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13. SUPPLEMENTARY NOTES					
14. ABSTRACT The abstract below is from the original proposal. We propose to investigate a new microcavity emitter based on 3-dimensional confinement of an optical mode coupled to an exciton-polariton quantum well (QW) light emitter. The microcavity is a novel dielectric structure based on both lateral native oxide (Al _x O _y) confinement and vertical confinement due to GaAs/Al _x O _y distributed Bragg reflectors (DBRs). The interest in this system stems from the QW-confined exciton-polariton's unique feature as a radiation source of superradiance into the QW normal direction (due to its lateral spatial extent). In principle, such an extended source is capable of coupling 100% of its spontaneous light emission into a planar microcavity optical mode. The nearly ideal coupling allows novel studies of quantum optics in semiconductor microcavities associated with unity β, such as Rabi oscillations, ultralow threshold lasing, and generation of nonclassical light. In practice, however, the coupling from the exciton-polariton to the semiconductor microcavity is limited by dephasing either due to inhomogeneous broadening associated with QW width fluctuations, or homogeneous broadening arising from phonon and carrier-carrier scattering.					
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AFOSR FINAL TECHNICAL REPORT

**Project Title: 97-AASERT Experimental Studies of
Mode Coupling and Prospects for Lasing in 3-
Dimensionally Confined Microcavities**

Grant No. F49620-97-1-0466

Period: August 1, 1997 - July 31, 2000

Dennis G. Deppe, Principal Investigator

**Microelectronics Research Center
The University of Texas at Austin
Austin, Texas 78712**

AFOSR Progress Report August 1, 1997 - July 31, 2000

Project Title: 97-AASERT Experimental Studies of Mode Coupling and Prospects for Lasing in 3-Dimensionally Confined Microcavities

Grant No.: F49620-976-1-0466

P.I.: D.G. Deppe, The University of Texas at Austin

2. Objectives:

This research program focuses on understanding the mode coupling due to excitons and other low dimensional electronic emitters in 3-dimensionally confined microcavities. We initially focused on excitons that can be excited in InGaAs/GaAs quantum wells, since there has been substantial interest in this system. However, from our initial studies we now believe that for room temperature experiments this system will inevitably suffer from thermal dephasing. The loss of coherence destroys the strong coupling to an optical microcavity.

On the other hand, excitons can also be realized in quantum dots (QDs). Due to the 3-dimensional electronic quantum confinement, excitons can be readily excited at room temperature, although the coherence properties of this system at high temperatures has not been (to our knowledge) investigated. However, to realize significant room temperature cavity effects the QDs appear to us to be a necessity.

We point out that the optical coupling of a QD exciton to a planar cavity is less than that for a quantum well. But ultimately the largest cavity effects are expected due to 3-dimensional optical confinement, discussed further below. Our work has been to show the microcavity effect due to the oxide-apertured microcavity, using both planar quantum well and quantum dot excitons, and to obtain lasing from these excitons.

3. Status of effort:

In the first year we demonstrated exciton coupling to an oxide/GaAs planar cavity, with Rabi splitting observed for temperatures near room temperature. The results are described in the publication of Ref. [1] given below. This work uses oxide/GaAs distributed Bragg reflectors (DBRs), and the high contrast DBRs allows the polariton response, measured as a spectral splitting in the transmission characteristics, to be achieved even close to room temperature. A similar demonstration has been made from Prof. Hyatt Gibbs group from Arizona (published also published in APL).

Today we have much more impressive results in demonstrating cavity controlled spontaneous emission due to a 3-dimensionally confined microcavity. From a sequence of growth experiments we have developed InGaAlAs/GaAs QDs that emit at $\sim 0.98 \mu\text{m}$ wavelength. Si APD photon counting modules can then be used to characterize the time resolved photoluminescence. The crystal growth is described in Refs. [2] and [3], which is partially supported by the DARPA Ultraphotonics Program. These QDs have been grown within semiconductor microcavities, and we have characterized how dielectrically apertured microcavities impact the spontaneous lifetime. At low temperature the QDs are spectrally and spatially decoupled, so that they radiate nearly independently. With inhomogeneous

broadening, each QD couples to the cavity with a dependence due to its own frequency of emission. Therefore, cavity effects can be determined simply by measuring the decay rate from the cavity-confined QDs for different frequencies.

We have obtained lasing in oxide-apertured VCSELs based on the QDs, but not really at the level of interest for this program. Most interesting would be to obtain lasing on the planar quantum well exciton or with a single QD. On the other hand, we have gained a great deal of knowledge of how QDs, especially, behave in a microcavity. We have demonstrated the first cavity controlled lifetimes based on the Purcell effect in this type of microcavity, reported in references [4]-[6] below. We believe that these devices will be the precursors to new types of high efficiency, high speed light emitting diodes and lasers. In related work we have shown how the Purcell effect can increase the modulation speed of microcavity lasers.

