

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                  |                                |                                         | Form Approved<br>OMB No. 0704-0188                             |                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|--------------------------------|-----------------------------------------|----------------------------------------------------------------|-----------------------------------------------------------|
| <p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.</b></p>                                                                                                                                                                                                                                                                           |                  |                                |                                         |                                                                |                                                           |
| 1. REPORT DATE (DD-MM-YYYY)<br>4/21/05                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  | 2. REPORT TYPE<br>FINAL REPORT |                                         | 3. DATES COVERED (From - To)<br>May 1, 2001 - January 31, 2005 |                                                           |
| 4. TITLE AND SUBTITLE<br>Optically Controlled Quantum Dots for Quantum Computing                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |                                |                                         | 5a. CONTRACT NUMBER<br>DAAD19-01-1-0478                        |                                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |                                |                                         | 5b. GRANT NUMBER                                               |                                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |                                |                                         | 5c. PROGRAM ELEMENT NUMBER                                     |                                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |                                |                                         | 5d. PROJECT NUMBER                                             |                                                           |
| 6. AUTHOR(S)<br>Duncan G. Steel and Lu J. Sham                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                  |                                |                                         | 5e. TASK NUMBER                                                |                                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |                                |                                         | 5f. WORK UNIT NUMBER                                           |                                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |                                |                                         |                                                                |                                                           |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>University of Michigan, EECS Department<br>1301 Beal Avenue, 1108 EECS Bldg.<br>Ann Arbor, MI 48109-2122                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                  |                                |                                         | 8. PERFORMING ORGANIZATION<br>REPORT NUMBER                    |                                                           |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>U.S. Army Research Office<br>ATTN: AMSRD-ARL-RO-OI<br>P.O. Box 12211<br>Research Triangle Park, NC 27709-2211                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |                                |                                         | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>ARO                        |                                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |                                |                                         | 11. SPONSOR/MONITOR'S REPORT<br>NUMBER(S)<br>42378-18-PH-QC    |                                                           |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br>Approved for public release; distribution unlimited                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                  |                                |                                         |                                                                |                                                           |
| 13. SUPPLEMENTARY NOTES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                  |                                |                                         |                                                                |                                                           |
| 14. ABSTRACT<br>This program conducted experimental & theoretical research aimed at developing an optically driven quantum dot quantum computer. In addition to the 2 Co-PI's, the work was done in collaboration with Dan Gammon at the Naval Research Laboratory. D. Gammon had responsibility for growing & characterizing the material, LJ Sham is responsible for theoretical support & concept development, & DG Steel is responsible for experimental demonstration of key experimental demonstrations for quantum computing. Key ideas have now been tested & verified on this system, including demonstration of a quantum controlled-NOT gate & a theoretical proposal to use pulse-shaping to reduce unintended dynamics leading to errors & to increase computation speed. For scalable quantum computation, the qubit for this system is the optically controlled electron spin vector. Initial experiments have now been completed demonstrating that we produce single charged quantum dots (Gammon at NRL), & that we can optically control & manipulate these states. A lower limit on the decoherence rate has also been determined. |                  |                                |                                         |                                                                |                                                           |
| 15. SUBJECT TERMS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                  |                                |                                         |                                                                |                                                           |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |                                | 17. LIMITATION OF<br>ABSTRACT<br><br>UU | 18. NUMBER<br>OF<br>PAGES<br><br>20                            | 19a. NAME OF RESPONSIBLE PERSON<br>Duncan G. Steel        |
| a. REPORT<br>U                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | b. ABSTRACT<br>U | c. THIS PAGE<br>U              |                                         |                                                                | 19b. TELEPHONE NUMBER (Include area code)<br>734-764-4469 |

## **FINAL REPORT**

Optically controlled Quantum Dots for Quantum Computing  
Principal Investigator: Duncan G. Steel, The Peter S. Fuss Professor  
Co-Principal Investigator: L.J. Sham  
Department of Electrical Engineering and Computer Science  
Department of Physics  
Harrison M. Randall Laboratory of Physics  
The University of Michigan  
Ann Arbor, MI 48109  
Phone: 734-764-4469  
Email: dst@umich.edu

ARO PROPOSAL NUMBER: 42378-PH-QC  
FUNDING PERIOD: DAAD19-01-1-0478  
GRANT NUMBER: DAAD19-01-1-0478  
Funding Period: 5/1/01-1/31/05

## **ABSTRACT**

This program conducted experimental and theoretical research aimed at developing an optically driven quantum dot quantum computer. In addition to the two co-principal investigators (Sham and Steel), the work was done in collaboration with Dan Gammon at the Naval Research Laboratory. D. Gammon had responsibility for growing and characterizing the material, LJ Sham is responsible for theoretical support and concept development, and DG Steel is responsible for experimental demonstration of key experimental demonstrations for quantum computing. For this program, the exciton Bloch vector was the initial qubit for preliminary experiments. Key ideas have now been tested and verified on this system, including demonstration of a quantum controlled-NOT gate and a theoretical proposal to use pulse-shaping to reduce unintended dynamics leading to errors and to increase computation speed. For scalable quantum computation, the qubit for this system is the optically controlled electron spin vector. Initial experiments have now been completed demonstrating that we produce single charged quantum dots (Gammon at NRL), and that we can optically control and manipulate these states. A lower limit on the decoherence rate has also been determined. Most importantly, we have constructed a proposal for a scalable architecture for optically driven spin based quantum computing.

## **PUBLICATIONS**

### **JOURNAL PUBLICATIONS**

1. Pochung Chen, C. Piermarocchi, and L.J. Sham, "Theory of coherent optical control of exciton spin dynamics in a semiconductor dot". *Physica E*, **10**, pp.7-12 (2001).
2. D Gammon, N.H. Bonadeo, Gang Chen, D.G. Steel, "Optically probing and controlling single quantum dots," *Physica E* **9**, 99 (2001)).
3. Pochung Chen, C. Piermarocchi, and L.J. Sham, "Control of exciton dynamics in nanodots for quantum operations", *Phys. Rev. Lett.* **87**, 067401 (2001).
4. J.R. Guest, T.H. Stievater, B. Orr, E. Tabak, D.G. Steel, D. Gammon, D.S. Katzer, D.Park, "Near-field coherent spectroscopy and microscopy of a quantum system: Addressing single eigenstates," *Science* **293**, pp2224-2227 (2001).
5. Gang Chen, Dan Gammon, L.J. Sham, D.G. Steel, "Zeeman Coherence in Single Quantum Dots," invited *Sol. St. Comm.* **119** pp199-205 (2001).
6. Todd Stievater, Xiaoqin Li and D. G. Steel, D. Gammon, D. S. Katzer and D. Park, L. J. Sham, C. Piermarocchi, "Rabi Oscillations of Excitons in Single Quantum Dots", *Phys. Rev. Lett.* **87**, pp133603-1-133603-4(2001).
7. T. H. Stievater, Xiaoqin Li, J. R. Guest, D. G. Steel, D. Gammon, D. S. Katzer and D. Park, "Wavelength Modulation Spectroscopy of Single Quantum Dot States," *Appl. Phys. Lett.* **80**, pp 1876-1878 (2002).
8. C. Piermarocchi, Pochung Chen, Y.S. Dale. and L.J. Sham, "Theory of fast quantum control of exciton dynamics in semiconductor quantum dots." *Phys. Rev. B*, **65**, 075307 (2002).
9. Gang Chen, T. H. Stievater, E. A. Tabak, Xiaoqin Li, D. G. Steel, D. Gammon, D. S. Katzer, D. Park, L. J. Sham, "Biexciton Quantum Coherence in a Single Quantum Dot," *Physical Review Letters* **88**, p117901 (2002).
10. A.S. Lenihan, M.V. Gurudev Dutt, D.G. Steel, S. Ghosh, and P.K. Bhattacharya, Raman Coherence Beats from Entangled Polarization Eigenstates in InAs Quantum Dots, in press, *Physical Review Letters* **88**, pp 223601-223604 (2002.)
11. T. H. Stievater, Xiaoqin Li, D. G. Steel, D. Gammon, D. S. Katzer, D. Park, "Transient Nonlinear Spectroscopy of Excitons and Biexcitons in Single Quantum Dots," *Phys. Rev. B* **65**, 205319 (2002).
12. J.R. Guest, T.H. Stievater, Xiaoqin Li, D.G. Steel, D. Gammon, D. S. Katzer and D. Park, C. Ell, A. Thränhardt, G. Khitrova, H. Gibbs, "Direct Observation of Optical Absorption by Single Quantum Dot Excitons," *Phys. Rev. B Rapid Communications* **65**, 241310 (2002).
13. J.R. Guest, Xiaoqin Li, T.H. Stievater, D.G. Steel, and D. Gammon "Direct Probing of Quantum Dots through Linear and Nonlinear Nano-optics," *Physica Status Solidi (b)* **234** pp435-442 (2002).

