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13. ABSTRACT (Maximum 200 words)

A detailed theoretical and experimental study of the application of quantum dot active regions to edge-emitting lasers and electro-optic modulators was undertaken. The theoretical work included calculation of the bandstructure and electronic properties of self-assembled quantum dots, carrier scattering rates and the oscillator strength and gain of interband and intersubband transitions. Experimental work included growth of self-organized dots and active devices, their fabrication and characterization. Very narrow PL linewidths in the dots were achieved (~19 meV) by the incorporation of buried stressor dots. The dynamics of hot carriers and carrier relaxation rates were characterized by differential transmission spectroscopy. It was established from a variety of measurements and calculations that electron-hole scattering is the dominant carrier relaxation mechanism in quantum dots. Modulation bandwidth measurements on QD lasers at cryogenic temperatures (f_{-3dB} ~30 GHz at $T = 100K$) confirmed the role of electron-hole scattering. The electron-optic coefficients of quantum dots was measured for the first time and a QD modulator has been demonstrated. Bistability and gain switching has also been observed and characterized. The unique carrier dynamics in quantum dots is favorable for the realization of intersubband emitters and detectors, and these have been investigated.

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1. INTRODUCTION

Some of the desirable attributes of semiconductor lasers are low threshold current, high output power and efficiency, temperature-independent operation, large modulation bandwidth, and negligible chirp. Many of these characteristics are determined by the density of states and electronic properties of the gain medium. The use of gain media of reduced dimensionality, in particular quantum wells, have greatly enhanced laser performance, particularly due to the non-zero density of states at the band edge and the resulting large gain and differential gain. Three dimensional confinement of carriers in an ideal quantum dot gives rise to atomic like discrete states with a delta function density of states. Therefore, a semiconductor laser with a quantum dot active region promises some of the desirable characteristics mentioned above. There has been worldwide interest in the development of quantum dot lasers, whose performance would eventually surpass that of other semiconductor lasers.

Conventionally, the most straightforward technique to realize quantum dots is the controlled etching of epitaxially grown quantum wells. However, even the best of dry etching techniques produce sufficient damage to preclude sufficient light emission. Recently, *self-organized* quantum dots have been proven to be the structures which best approach the desired properties, and almost all groups actively pursuing quantum dot device development are utilizing strain-induced self organized growth. Much progress has been made in the area of growth - where focus has been size control, and optical characterization - where the goal has been the application to quantum dot lasers and detectors. The use of defect-free strain-induced self-organized quantum dots provides several advantages. Due to the pyramidal shape of these dots and the complicated strain tensor with a strong hydrostatic component within them, large modulation of the interband photon energy can be produced. For example InAs/GaAs quantum dot lasers emit at ~1μm, a wavelength much smaller than that corresponding to the bandgap. Recently, 1.3 μm emission has also been achieved. Since the first demonstration of room temperature self-organized quantum dot lasers by the P-I's of this program, much progress has been made in improving the device characteristics. Thus, in spite of the broad spontaneous emission spectrum resulting from the size non-uniformity in the self-organization process, threshold current densities as low as 20 A/cm^2 at 300K and T_0 as high as 385K up to 330K in InGaAs/GaAs quantum dot lasers been reported. Low threshold currents are being realized in surface-emitting quantum dot lasers also. The P-I's of this program have demonstrated modulation bandwidths ~30GHz at 100K. The recent progress in the DC and modulation characteristics of these devices has been summarized in recent publications. In what follows, the technical progress achieved in this program is highlighted.

2. RESULTS

In the program of research funded by the ARO, we have focussed on developing a reliable technique for making quantum dot heterostructures, understanding the bandstructure, optical properties and carrier dynamics in the dots. In what follows, we will describe the highlights of our overall achievements in the context of what has been said above.

• Growth of Tailored Self-Organized Quantum Dots

We have grown self-organized quantum dots with In(Ga,Al)As/Al(Ga)As strained heterostructures, which emit at wavelengths ranging from 0.7μm to 1.35μm. Defect-free vertically coupled dots, up to ten dot layers show size filtering effects, resulting in a dramatic narrowing of PL linewidths. This is depicted in Fig 1. We have reduced PL linewidths further, to values as low as 3 meV, by growing on patterned mesas and on misoriented substrates [*Appl. Phys. Lett., 71, 927, 1997; Jour. Crystal Growth, 175, 720, 1997*].

- **First Room Temperature Interband Quantum Dot Lasers**

The first room-temperature cw quantum dot lasers were demonstrated by our group [*Electronics Letters, 32, 1374, 1996*]. These lasers, made with $In_{0.4}Ga_{0.6}As/GaAs$ quantum dot active regions, had an emission wavelength of 0.98μm and threshold current density of 650A/cm^2 (300K) and 50A/cm^2 (40K). The measured differential gain, dg/dn, in these devices is larger than 5×10^{-13}cm^2. Relevant data are shown in Fig. 2. These devices will be used as pump lasers for the proposed intersubband lasers.