We are now applying the knowledge we have learned on this program to designs of single QD microcavity devices. This work is being performed both as stand-alone experiments in our UT laboratory and in collaborative experiments with Profs. Hyatt Gibbs and Galina Khitrova from the University of Arizona and Prof. Axel Scherer from the California Institute of Technology. We believe that with novel types of QDs designed for short radiative lifetimes and high gain that single QD lasing may be possible.

4. New Findings

The new demonstrations from this program are described references [4]-[6]. We have shown that the Purcell effect can be observed using self-organized QDs placed in dielectrically apertured microcavities. This device scheme opens up new possibilities for high efficiency, high speed, low power light emitters. Our group continues to be on the forefront in developing these types of devices.

5. Personnel Supported

- 1.) Luke A. Graham, Graduate Research Assistant, now at Picolight, Inc.

6. Publications

- [1] L.A. Graham, Q. Deng, D.G. Deppe, and D.L. Huffaker, "Exciton Spectral Splitting Near Room Temperature From High Contrast Semiconductor Microcavities," *Appl. Phys. Lett.* 70, 814 (1997).
- [2] O. Baklenov, D.L. Huffaker, A. Anselm, D.G. Deppe, and B.G. Streetman, "Influence of Al content on formation of InAlGaAs quantum dots grown by molecular beam epitaxy," *J. Appl. Phys.* 82, 6362 (1997).
- [3] D.L. Huffaker, L.A. Graham, and D.G. Deppe, "Ultra-Narrow Electroluminescence Spectrum From the Ground State of an Ensemble of Self-Organized Quantum Dots," *Appl. Phys. Lett.* 72, 214 (1998).
- [4] L.A. Graham, D.L. Huffaker, Q. Deng, and D.G. Deppe, "Controlled spontaneous lifetime in microcavity confined InGaAlAs/GaAs quantum dots," *Appl. Phys. Lett.* 72, 1670 (1998).
- [5] L.A. Graham, D.L. Huffaker, S.M. Csutak, Q. Deng, and D.G. Deppe, "Spontaneous Lifetime Control For Quantum Dot Light Emitters in Dielectrically-Apertured Fabry-Perot Microcavities," *J. Appl. Phys.* 85, 3383-3385 (15 March, 1999).

- [6] L.A. Graham, D.L. Huffaker, and D.G. Deppe, "Spontaneous Lifetime Control in a Native-Oxide-Apertured-Microcavity," *Appl. Phys. Lett.* 74, 2408-2410 (26 April, 1999).

7. Interactions/Transitions:

a. Participation/presentations at meetings:

- [1] (Invited) D.G. Deppe, D.L. Huffaker, L.A. Graham, and Q. Deng, "Oxide Microcavities," Optical Society of America Topical Meeting on Radiative Processes and Dephasing in Semiconductors, February 2-4, 1998, Coeur d'Alene, Idaho.
- [2] L.A. Graham, D.L. Huffaker, and D.G. Deppe, "Controlled Spontaneous Lifetime From Quantum Dots Confined in Microcavities," 40th Electronic Materials Conference, Technical Program, June 24-26, 1998, Charlottesville, VA, pg. 32.
- [3] D.L. Huffaker, L.A. Graham, and D.G. Deppe, "Ultra-Narrow Electroluminescence Spectrum From the Ground State of an Ensemble of Self-Organized Quantum Dots," Optical Society of America Topical Meeting on Radiative Processes and Dephasing in Semiconductors, February 2-4, 1998, Coeur d'Alene, Idaho.
- [4] D.L. Huffaker, L.A. Graham, and D.G. Deppe, "Carrier Confinement in InGa(Al)As Tunnel Coupled Quantum Dot Light Emitters Based on Ultra Small Apertures," Conference on Lasers and Electro-Optics, May 5-7, 1998, San Francisco.
- [5] L.A. Graham, D.L. Huffaker, and D.G. Deppe, "Controlled Spontaneous Lifetime From Quantum Dots Confined in Microcavities," 40th Electronic Materials Conference, Technical Program, June 24-26, 1998, Charlottesville, VA, pg. 32.

Presented in seminars at the Optical Science Center, University of Arizona, at the invitation of Hyatt Gibbs, and the Electrical and Computer Engineering Department, University of Michigan, at the invitation of Pallab Bhattacharya that included findings reported above.

b. Consultative and advisory functions: None.

c. Transitions: None

8. **New Discoveries, inventions, patent disclosures:** We have succeeded in the first clear demonstration of cavity controlled spontaneous lifetime in dielectrically-apertured 3-dimensionally confined microcavities. This work has been presented at the conferences listed above, and in journals [4]-[6]. Other groups have now demonstrated similar effects in etched-pillar Fabry-Perot microcavities and microdisk microcavities. All these demonstrations are based on exciton confined quantum dots.

9. **Honors/Awards:** D.G. Deppe, Optical Society of America Nicholas Holonyak Jr. Award (1999) for the development of the oxide-confined vertical-cavity surface-emitting laser.