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14. ABSTRACT

Various instruments have been purchased and tested that extend existing nanotechnology capabilities and complement existing equipment. The fact that these laboratories have worked for several years on 3D microcavities and micron-size spectroscopic measurements clarified the need for several complementary instruments. The major new thrust made possible by this grant is spectroscopic capability at 1300 nm. A CCD camera system provides very sensitive detection from 800 to 1600 nm. The existing fs Ti:Sa laser was modified to optimize it for pumping a new optical parametric oscillator, providing short pulses from 1100 to 1600 nm, and the new Millennium X solid state pump provides improved beam stability and efficiency. These instruments have enabled the study of quantum dots and 3D nanocavities, both photonic-crystals and microdisks, in the 1000 – 1300 nm range. A cryostat with nanopositioners within the vacuum has greatly facilitated these measurements, requiring micron stability for minutes. Its temperature control enables scanning of the dot-nanocavity detuning and temperature-dependent measurements.

15. SUBJECT TERMS
Quantum dots, nanocavities emitting at about 1300 nm at room temperature.

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Nanotechnology Instrumentation

Final Performance Report
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4. Accomplishments/New Findings

The actual purchases made are the following. The major items are as proposed. But some savings and slight modifications permitted additional cryostat purchases.

Vendor	Description	PO#	Amount
Roper Scientific	Princeton Instruments Digital CCD Camera System	P655182	$ 30,690.45
Spectra Physics	High Power Diode Pumped Solid State Laser, etc	P610361	$166,000.00
Janis Research	^{3}He Cryostat	P618898	$ 11,600.00
Varian, Inc	Triscoll 300 1 Phase Current Pump	P615539	$ 4,701.22
Hamamatsu	Assembly GaAsP Photon Counting Head with Cooler	P622643	$ 983.00
CryoVac	Konti-Cryostat for Microscopic Measurements	P615431	$ 26,212.80
TOTAL			$240,187.47

The primary objective was to acquire new instruments enabling us to study single quantum dots and 3D nanocavities in the 1000 -1300 nm wavelength range (Fig. 1).

Objective	**Study single quantum dots and 3D nanocavities. Couple quantum dots to a confined light field, demonstrate true strong coupling and quantum entanglement**
Approach	**Control and interrogate quantum dots and quantum-dot nanocavities as e.g. a strongly confined InAs quantum dot in a photonic-crystal point-defect nanocavity.**
Relevance	**The reversible regime of quantum mechanics can be useful for quantum information exchange and can lead to novel high-speed optoelectronic devices.**

Fig. 1: Objective, approach and relevance.

In order of descending expenses, the instruments acquired were: Millennium X pump laser for the fs Ti:Sa laser, OPAL optical parametric oscillator, and corresponding modification of the fs Ti:Sa laser; 800 – 1600 nm InGaAs linear detector array; cryostat with internal nanopositioners, 16% purchase of ^{3}He 0.4K cryostat; vacuum pump for pumping cryostats; and single-photon-counting photomultiplier. See Fig 2.

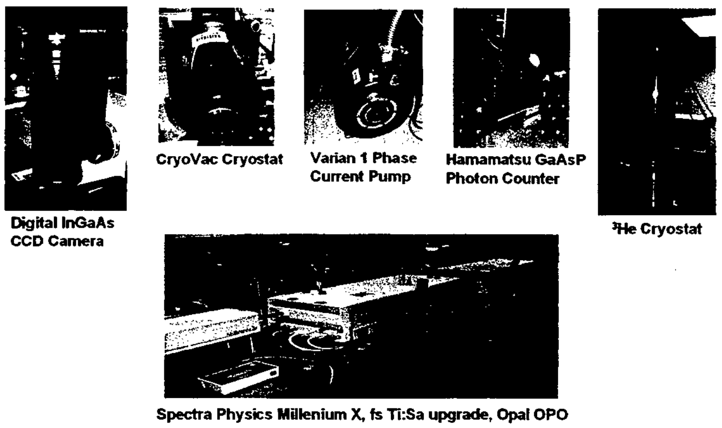
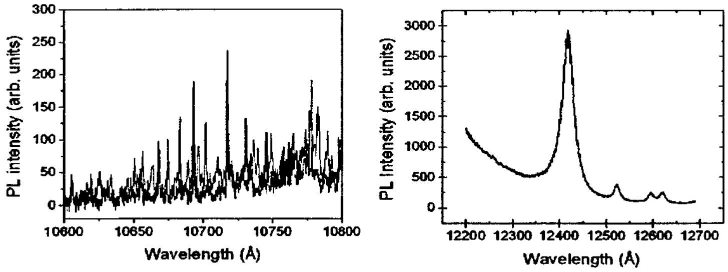


Fig. 2: Photographs of the purchased equipment.