- **Strain Tensor and Bandstructure of Self-Organized Quantum Dots and Calculation of Intersubband Absorption**

We have addressed the following issues:

i) What is the general nature of the strain tensor in self assembled quantum dots?

ii) What are the electron and hole spectra for InAs/GaAs quantum dots and what are the differences between the theoretical results based on an effective mass approximation and an eight-band **k • p** approximation in which the influence of remote bands is included?

(iii) what is the nature of the electron-phonon interaction along with other carrier thermalization mechanisms in self assembled quantum dot structures?

(iv) what are some implications of our findings in devices based on self-assembled dots?

Our formalism is based on the valence force field (VFF) Hamiltonian model by Keating and Martin to calculate the strain distribution. Based on this approach we are able to find a very detailed strain profile in the quantum dot and the surrounding media for the first time. This is shown in Fig. 3 [*Phys. Rev.* ***B56****, 4696, 1997*]. Also, in principle, this approach can be used to calculate the most likely shape of a dot for a given strain. This would require comparing the energy minimum for various shapes. We hope to address this problem in the new proposal.

It is evident that the strain components are very large and the resultant splittings in the bands are comparable to the inter-band separations in the bulk material. All these considerations suggest that the simple decoupled conduction-valence band picture and the effective mass description may not be adequate. We use the eight-band **k•p** description where the influence of remote bands on the conduction and valence band states is included. We have calculated the bandstructure of self assembled dots and for the first time (Fig. 4) explained not only the ground state transitions but also the excited state transitions [*Phys. Rev.,* ***B56****, 4696, 1997*].

An important potential application of the self assembled quantum dots is in the area of inter-subband detectors and lasers. We have calculated the absorption and emission rates for intersubband dots. The strengths of these transitions show that *if the dot uniformity can be controlled and inhomogeneous linewidth can be reduced to less than ~10 meV, these structures would make excellent intersubband devices.*

- **High Pressure Measurements on Quantum Dots**

We have performed hydrostatic pressure measurements on In(Al)As/AlGaAs self-organized quantum dots in a diamond anvil cell. We have done these measurements up to pressure of 80 Kbars. From these measurements we have elucidated the band crossovers in the dots for the first time. We also have information on dot size distribution and their dependence on growth conditions [*Appl. Phys. Lett.*, **74**, 1549, 1999].

- **Carrier Dynamics in Self-Organized Quantum Dots - Theory and Experiment**

An important result, hitherto unknown, that has emerged from the present study, is the identification of *electron-hole (e-h) scattering* as a dominant mechanism responsible for the relaxation of carriers between dot excited and ground states [*Jour. Quantum Electronics, 34, 7, 1998*]. In this process, hot electrons in excited conduction band levels can scatter from holes and transfer their energy to the holes. The holes can then lose their energy via phonons. We have also established that, because of the large energy separation between these states, rates for single- and multi-phonon scattering are extremely small and the role of these processes are insignificant. The rate of e-h scattering depends on the occupation of the hole ground states and therefore is dependent on temperature. The calculated scattering time from dot electron excited to ground state is ~8ps at 4K and increases to ~100ps at 300K. In structures where only electrons are injected, such as in intersubband detectors, we find that the relaxation times are much longer, approaching a nanosecond. *The longer relaxation time makes QD intersubband detectors attractive for room temperature applications due to the high carrier collection efficiency. The long relaxation time also provides the recipe for gain and population inversion in intersubband lasers.*

Carrier relaxation in self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dots was experimentally investigated by time-resolved femtosecond differential transmission spectroscopy. Our measurements (Fig. 5) indicate that, even at low carrier densities (less than one electron-hole pair per dot), the electron and hole relaxation time constants are ~6ps and 0.6ps, respectively;