14. D. Gammon and D.G. Steel, "Optical studies of single quantum dots," *Physics Today* **55**, pp36-41 (2002).
15. C. Piermarocchi, Pochung Chen, L.J. Sham, D.G. Steel "Optical RKKY interaction between charged semiconductor quantum dots," *Physical Review Letters* **89**, 167402 (2002)
16. T. H. Stievater, Xiaoqin Li, T. Cubel, D. G. Steel, D. Gammon, D. S. Katzer and D. Park. "Measurement of Relaxation Between Polarization Eigenstates in Single Quantum Dots," *Applied Physics Letters* **81**, 4251 (2002). Reprinted in *Virtual Journal of Nanoscale Science and Technology*. **6** (23) (2002).
17. Pochung Chen, C. Piermarocchi, and L. J. Sham, "Control of Exciton Dynamics in Nanodots for Quantum Operations" *Phys. Rev. Lett.* **87**, 067401 (2001)
18. Xiaoqin Li, Yanwen Wu, Duncan Steel, D. Gammon, T.H. Stievater, D.S. Katzer, D. Park, C. Piermarocchi, L.J. Sham, "An all-optical quantum gate in a semiconductor quantum dot," *Science*. **301**, pp809-811 (2003).
19. C. Piermarocchi, Pochung Chen, L. J. Sham, and D. G. Steel, Quantum Control of Spins and Excitons in Semiconductor Quantum Dots, in *Proceedings of the International School of Physics "Enrico Fermi", Course CL*, edited by B. Deveaud, A. Quattropani, and P. Schwendimann, Vol. 150 (IOS Press, Amsterdam, 2003) pp. 289-302.
20. Gang Chen, E.A. Tabak, D.G. Steel, D. Gammon, and D.S. Katzer, "Spectral Zeeman hole burning in a quantum dot ensemble," *Phys. Rev. B* **68**, 115303 (2003).
21. Pochung Chen, C. Piermarocchi, L.J. Sham, D. Gammon, D.G. Steel, "Theory of quantum optical control of a single spin in a quantum dot," *Phys. Rev. B* **69**, 075320(2004).
22. A.S. Lenihan, M.V. Dutt, and D.G. Steel, S. Ghosh, P.K. Bhattacharya, "Biexciton resonance in the nonlinear optical response of an InAs quantum dot ensemble," *Phys. Rev. B* **69**, 045306 (2004)
23. E.T. Batteh, Jun Cheng, Gang Chen, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, "Coherent nonlinear optical spectroscopy of single quantum dot excited states," *Appl. Phys. Lett.* **84**, 1928 (2004).
24. E.T. Batteh, Jun Cheng, Gang Chen, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, "Coherent nonlinear optical spectroscopy of fluctuation quantum dots: evidence of coupling between quantum dots," in press *Phys. Rev. B*. (2005).
25. Xiaoqin Li, Yanwen Wu, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, L.J. Sham, "Raman coherent beats from the entangle exciton Zeeman doublet in a single quantum dot," *Phys. Rev. B* **70**, 195330 (2004).
26. Pochung Chen, C. Piermarocchi, L. J. Sham, D. Gammon, and D. G. Steel, Theory of quantum optical control of a single spin in a quantum dot, *Phys. Rev. B* **69**, 075320 (2004)
27. Yanwen Wu, D. Gammon, L.J. Sham, D.G. Steel, "Coherent Optical Control on the Semiconductor Quantum Dots for Quantum Information Processing" *Physica E*. **25**, pp242-248(2004).
28. Xiaoqin Li, Duncan Steel, Daniel Gammon, L.J. Sham, "Optically driven quantum computing devices based on semiconductor quantum

- dots," Invited, *Quantum Information Processing* **3**, p. 147 (2004).
29. Xiaoqin Li, Duncan Steel, Daniel Gammon, L.J. Sham, "Quantum Information Processing Based on Optically Driven Semiconductor Quantum Dots, invited "Optics and Photonics News (2004).
  30. M.V. Gurudev Dutt, Jun Cheng, Bo Li, Xiaodong Xu, Xiaoqin Li, P.R. Berman, D.G. Steel, A.S. Bracker, D. Gammon, Sophia E Economou, Renbao Liu and L.J. Sham, "Stimulated and spontaneous optical generation of electron spin coherence in charged GaAs quantum dots," submitted (2004).
  31. M.V. Gurudev Dutt, Yanwen Wu, Xiaoqin Li, D.G. Steel, D. Gammon, L.J. Sham, "Semiconductor quantum dots for quantum information processing : An optical approach", Proceedings, ICPS, American Institute of Physics (2004).
  32. G. Ramon, Y. Lyanda-Geller, T. L. Reinecke, and L. J. Sham, "Indirect coupling between spins in semiconductor quantum dots", condmat/0412003, *Phys. Rev. B*, in press.
  33. Sophia E. Economou, Ren-Bao Liu, L.J. Sham, and D.G. Steel, "A Unified Theory of Consequences of Spontaneous Emission in a  $\Lambda$  System", cond-mat/0501474, in press *Phys. Rev. B*.
- subject of "Ultrafast processes in solid state nanostructures".
3. Duncan G. Steel "Quantum Dots: Artificial Atoms for Quantum Computing," *Nonlinear Optics Conference Topical* (2002).
  4. Xiaoqin Li, T.H. Stievater, Yanwen Wu, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, Pochung Chen, C. Piermarocchi, L.J. Sham, "Quantum-Bit Rotations in Single Quantum Dots: Rabi Oscillations of Excitons and Biexcitons," *QELS 2002*.
  5. S. Lenihan, Gang Chen, T. H. Stievater, E. A. Tabak, X. Li, M. V. G. Dutt, and D. G. Steel, S. Ghosh and P. K. Bhattacharya D. S. Katzer, D. Park, and D. Gammon, L. J. Sham, *Quantum Dots: Artificial Atoms and Quantum Computing International Workshop for Quantum Dots and Quantum Computing*, Kochi, Japan (2002)
  6. D. Steel "Single Biomolecule Spectroscopy: Watching Proteins One at a Time" *Micro and Nanotechnology in the Life Sciences*, Michigan 2002.
  7. D.G. Steel, A. Bracker, Gang Chen, Pochung Chen, Jung Cheng, J. Guest, Gurudev Dutt, D.G. Gammon, D. S. Katzer, A. Lenihan, Xiaoqin Li, D. Park, C. Piermarocchi, L.J. Sham, T. H. Stievater, E. A. Tabak, "Optically Driven Semiconductor Quantum Dots for Quantum Computing" , *Midwest Solid State Conference*, University of Illinois (2002).
  8. Xiaoqin (Elaine) Li and Duncan Steel, "Coherent Nonlinear Optical Spectroscopy and Control of Single GaAs Quantum Dots: Towards Quantum Logic Gates" *International Workshop on Spintronics*, Purdue (2002).

#### INVITED CONFERENCE PAPERS

1. Duncan G. Steel, "Coherent Optical Control of Quantum Dots", *CLEO/QELS (2001) OSA Technical Digest*, pp 160 (2001).
2. Duncan G. Steel "Quantum Dots for Optically Driven Quantum Computing," *Euro-Conference*, March 2002 in Les Houches, on the

9. Xiaoqin (Elaine) Li and Duncan Steel, "Coherent Nonlinear Spectroscopy and Control of Single Quantum Dots: Towards Quantum Logic Gates" Materials Research Society (2002)
10. D.G. Steel, "Coherent Nonlinear Optical Control and Manipulation of Single Quantum Dots: Toward a Quantum Logic Device", Nonlinear Optics Gordon Conference (2003)
11. D.G. Steel, "Optical excitations in quantum dots for quantum information processing" Frontiers in Optics Meeting, LSI XIX-OSA Annual (2003)
12. Xiaoqin Li, Yanwen Wu, Gurudev Dutt, Duncan Steel, D. Gammon, T.H. Stievater, D.S. Katzer, D. Park, C. Piermarocchi, L.J. Sham, "Quantum Dots as Artificial Atoms: Towards a Quantum Dot Quantum Computer" (IWQDQC) Notre Dame (2003).
13. M. V. Gurudev Dutt, Jun Cheng, Bo Li, Wencan He, D. G. Steel, A. S. Bracker, D. Gammon, L. J. Sham, "Coherent Optical Manipulation of Quantum dot Electron Spins" Gordon Conference (2003).
14. D.G. Steel, "Coherent Optical Control of Single Quantum Dots: A Step Towards Quantum Computing" Winter school Mauterndorf (2004).
15. D.G. Steel, "Coherent Optical Control of Quantum Dots: Application to Quantum Computing," March Meeting, APS, Montreal (2004).
16. Duncan Steel, Gurudev Dutt, Xiaoqin Li, Yanwen Wu, Jun Chen, D. Gammon, LJ Sham, "Optical control of spin in semiconductor dots for quantum operation," ITAMP, Harvard, 2004
17. D.G. Steel, "Optical control in semiconductor dots for quantum operations", ICPS-27 (2004), Flagstaff, AZ.
18. Jun Cheng D. Steel, L.J. Sham, D. Gammon, "Coherent Optical Spectroscopy of Electron Spins in Charged Semiconductor Quantum Dots," Third International Workshop on Nanoscale Spectroscopy and Nanotechnology, College Park 2004.
19. D.G. Steel, "Coherent optical manipulation of quantum dot spins: A path into quantum computing." QELS (2005).

