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Changes in luminescence emission induced by proton irradiation: InGaAs/GaAs quantum wells and quantum dots

R. Leon and G. M. Swift
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109

B. Magness and W. A. Taylor
Department of Physics and Astronomy, California State University, Los Angeles, California 90032

Y. S. Tang[a] and K. L. Wang
Department of Electrical Engineering, University of California, Los Angeles, California 90095

P. Dowd[b] and Y. H. Zhang
Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, Arizona 85287

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The photoluminescence (PL) emission from InGaAs/GaAs quantum-well and quantum-dot (QD) structures are compared after controlled irradiation with 1.5 MeV proton fluxes. Results presented here show a significant enhancement in radiation tolerance with three-dimensional quantum confinement. Some additional radiation-induced changes in photocarrier recombination from QDs, which include a slight increase in PL emission with low and intermediate proton doses, are also examined. © *2000 American Institute of Physics.* [S0003-6951(00)01615-6]

Semiconductor quantum dot (QD) lasers with low threshold currents and high gain,[1,2] and QD infrared photodetectors[3] capable of incident photon absorption are showing successful implementations of the unique optical properties of self-forming semiconductor QDs. Future device applications include the use of coupled QDs as the basic structures in the fabrication of cellular automata in novel computing architectures[4] and frequency domain optical storage[5] based on self-assembled QDs.

Minimizing the impact of radiation induced degradation in optoelectronic devices is important for several applications. In space, protons pose a particularly severe threat to both planetary and Earth-orbiting spacecraft because they produce damage effects by several mechanisms. Due to their mass, protons can cause significant displacement damage in the semiconductor lattice, which is the primary cause of performance degradation and failure in several types of semiconductor devices. The effects of proton irradiation are also of interest in the use of ion beam modification or ‘‘defect engineering’’ in electronic materials. Proton implantation is often used for device isolation in compound semiconductors,[6] and can also be used to induce interfacial compositional disordering in both quantum wells[7] and quantum dots,[8] which in turn, results in blue-shifted photoluminescence emission from both types of quantum structures.[9] Some of the fundamental properties of QDs suggest that optoelectronic devices incorporating QDs could tolerate more displacement damage than other heterostructures. One of them is based on a simple geometrical argument: the total volume percentage of the active region is very small (in self-forming InGaAs/GaAs QDs surface coverage range from 5% to 25%, depending on growth conditions[10]). Therefore exciton localization in the QDs due to three-dimensional confinement (the InGaAs dots used here average 5 nm height and 25 nm diameter) will reduce the probability of carrier nonradiative recombination at radiation induced defect centers outside the QDs. Here we compare the optical emission from InGaAs quantum well (QW) and QD structures after controlled irradiation with 1.5 MeV protons.

Details of the growth conditions of InGaAs/GaAs QDs by metal organic chemical vapor deposition have been described in previous work.[10] After deposition of GaAs buffer layers at 650 °C, the temperature was lowered to 550 °C and nanometer sized InGaAs islands were grown by depositing $\sim$5 ML of $In_{0.6}Ga_{0.4}As$. QW samples were obtained by stopping the growth of InGaAs before the onset of the Stranski–Krastanow transformation, giving thin (1 nm) QWs. Ternary compositions between the samples were identical, and so was the capping layer thickness (100 nm for both QDs and QWs), therefore these results are not dependent on material or proton energy loss differences. Atomic force microscopy and transmission electron microscopy[10–13] have given structural information on island sizes and surface densities in capped and uncapped InGaAs QDs. Samples were irradiated at room temperature using a Van De Graaff accelerator with 1.5 MeV protons at doses ranging from 7×10^{11} to $2\times10^{15}\,\mathrm{cm}^2$ and a dose rate of 6×10^{12} proton/s. Dose uniformity was monitored using radiochromic film at low doses. Variable temperature photoluminescence (PL) measurements (from 4 K) were done using the 514 nm line of an Argon ion laser for excitation and a cooled Ge detector with lock-in techniques for signal detection.

Figure 1 shows the effects of different proton fluences on the measured PL emission from both types of samples,

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[a] Present address: Research and Development Laboratories, Culver City, CA 90230.

[b] Present address: Nanyang Technological University, School of Electrical and Electronic Engineering, Singapore 639798.