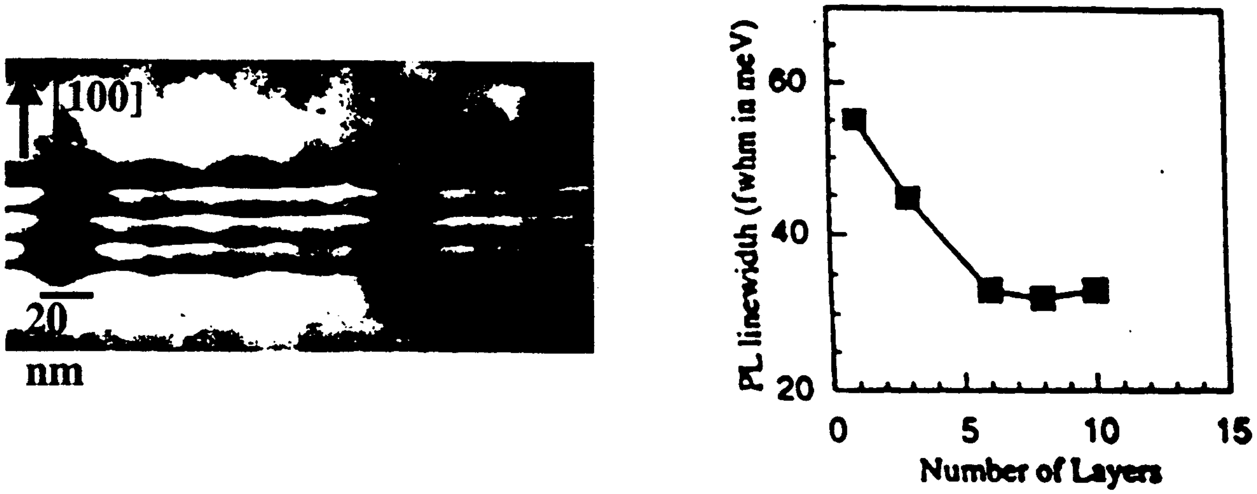


Figure 1: (a) TEM image of four layers of vertically aligned InGaAs quantum dots and (b) photoluminescence linewidth reduction in multiple quantum dot layers.

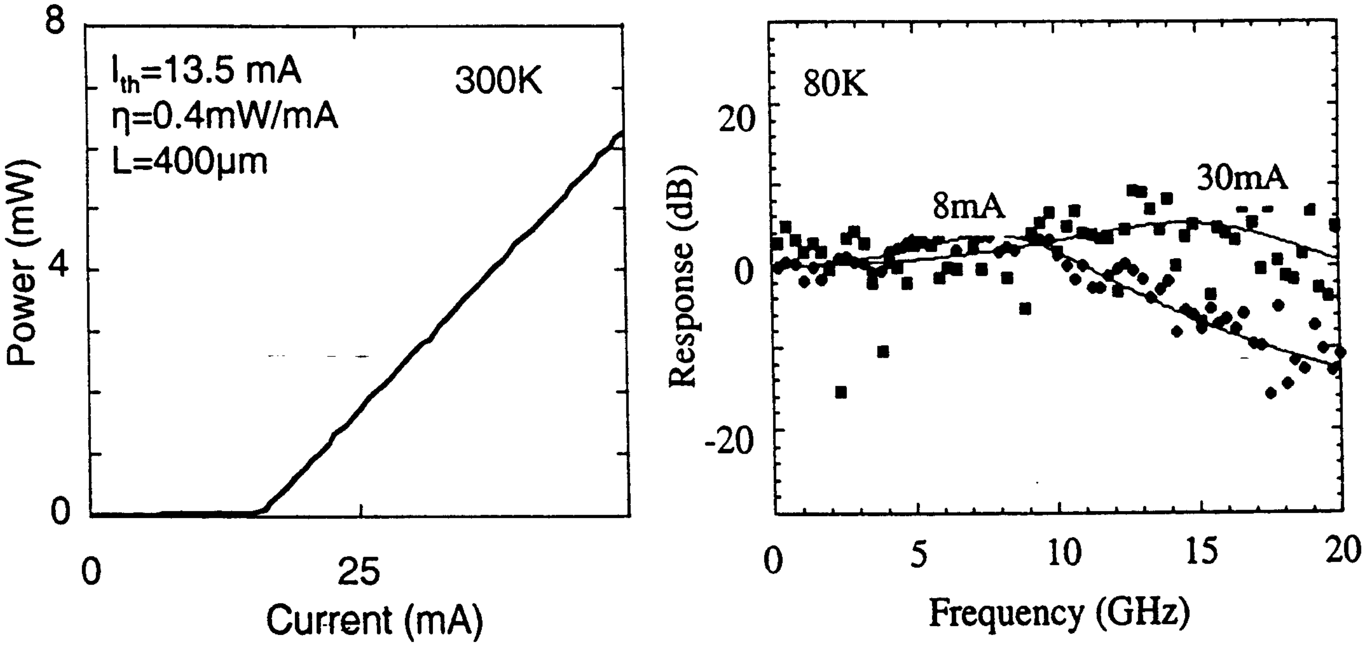
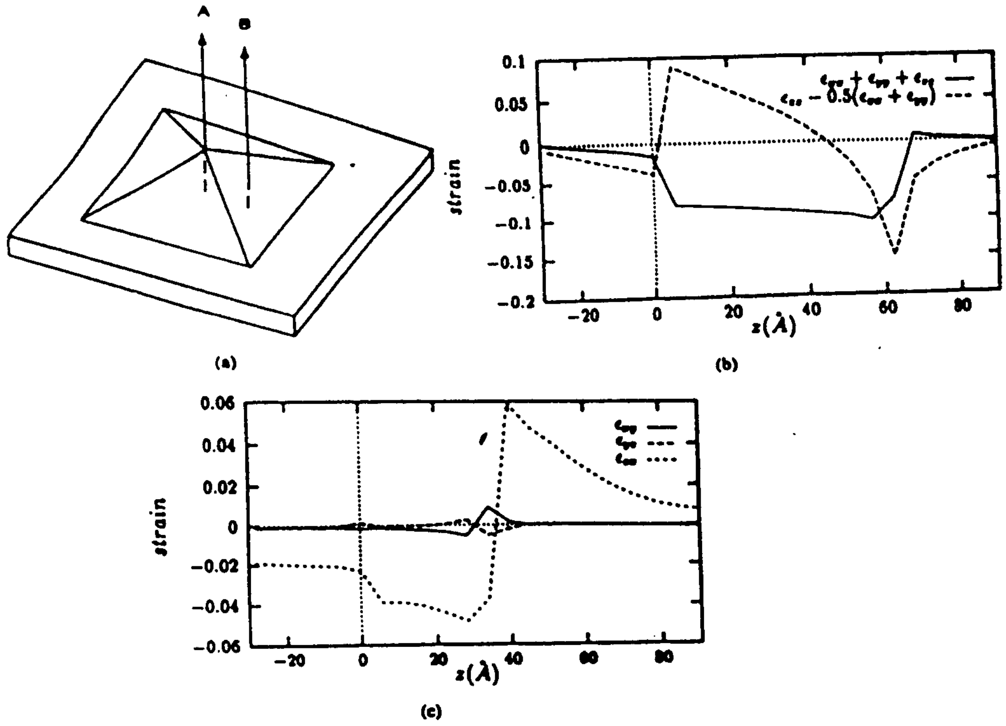