# CONTRIBUTED

1. A.S. Lenihan, M.V.G. Dutt, D.G. Steel, S. Ghosh, and P.K. Bhattacharya, "Spin Relaxation in InAs Quantum Dots Probed by Transient Nonlinear Optical Spectroscopy, CLEO/QELS'01, OSA Technical Digest, pp 5-6 (2001).
2. Xiaoqin Li, T.H. Stievater, J.R. Guest, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, "Optical absorption measurements from single semiconductor quantum dots," CLEO/QELS'01, OSA Technical Digest, pp 84-85 (2001)
3. Gang Chen, T. H. Stievater, E. A. Tabak, Xiaoqin Li, D. G. Steel, D. Gammon, D. S. Katzer, D. Park, "Nondegenerate Two-Photon Absorption from Single Quantum Dot Biexcitons," CLEO/QELS'01, OSA Technical Digest, pp 34-35 (2001)
4. E. A. Tabak, Gang Chen, D. G. Steel, A. S. Bracker, D. Gammon, "Nonlinear Spectroscopy of Coupled Quantum Dots," CLEO/QELS'01, OSA Technical Digest, pp 87-88 (2001)

5. T. H. Stievater, Xiaoqin Li, D. G. Steel, D. Gammon, D. S. Katzer, and Dots", CLEO/QELS'01, OSA Technical Digest, pp 18-19 (2001)
6. E.T. Batteh, Gang Chen, Jun Cheng, D.G. Steel, A.S. Bracker, D. Gammon, Po-Chung Chen, Carlo Piermarocchi, L.J. Sham, "Quantum Coherence in a Coupled Exciton-Quantum-Dot System" QELS 2002
7. C. Piermarocchi, Pochung Chen, L.J. Sham, T.H. Stievater, Xiaoqin Li, D.G. Steel, "Optical quantum control in a single quantum dot: toward a prototype semiconductor quantum computer," QELS 2002.
8. T.H. Stievater, Xiaoqin Li, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, "Transient nonlinear spectroscopy of biexcitons in single quantum dots," QELS 2002.
9. Gang Chen, E. A. Tabak, Xiaoqin Li, D. G. Steel, D. Gammon, L. J. Sham, "An Optically Induced and Detected Bell-Like State in a Single Quantum Dot, QELS 2002
10. Jun Cheng, M. V. Gurudev Dutt, D. G. Steel, A. S. Bracker, D. Gammon and L. J. Sham "Nonlinear spectroscopy of a charged GaAs quantum dot ensemble" QELS 2003.
11. Yanwen Wu, Xiaoqin Li, D. G. Steel, D. Gammon, D. S. Katzer, D. Park, L. J. Sham, "Qubit Rotation with Multiple Phase-locked Pulses in Single Quantum Dots," QELS 2003.
12. Xiaoqin Li, Yanwen Wu, D. G. Steel, D. Gammon, D. S. Katzer, D. Parker and L. J. Sham, "Raman Quantum Beats from the Entangled Exciton Zeeman Doublet in a Single Quantum Dot," QELS 2003
13. M. V. Gurudev Dutt, Jun Cheng, D. G. Steel, A. S. Bracker, D. Gammon, L. J. Sham "Coherent Nonlinear Optical Response from Single GaAs Quantum Dot Trions," QELS 2003
14. M. V. Gurudev Dutt, Jun Cheng, Bo Li, Wencan He, D. G. Steel, A. S. Bracker, D. Gammon, L. J. Sham, "Coherent Optical Manipulation of Quantum dot Electron Spins" QELS/CLEO Postdeadline (2003).
15. Yanwen Wu, Xiaoqin Li, D.G. Steel, A.S. Bracker, D. Gammon, L.J. Sham "A complete mapping of the density matrix of a qubit in a single quantum dot," IQEC (2004).
16. Jun Cheng, M.V. Gurudev Dutt, Wencan he, D.G. Steel, A.S. Bracker, D. Gammon, L.J. Sham, "Coherent nonlinear optical spectroscopy of single charged GaAs Quantum Dots," IQEC (2004).
17. M.V. Gurudev Dutt, Jun Cheng, Bo Li, Wencan He, D.G. Steel, A.S. Bracker, D. Gammon, L.J. Sham, "Optically Generated Single Electron Spin Coherence," IQEC (2004).
18. Xiaoqin Li, Yanwen Wu, D.G. Steel, D. Gammon, L.J. Sham "An optical Controlled-NOT gate in a single quantum dot," IQEC (2004).
19. E. T. Batteh, Gang Chen, Jun Cheng, D.G. Steel, D. Gammon, D. S. Katzer, D. Park, Pochung Chen, C. Piermarocchi, L. J. Sham, "Two Exciton States in Semiconductor Quantum Dots" APS March Meeting 2002.
20. Xiaoqin Li, T.H. Stievater, Yanwen Wu, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, Pochung Chen, C. Piermarocchi, L. J. Sham, "Rabi Oscillations of Excitons and Biexcitons in Single Semiconductor Quantum Dots" APS March Meeting 2002.
21. M. V. Gurudev Dutt, J. Cheng, D. G. Steel, A. S. Bracker, D. Gammon, L. J. Sham "Coherent Nonlinear Optical

Spectroscopy of Single Charged Quantum Dots,” APS March Meeting (2003).

22. Xiaodong Xu, Jun Cheng, M. V. Gurudev Dutt, Yanwen Wu and D. G. Steel A. S. Bracker and D. Gammon, Renbao Liu, Sophia E. Economou and L. J. Sham, “Optically Stimulated and Spontaneously Generated Electron Spin Coherence in Quantum Dots” to be presented QELS/CLEO 2005
23. Jun Cheng, Xiaodong Xu, and D. G. Steel, A. S. Bracker and D. Gammon, L. J. Sham, “Spin-coherence-induced Hole Burning in Charged GaAs Quantum Dots,” to be presented QELS/CLEO 2005.

### **Educational Activity**

A number of students participated in the experimental program as evidenced in the above publications. Six of the students have since graduated with a Ph.D (Todd Stievator (NRL), Anthony Lenihan (UMd), Xiaoqin Li (JILA/NIST), Gang Chen (Lucent), Elizabeth Batteh (General Dynamics), Gurudev Dutt (Harvard)). At the end of this program, there were six students continuing to work towards their Ph.D.

In the theory group, a postdoc, Carlo Piermarocchi, was appointed to a faculty position in Michigan State University and has now built a robust and funded research program. A student, Pochung Chan, completed his Ph.D., was postdoc for Birgitta Whaley at UC Berkeley for about a year and then recruited as a faculty in Tsing-Hwa University in Taiwan. Of the two summer undergraduate interns, Yseulte Dale from Stanford did a great job for us, coauthored a paper on pulse-shaping and decided on graduation to teach science and

build a chain of high schools. Raiser Karasik from NYU got really interested in quantum computing through the summer research and she was admitted to the graduate program in Berkeley, working in Whaley's group.

### **Brief Outline of Research Findings:**

Nearly all of the research findings presented in this report have been presented in the annual reports resulting in 33 journal publications. However, for completeness, we summarize some of the most exciting results. The work in this program is done in collaboration with the fabrication group headed by Dan Gammon at NRL and the theory group headed by Lu Sham at UC-SD.

### **Experimental Results**

*(Done with close collaboration with theory, see discussion below.)*

This work focuses on developing and applying the necessary methodology for the understanding and application of semiconductor quantum dots for quantum computing. Several major mile stones were achieved during the present program including the demonstration of an all optically controlled semiconductor quantum dot based quantum NOT-gate, publications of a model for a scalable quantum computer based on optically controlled quantum dot spins, and demonstration of optically induced electronic spin coherence and optical control. Future work is focusing on demonstrating a scalable spin based system as well as working to develop long-lived coherent states.

During this program, some of the major developments include:

## 1. Demonstration of conditional quantum logic gate with optical readout

While we are now moving on aggressively to work on single spin qubits to develop a quantum gate of the type first described by our collaborators in their recent Phys. Rev. Lett., we are completing the demonstration experiments of quantum operations using exciton qubits which demonstrate that the manybody effects that characterize the fast decoherence and coherent optical control are suppressed in quantum dots leading to more atomic like behavior.

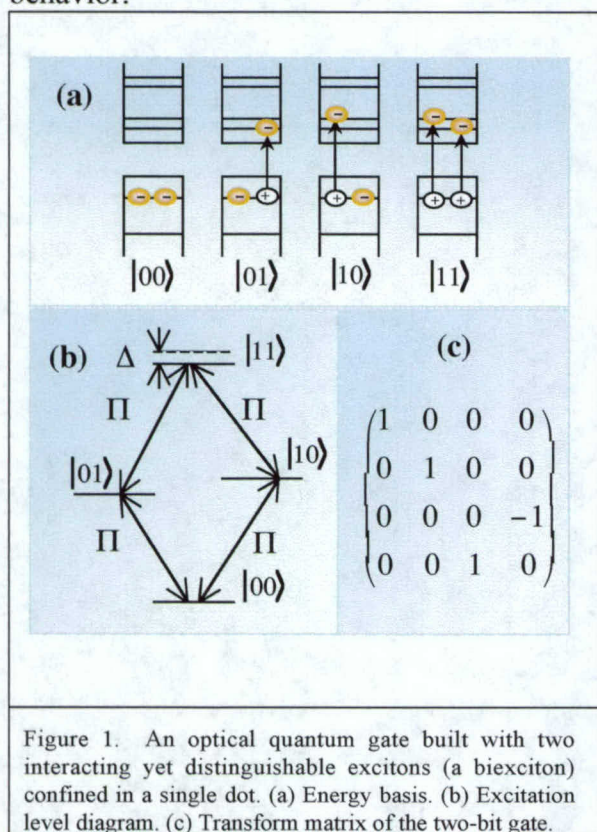


Figure 1. An optical quantum gate built with two interacting yet distinguishable excitons (a biexciton) confined in a single dot. (a) Energy basis. (b) Excitation level diagram. (c) Transform matrix of the two-bit gate.

In this program, we succeeded in achieving the basic demonstration needed for proving feasibility of an optically driven solid state quantum computer. Specifically, we demonstrated coherent optical control of the quantum motion of one or two electrons in effective isolation in a semiconductor

nanosystem leading to the first demonstration of an all optically controlled semiconductor quantum NOT-gate with optical readout.

