

FINAL REPORT TO DARPA

Optically Controlled Quantum Dot Spins for Scaleable Quantum Computing

Contract Period: 8/30/02-7/31/05 NCTX 12/31/05

Grant No.: N00014-02-1-0981

Principle Investigator: Duncan G. Steel

The University of Michigan

Ann Arbor, MI 48109

734-764-4469

dst@umich.edu

ABSTRACT

The objective of this program has been to work towards development of spin based quantum dots for optically driven quantum information processing. Using a combination of ultrahigh resolution laser spectroscopy to study the physics of the dots and ultrafast laser technology to coherently control the spins, we made several advances. Our main achievements include working with a model system based on the exciton optical Bloch vector where we demonstrated the first solid state quantum logic device and made the first demonstration of quantum state tomography in a solid. We also were successful in taking the new quantum dot structures produced by our collaborator, Dan Gammon at NRL that contained one electron, and demonstrated optically induced and detected quantum spin coherence and coherent optical control of the spin state. Our high resolution measurements also provided a measurement of the spin relaxation rate. The funding level in this program was primarily to support one graduate student and purchase equipment. The remaining support for the work comes from ARO, NSA (formerly ARDA), AFOSR, NSF.

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20060608014

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
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.						
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.						
1. REPORT DATE (DD-MM-YYYY) 5/15/06		2. REPORT TYPE FINAL TECHNICAL REPORT			3. DATES COVERED (From - To) August 30, 2002 - December 31, 2005	
4. TITLE AND SUBTITLE Optically Controlled Quantum Dot Spins for Scaleable Quantum Computing					5a. CONTRACT NUMBER N00014-02-1-0981	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
					5d. PROJECT NUMBER	
6. AUTHOR(S) Duncan G. Steel					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Michigan, EECS Department 1301 Beal Avenue, 1106 EECS Bldg. Ann Arbor, MI 48109-2122					8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Advanced Research Projects Agency					10. SPONSOR/MONITOR'S ACRONYM(S) DARPA	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The objective of this program has been to work towards development of spin based quantum dots for optically driven quantum information processing. Using a combination of ultrahigh resolution laser spectroscopy to study the physics of the dots and ultrafast laser technology to coherently control the spins, we made several advances. Our main achievements include working with a model system based on the exciton optical Bloch vector where we demonstrated the first solid state quantum logic device and made the first demonstration of quantum state tomography in a solid. We also were successful in taking the new quantum dot structures produced by our collaborator, Dan Gammon at NRL that contained one electron, and demonstrated optically induced and detected quantum spin coherence and coherent optical control of the spin state. Our high resolution measurements also provided a measurement of the spin relaxation rate. The funding level in this program was primarily to support one graduate student and purchase equipment. The remaining support for the work comes from ARO, NSA (formerly ARDA), AFOSR, NSF.						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 9	19a. NAME OF RESPONSIBLE PERSON Duncan G. Steel	
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) 734-764-4469	