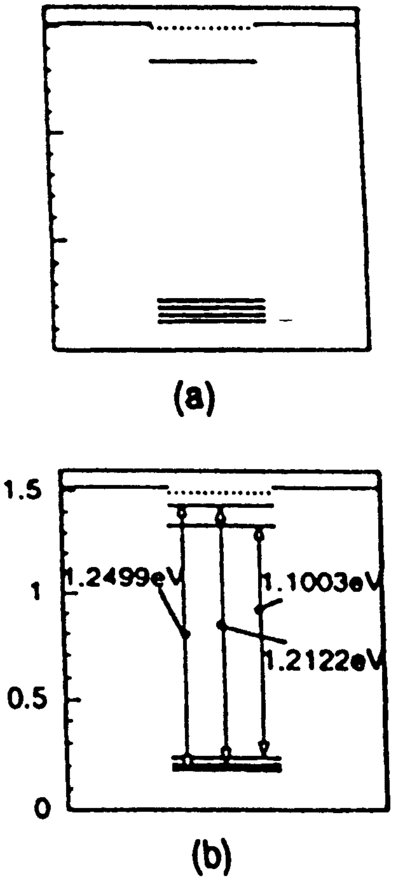
Figure 2: Light-current (a) and (b) small signal modulation of an InGaAs/GaAs quantum dot laser.



(a) (b)

(c)

Figure 3: Calculated strain profile for a pyramidal InAs quantum dot.



(a)

(b)

Figure 4: Calculated bandstructure for InGaAs/GaAs quantum dot

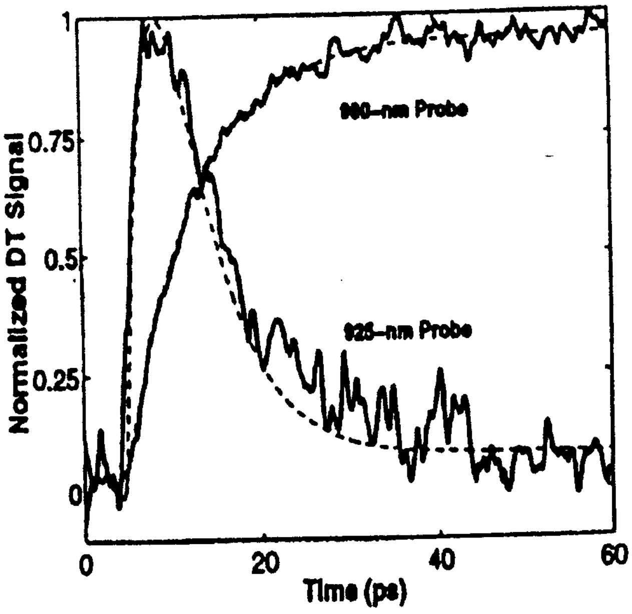


Figure 5: Differential transmission signal measured with a 800 nm pump and 925 nm or 980 nm probe.

this indicates a lack of any "phonon bottleneck" and is consistent with a model of electrons scattering from holes which can relax rapidly via phonon emission [*Phys. Rev.*, ***B57***, *R9423, 1998*].