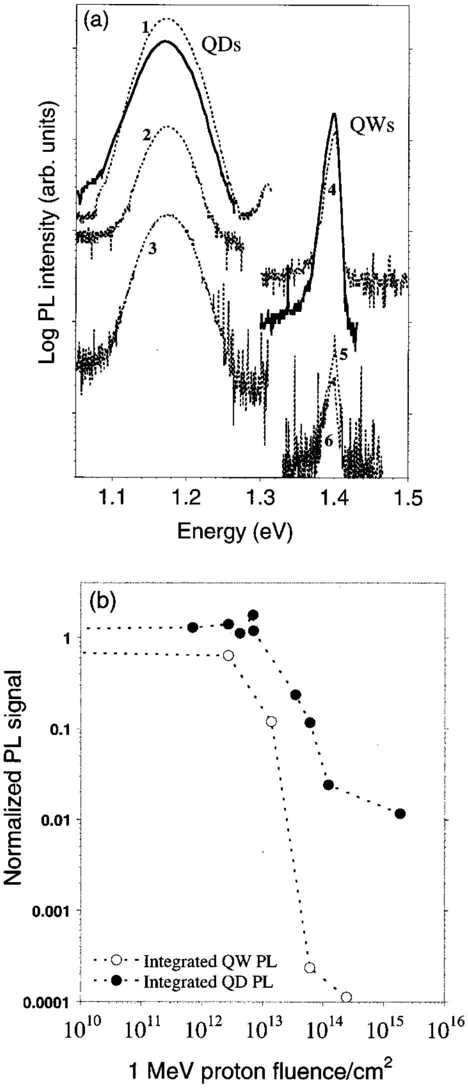

FIG. 1. (a) Comparison of PL spectra (measured at 5 K) from InGaAs/GaAs quantum wells and from quantum dots in high surface densities (2.4×10^{10} dots per cm^2) after irradiation with selected proton fluxes. The solid lines show spectra before irradiation. The dotted lines show spectra after 1.5 MeV proton irradiation in doses (per cm^2) of (1) 7×10^{12}, (2) 6×10^{13}, (3) 2×10^{15}, (4) 3×10^{12}, (5) 6×10^{13}, and (6) 2×10^{14}. (b) Integrated PL emission normalized to the as-grown samples for QW and QDs as a function of proton dose.

InGaAs/GaAs QDs and QWs. The differences in the nonirradiated (as-grown) PL emission are apparent and have been discussed in previous work[9,12–14] Due to increased excitonic oscillator strength in the structures with three-dimensional confinement,[15] the integrated emission intensity is greater, even though only a fraction of the area is covered by QDs. Figure 1(a) also shows that the luminescence from the QDs is broader. This inhomogeneous broadening originates from slight size nonuniformities and from the effects of varying lateral strain in disordered dense dot ensembles.[11] The PL emission from the QW is at a higher energy than the QDs because very thin QWs (1 nm) are used to obtain dislocation-free $\text{In}_{0.6}\text{Ga}_{0.4}\text{As}$ QWs. Figure 1(a) also shows that proton irradiation did not shift the emission wavelength in either QD or QW structures. Figure 1(b) compares the measured integrated PL intensities from QWs and QDs (normalized to the nonirradiated values) as a function of proton dose. InGaAs QDs are seen to be more radiation tolerant than QWs. This increase in radiation hardness is significant, because QW based devices already represent a vast improvement in radiation tolerance over bulk devices like optocouplers, which show significant degradation with proton irradiation;[16] and light emitting diodes (LEDs) based on QWs have shown an order of magnitude greater tolerance to proton induced damage when compared to LEDs based on $p-n$ junction geometries.[17] These results show that QDs can be used in radiation hard optoelectronic devices. This is confirmed by recent data showing effects of phosphorus ion irradiation on QD laser diodes and detectors.[18]

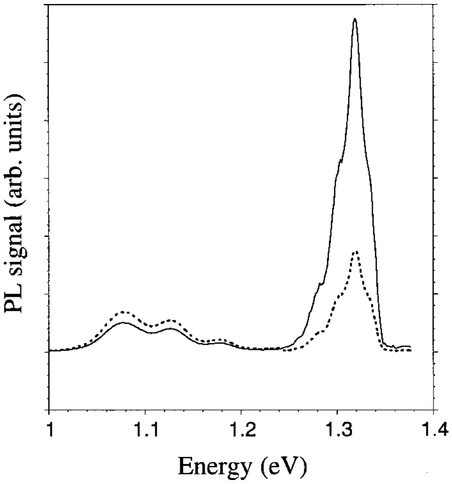

FIG. 2. Comparison of initial (solid line) and postirradiation (dotted line) PL spectra (measured at 5 K) at a proton dose of $2.7\times10^{12}\,\text{cm}^2$ from QD structures with low QD density (3.5×10^{8} dots per cm^2). The spectra were obtained at constant excitation and show simultaneous emission from QD and wetting layer states.