In a single quantum dot (Fig. 1) the two qubits correspond to the optical Bloch vectors leading to formation of the biexciton (two electron-hole pairs, a four-particle state) which have been proposed as the physical realization of universal quantum logic gates.

In a single QD, quantum confinement greatly enhances the higher order Coulomb interaction, leading to the formation of a bound state of two orthogonally polarized excitons and decreases the role of manybody physics which leads to rapid decoherence and great complexity in the nonlinear response. The excitation of one exciton affects the resonant energy of the other, which corresponds to the characteristic conditional quantum dynamics needed for quantum computing. In this system, the optical Bloch vector of each exciton transition corresponds to a qubit.

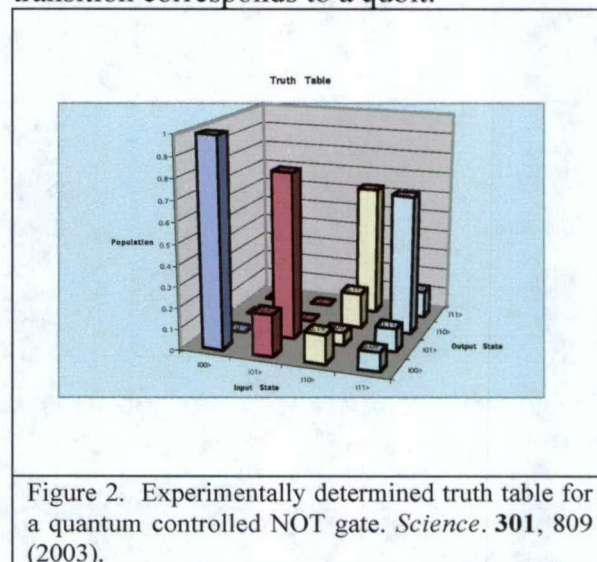


Figure 2. Experimentally determined truth table for a quantum controlled NOT gate. *Science*. **301**, 809 (2003).

The pulse control of the biexciton dynamics, combined with the demonstrated control of the single exciton Rabi rotation, serves as the physical basis for a two-bit

conditional quantum logic gate. The experimentally determined truth table for the gate (see Fig. 2 which shows the magnitude of the density matrix terms based on the experiments) shows the features of an all-optical quantum gate using interacting, yet distinguishable exciton transitions. Based on various optically initialized starting state, evaluation of the fidelity yields a calculated value of order 0.7 for the gate operation. This logic gate is the basis for further development of inter-dot logic gates for universal quantum computation.

## 2. Density Matrix Tomography

Coherent control enabling an arbitrary rotation of the optical Bloch spin vector associated with either the optical dipole or the electron spin is an essential step in demonstrating coherent optical control of any electronic system for many proposed applications, including quantum computing. In the case of quantum computing, for example, single qubit (Bloch vector) rotations are often used to prepare the input states for logic operations. Fully characterizing the density matrix associated with this rotation is called density matrix tomography. Alternatively, the performance of a quantum logical gate, such as a controlled-NOT gate in a semiconductor quantum dot, is characterized by its gate fidelity. In order to calculate the realistic gate fidelity of a particular gate, one must have full knowledge of the output state created by the gate operation, namely all values of the complex density matrix must be measured. Here we demonstrate the ability to measure the off-diagonal matrix elements ( $\rho_{12}$ ,  $\rho_{21}$ ) as well as the diagonal density matrix elements ( $\rho_{11}$ ,  $\rho_{22}$ ) of a closed two-level system, which leads to a complete mapping of the density matrix of a given qubit in a single quantum dot (QD).

This requires new capability of the laser system, so our objective in this was to use the exciton system (rather than spin), which is more established, and demonstrate that our new optical capability can achieve this new result.

In the exciton regime, optical excitation driving transitions between the crystal ground state and the exciton state translates to a rotation of the Bloch vector or qubit from state  $|0\rangle$  to  $|1\rangle$ . The optical pulse area,  $\theta$ , is defined by  $\theta(t) = [\mu_{eg}/\hbar] \int_{-\infty}^{\infty} dt E(t)$ . A pulse area of  $\pi$  exchanges the two basis states,  $|0\rangle$  and  $|1\rangle$ , of the qubit, in particular, the populations between these states, i.e., population in qubit state  $|0\rangle$  will be fully inverted to state  $|1\rangle$  or vice versa. In general, we can apply pulses with corresponding pulse areas from 0 to  $\pi$  to create from the ground state (say  $|0\rangle$ ) an arbitrary superposition of  $|0\rangle$  and  $|1\rangle$ . This ability is demonstrated in the optically driven single exciton Rabi oscillations

Rabi oscillations manifest themselves in the fact that the population of the exciton population can be controlled coherently with a single laser pulse. However, multiple consecutive rotations of a qubit are required in practical quantum computation processes or to reconstruct the density matrix. Maintaining the relative phase information between consecutive single rotations is essential for these applications (e.g. the Hadamard gates, similar to an excitation with a  $\pi/2$  pulse, that are used to prepare and collapse the qubit in logic operations in error correction codes and in the DJ problem, need to have a strict phase relation with each other in order to achieve the correct output). Coherent optical studies show that the phase coherence of an exciton qubit is of the order of the exciton lifetime, implying negligible pure dephasing. In other proposed quantum

systems such as nuclear magnetic resonance (NMR) and trapped ions where microsecond wide pulses are used, phase locking between rotations can be done electronically. In the QD systems, the THz computational speed is beyond the phase locking capability of even the fastest electronics available.

To maintain the phase coherence between rotations without compromising the speed of computation, an optical approach to phase locking is used. An experiment demonstrating the capacity of optical phase locking is conducted using two actively phase-locked pulses from a Michelson interferometer on an exciton-based qubit. The delay and the phase between the two pump pulses can be adjusted with a translation stage and a piezoelectric mount, respectively. The piezoelectric mount is controlled by a feedback loop to compensate any phase jitter in the optical system.

The experiment is conducted with a 4 ps pulse width laser in a pump and probe geometry. A Michelson interferometer in the path of the pump beam creates two pump pulses ( $P_1$ ,  $P_2$ ) with tunable coarse ( $\tau$ ) and phase ( $\phi$ ) delays between the pulses. The differential transmission (DT) signal is homodyne detected with the transmitted probe beam. The first pump pulse ( $P_1$ ) with an arbitrary pulse area ( $P_1\theta$ ) creates a state with an arbitrary density matrix,

$$M1 = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix} \quad (1)$$

We can measure  $\rho_{22}$  with a simple population readout via DT which has a definite relation with the excited state population, then  $\rho_{11}$  is inferred from  $1-\rho_{22}$ . The second pump pulse ( $P_2$ ) with a pulse area ( $P_2\theta$ ) performs a rotation ( $R_{P_2\theta}$ ) to a new state characterized by a new density matrix,

$$M2 = \begin{bmatrix} \rho'_{11} & \rho'_{12} \\ \rho'_{21} & \rho'_{22} \end{bmatrix} = R_{P_2\theta} M1 R_{P_2\theta}^\dagger \quad (2)$$

For  $P_2\theta = \pi/2$ ,  $\rho'_{22} = 1/2 + \text{Im}(\rho_{12})$  at  $\phi = 0$  and  $\rho'_{22} = 1/2 - \text{Re}(\rho_{12})$  at  $\phi = \pi/2$  for a closed two-level system. Since we can measure  $\rho'_{22}$  through population readout, we can extract the values of  $\rho_{12}$  and  $\rho_{21}$ . In the Bloch picture, the second pump pulse ( $P_2$ ) corresponds to an active rotation of the Bloch state vector on the Bloch sphere, which projects the off-diagonal components of the vector onto the diagonal component axis of the Bloch sphere, making them extractable through population readout. This active  $\pi/2$  rotation technique is widely used with magnetic fields in nuclear magnetic resonance (NMR). Here the method is extended to optical fields in a semiconductor system.

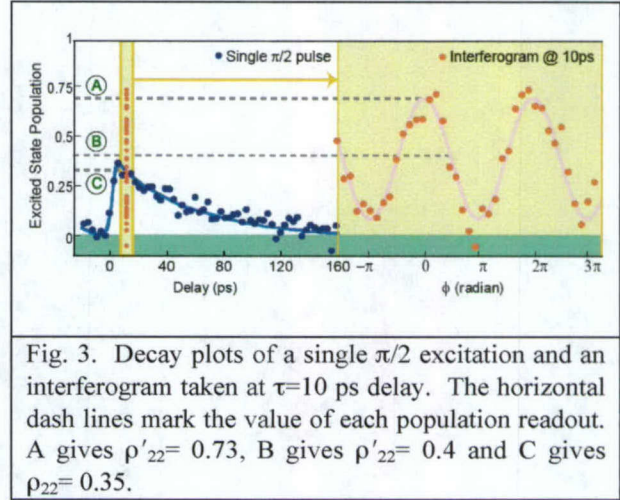
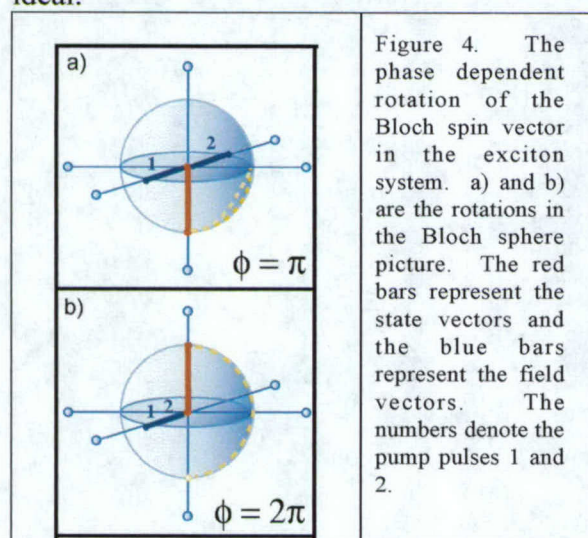


Fig. 3. Decay plots of a single  $\pi/2$  excitation and an interferogram taken at  $\tau=10$  ps delay. The horizontal dash lines mark the value of each population readout. A gives  $\rho'_{22} = 0.73$ , B gives  $\rho'_{22} = 0.4$  and C gives  $\rho_{22} = 0.35$ .