From time-resolved photoluminescence measurements we have also determined the interband luminescence decay times of ground and excited state transitions. In single and multi dot layer structures the relaxation times are 1.2ns and 700ps, respectively, for ground state transitions and 200 ps for excited state transitions (Fig. 6).

- **Modulation of High Speed Quantum Dot Lasers - Temperature Dependent Measurements**

We have been the first group to demonstrate high-speed small signal modulation in quantum dot lasers [*Appl. Phys. Lett.*, ***70***, *2952, 1997*]. The maximum measured bandwidth increased from 7.5 GHz at room temperature to >20 GHz at 80K (Fig. 2). This is consistent with the bandwidth being limited by carrier relaxation time through electron-hole scattering [*IEEE Photonics Tech. Lett.*, ***10***, *932, 1998*].

- **Preliminary Measurements of Gain and Population Inversion in Intersubband Quantum Dot Lasers**

We have measured spontaneous emission at ~10-11μm due to electron intersubband transitions. The emission spectra is shown in Fig. 7. We are in the process of making measurements with laser Fabry-Perot cavities appropriate for this wavelength.

- **First Intersubband Quantum Dot Detectors**

We have demonstrated the first quantum dot long-wavelength intersubband detectors. Far-infrared absorption measurements using a Fourier transform infrared spectrometer show absorption in the range of 15-18μm for quantum dots with $Al_{0.15}Ga_{0.85}As$ and GaAs as the barrier material. A photoconductivity signal peaked at 17μm is observed at 80K from a *n-i-n* detector structure with doped InAs quantum dots in the intrinsic region (Fig. 8). The responsivity and detectivity (D*) in the devices, with normal incidence, are 0.12 A/W and 1.2×10^{10}cm.$Hz^{1/2}$.W, respectively [*Applied Phys. Lett., 72, 2020, 1998].*

- **Electro-optic coefficients in Quantum dots**

The electro-optic properties of self-organized $In_{0.4}Ga_{0.6}As$/GaAs quantum dots in the guiding region. The measured linear and quadratic electro-optic coefficients are 2.58×10^{-11} m/V and 6.25×10^{-17} m^2/V^2, respectively, which are much higher than those obtained for bulk GaAs or quantum well structures. The measured transmission characteristics indicate that low-voltage amplitude modulators can be realized with quantum dot active regions. This is the first reliable measurement of the E-O coefficients [*Appl. Phys. Lett.* **72**, 1275, 1998] in quantum dots and the linear coefficient is as large as that in lithium niobate. It is expected that the value will be even larger as the size uniformity of the dots is improved. We will then have, for the first time, a III-V based electro-optic material with very large E-O coefficients.

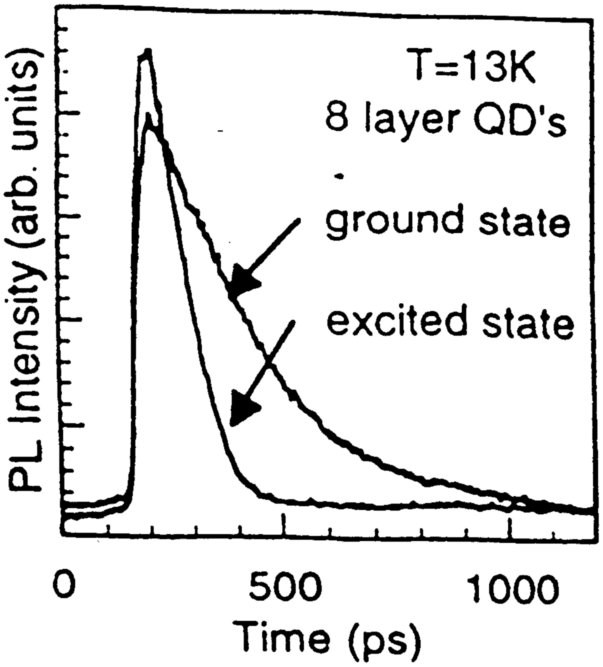


Figure 6 : Time-resolved photoluminescence of InGaAs quantum dots for ground state and excited state transition energies.