FINAL REPORT TO DARPA

Optically Controlled Quantum Dot Spins for Scaleable Quantum Computing

Contract Period: 8/30/02-7/31/05 NCTX 12/31/05

Grant No.: N00014-02-1-0981

Principle Investigator: Duncan G. Steel

The University of Michigan

Ann Arbor, MI 48109

734-764-4469

dst@umich.edu

Publications that reference this grant for support

Refereed Journal Articles

- 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).
- 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.
- 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).
- 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).
- 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)
- 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).
- 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).
- 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).
- 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).
- 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).
- 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", Physics of Semiconductor, José Menéndez and Chris G. Van de Walle, eds, Proceedings of the 27th ICPS, Flagstaff, AZ, American Institute of Physics Vol 772, p32-37, (2005).
- 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," Phys. Rev. B 71 p155327 (2005).
- Sophia E. Economou, Ren-Bao Liu, L.J. Sham, and D.G. Steel, "A Unified Theory of Consequences of Spontaneous Emission in a Λ System", Phys. Rev. B 71, 195327 (2005)
- 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," Phys. Rev. Lett. 94, 227403 (2005).
- Xiaoqin Li, Yanwen Wu, Xiaodong Xu, D.G. Steel, and D. Gammon, "Transient nonlinear optical spectroscopy studies involving biexciton coherence in single quantum dots," submitted (2005).
- Yanwen Wu, Xiaoqin Li, L. M. Duan, and D. G. Steel, D. Gammon, Lu Sham, "Density Matrix Tomography through Coherent Optical Rotation of an Exciton Qubit in a Single Quantum Dot," in press, Phys. Rev. Lett. (2006).
- M. V. Gurudev Dutt, Jun Cheng, Yanwen Wu, Xiaodong Xu, D. G. Steel, A. S. Bracker, D. Gammon, Sophia E. Economou, Ren-Bao Liu, and L. J. Sham "Impulsive Stimulated Raman Control of Electron Spin Coherence in a Quantum Dot Ensemble", submitted (2005).
- Yanwen Wu, Xiaoqin Li, L. M. Duan, and D. G. Steel, D. Gammon, "Density Matrix Tomography through Coherent Optical Rotation of an Exciton Qubit in a Single Quantum Dot," Phys. Rev. Lett. 96, 087402 (2006).
- Yanwen Wu, Sophia Economou, Dan Gammon, Lu Sham, Duncan Steel, "Optically initialization and rotation in of an electron spin qubit," in preparation.

Invited Presentations

- D.G. Steel, "Coherent Nonlinear Optical Control and Manipulation of Single Quantum Dots: Toward a Quantum Logic Device", Nonlinear Optics Gordon Conference (2003)
- D.G. Steel, "Optical excitations in quantum dots for quantum information processing" Frontiers in Optics Meeting, LSI XIX-OSA Annual (2003)
- 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).
- 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).
- Xiaoqin Li, T.H. 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," NOEKS 2003.
- L. J. Sham, Pochung Chen, and C. Piermarocchi, D.G. Steel. "Optical control of electron spins for quantum computation," NOEKS 2003
- D.G. Steel, "Coherent Optical Control of Single Quantum Dots: A Step Towards

- Quantum Computing" Winter school Mauterndorf (2004).
- D.G. Steel, "Coherent Optical Control of Quantum Dots: Application to Quantum Computing," March Meeting, APS, Montreal (2004).
- Duncan Steel, Gurudev Dutt, Xiaoqin Li, Yanwen Wu, Jun Chen, D. Gammon, L.J. Sham, "Optical control of spin in semiconductor dots for quantum operation," ITAMP, Harvard, 2004
- D.G. Steel, "Optical control in semiconductor dots for quantum operations", ICPS-27 (2004), Flagstaff, AZ..
- 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.
- D.G. Steel, "Coherent optical manipulation of quantum dot spins: A path into quantum computing." QELS (2005).
- D.G. Steel, "Coherent Optical Control of Quantum Dots: Progress Towards Quantum Computing." NOEKS 2006

Conference Papers

- 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.
- 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.
- 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
- 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
- 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).
- 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).
- 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).
- 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).
- 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).
- Xiaoqin Li, Yanwen Wu, D.G. Steel, D. Gammon, L.J. Sham "An optical Controlled-NOT gate in a single quantum dot," IQEC (2004).
- 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" QELS/CLEO 2005
- 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," QELS/CLEO 2005.

Jun Cheng, Yanwen Wu, Xiaodong Xu, Dong Sun, D. G. Steel, A. S. Bracker D. Gammon, L. J. Sham, "Measurement of Electron Spin Relaxation in Charged GaAs Quantum Dots: Application of Nonlinear Optical Phase-Modulation Spectroscopy," QELS 2006 Submitted.