Using equation 2 and values A, B and C from Figure 3, we obtained  $\rho_{11}=0.65$ ,  $\rho_{22}=0.35$ ,  $\rho_{12}=\rho_{12}^*=0.11+i0.21$  at  $\tau=10$  ps. In a simulation calculation, the values of  $\rho_{11}=0.60$ ,  $\rho_{22}=0.40$ , and  $\rho_{12}=\rho_{12}^*=0.08+i0.21$  are comparable to the measured values. Due to the finite population decay and dephasing of this two-level system, there exist discrepancies between the decoherence-free values ( $\rho_{11} =$

0.5,  $\rho_{22} = 0.5$ ,  $\rho_{12} = \rho_{12}^* = i0.5$ ) and the measured values of the density matrix elements created by  $P_1$ . These discrepancies can be minimized by using shorter pulse widths and systems with longer decay times.

In an ideal Bloch sphere representation (Fig. 4), the qubit state prepared in  $(|0\rangle + |1\rangle)/2$  is driven to the pseudo-spin down state for  $\phi = \pi$  (Fig. 4a) and to the pseudo-spin up state for  $\phi = 2\pi$  (Fig. 4b). In reality, the experimental results deviate from the ideal.



Even though the lifetime of the qubit given the pulse width used is inadequate for the demonstration of a complete algorithm, it is enough to illustrate another important point: the quantum memory of the system. Due to the memory of the system, the exciton still 'remembers' the information imposed by the first pulse beyond the pulse duration, enabling the second pulse to access this information at a later time. The interferogram in Fig. 3 presents a clear example of the quantum memory, which allows two pulses to interfere with each other even when they are not overlapped in time. The span of the memory and the coherence lifetime of the system are essentially equivalent. For practical

computation, a system with long coherence time, such as the spin system, is needed.

### 3. Coherent Optical Control of Single Spin States

Figure 5 shows the basic idea of a quantum dot spin qubit shown in the single particle picture and shows the difference between the two degenerate ground states. By adding a single electron to the quantum dot, the ground state of this system becomes doubly degenerate and is known to exhibit long relaxation times, relative to the exciton relaxation time. The long relaxation time is expected to lead to long coherence times. A scalable system is achieved by creating an array of such dots within a few 10's of nanometers of each other.

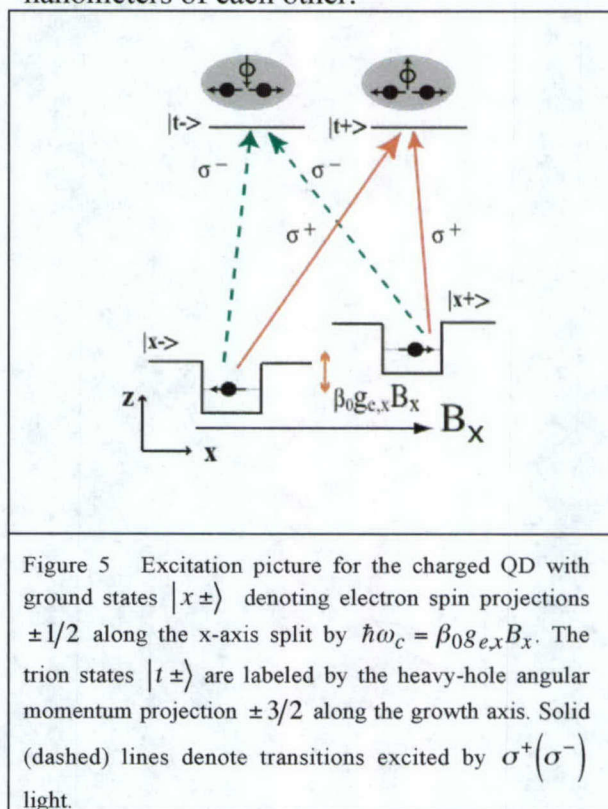


Figure 6 shows the quantum beat experiments we performed in ensemble measurements in this system. For comparison, the inset of Fig. 6b shows the beats obtained in a single uncharged

quantum dot. The results are quite remarkable. The data show that the coherence decay time of the beats is much longer in the doped system. Physically, the beats arise from a Raman type coherence induced between two states. In the case of the neutral dot, the coherence is between the two excited states of the neutral exciton. The decay time in that system is limited by the radiative recombination time that is very fast. In the case of the charged dot, the coherence is between two orthogonally polarized spin states ( $|x\pm\rangle$ ) that are the ground states of the trion.

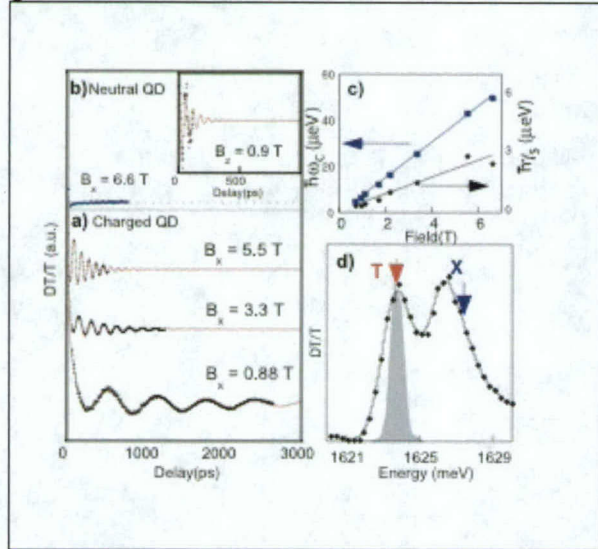


Figure 6 Differential transmission (DT) signal as a function of in-plane magnetic field  $B_x$  obtained when the laser pulse is tuned to selectively excite the trion resonance. Data shown is the difference between PCP and OCP signals. Solid lines show obtained fits to the data. (b) DT signal at X for  $B_x = 6.6T$  showing no oscillations. Inset: Single QD exciton beats obtained in the Faraday geometry with  $B_z = 0.9T$ . (c) Variation of the decay rate and the oscillation frequency with the field in the doped dots. We extract the g-factor to be  $g_{e,x} = \pm 0.13$ . The coherence relaxation time at low fields exceeds 10 nsec. (d) DT spectrum with the pulse delay fixed at +10 ps. The shaded region is the pulse spectrum, and arrows at T (X) label the trion (exciton) resonances.

We note that while this coupling between two orthogonally polarized spin states is normally dipole forbidden, the

magnetic field perpendicular to the growth direction mixes the states, allowing the transition. The insets show that the spin coherence time exceeds 10 nsec at  $B=0$ , but this is a lower limit since the measurements are made in the ensemble and are likely inhomogeneously broadened (i.e., we are measuring  $T_2^*$ .)

The data however, also shows new physics. A measurement of the phase and amplitude of the beats shows an anomalous dependence on Zeeman splitting as seen in Fig. 7. The dashed line shows the prediction from the standard theory. The standard theory is the result of tracing over the radiation field giving rise to spontaneous emission assuming the selection rules are determined by spherical symmetry of the electron-hole interaction, typical of atomic systems.

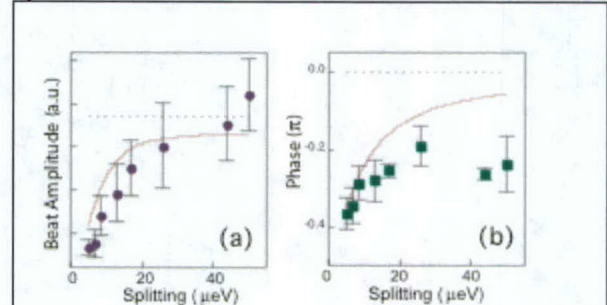


Figure 7 (a) and (b) show the change in the amplitude and phase of the oscillations as a function of the splitting. Solid (dashed) lines denote theoretical predictions for these parameters with (without) the effects of SGC included. In numerical calculations, the optical pulses are assumed Gaussian with the intensity given by  $I(\omega) = \exp(-\omega^2/2\sigma^2)$  ( $\sigma = 0.35$  meV).

However, confinement by the quantum dot structure breaks this symmetry, and a new term must be included in the density matrix description. Specifically, we must account for spontaneous emission leading to spin coherence. Such spontaneously generated coherence has not been observed before, but is readily anticipated in these

systems. The theoretical prediction for the results of Fig. 7 are seen to be in excellent qualitative agreement.