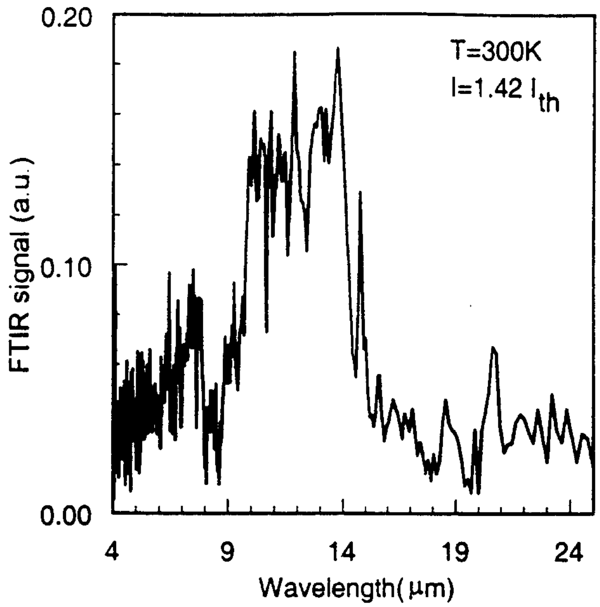


Figure 7 : Room temperature far infrared emission from interband $In_{0.4}Ga_{0.6}As/GaAs$ quantum dot lasers.

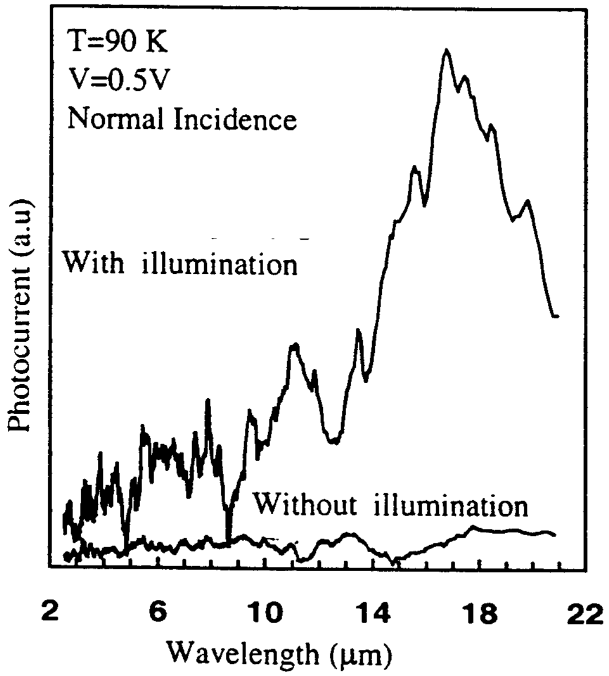


Figure 8 :Photoconductive response of InAs/GaAs intersubband quantum dot detector.

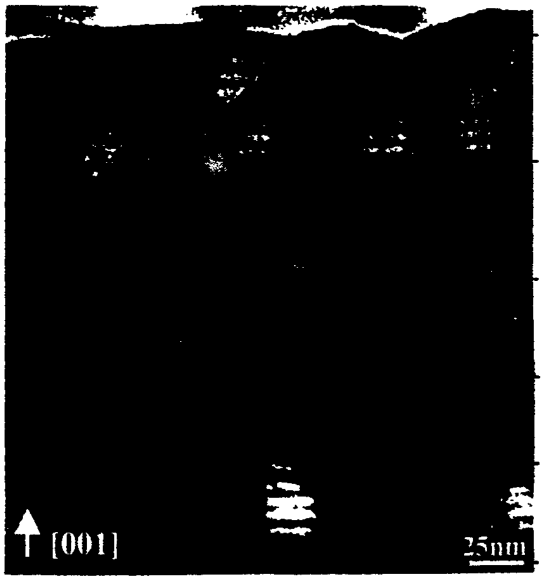


Figure 9 :Cross-sectional scanning tunneling microscopy images showing the strain field around 5 and 10 layer stacks of InAs/GaAs quantum dots.

3. PUBLICATIONS AND CONFERENCE PRESENTATIONS

1. Strain Tensor, Electronics Spectra and Carrier Dynamics in Ga(In)As/GaAs Self-Assembled Quantum Dots", K. Kamath, H-T. Jiang, D. Klotzkin, J. Phillips, T. Sosnowski, T. Norris, J. Singh and P. Bhattacharya, presented at the *24th International Symposium on Compound Semiconductors*, San Diego, California, September 8-11, 1997.

2. Paper entitled, "Intersubband Absorption and Photoluminescence in Si-doped Self-0rganized InAs/Ga(Al)As Quantum Dots", J. Phillips, K. Kamath, N. Chervela, X. Zhou and P. Bhattacharya, presented at the *16th Annual North American Conference on Molecular Beam Epitaxy*, October 5-8, 1997, was made the best student paper (J. Phillips) award.