Sophia Economou, L. J. Sham, Yanwen Wu, and D. G. Steel "Theory proposal of electron spin rotation in a quantum dot," QELS 2006 Submitted.

Yanwen Wu, Erik D. Kim, Jun Cheng, Xiaodong Xu, D. G. Steel A. S. Bracker D. Gammon Sophia Economou and L. J. Sham, "Coherent Ultrafast Optically Controlled Rotation of Electron Spins in Charged Quantum Dots," QELS 2006 Submitted.

Technical Summary of the Progress

Most of the progress in this program has been summarized in the annual reports we have submitted. In this Final Report, we summarize the major achievements of the program, providing illustrative data where appropriate. Note that the funding level in this program was primarily to support one graduate student and purchase equipment. The remaining support for the work comes from ARO, NSA (formerly ARDA), AFOSR, NSF.

Technical Objectives

The objective of this program is to work in collaboration with the group at NRL directed by Dan Gammon to develop spin based quantum dots for optically driven quantum information processing. Our approach is based on using quantum dots fabricated in MBE grown III-V based materials. Our initial experiments are based

on the dots produced by controlled interface fluctuations. However, long-term architectures are based on patterned self-assembled structures. Ultimately, we are working to demonstrate quantum entanglement and gate operations involving 3 distinct quantum dots that are located near each other which will demonstrate full scalability.

Technical Approach

The quantum bit in this approach is the electron spin in a doped quantum dot and our approach is to coherently control the state of the single electron spin via a stimulated Raman transition involving the trion (electron-exciton). The exciton transition represents the first optical step in a two step optical process necessary to coherently control the state of qubit rotation and then ultimately to entangle two-spins in separate dots through a transient interaction between the dots.

The ideal quantum computing architecture we envision is a two dimensional array of quantum dots, each containing an electron. In its lowest orbital state, the two spin states of the electron form a qubit. The vertical dimension of a dot is about 2-3 nm and the lateral dimension of the dot in the plane of the dots is 10-30 nm in each direction. The interdot distance between two centers of the dots is about twice the lateral dot dimension. The spin-spin interaction between dots in the absence of laser radiation is negligible and any required interaction is induced by optical excitation of excitons which overlap two nearest neighbors. All electron spin rotations are controlled optically. A laser spot at the current level of optical technology covers about 10 dots. Within this optical field, we shape the pulse to control either single spin rotation or the conditional dynamics between two spins. Since each operation

involves only a small number of qubits and a quantum algorithm provides an exponential saving, then the overhead of the physical resources required by the pulse-shaping can be limited to preserve the exponential saving. Hence, with current MBE and III-V processing technology under development and by positioning optical fields and shaping pulses as required, we have the essence of a scalable quantum computer.

Demonstration of an all optical quantum dot NOT-Gate

Prior to the start of this program, we had demonstrated that the exciton spin represented by the optical Bloch vector was an excellent model for testing the viability for optical manipulation of quantum states in semiconductor quantum dots. We had demonstrated Rabi oscillations, quantum entanglement of the two exciton spins and coherent control over all four possible spin states of the two spin-state system.