#### 4. Coherent Optical Control of Spin Coherence

The next class of experiments we are working on is the demonstration of coherent optical control of spin coherence, similar to the coherent optical experiments we performed on the exciton and published in Science in the previous program. Figure 8 shows the 3 Feynman diagrams for the density matrix operator that lead to spin coherence. Controlling the phase between any one of these diagrams can lead to constructive or destructive interference and serve to control the spin coherence of the system following excitation by the first pulse. The time scale for control between the first two diagrams will be on the order of spin precession frequency while the third diagram controls the dipole coherence that effects the spin coherence and has a time scale of the inverse optical frequency (fsec). A critical result of these experiments will be to prove that the measurement of decoherence rate of the spin coherence is real.

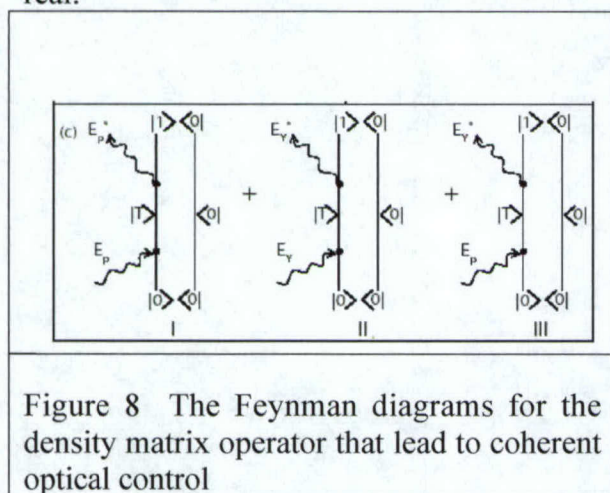


Figure 8 The Feynman diagrams for the density matrix operator that lead to coherent optical control

## THEORY

The theory group works very closely with the experimentalists, investigating the method of implementation of a scalable quantum computer by optical control of electron spins in semiconductor dots. The theory group serves both the function of finding the methods of implementation governed by the existing and potential experimental boundaries and the supporting role in understanding the experiments. The publication record of the collaboration demonstrates the fruitfulness of the close interaction. This part of the report contains (1) a designed route to a scalable computer, (2) a summary of results of detailed descriptions of steps in the theoretical implementation, (3) a summary of results of simulations of optical controls for three algorithms and an estimate of the optical resources required for a typical algorithm, and (4) a description of specific roles which our theory plays in the experiments. We conclude with a brief description of the continuing research effort.

### 1. The route to a scalable quantum computer based on opto-spintronics in the quantum limit

Our scheme of scalable quantum computation includes these basic elements:

1. **Qubits:** In a system of self-assembled InAs quantum dots in a GaAs layer, each carries one conduction electron whose spin represents the qubit.
2. **Gates:** Optical control of the Raman process between the two spin levels of an electron and a trion state in an in plane static magnetic field (always on) is designed for arbitrary single qubit operations. Adiabatic control of optically induced spin-spin interaction between two electrons residing in neighboring dots is used for an entangling gate between two qubits. Together these two

groups of gates are sufficient for universal computation.

3. **Addressing the qubits:** The quantum dots are arranged in two dimension. Each laser spot is focused to a diameter of about  $0.1 \mu\text{m}$  on 6-12 dots. These dots all have different conduction electron energy levels. Within this spot, the spin rotation on a single dot is carried out by frequency selection. For the logic operation on the spins in two neighboring dots, the AC Stark shift is used to bring the excited exciton states in two dots into resonance for coupling of the two dots, illustrated by the optical transition labeled "AC Stark" in Fig. 9(b). For more details see below.
4. **Initialization:** Laser excitation to an excited trion followed by rapid decay to the lowest energy trion by optical phonon emission and by optical cooling

of one spin component to the grounds state is used to prepare a pure spin state.

5. **Readout:** We have in principle a scheme for a single photon measurement of a single spin. The photon path is split into one through the dot and one bypassing it. The polarized photon through the dot is designed to measure the absorption of the photon by a spin state. The occurrence of the event is discriminated by homodyning the resultant photons from the two paths. Continuing effort is being made to design better readout schemes. In the meantime, the existing measurement of differential transmission is used to carry out time averaged (and, therefore, not scalable) spin measurement.

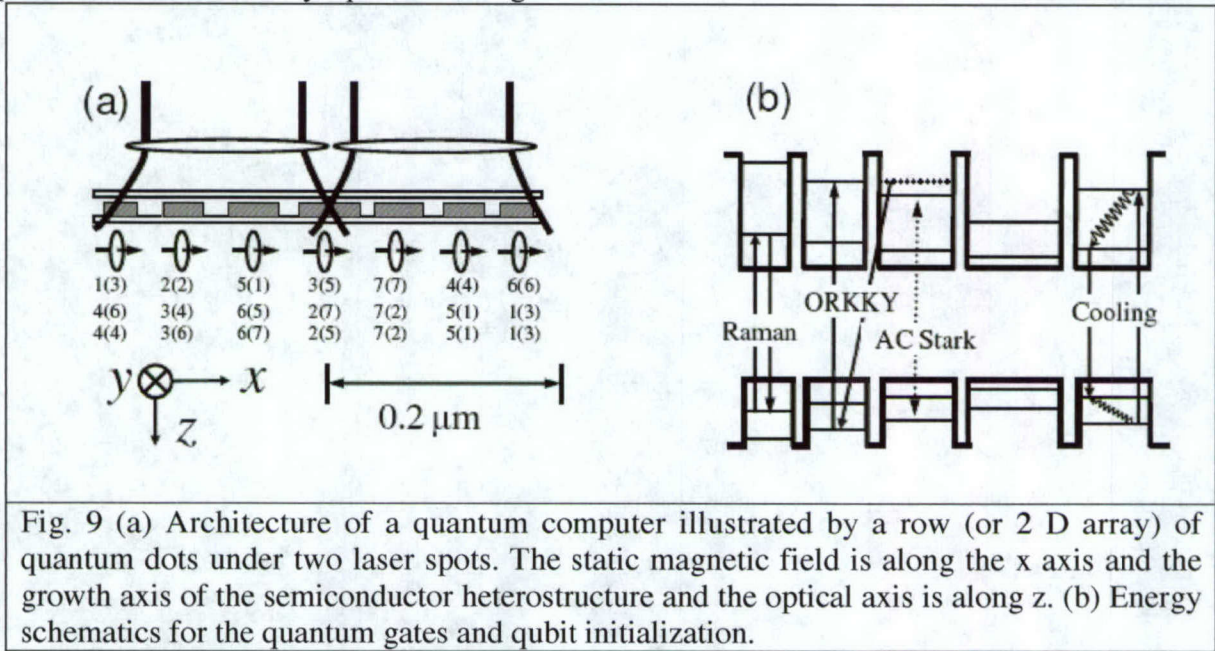


Fig. 9 (a) Architecture of a quantum computer illustrated by a row (or 2 D array) of quantum dots under two laser spots. The static magnetic field is along the x axis and the growth axis of the semiconductor heterostructure and the optical axis is along z. (b) Energy schematics for the quantum gates and qubit initialization.

## 2. Components of the quantum opto-spintronic computer

### 1.a. The gates

For arbitrary one-qubit gates, we constructed a theory of the optical pulse controlled Raman process together with a static field. The clock speed may be down to about 10 ps by not using the starting adiabatic Raman process. For two-qubit gates, we created a theory of optically controlled Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange interaction between spins of two neighboring dots. For the experimental implementation, we have modified the intermediate state to be an excited quadrion (three electrons and one hole) state which covers both dots and added the element of optical Stark effect to move the lowest excited conduction state of one dot into resonance with the other dot. The ability of an electron in the excited state to

oscillate between these two dots is utilized to bring the associated excitons in two dots to resonance for the appropriate quadrion state. The process of optical excitation of excitons which induces spin-spin interaction between two local spins is illustrated in Fig. 10(a). The optically (wavy arrows) excited electron (straight arrow) in the excited state with wave function spread in the two neighboring dots exchanges with both electrons in the ground states of the two dots. The broken arrows with the cross vertex denote the tunneling process of the excited electron between two dots. The left hand diagram of Fig. 2 (b) depicts the single electron energy levels of two dots and the right hand diagram depicts the spin structure of the state of three electrons and one hole (the latter spin being understood). Different choices of optical paths lead to different logic operations. For example, the dotted arrows lead to a swap gate, described in and the dashed arrows lead to a phase gate.

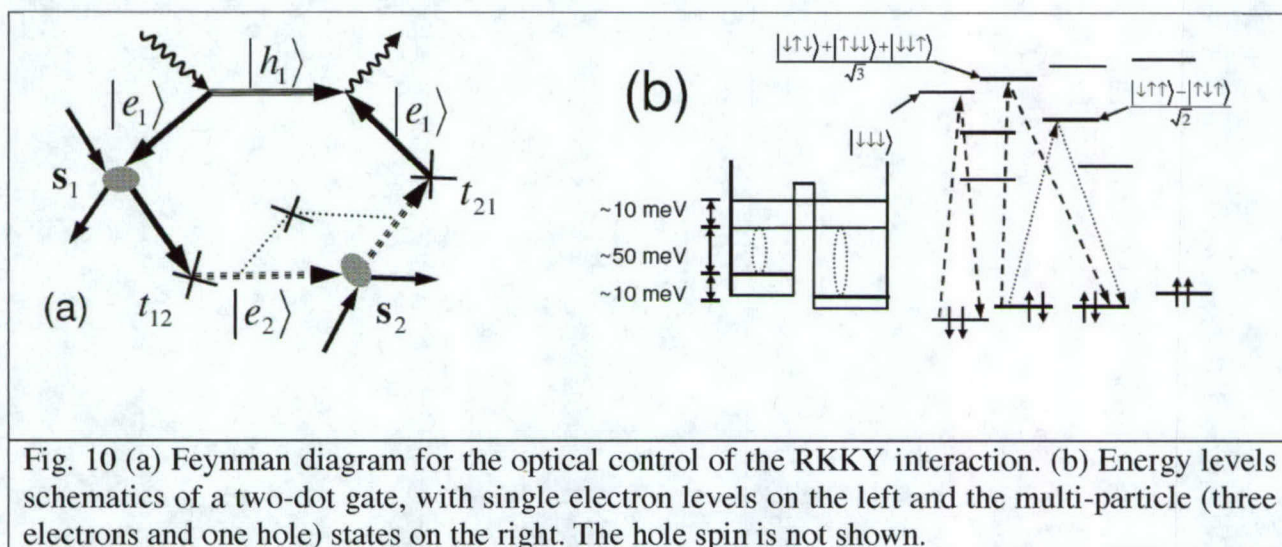


Fig. 10 (a) Feynman diagram for the optical control of the RKKY interaction. (b) Energy levels schematics of a two-dot gate, with single electron levels on the left and the multi-particle (three electrons and one hole) states on the right. The hole spin is not shown.

