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13. ABSTRACT (Maximum 200 words)  An experimental project was undertaken to develop means to achieve quantum optical strong coupling between a single GaAs quantum dot and the optical mode of a microcavity for the purpose of quantum control of dot and photon states for quantum information processing. Good progress was made in design and fabrication of the quantum dot structure and the microcavity and initial results were obtained.				
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## FINAL PROGRESS REPORT

DAAD19-99-1-0344, UNIV. OF OREGON

"Quantum Logic Using Excitonic Quantum Dots in External Optical Microcavities".

### (4) Statement of the problem studied

To develop means to achieve cavity-QED strong coupling between a single GaAs quantum dot and the optical mode of a microcavity for the purpose of quantum control of dot and photon states for quantum information processing.

### (5) Summary of the most important results (for more detail see renewal proposal)

## 1. THEORETICAL AND CONCEPTUAL:

1.a. Through calculation we learned that the Kerr-effect-driven photonic-qubit optical-phase gate that was originally envisioned will not work. Pulse reshaping acts as a loss channel for photon qubits. For this reason early in the project we adopted more powerful schemes for QIP.

1.b. Three-dimensional electromagnetic vector simulations for the modes of our hemispherical optical cavity showed that the mode waist at the location of the QD can be as small as an optical wavelength (0.8 micron), as conjectured in the original proposal. Multiple reflection of light within the semiconductor distributed Bragg reflector (DBR) mirror does not lead to larger waist size by diffractive spreading, as some had feared. Further, the simulations showed that the transverse component of the electric field can be well maximized at the QD location, as needed for strong coupling. These results show that our cavity design, which is unique in that it uses a hemispherical configuration, is among the best of those that have been employed in previous attempts to reach the cavity-QED strong-coupling regime in semiconductors. Simulations show that our cavity system has an excellent chance of being the first to reach this regime.

1.c. Through a critical study of the possible roles of cavity-QED in QD quantum computing architectures, we learned that the requirements and likely roles of cavity-QED are different in solid-state systems than in atomic systems, where they have been first and furthest developed. We found that in the foreseeable future it is unlikely that the optical cavity field will be useful as a quantum information bus for QD entangling operations, due to fundamental mechanisms that make it difficult to achieve "super-strong coupling" in QD systems.

1.d. We have developed an understanding that cavity-QED techniques are very likely to be essential to the architecture of a quantum information processor based on optically-driven QDs. The requirements for coherent-optical-control and individual qubit readout point directly to the need for enhanced coupling between QDs and the optical field that can be achieved only through cavity-QED techniques. The optical route to these operations in solid-state systems is one of the major thrusts of QIP research, and needs to be evaluated seriously. For this discussion we define two levels of strong coupling:

(i) Medium-strong coupling:  $g/(\kappa, \gamma) = 1 - 10$  (where  $g$  is the light-matter coupling parameter and  $\kappa, \gamma$  are the cavity and QD decay rates). In this regime lie the essential roles of cavity-QED in quantum computing by optically-driven QDs:

- The enhancement of the light-matter coupling that can be achieved in this regime allows one to replace intense coherent control pulses (millions of photons) with weak but effective control pulses (tens to thousands of photons), thereby removing a major obstacle to using QDs : the multiphoton and excess-carrier-induced qubit ionization and decoherence that results from driving such a system too hard. This is an important realization that has not been emphasized in previous work.
- The enhanced coupling aids in the important and challenging task of individual qubit readout. We propose here a new scheme to use cavity-QED-enhanced absorption with very weak probe pulses for efficient and fast readout.

(ii) Super-strong coupling.  $g/(\kappa, \gamma) = 10 - 10,000$ . In this regime (accessible only in atomic systems for the near future) one can use the cavity field as an information bus to move entanglement around.

1.e. We have concluded that in these systems single-electron spins in singly-charged doped QDs are the best candidates for employing as qubits. Such spins (which are *not* many-body excitations of the system, but single particles) have decoherence times in the range ns  $-\mu$ sec. In this aspect our scheme is identical to those being studied in the all-electronic (silicon) QD schemes. There are other aspects, such as readout, where our scheme may prove to be superior. Further, we have discovered a realistic and, in principle, complete architecture for quantum computing in optically-driven QD spins. In this architecture two electron spins confined in separated QDs interact through Coulomb correlations mediated by temporarily created excitons. Either the Pazi-Rossi-Zoller [Paz01] (dipole-dipole) or the Sham [Pie02] Raman-transition scheme can be employed for gate operations. State initialization is carried out by optical pumping, and readout is performed by cavity-enhanced absorption.

