Proton induced Optical Degradation in InGaAs/GaAs Quantum Confined Structures

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Objective/Motivation

To compare the effects of 3-dimensional and 1-dimensional quantum confinement on tolerance to proton irradiation.

Why? Some of the fundamental properties of QDs suggest that optoelectronic devices incorporating QDs could tolerate greater radiation damage than other heterostructures.

Approach

The photoluminescence (PL) emission from equivalent InGaAs/GaAs quantum well (QW) and quantum dot (QD) structures are compared after controlled irradiation with 1.5 MeV proton fluxes.

Experimental Details

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 ~ 5 ML of $In_{0.6}Ga_{0.4}As$ using MOCVD. 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.

Force microscopy and transmission electron microscopy have been used to give information InGaAs QDs sizes and surface densities.

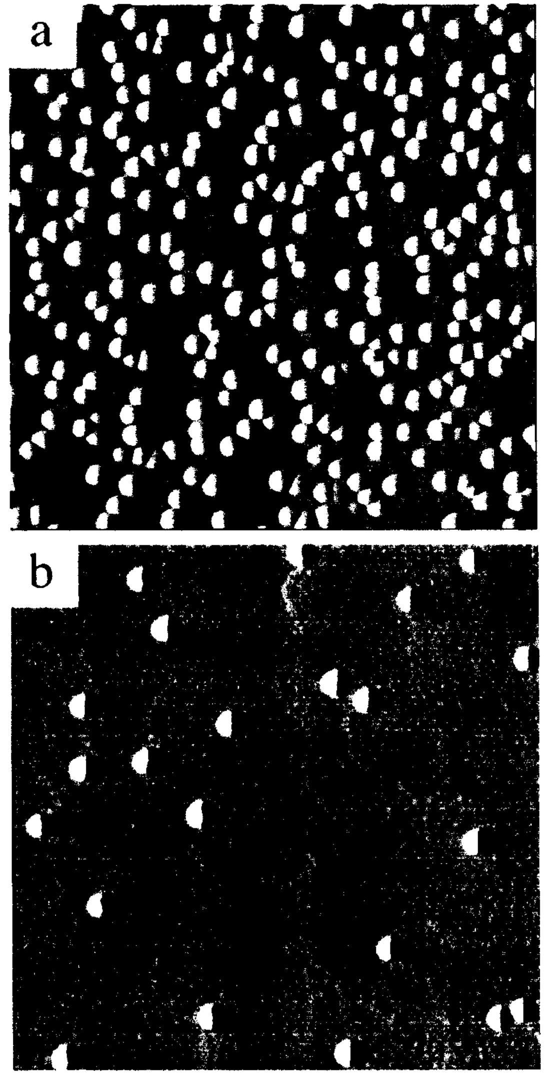
Proton irradiations were carried out using a Van De Graaff accelerator. Samples were irradiated at room temperature using 1.5 MeV protons at doses ranging from 7×10^{11} to $2 \times 10^{15}/cm^2$, with a dose rate of 6×10^{12} protons/sec.

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.

Stranski-Krastanow Quantum Dots

This type of growth occurs for crystals of dissimilar lattice parameters but low interfacial energy, like **Ge on Si** and **InAs on GaAs**. After an initial layer-by-layer growth, islands form spontaneously, leaving a thin "wetting layer" underneath.