### 1.b. Qubit initialization

The initialization of spins in quantum dots may be realized by laser cooling process as depicted in Fig. 11(a). We

assume that the spins are completely unpolarized. A laser pulse resonantly pumps both the electron spin states parallel and antiparallel to the z-axis to the excited states. The two excited trion states relax rapidly to

the ground trion states  $|\uparrow\downarrow\uparrow\rangle$  and  $|\uparrow\downarrow\downarrow\rangle$  by emission of LO-phonons. The hole spins will not be conserved during this relaxation because of the strong spin-orbit mixing of the valence bands in the excited hole states. A second optical pulse rotates the unwanted ground trion state  $|\uparrow\downarrow\uparrow\rangle$  back to the electron spin state, establishing a fast decay channel to build up the ground trion state  $|\uparrow\downarrow\downarrow\rangle$ .

When the ground spin trion state  $|\uparrow\downarrow\downarrow\rangle$  is nearly 100% occupied, a  $\pi$ -Rabi rotation brings it down to a pure spin polarized state  $|\downarrow\rangle$ . The most time-consuming step of this laser cooling process is the phonon emission which has the rate of about 25 GHz (equivalent to 0.1 meV), so the full initialization process can be completed in about 100 ps using 3 optical pulses.

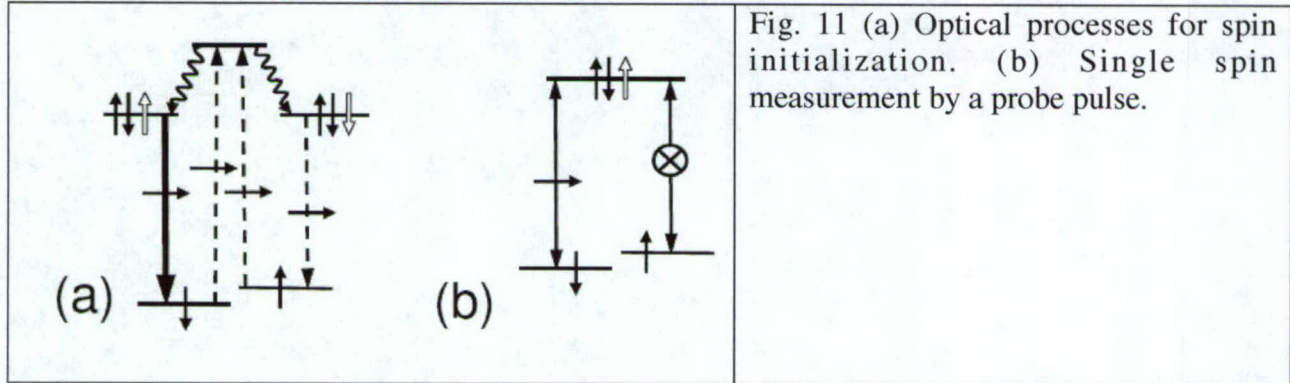


Fig. 11 (a) Optical processes for spin initialization. (b) Single spin measurement by a probe pulse.

### 1.c. Readout

The whole computation procedure may be regarded as analogous to the time-resolved pump and probe spectroscopy. The whole initialization and computation steps form a sequence of pump pulses. The probe pulses perform the readout of the spins by differential transmission measurement of each dot. The practical difficulties lie in the single shot detection of the photon. For demonstration purposes, we may adopt the current measurement procedure of repeating the computation process at 13 ns intervals and collect sufficient photons for measurement. We are aware of the fact that such processes are the time averaging equivalent of the ensemble average and are, therefore, not scalable.

## 2. Simulation of algorithms, fidelity, and resource requirement

A major concern in the efficient implementation of quantum operations and

algorithms is the minimization of errors. We divide the sources of errors into two classes, one which involves the discrete states in the quantum dots inside or outside the qubit Hilbert space, labeled as unintended dynamics, and one which involves systems with continua, in our case the electromagnetic vacuum and the many-electron continuum, commonly known as the environment. To control unintended dynamics, we investigated the use of pulse shaping. The study of the environmental noise and its avoidance is now a key topic in our ongoing research.

In concert with the experimental development in this project, we study first the theoretical aspects of the control of excitons in quantum dots which form the basis of control of the electron spin. Thus, our results are couched first as studies of the exciton qubits and then of the spin qubits via trions (exciton plus spin) and quadrions (exciton plus two spins).

## 2.a. Pulse-shaping for quantum operations

We illustrate here with an example of the motivation for pulse shaping and its execution. In a two qubit system, the interaction between two qubits enables a logic gate which consists in the conditional dynamics of one qubit on the state of the other. The insert of Fig. 12 illustrates the control-NOT operation that may be carried out by a  $\pi$  rotation of the  $|-\rangle$  qubit when the

$|+\rangle$  qubit is present but not when the  $|+\rangle$  qubit is absent. In the case of two interaction excitons, the energy difference in the transition between  $|+\rangle$  and  $|+-\rangle$  differs from that between  $|0\rangle$  and  $|-\rangle$  due to the interaction between excitons. Under ideal circumstances, one could use a  $\pi$  pulse with a frequency range much less than the energy difference between the two transitions to perform the rotation between  $|+\rangle$  and  $|+-\rangle$  without incurring the transition between  $|0\rangle$  and  $|-\rangle$ .

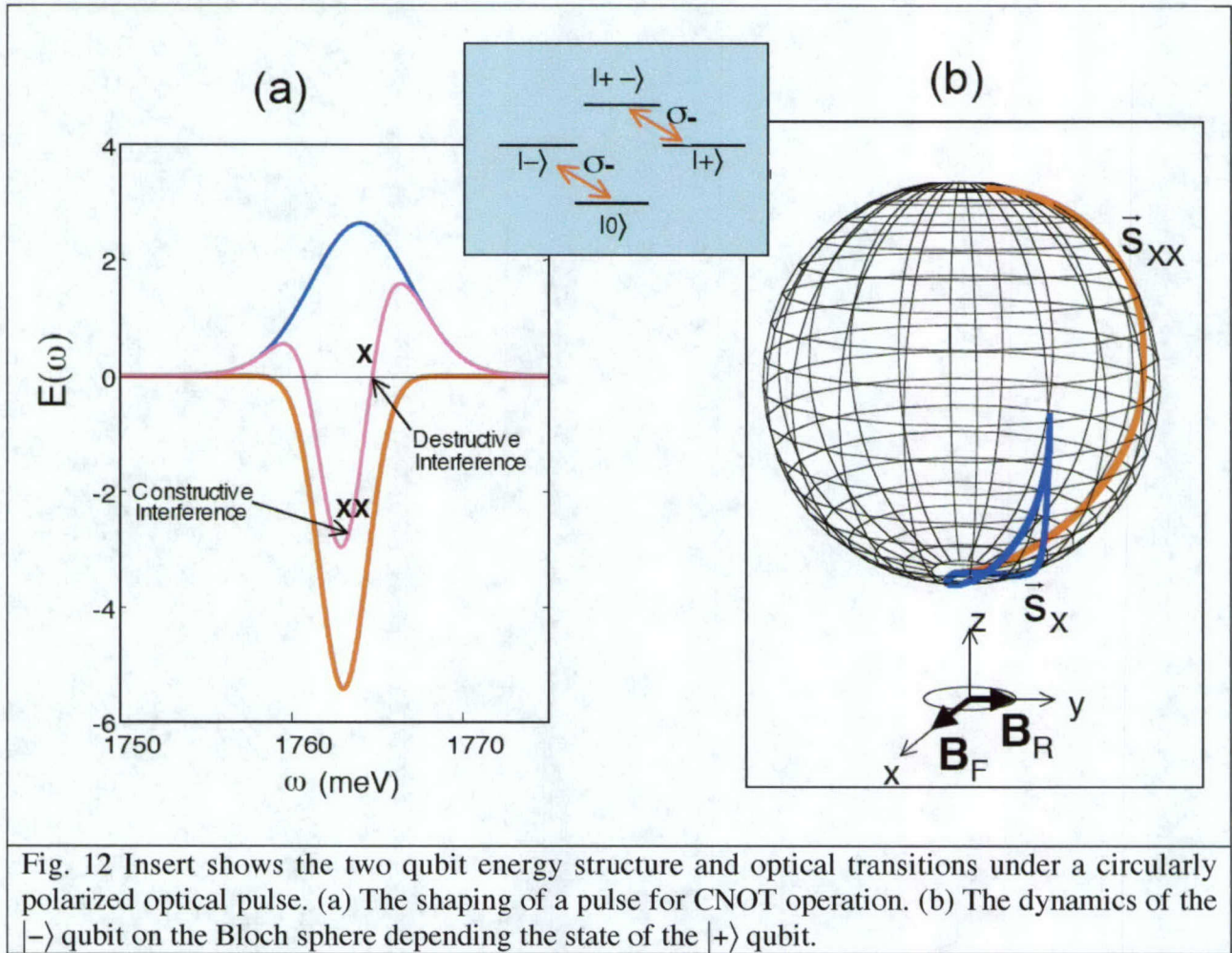


Fig. 12 Insert shows the two qubit energy structure and optical transitions under a circularly polarized optical pulse. (a) The shaping of a pulse for CNOT operation. (b) The dynamics of the  $|-\rangle$  qubit on the Bloch sphere depending the state of the  $|+\rangle$  qubit.