3. Quantum Capture Times at Room Temperature in High-Speed $In_{0.4}Ga_{0.6}As$-GaAs Self-Organized Quantum-Dot Lasers". D. Klotzkin, K. Kamath and P. Bhattacharya, *IEEE Photon. Techn. Lett.* **9**, October 1997.

4. "High Speed Tunnel Injection Quantum Well and Quantum Dot Lasers", P. Bhattacharya, X. Zhang, Y. Yuan, K. Kamath, D. Klotzkin, C. Caneau and R. Bhat (INVITED) presented to the *Society of Photo-Optical Instrumentation Engineers,* Photonics West, San Jose, CA, December 1997.

5. "Self-Assembled In(Ga)As/Ga(Al)As Quantum Dots: High Speed Lasers and Novel Quantum Dot Detectors and Transistors", P. Bhattacharya, J. Phillips and D. Klotzkin, presented at the *Semiconductor Science & Technology 1998 Conference*, La Jolla, CA, September 9-13, 1998.

6. "Growth and Electroluminescent Properties of Self-Organized $In_{0.4}Ga_{0.6}As$/GaAs Quantum Dots Grown on Silicon", K. Linder. J. Phillips, O. Qasaimeh, X.F. Liu, S. Krishna and P. Bhattacharya, presented at the *17th North American Molecular Beam Epitaxy Conference*, State College, PA, October 4-7, 1998.

7. "Self-Organized Growth of In(Ga)As/GaAs Quantum Dots and their Opto-Electronic Device Applications", P. Bhattacharya, K. Kamath, J. Phillips and D. Klotzkin, presented at the *International Union of Materials Research Societies Conference*, Bangalore, India, October 13-16, 1998.

8. "Self-Organized Growth of In(Ga)As/GaAs Quantum Dots and their Device Applications", P. Bhattacharya, K. Kamath, J. Phillips and D. Klotzkin, presented at the *International Electron Devices and Materials Symposium*, Taiwan, December 20-23, 1998.

9. “Photoluminescence Studies of Self-Organized InAlAs/AlGaAs Quantum Dots Under Pressure”, J. D. Phillips, P.K. Bhattacharya, and U.D. Venkateswaran, *Phys. Stat. Solidi(b),* **211**, 85, 1999.

10. "Nanometer-Scale Studies of Vertical Organization and Evolution of Stacked Self-Assembled InAs/GaAs Quantum Dots", B. Lita, R. S. Goldman, J. D. Phillips, and P. Bhattacharya, *Appl. Phys. Lett.* **74**, 2824, 1999.

11. "Non-Equilibrium Distribution in Quantum Dot Lasers and Influence of Laser Spectral Output", H. Jiang and J. Singh, *J. Appl. Phys.* **85**, 7438 1999.

12. "In(Ga)As/GaAs Self-Organized Quantum Dot Lasers: DC and Small-Signal Modulation Properties", P. Bhattacharya, K. Kamath, J. Singh, D. Klotzkin, J. Phillips, H-T. Jiang, N. Chervela, T. Norris, T. Sosnowski, J. Laskar and R. Murty, *IEEE Transactions on Electron Devices* **46**, 871, 1999.

13. "Self-Assembled InAs/GaAs Quantum Dot Intersubband Detectors", J. Phillips, P. Bhattacharya, S. W. Kennerly, D.W. Beekman and M. Dutta, *J. of Quantum Electronics,* **35**, 936, 1999.

14. "Pressure Induced Energy Level Crossings and Narrowing of Photoluminescence Linewidth In Self-Assembled InAlAs/AlGaAs Quantum Dots", J. Phillips, P. Bhattacharya and U. Venkateswaran, *Applied Physics Letters,* **74**, 1549, 1999.

15. "Bistability and Self-Pulsation in Quantum Well Dot Lasers with Interactivity Quantum Dot Saturable Absorbers", O. Qasaimeh, W.-D. Zhou, J. Phillips, S. Krishna, P. Bhattacharya and M. Dutta, *Appl. Phys. Lett.*, **74**, 1654, 1999.

16. "Growth and Electroluminescent Properties of Self-Organized $In_{0.4}Ga_{0.6}As$/GaAs Quantum Dots Grown on Silicon", K. Linder, J. Phillips, O. Qasaimeh, X.F. Liu, S. Krishna and P. Bhattacharya, *Jorunal of Vacuum Science and Technology*, **B17(3)**, 1116, 1999.

17. "In(Ga)As/GaAs Self-Organized Quantum Dot Light Emitters Grown on Silicon Substrates", K. Linder, J. Phillips, O. Qasaimeh, P. Bhattacharya and J.C. Jiang, *Journal of Crystal Growth*, **201/202**, 1186, 1999.

