukin. Optimal approach to quantum communication algorithms using dynamics programming, Proc. Natl. Acad. Sci. U.S.A. (04 2007)

TOTAL: 2

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Marcus, Fellow, American Physical Society, 2009
Marcus, Yacoby, Lukin: AAAS Newcomb-Cleveland Prize, 2006
Lukin, Rabi Prize, 2009

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Alexander Johnson	1.00	
Edward Laird	1.00	
Sandra Foletti	1.00	
Christian Barthel	1.00	
Vivek Venkatshalam	0.50	
FTE Equivalent:	**4.50**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Jason Petta	1.00
Jacob Taylor	1.00
David Reilly	1.00
Derrick Chang	1.00
Henrik Bluhm	1.00
FTE Equivalent:	**5.00**
Total Number:	**5**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Charles Marcus	0.10	
Amir Yacoby	0.10	
Mikhail Lukin	0.10	
FTE Equivalent:	**0.30**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Andrew J. Bestwick	0.30	
Jennifer Harlow	0.30	
FTE Equivalent:	**0.60**	
Total Number:	**2**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	2.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	2.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	2.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	2.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	2.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Sandra Foletti

Alex Johnson

Edward Laird

Christian Barthel

Vivek Venkatshalam

Total Number: **5**

Names of other research staff

NAME	PERCENT_SUPPORTED
Jens Martin	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Sub Contractors (DD882)

1 a. Bell Lucent

1 b.

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Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): Loren Pfeiffer to provide high-mobility GaAs wafers

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

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1 a. Bell Lucent

1 b.

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Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): Loren Pfeiffer to provide high-mobility GaAs wafers

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

Inventions (DD882)

Scientific Progress

Technology Transfer

For spin-based quantum information, the period covered by STIC funding, 2005 to 2010, was one of particularly rapid advancement. At the beginning of the grant, a major breakthrough, the measurement of spin echo of a singlet-triplet spin qubit by Petta, et al. was realized [1]. This development justified a major refocussing of the grant toward extending these results. The original proposal was substantially revised, and the revisions accepted by ARO.

Besides a refocussing of research goals, there was a change in personnel, with the addition of Amir Yacoby as a co-PI. This occurred because Yacoby accepted a faculty position at Harvard after participating in the research leading to Refs. [1, 2]. He established his own group on related topics.

Over the course of the grant, four significant developments occurred, two theoretical and two experimental. The two major theoretical accomplishment were:

(i) The formulation of a complete, fault-tolerant design for a quantum computer based on the singlet-triplet qubit, using measured performance parameters to evaluate fault tolerance [3]. The scheme laid out in Ref. [3] continues to be the standard for the extension of singlet-triplet spin qubits into multi-qubit systems.

(ii) A detailed theoretical analysis of the influence of hyperfine coupling combined with electrical (gate) noise on the performance of the singlet-triplet qubit [4]. This paper emphasizes a key property of the hyperfine coupling, which is the long time scale on which it evolves compared to gate operation time. The slow dynamics of the hyperfine coupling allows coherence to be preserved using a variety of dynamical decoupling schemes.

The major experimental advances under STIC funding were:

(i) The realization of sub-microsecond readout of the charge state of the double quantum dot, allowing single-shot measurement on time scales fast compared to the evolution of the hyperfine coupling [5]. On such fast time scales, the hyperfine field is effectively static, so evolution appears periodic, with periodic oscillations between singlet and triplet states. Single-shot measurement means that results from a repeated measurement can be recorded and later analyzed shot by shot, allowing the fidelity of readout to be extracted from these statistics. The technique is based on a reflectometer measurement of a high quality factor LC resonator, also developed under STIC funding [6]. In a subsequent publication, another factor of 5 in performance was reported by changing the proximal sensor from a QPC into a quantum dot [7].

(ii) The use of controlled dynamic nuclear polarization to reduce hyperfine-induced dephasing, and to provide a controlled gradient for two-axis rotation of the singlet-triplet qubit [8]. A drawback of the singlet-triplet qubit is the lack of a second natural axis of control. By refining single-electron dynamic nuclear polarization, also developed under STIC funding [9], a second axis of spin rotation could be realized, thus making completing the requirement for full qubit control. In addition, the use of feedback to *control* the gradient of hyperfine fields narrowed the fluctuations of the gradient, leading to enhanced coherence.

These two experimental accomplishments have both carried forward with further improvements, and constitute breakthroughs for the field.

A number of Ph.D.'s were earned during STIC funding, as given elsewhere in the final report.

Bibliography

1. J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Coherent manipulation of coupled electron spins in semiconductor quantum dots*, Science **309**, 2180 (2005).

2. A. C. Johnson, J. R. Petta, J. M. Taylor, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Triplet-singlet spin relaxation via nuclei in a double quantum dot*, Nature **435**, 925 (2005).

3. J. M. Taylor, H. A. Engel, W. Dur, A. Yacoby, C. M. Marcus, P. Zoller, and M. D. Lukin, *Fault-tolerant architecture for quantum computation using electrically controlled semiconductor spins*, Nature Physics **1**, 177 (2005).

4. J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, *Relaxation, dephasing, and quantum control of electron spins in double quantum dots*, Phys. Rev. B **76**, 035315 (2007).

5. C. Barthel, D. J. Reilly, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Rapid Single-Shot Measurement of a Singlet-Triplet Qubit*, Phys. Rev. Lett. **103** (2009).

6. D. J. Reilly, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Fast single-charge sensing with a rf quantum point contact*, Appl. Phys. Lett. **91**, 162101 (2007).

7. C. Barthel, M. Kjaergaard, J. Medford, M. Stopa, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Fast sensing of double-dot charge arrangement and spin state with a radio-frequency sensor quantum dot*, Phys. Rev. B **81**, 161308(R) (2010).

8. S. Foletti, H. Bluhm, D. Mahalu, V. Umansky, and A. Yacoby, *Universal quantum control of two-electron spin quantum bits using dynamic nuclear polarization*, Nature Physics **5**, 903 (2009).

9. J. R. Petta, J. M. Taylor, A. C. Johnson, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Dynamic nuclear polarization with single electron spins*, Phys. Rev. Lett. **100**, 067601 (2008).