## 2. EXPERIMENTAL:

2.a. We learned by experience that semiconductor DBR mirrors with exceptionally good surface smoothness can be grown by MBE techniques. We found that the surface roughness on transverse length scales relevant for our needs ( $\sim$  one micron) is equal to that of the very best super-polished dielectric mirrors of the type used in atomic cavity-QED experiments. The relevant length scale is about one micron because our unique cavity design yields a waist size at the DBR of this size (see 1.b). This means that our unique hemispherical configuration is likely the best possible, given the properties of GaAs materials and fabrication characteristics.

2.b. We learned by experience that good quality interface-fluctuation quantum dots (IFQD) can be grown on the top surface of a high-quality DBR.

2.c. We learned by transfer-matrix computations that large enhancement of light absorption by a QD can be achieved by fabricating the QD at the center of a one-wavelength GaAs "spacer" layer on top of the semiconductor DBR mirror. This is an important step in developing individual-qubit readout by cavity absorption, for which enhancements by several orders of magnitude or more can be expected in a high-finesse cavity.

2.d We learned how to design (in our lab) and fabricate (commercially) hemispherical cavities with a 1mm-radius-of-curvature mirror. This world's smallest (at the time) hemispherical cavity proved useful

in prototyping our optical system and in learning how to recognize signatures of properly aligned hemispherical cavities. This cavity was then superceded by our smaller cavity.

2.e After much effort, we learned how to fabricate (in our lab) 40-60-micron-radius-of-curvature mirror surfaces with surface roughness comparable to the best super-polished dielectric mirrors.

2.f. We learned how to design (in our lab) and fabricate (commercially) multilayer dielectric mirror coatings having high reflectivity (99.5% or higher) over an angular range of +/- 40 degrees from the center of curvature. This wide range is crucial for hemispherical cavities, whose light rays emerge from the waist at the center of curvature with an angular range of about +/- 35%.

2.g. We learned how to construct and control a high-quality hemispherical cavity using this 60-micron mirror and the planar semiconductor DBR containing QDs located at the center of the one-wavelength spacer layer. We installed this cavity and control system in our newly constructed UHV, cryogenic (4K) chamber.

2.h. The measured mode spectra of this 60-micron cavity (at room temperature) indicates the presence of cavity-enhanced absorption of roughly the expected magnitude.

2.i. We have measured all important system parameters and determined that the needed levels of "medium-strong" cavity-QED coupling should be achievable in the near future in our system. This is likely the best system constructed so far anywhere (after many years of work by various groups) that looks promising for achieving such coupling in semiconductors. This seems to pave the way for rapid advances in this area.

### References

Paz01 E. Pazy, E. Biolatti, T. Calarco, I. D'Amico, P. Zanardi, F. Rossi, and P. Zoller, "Spin-based optical quantum gates via Pauli blocking in semiconductor quantum dots," submitted to Science (2001).

Pie02 Piermarocchi, C. Chen, P., Sham, L.J., and Steel, D.G., "Optical RKKY Interaction between Charged Semiconductor Quantum Dots," arXiv:cond-mat/0202331 v4 7 Jun 2002.

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(6) Listing of all publications and technical reports supported under this grant or contract.

(a) Papers published in peer-reviewed journals – None

(b) Papers published in non-peer-reviewed journals or in conference proceedings

"Toward quantum information processing using semiconductor quantum dots in the strong cavity-QED coupling regime," Meeting of the Southwest Quantum Information and Technology (SQUiNT) Network, Santa Fe, Feb. 2003.

“Toward cavity-QED strong coupling of a semiconductor quantum dot to an external optical micro-cavity,” Symposium on quantum optics and cavity QED in semiconductor microcavities,” Laser Science Annual Meeting Tucson, Arizona, Oct. 2003.

“Quantum logic with quantum dots in optical microcavities,” Quantum Computing Program Review Workshop, Army Research Office and National Security Agency, Baltimore, Md, August 2000.

“Quantum logic with quantum dots in optical microcavities,” Quantum Computing Program Review Workshop, Army Research Office and National Security Agency, Baltimore, Md, August 2001.

“Quantum logic with quantum dots in optical microcavities,” NSA/ARO Workshop on Quantum Information, Nashville, Aug. 2002

(c) Papers presented at meetings, but not published in conference proceedings

“Toward cavity-QED strong coupling of a semiconductor quantum dot to an external optical micro-cavity,” QELS 2003, Baltimore, May 2003.

(d) Manuscripts submitted, but not published – None

(e) Technical reports submitted to ARO

(7) List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project

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(8) Report of Inventions (by title only) – None

(9) Bibliography – none