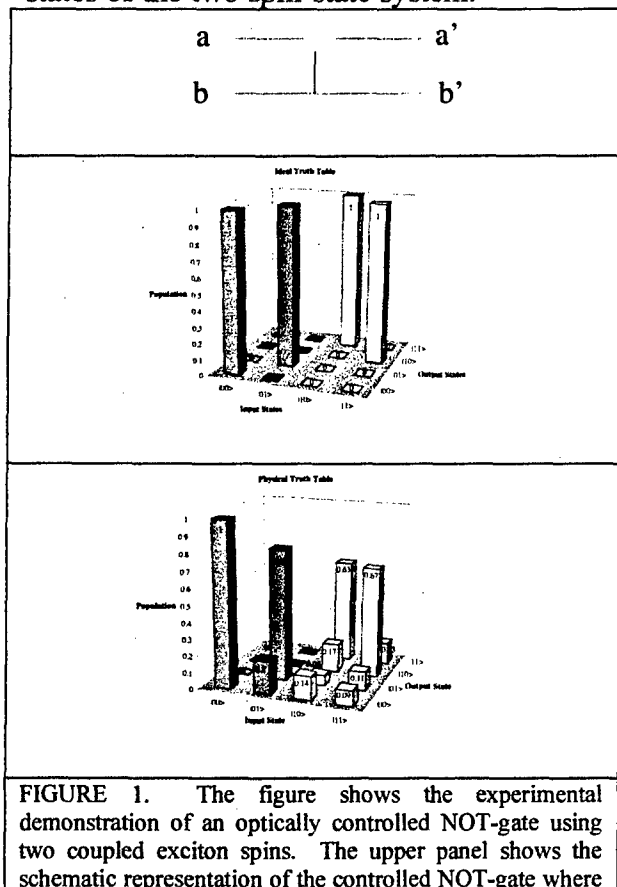


FIGURE 1. The figure shows the experimental demonstration of an optically controlled NOT-gate using two coupled exciton spins. The upper panel shows the schematic representation of the controlled NOT-gate where

"a" is the control bit and "b" is the target bit. The middle panel shows the ideal truth table for the 4 different possible initial states of the system. The lower panel shows the experimentally determined truth table. All differences between the experimental and ideal truth table are fully accounted for by finite pulsewidth effects and state decay.

Quantum State Tomography of an Optically Controlled Quantum Dot

A key step along the way of building a quantum computer is to fully characterize the quantum state of a qubit. The means mapping out the 4 values for the corresponding density matrix.

Our first challenge was to develop an optical means to calibrate the system so that we could accurately determine the probabilities (diagonal terms) for occupation of the zero (ground) and one (excited) state of a single qubit system. We then applied the techniques developed in NMR to rotate the Bloch vector of the spin so that we could project either the real or the imaginary parts of the off-diagonal density matrix terms on to the diagonal elements which we can then measure using our calibrated technique. The results are shown in Fig. 2 for a qubit excited by a $\pi/2$ pulse. The experimental results differ from the ideal results because of decay in the system. A complete calculation of the state and measurement include finite pulsewidth effects and measured decay rates (i.e., no adjustable parameters) shows complete agreement. The result is published in *Phys. Rev. Lett.* 2006.

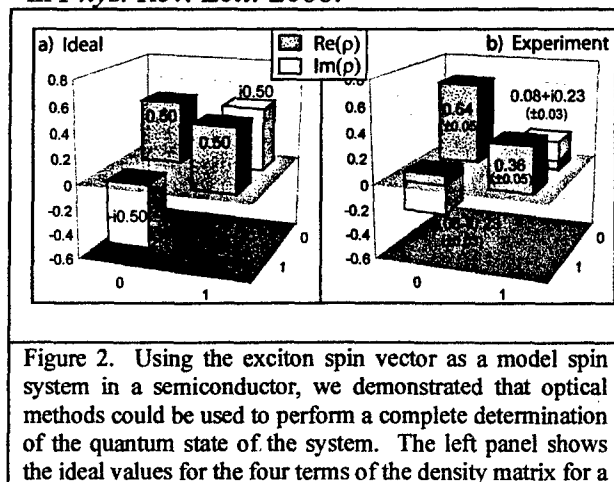


Figure 2. Using the exciton spin vector as a model spin system in a semiconductor, we demonstrated that optical methods could be used to perform a complete determination of the quantum state of the system. The left panel shows the ideal values for the four terms of the density matrix for a

system initial excited by a $\pi/2$ pulse. The right panel shows the experimentally determined values. A complete calculation of the system including the effects of measured decay and decoherence rates and finite pulsewidth effects gives a diagram identical to the panel on the right, demonstrating that we have complete knowledge of this system.