Figure 2 shows some of the effects of proton irradiation in QD structures with a low QD density. These structures show a strong PL peak from the wetting layer (WL). The WL is a very thin QW which forms prior to the dots in Stranski–Krastanow growth. If the average QD separation is greater than the two-dimensional (2D) diffusion lengths in the WL, recombination from WL states will occur for photocarriers generated in the WL[12–14] and PL peaks will be observed from both structures. Figure 2 shows that proton irradiation has different effects on the WL peak (at 1.3 eV) than on the QD peaks (1.7 eV for the ground state—excited states emission is seen here).

Figure 1 (and Fig. 2) show a slight increase in PL signal (from ~10% to 70%) after low to intermediate proton doses (from 7×10^{11} to $7\times10^{12}\,\text{cm}^2$). Since no such increase is observed in the QWs we attribute this PL enhancement to effects from three-dimensional quantum confinement. Reduction of the phonon bottleneck by defect assisted phonon emission has been proposed[19] as a mechanism to explain the bright PL emission in QDs. Introduction of deep level defects as those originated from displacement damage might provide additional relaxation paths[20] for thermalization of carriers and therefore increase the luminescence emission.

The mechanisms responsible for the small degradation observed in the optical emission from QD structures (with proton fluences above $10^{13}\,\text{cm}^2$) also remain to be fully investigated. Carrier generation, capture, transfer, and recombination in InGaAs QDs[12–14] are limited by the photogener-

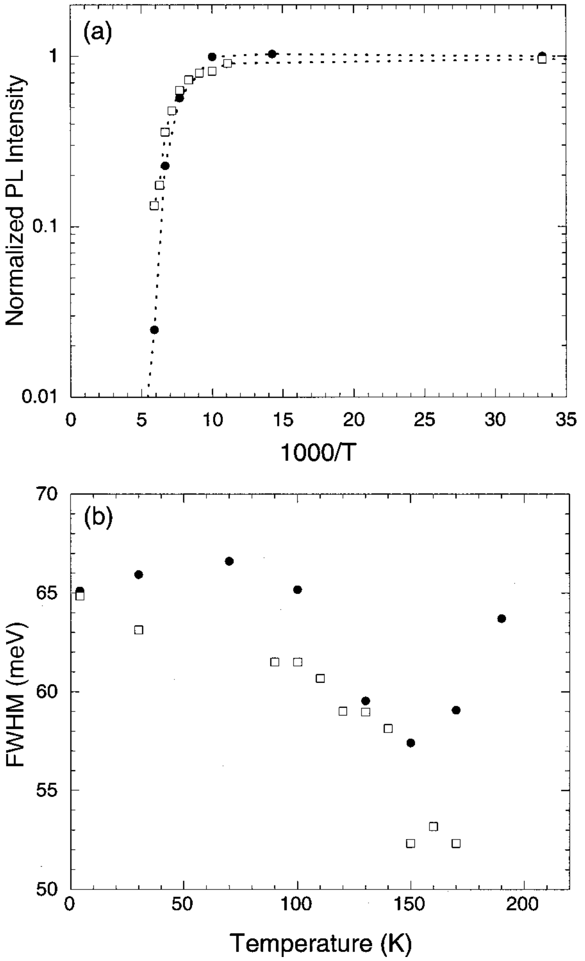

FIG. 3. Radiation induced changes (with 1.5 MeV protons at a dose of $3.5\times10^{13}\,\mathrm{cm}^2$) in the QD PL temperature dependence. (a) Total integrated PL emission from QD structures, filled circles show signal before proton irradiation, hollow squares indicate signal after irradiation. (b) Temperature dependence of the inhomogeneous broadening of the PL emission from QDs before (filled circles) and after irradiation (hollow squares).

ated carrier diffusion lengths in the barrier and wetting layer materials. These will be affected by radiation induced damage and will contribute to degradation in QD PL emission, by limiting carrier capture into the dots. The rate of carrier transfer to the QDs is limited by the rate of lateral transport in the InGaAs WL, which for photogenerated carriers is governed by hole diffusion. Reduction in diffusion lengths or mobilities in the barrier material (GaAs) and in the InGaAs WL is the main cause for the first PL degradation observed in QDs with very high proton doses.