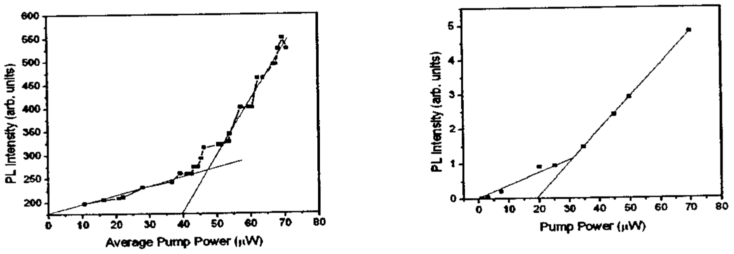
The InGaAs detector array has been used to detect photoluminescence (PL) from individual quantum dots and photonic crystal nanocavities (Fig. 3) as well as 300K and 8K lasing of a quantum-dot microdisk (Fig. 4). The CryoVac cryostat enables its case and helium transfer lines to be secured to the table while the sample can be translated in two dimensions by internal nanopositioners (Fig. 5). It has been used for the PL (Fig. 3) and lasing (Fig 4) experiments, for surveying large areas of samples in search of photonic-crystal cavities (Fig. 6, left), and for measuring the increase in quantum-well linewidth with temperature (Fig. 6, right).



PL spectrum of individual InAs quantum dots at two different positions on the sample at 4.5 K.

Photonic-crystal cavity mode sitting on the low-energy tail of the dot distribution at 4.5 K. The Q is 427.

Fig. 3: PL from individual quantum dots and photonic crystal nanocavities.



PL intensity versus averaged pump power at room temperature of a microdisk containing InAs quantum dots. Lasing occurs at ~*1300 nm*.

PL intensity versus averaged pump power at 8 K of the same microdisk. The threshold pump power is a factor of two lower.

Fig. 4: Room temperature and 8K lasing of a quantum-dot microdisk.

CryoVac Cryostat

- With in-vacuum motor-driven x-y stage:
  - ⇨ exact positioning of nanocavities and quantum dots at all temperatures
- High-temperature stability: low drift at constant temperature and low drift with temperature change
  - ⇨ temperature dependent lineshape of quantum wells

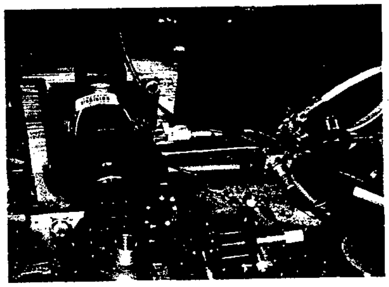
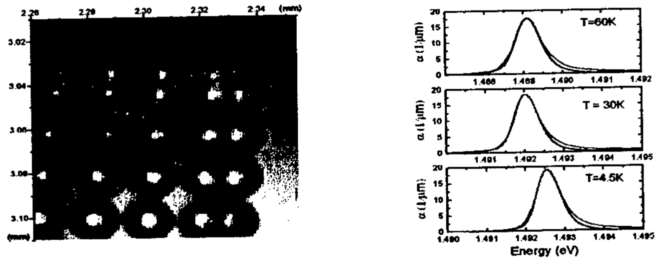


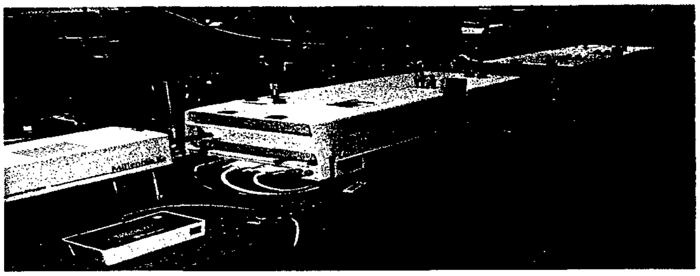
Fig. 5: CryoVac cryostat with internal x-y nanopositioners.



Reflectivity of a sample containing photonic crystals showing their positions. Such an image allows us to find a specific photonic crystal again and again.

Interplay of acoustic phonon and disorder broadening of the 1s-exciton in an $In_{0.04}Ga_{0.96}As$ quantum well. Red: calculated. black: measured.

Fig. 6: 2D image of photonic crystals (left), and temperature-dependent change of the excitonic lineshape of an InGaAs quantum well (right).



Spectra Physics Millenium X, fs Ti:Sa upgrade, Opal OPO

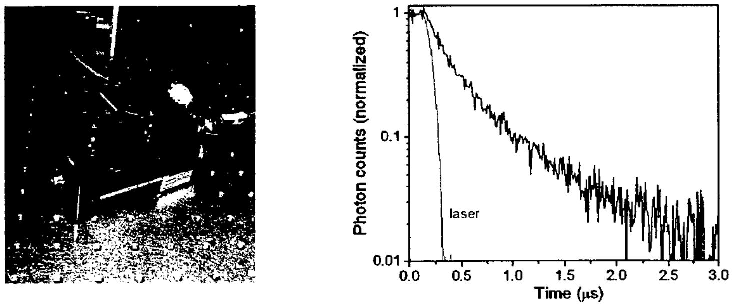
Fig. 7: Femtosecond laser system: solid-state pump, 100fs Ti:Sa oscillator and opto-parametric oscillator (OPO).