Optically Induced and Detected Electronic Spin Coherence in a Quantum Dot: Discovery of Spontaneously Generated Coherence

Adding a single electron to the quantum dot enables us to move from using the exciton spin as the qubit to optically controlling the quantum state of individual electron spins. The clear motivation for this is that exciton spin coherence times are limited by recombination (<1 nsec) while electron spin coherence times are now expected to be longer than a microsecond. We note that this also changes the electronic structure of the system to a system generally characterized as a 3-level lambda system of the type also important for electromagnetic induced transparency (EIT).

Figure 3 shows the first demonstration of optically induced and detected electronic spin coherence using the doped quantum dots produced by our collaborator Dan Gammon at NRL. The electron spin states are controlled optically by using impulsive stimulated Raman excitation, where the trion (charged exciton) serves as the resonant intermediate state. In the usual pump/probe configuration, Fig.3 (upper panel) shows the quantum beats of a single spin and ensemble. The measurements show a dephasing time limited by inhomogeneous broadening (T_2^*) of order 10 nsec.

An unexpected result is shown in the lower panel of Fig. 3. The theory for impulsive Raman in this 3-level lambda system has been established for many years. It has been well known that neither the phase of the oscillations or the amplitude depend on the Zeeman splitting. However, contrary to this expectation, we clearly see

that both parameters depend on the splitting. A complete theory for this system worked out by our theory collaborators, Lu Sham and his group at UC-SD, shows that in this system, symmetry breaking destroys the distinctness of the spontaneous emission decay from the trion state to the two spin states as long as the spin splitting is small compared to the natural radiative line width. In this case, the trion state can radiatively decay to both spin states with identical optical polarization, giving rise to spin coherence. This is forbidden in typical atomic systems because parity is a good quantum number. The solid lines are the theoretical predictions which are in good agreement. The results were published in *Phys. Rev. Lett.* (2005).