18. "Bias-Controlled Wavelength Switching in Coupled-Cavity $In_{0.4}Ga_{0.6}As$/GaAs Self-Organized Quantum Dot Lasers", W. Zhou, O. Qasaimeh, J. Phillips, S. Krishna and P. Bhattacharya, *Applied Phys. Lett.,* **74**, 783, 1999.

19. "Self-Organized $In_{0.4}Ga_{0.6}As$ Quantum Dot Lasers Grown on Si Substrates", K.K. Linder, J. Phillips, O. Qasaimeh, X.F. Liu, S. Krishna, P. Bhattacharya and J.C. Jiang, *Applied Phys. Lett.,* **74**, 1355 (1999).

20. "Temperature Dependent Photoluminescence of $In_{0.5}Al_{0.5}As/Al_{0.25}Ga_{0.75}As$ Self-Organized Quantum Dots", J. Phillips, K. Kamath, P. Bhattacharya and U. Venkateswaran, *Journal of Applied Physics,* **85**, 2997, 1999.

21. "Photoluminescence Linewidth of Self-Organized $In_{0.4}Ga_{0.6}As$/GaAs Quantum Dots Grown on InGaAlAs Stressor Dots", S. Krishna, K. Linder and P. Bhattacharya, *Journal of Applied Physics*, **86**, 4691, 1999.

22. "Temperature Dependence of Dynamic and DC Characteristics of Quantum Well and Quantum Dot Lasers: A Comparative Study", D. Klotzkin and P. Bhattacharya, *J. Lightwave Techn.*, **17**, 1634, 1999.

23. "Mechanisms of Vertical Organization and Evolution of Stacked Self-Assembled InAs/GaAs Quantum Dots", B. Lita, R.S. Goldman, J. D. Phillips and P.K. Bhattacharya, *Conference on the Physics and Chemistry of Semiconductor Interfaces (PCSI)*, San Diego, CA, January, 1999.

24. "Lateral Uniformity and Mechanisms of Vertical Organization of Stacked InAs/GaAs Quantum Dots", B. Lita, R.S. Goldman, J. Phillips and P. Bhattacharya, *Materials Research Society Spring Meeting*, San Francisco, CA, April, 1999.

25. "Self-Organized Quantum Dots for Ultrafast Photonic Devices", (PLENARY), P. Bhattacharya, *International Workshop on Femtosecond Science and Technology*, Chiba, Japan, July, 1999.

26. "Carrier Dynamics in Self-Assembled InGaAs/GaAs Quantum Dots and its Effects on Lasers and Intersubband Detectors", (INVITED), J. Phillips, S. Krishna, D. Klotzkin and P Bhattacharya, *IEEE/LEOS Summer Topical Meetings*, San Diego, CA, July, 1999.

27. "Growth of High-Density Self-Organized (In, Ga)As Quantum Dots with Ultranarrow Photoluminescence Linewidths Using Buried In(Ga, Al)As Stressor Dots," S. Krishna, J. Sabarinathan, K. Linder, P. Bhattacharya, B. Lita and R. S. Goldman, *North-American Molecular Beam Epitaxy Conference*, Banff, Canada, October, 1999, and *J. Vac. Sci. Technol.*, **B18**(3), May/June, 2000.

28. "High-Speed Modulation and Switching Characteristics of In(Ga)As/Al(Ga)As Self-Organized Quantum Dot Lasers", (INVITED), P. Bhattacharya, D. Klotzkin, O. Qasaimeh, W. Zhou, S. Krishna and D. Zhu, *IEEE Journal of Selected Topics in Quantum Electronics* to be published, May/June, 2000.

29. "Quantum Well and Quantum Dot Lasers: From Strained-layer and Self-Organized Epitaxy to High-Performance Devices", (INVITED), P. Bhattacharya, *Optical and Quantum Electronics*, Kluwer Academic Publishers, **32**, May, 2000.

30. "Interdiffusion and Surface Segregation in Stacked Self-Assembled InAs/GaAs Quantum Dots," B. Lita, R. S. Goldman, J. D. Phillips and P. Bhattacharya, *Appl. Phys. Lett.*, **73**, 2797, 1999.

31. "Bringing Quantum Dots up to Speed," (INVITED), D. Klotzkin and P. Bhattacharya, *IEEE Circuits and Devices*, **16**(1), 17, 2000.

32. "Conduction Band Offset in InAs/GaAs Self-Organized Quantum Dots Measured by Deep Level Transient Spectroscopy," S. Ghosh, B. Kochman, J. Singh and P. Bhattacharya, *Appl. Phys. Lett.*, **76**, 2571, 2000.

4. AWARDS AND HONORS

1. 1999 IEEE (EDS) Paul Rappaport Award for best paper (No. 12 on list above).
2. Best student paper award in 1999 North-American MBE Conference (No. 27 on list above).
3. P. Bhattacharya was elected Fellow of the Optical Society of America.