The Millennium X is an all-solid-state laser providing up to 10 W at 530 nm to pump the fs Ti:Sa oscillator (Fig. 7). It has far superior pointing stability, much higher wall-plug efficiency, and lower maintenance cost than the ten-year-old argon laser it replaced. This pump-oscillator pair has been used for preliminary studies on PL from InGaAs quantum wells (Fig. 8). This study has delayed the use of the OPAL OPO to excite quantum dot sample for lifetime measurements by upconversion.

Objective	**Determine what fraction of carriers form excitons before recombining in InGaAs QWs after nonresonant excitation.**
Motivation	**PL at 1s exciton resonance maybe mostly electron-hole plasma emission, rather than excitonic.**
Approach	**Ratio PL(E)/absorption(E) allows to determine deviation from purely plasma PL.**
Relevance	**Possible exciton condensation, when excitonic population is large enough and lifetime is long enough.**

Fig. 8: Studies on PL from InGaAs quantum wells.

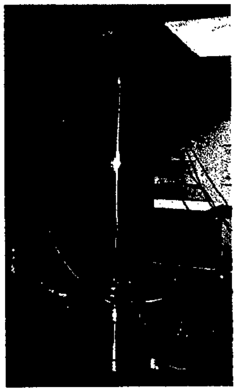
The Hamamatsu photon-counting photomultiplier has been used to determine the lifetimes of type-II excitons in a GaAs/AlAs superlattice structure (Fig. 9). By obtaining manufacturer discounts and eliminating the OPAL doubler that we can build ourselves, we had $11,600.00 left that we added to other funds to purchase a ^{3}He cryostat (Fig. 10). Before we could reach just below 2K by pumping on ^{4}He; the ^{3}He cryostat can go below 400 mK. This new capability may be crucial if exciton condensation is to be achieved.



Hamamatsu GaAsP Photon Counter

Lifetime measurement of the exciton in a type II GaAs/AlAs superlattice.

Fig. 9: Long-lifetime measurement of an exciton in a type II superlattice.



^{3}He Cryostat

This cryostat operates at 350 mK. Ultimate goal is to use it for future exciton condensation experiments.

Fig. 10: ^{3}He cryostat for optical measurements at temperatures below 400 mK.

Experiments on single quantum dots and submicron-diameter photonic crystal nanocavities are tedious and time consuming even with these new state-of-the-art instruments. This is because of the difficulty of isolating the samples from environmental perturbations that can move them by more than a micron in one to five minutes, typical integration times for these weak signals. Nonetheless we are succeeding in seeing PL from single quantum dots and 3D nanocavities. All of our runs at present center on studying InAs quantum dot samples grown by Prof. Dennis Deppe, University Texas at Austin, and fabricated into phonic-crystal cavities by Prof. Axel Scherer and Tomo Yoshie, of Caltech, or microdisk cavities by Prof. John O'Brien, USC. The primary goal is to see strong coupling between a single quantum dot and a single cavity mode, characterized by a double-peaked PL spectrum that should exhibit an anti-crossing as the quantum dot transition is temperature scanned through the cavity resonance. So far the cavity linewidth has been larger than the calculated splitting, or the dot density has been too high to isolate a single dot. A sample with a single layer of dots has been grown and will soon be processed and sent to us. The instruments purchased with this grant are essential to this research program.

5. Personnel supported

None supported directly by this equipment grant, but associated with the use of the instruments are:

Professors H. M. Gibbs and G. Khitrova
Research Professors C. Ell and J. Xu
Graduate Students G. Rupper, S. Chatterjee, and S. Mosor

6. Publications

A. Thränhardt, C. Ell, S. Mosor, G. Rupper, G. Khitrova, H.M. Gibbs, and S. W. Koch, "Interplay of phonon and disorder scattering in semiconductor quantum wells", submitted to Physical Review B, 2003.

7. Interaction/Transitions

W. Hoyer, M. Kira, S. W. Koch, P. Brick, S. Chatterjee, C. Ell, G. Khitrova, and H. M. Gibbs, "Nonequilibrium characteristics of excitonic luminescence", in *OSA Trends in Optics and Photonics (TOPS) Vol. 74, Quantum Electronics and Laser Science Conference (QELS 2002)*, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2002, p. 106).

S. Chatterjee, C. Ell, G. Khitrova, H. M. Gibbs, W. Hoyer, M. Kira, and S. W. Koch, "Exciton formation in semiconductor quantum wells", Seminar talk at the University of Marburg, Germany, 2002.

S. Chatterjee, S. Mosor, C. Ell, G. Khitrova, H. M. Gibbs, W. Hoyer, M. Kira, and S. W. Koch, "Exciton formation in semiconductor quantum wells", Poster at the Photonics Initiative Workshop, Tucson, 2003.

8. New discoveries, inventions, or patent disclosures

None.

9. Honors/Awards:

H. M. Gibbs: Michelson Medal 1994.
H. M. Gibbs: Humboldt Research Award 1998.