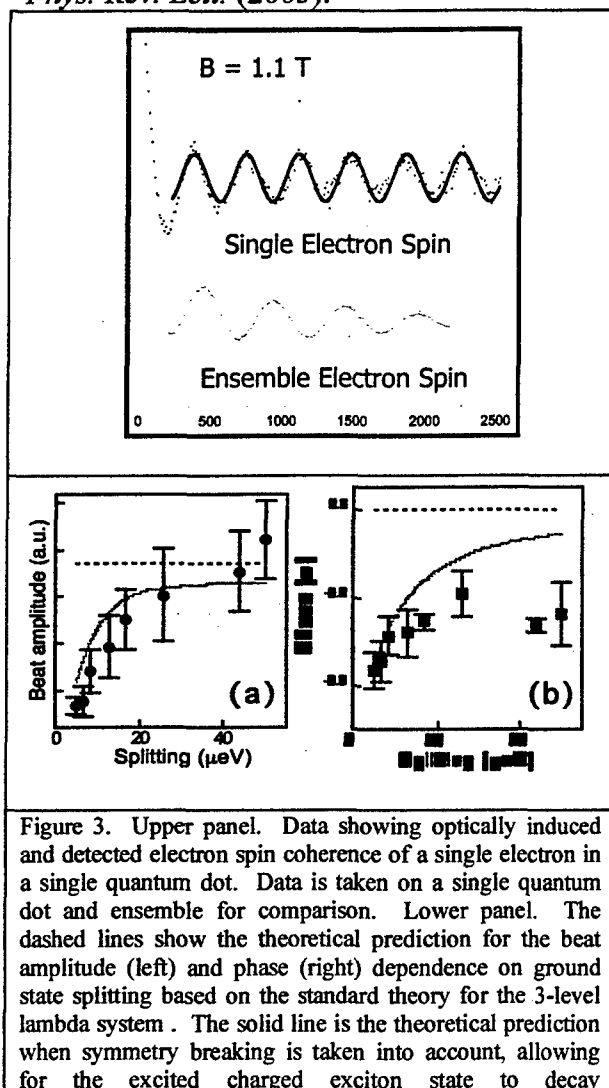


Figure 3. Upper panel. Data showing optically induced and detected electron spin coherence of a single electron in a single quantum dot. Data is taken on a single quantum dot and ensemble for comparison. Lower panel. The dashed lines show the theoretical prediction for the beat amplitude (left) and phase (right) dependence on ground state splitting based on the standard theory for the 3-level lambda system. The solid line is the theoretical prediction when symmetry breaking is taken into account, allowing for the excited charged exciton state to decay

simultaneously with identical polarization to either of the two spin states.

Demonstration of Optical Electron Spin Initialization and Control

Initialization and coherent control of the spin state is an essential step towards quantum computing and are part of the DiVincenzo criteria for establishing a viable quantum computer. In this program, we have successfully demonstrated these essential features for the electron spin qubit in a charged quantum dot.

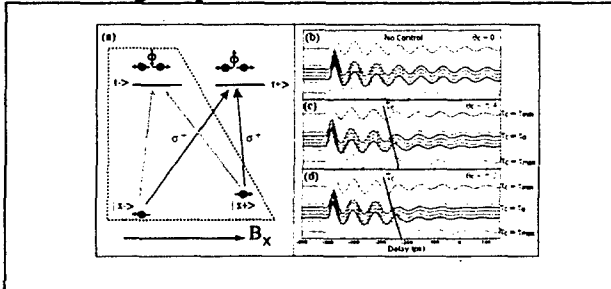


Figure 4. Left panel. The energy level for the single charged quantum dot with a magnetic field in the x-direction (Voigt profile) leads to a 4-level system where polarization coupling (red and blue lines) show 2 3-level lambda systems. Right pane. Demonstration of qubit initialization, control and readout. The first optical pulse initializes the system and the readout follows the precession about the x-axis. A control pulse then rotates the spin vector on the Bloch sphere, as determined by its amplitude and phase. At $\tau_c = \tau_0$, the phase is correct to completely rotate the Bloch vector to the x-axis, showing a suppression of oscillations (i.e., no precession).

Figure 4 shows the key experimental results. In this data, a laser pulse of pulse area θ initializes the spin polarization. A probe pulse samples the system and shows the coherent oscillations seen in Fig. 3. In this case, the spin vector is rotating about the x-axis (the axis of the magnetic field). At time τ_c , a control pulse of area θ' then rotates the spin vector around the Bloch sphere, following the standard equation of motion. The data shows that depending on the phase between the initialization pulse and control pulse, it is possible for the control pulse to completely rotate the spin along the x-axis. Specifically, at $\tau_c = \tau_0$, we see that the spin is aligned on the y-axis. When the control pulse arrives, it rotates the

spin so that it points along the x-axis, leading to the disappearance of the oscillations, as expected. The data demonstrates that we can initialize the spin state of the system and perform an arbitrary rotation of the spin vector. A manuscript is in preparation.

Measurement of Spin Relaxation Time

Ultrahigh resolution spectral hole burning measurements (data not shown) revealed various relaxation channels present in both the trion relaxation as well as the spin relaxation. The measurements showed a spin decoherence time in agreement with the coherent transient data (not shown) with the decoherence dominated by various aspects of inhomogeneous broadening. Interestingly, the relationship $T_2 = 2T_1$, held only at zero magnetic field. $T_2(-T_2^*)$ increased with increasing magnetic field, while the state relaxation rate, T_1 , remained constant, independent of magnetic field. This suggested the measured state relaxation rate was not the slowest rate in the system, but rather was associated with a scattering rate leading possibly to spectral diffusion. This coupled with the fact that the measured rate was much faster than expected from theory for spin flip relaxation suggested there was a much longer relaxation process still to be observed. However, strong scattering by the sample lead to strong overwhelming noise in the megahertz region of the data, prohibiting higher resolution data by this means.