In the semiconductor quantum dot, this would entail a time duration of the pulse which would push a long sequence of operations over the limit of decoherence. In

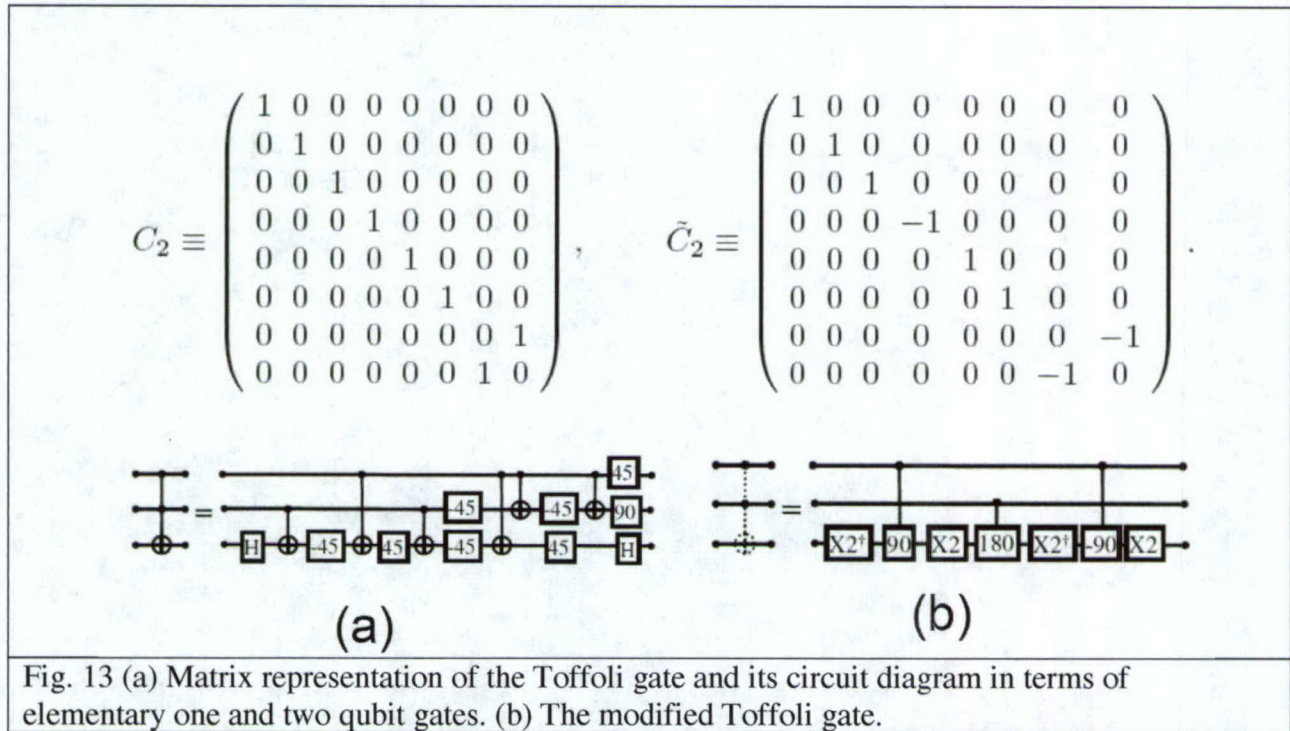
any case, it would vitiate our goal of a clock speed of 10-100 ps. Fig. 12(a) illustrates an intuitive pulse shaping procedure where two out of phase pulses are taken to overlap the resonance frequencies of both transitions but

with the resultant interference being constructive at the desired rotation and destructive at the other transition. The net result of the dynamics of the  $|-\rangle$  exciton is illustrated in Fig. 12(b). It undergoes the desired  $\pi$  rotation (the red line) when the  $|+\rangle$  exciton is present and returns to the original state (absence of the  $|-\rangle$  exciton) when the  $|+\rangle$  exciton is absent. Because of the broader frequency range, the duration of operation is limited to the 1-10 ps range.

More thorough analytical study with the cluster expansion and numeral search of maximal fidelity is shown to improve on the naive construction of pulse shape in the example.

## 2.b. Polynomial savings on qubit operations

Within the stricture of exponential savings of quantum algorithms, pulse shaping and error corrections do add polynomial steps and resources to the computation. Because in preliminary experimental demonstrations of short algorithms, the reduction of steps and resources for the procedure, even if it is only polynomial in savings, may well increase the chance of success, we examine the quantum operations and find ways to economize.



Optical operations give most directly operations from two generators of  $SU(2)$ , for example, in the case of exciton qubit, those of rotations about the x and y axis, or in the spin rotation, the Raman process generating only the phase gates about the z (optical) axis plus the magnetic field generating the precession about the x axis. While it is

possible in principle to generate any rotation, we can economize to eliminate the unnecessary steps involving rotation about the third axis. For example, in the x and y rotation case, instead of the improper rotation in which form the common Hadamard transformation is written and would, thus, entail a mirror operation or

inversion, we can use the proper (determinant +1) of the  $\pi/2$  rotation throughout an algorithm. In factorization of the number 15, we have found it more economical to replace the Toffoli gate by a

modified one. Fig. 13 shows that the former is made up of 6 CNOT gates plus single qubit operations whereas the latter 3 CNOT gates plus single qubit operations.

**Table I: Resource estimates for factorizing 15**

| Value of a/operations             | a=4/standard | a=13/standard | a=13/modified |
|-----------------------------------|--------------|---------------|---------------|
| No. of one-bit gates <sup>a</sup> | 4            | 19            | 12            |
| No. of swap gates                 | 1            | 8             | 6             |
| No. of phase gates                | 3            | 15            | 7             |
| No. of pulses <sup>b</sup>        | 48           | 159           | 102           |
| Duration <sup>c</sup>             | 0.8 ns       | 1.2 ns        | 1.0 ns        |

<sup>a</sup> All one-bit gates between controlled gates are counted as one gate requiring 4 pulses whose total duration is estimated to be less than 10 ps.

<sup>b</sup> Including 21 pulses for initialization.

<sup>c</sup> Including the time for initialization, estimated to be 100 ps for qubit.

## 2.c. Quantum Algorithms

To test our theory of the quantum operations and pulse-shaping, we simulated with the exciton qubits the Deutsch-Jozsa algorithm and the quantum Fourier transform and computed the fidelity. For the optical control of the spin qubits, we have designed the whole process for factoring the number 15 and counted the number of pulses and the time needed. The symbol  $a$  denotes the arbitrarily chosen integer whose order modulo 15 is to be found. Table I shows the results for three cases, an "easy" case of finding the order  $a=4$  modulo 15 and a "difficult" case of finding the order of  $a=13$  modulo 15, where the efficiency of the standard operations versus that of the modified operations are compared.

## 3. Theoretical support of experiments

### 3.a. Spectroscopy and Rabi oscillations of the exciton qubit

Using experimental input (exciton energy levels, linewidths, dipole moments, etc.), we built simple models and studied coherent nonlinear spectroscopy of excitons in a quantum dot and time-dependent phenomena such as the Rabi oscillations and constructed the theoretical steps for one and two exciton quantum operations in a single semiconductor quantum dot. In particular, we interpreted the first experimental measured Rabi oscillation spectra with a decaying mechanism due to an incoherent population of excitons excited by the laser, after simulating the results of a number of possible mechanisms of decoherence.

### ***3.b. Spectroscopy and quantum operations of two excitons in a single qubit***

We supply methods of assessing the entanglement in the two-qubit operations and the overview of the implementation.

optical measurement of the pure transverse spin relaxation time.

## **4. Current and future work**

### ***4.a. More quantitative assessment of the performance of the two-qubit gate using optical RKKY***

Improvement on the many electron interaction between the two local electrons and the optically excited electron-hole pair was carried out in collaboration with Reinecke's group at NRL. More detailed dot structures than those used in will be included for the next generation dots being produced by Gammon's group.

### ***4.b. Spectroscopy of the Raman processes in the quantum operation of a single qubit***

Theoretical support has been provided to the experimental measurements of spin coherence in ensemble and in single dot. Decoherence studies have led to discovery of the effects of simultaneously generated spin coherence on the amplitude and phase of the spin beatings. Further collaboration is ongoing in the simple ways to demonstrate optical control of spin rotation.

### ***4.c. Sources of decoherence for spins in the dot system***

We are working on the mechanisms of decoherence and their effects on short-time effects on individual quantum operations and long-time effects on the whole sequence of computation. This effort includes the theoretical investigations of methods of