Figure 3 shows some subtle effects of proton radiation on the temperature dependence of the QD luminescence signal (these are normalized over the degraded signal measured at 5 K). In the absence of midgap levels (nonradiative recombination) the temperature dependence of the integrated PL signal from dense QD ensembles is closely related to their confining potential[21] just as in QWs.[22] Defect induced recombination could lower the values for this activation energy. This could explain the slightly lower activation energy shown in Fig. 3(a) after radiation damage. The lower normalized PL at temperatures ~100 K can be explained from the degradation of the hole mobility in the GaAs barrier and InGaAs wetting layer,[13] which peaks at ~80–100 K for nonirradiated structures. Mobility degradation due to proton damage in the barrier and WL would then affect carrier capture and transfer into the dots. Figure 3(b) shows a more pronounced decrease in the inhomogenous PL broadening with temperature after radiation damage. This decrease in the full width at half maximum (FWHM) of the PL band has been attributed to carrier thermal emission from the smaller dots in the ensemble.[13] With radiation damage, the onset of thermionic emission will also be acompanied by defect assisted nonradiative recombination, making this effect even stronger, which might explain the stronger decrease in inhomogeneous PL broadening seen in Fig. 3(b).

In summary, results presented here show that the luminescence from QDs structures is inherently radiation tolerant due to the effects of three-dimensional quantum confinement. An increase in radiation hardness of as much as two orders of magnitude has been obtained by comparisons with similar quantum wells. Additionally, we show that a slight increase in PL emission from InGaAs/GaAs QDs can be observed with low to moderate proton doses.

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[1] D. L. Huffaker and D. G. Deppe, Appl. Phys. Lett. **73**, 520 (1998).
[2] A. V. Uskov, K. Nishi, and R. Lang, Appl. Phys. Lett. **74**, 3081 (1999).
[3] J. Phillips, K. Kamath, and P. Bhattacharya, Appl. Phys. Lett. **72**, 2020 (1998).
[4] A. O. Orlov, I. Amlani, G. Toth, C. S. Lent, G. H. Bernstein, and G. L. Snyder, Appl. Phys. Lett. **74**, 2875 (1999).
[5] S. Muto, Jpn. J. Appl. Phys., Part 2 **34**, L210 (1995).
[6] K. T. Short and S. J. Pearton, J. Electrochem. Soc. **135**, 2835 (1988).
[7] P. G. Piva, R. D. Goldberg, I. V. Mitchell, H. J. Chen, R. M. Feenstra, G. C. Weatherly, D. W. McComb, G. C. Aers, P. J. Poole, and S. Charbonneau, Appl. Phys. Lett. **72**, 1599 (1998).
[8] P. J. Wellmann, W. V. Schoenfeld, J. M. Garcia, and P. M. Petroff, J. Electron. Mater. **27**, 1030 (1998).
[9] R. Leon, D. R. M. Williams, J. Krueger, E. R. Weber, and M. R. Melloch, Phys. Rev. B **56**, R4336 (1997).
[10] R. Leon, C. Lobo, J. Zou, T. Romeo, and D. J. H. Cockayne, Phys. Rev. Lett. **81**, 2486 (1998).
[11] X. Z. Liao, J. Zou, X. F. Duan, D. J. H. Cockayne, R. Leon, and C. Lobo, Phys. Rev. B **58**, R4235 (1998).
[12] R. Leon, S. Marcinkevičius, X. Z. Liao, J. Zou, D. J. H. Cockayne, and S. Fafard, Phys. Rev. B **60**, R8517 (1999).
[13] C. Lobo, R. Leon, S. Marcinkevičius, W. Yang, P. C. Sercel, X. Z. Liao, J. Zou, and D. J. H. Cockayne, Phys. Rev. B **60**, 16647 (1999).
[14] R. Leon and S. Fafard, Phys. Rev. B **58**, R1726 (1998).
[15] S. V. Nair and T. Takagahara, Phys. Rev. B **55**, 5153 (1997).
[16] B. G. Rax, C. I. Lee, A. H. Johnston, and C. E. Barnes, IEEE Trans. Nucl. Sci. **43**, 3167 (1996).
[17] B. D. Evans, H. E. Hager, and B. W. Hughlock, IEEE Trans. Nucl. Sci. **40**, 1645 (1993).
[18] P. G. Piva, R. D. Goldberg, I. V. Mitchell, D. Labrie, R. Leon, S. Charbonneau, Z. R. Wasilewski, and S. Fafard (unpublished).
[19] P. C. Sercel, Phys. Rev. B **51**, 14532 (1995).
[20] H. Benisty, C. M. Sotomayor-Torres, and C. Weisbuch, Phys. Rev. B **44**, 10945 (1991).
[21] S. Fafard, S. Raymond, G. Wang, R. Leon, D. Leonard, S. Charbonneau, J. L. Merz, P. M. Petroff, and J. E. Bowers, Surf. Sci. **362**, 778 (1996).
[22] G. Bacher, C. Hartmann, H. Schweizer, T. Held, G. Mahler, and H. Nickel, Phys. Rev. B **47**, 9545 (1993).