To obtain measurements in this frequency range, we developed a new kind of high resolution coherent spectroscopy based on amplitude modulation induced phase shifts. Details will be presented in a manuscript which is in preparation. However, the basic idea is that measurements are made using differential transmission using two cw optical fields (a

pump and a probe). The pump field is amplitude modulated, as usual. However, the pump modulation frequency is changed and the phase of the coherent nonlinear optical response is then measured using phase sensitive detection.

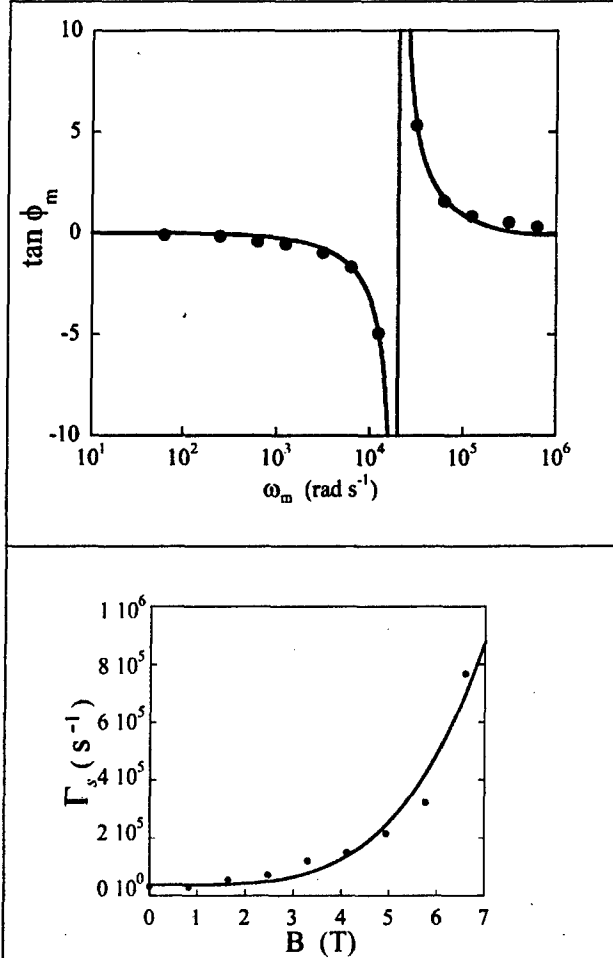


Figure 5. Measurement of the spin relaxation based on a new kind of coherent nonlinear optical spectroscopy (see text for discussion). In this approach, (upper panel) the cw pump field is amplitude modulated and the phase of the signal field is measured as a function of amplitude modulation frequency. Lower panel. The measured spin relaxation rate varies as the magnetic field to the fourth power as predicted in this field regime due to state mixing.

The upper panel of Fig. 5 shows the tangent of the angle as a function of pump modulation frequency. Using the density matrix equations and our model for the nonlinear optical response, we have extracted the relaxation rate (the phase determined by modulation frequency relative to the relaxation rate) as a function of magnetic field shown in the lower panel

of Fig. 5. The solid curve varies as the magnetic field to the fourth power, a result consistent with the theory of Khaetskii and Nazarov [PRB 64, 125316 (2001)]. The spin relaxation rate at zero-magnetic field was determined to be 27 μ sec. This is the first measurement of the spin relaxation rate in the large area fluctuation dots, and when scaled for dot size, is in good agreement with the relaxation rate measured in the much smaller self-assembled quantum dot. Physically, the relaxation mechanism in this field and temperature region is dominated by state mixing of the spin states.

Conclusion

In summary considerable progress was made during this research period on development of methods for optical control of qubits in semiconductor quantum dots. The measurements also included a number of fundamental physics measurements of intrinsic phenomena on these systems. The support enabled a number of critical publications in this area as well as support of students working towards their doctoral degree.