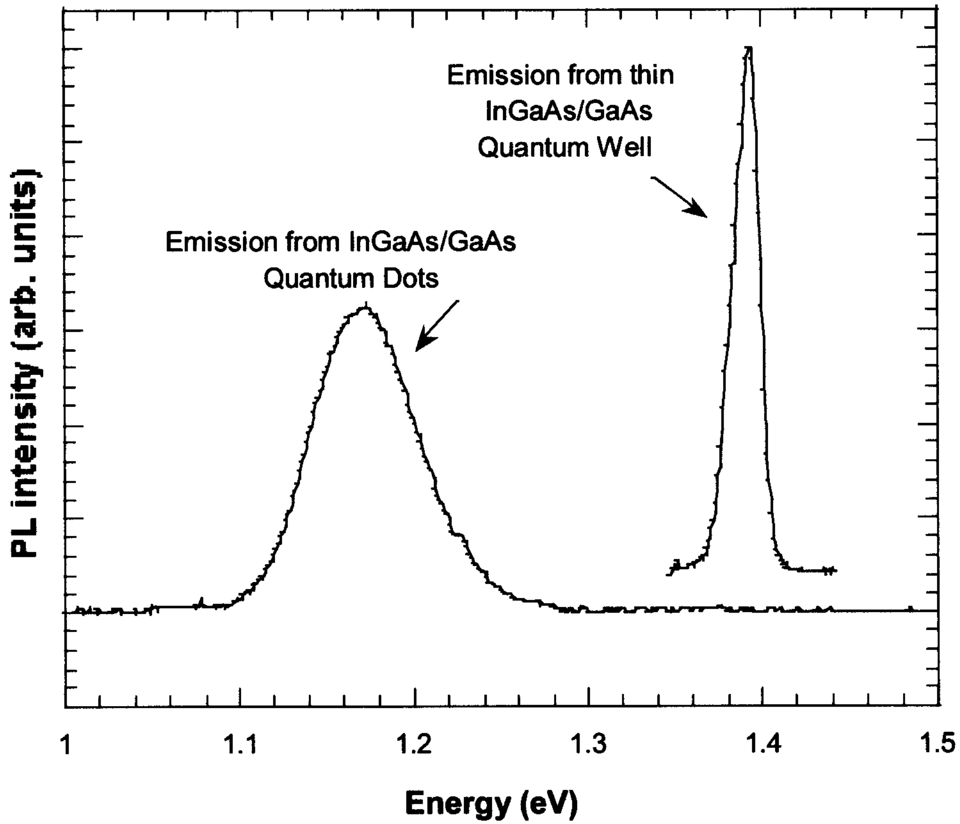
Self-forming InGaAs/GaAs QDs surface coverage range from 5% to 25%, depending on growth conditions →



R. Leon, C. Lobo, J. Zou, T. Romeo, and D. J. H. Cockayne, *Phys. Rev. Lett.* **81**, 2486 (1998).

Boxes are 1 X 1 microns

Low temperature (77 K) photoluminescence spectra for InGaAs/GaAs quan quantum dots.

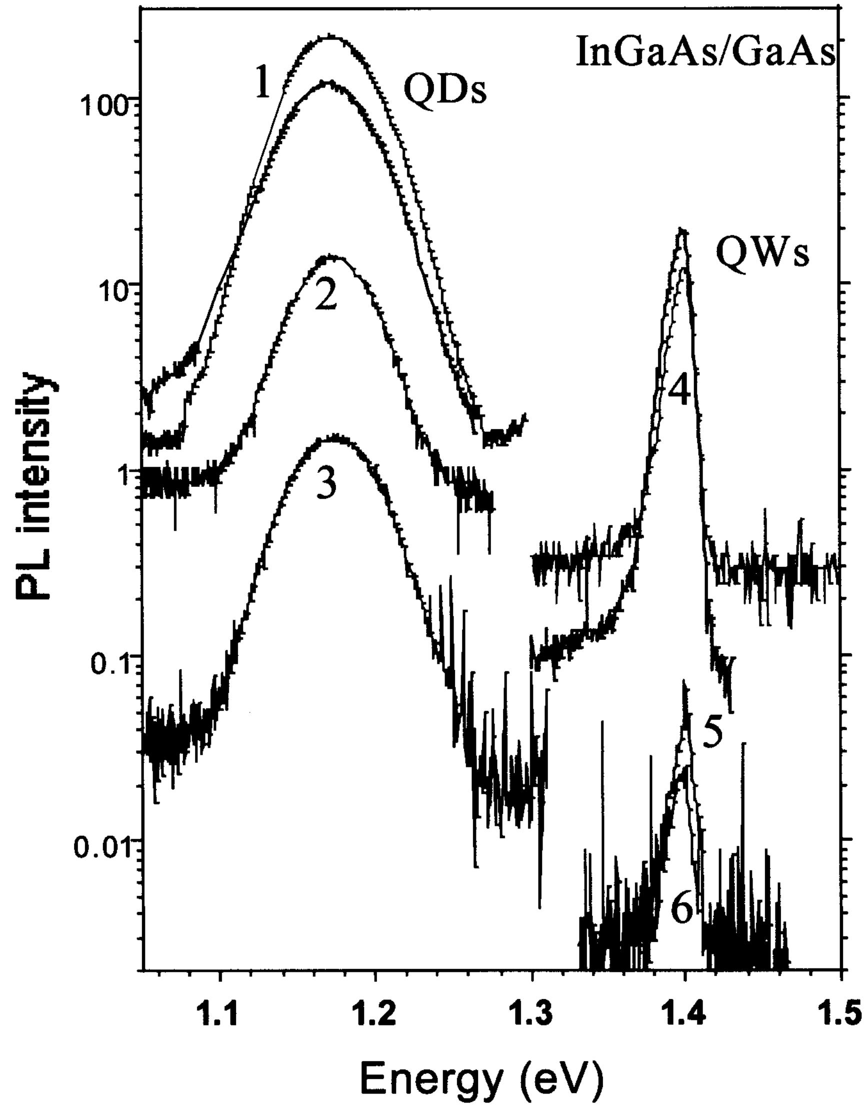


Differences in the PL emission prior to proton radiation:

•Peak from QW is at higher energy (very thin ~ 1nm)

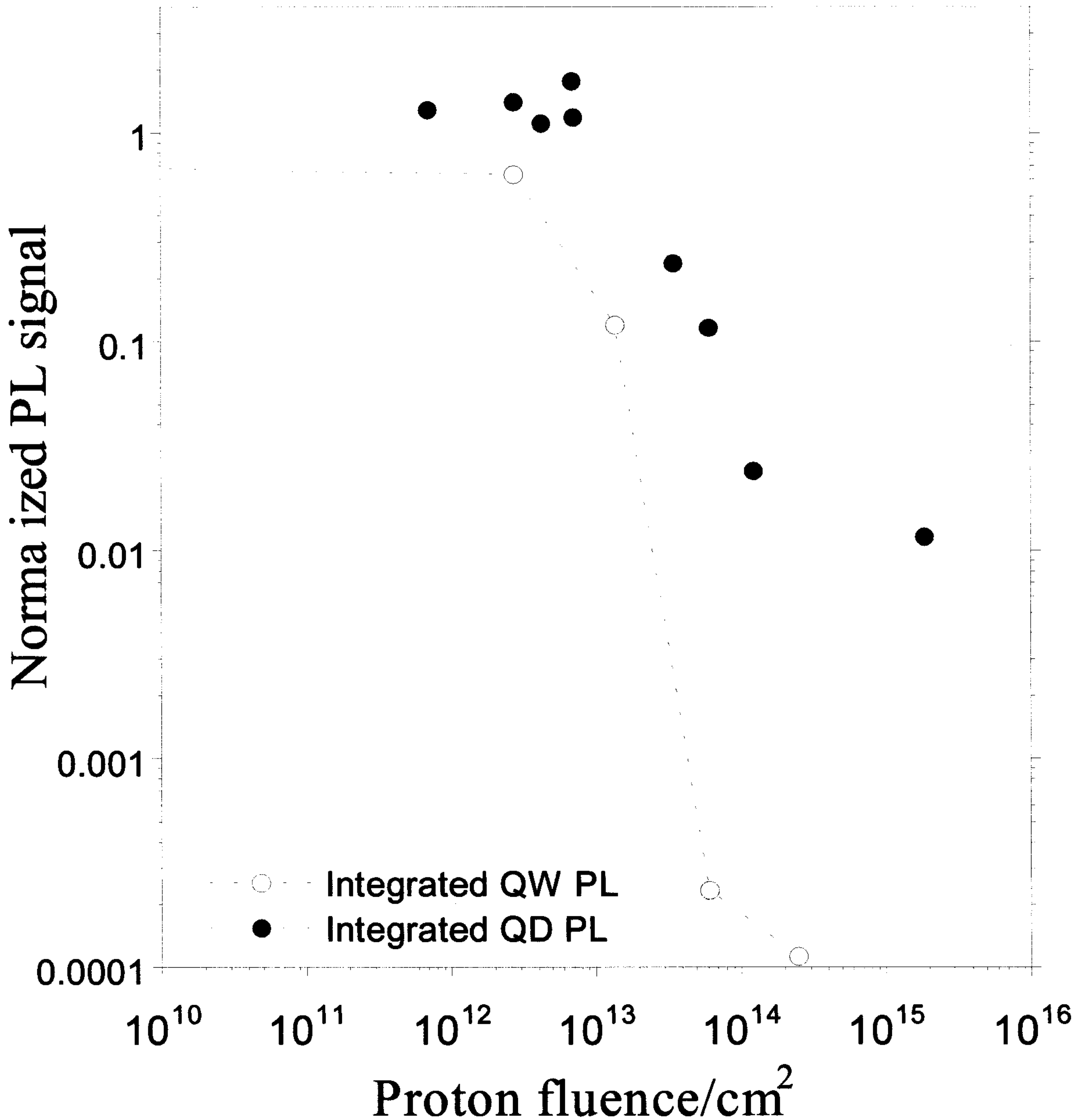
•Peak from QD is broader:

1. Because of slight size fluctuations
2. Because of positional disorder in dense dot ensembles



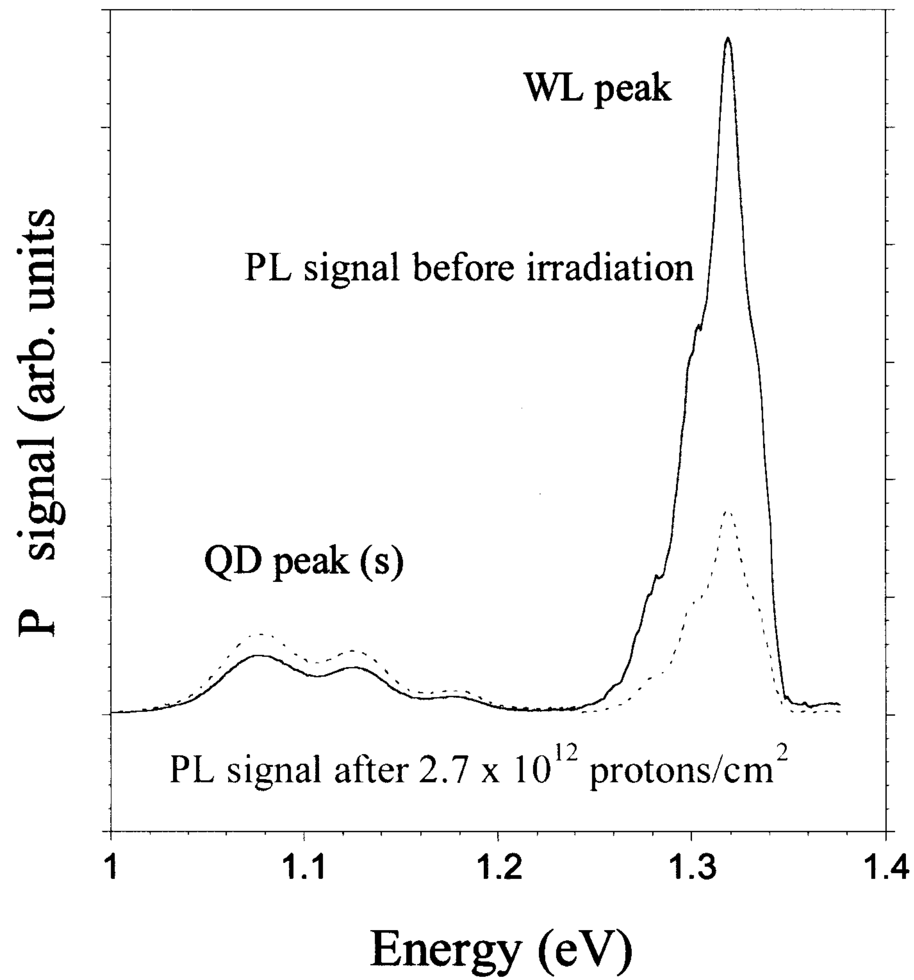
Proton irradiations/cm^2

1) 7×10^{12},
2) 6×10^{13},
3) 2×10^{15},
4) 3×10^{12},
5) 6×10^{13},
6) 2×10^{14}



Normalized PL signal
1
0.1
0.01
0.001
0.0001
Integrated QW PL
Integrated QD PL
10^10
10^11
10^12
10^13
10^14
10^15
10^16
Proton fluence/cm^2

Effects of proton irradiation in QD structures with low surface densities



Low surface density QDs (here 3-4 x 10^8 dots/cm^2) show distinct features: strong WL emission, emission from excited states and they are red shifted with respect to dots in high surface densities [R. Leon, S. Marcinkevičius, X. Z. Liao, J. Zou, D. J. H. Cockayne, and S. Fafard, ***Phys. Rev. B*** 60, R8517 (1999)]

We show a significant enhancement in radiation tolerance with three-dimensional quantum confinement

Why is this?

The total volume percentage of the active QD region is very small (from 5% to 25%, depending on growth conditions) Exciton localization in the quantum dots due to three-dimensional confinement (here QDs are 5 nm height and 25 nm diameter) will reduce the probability of carrier non-radiative recombination at radiation induced defect centers. Therefore, the chance of finding radiation-induced defects in the active region is reduced.

Are there other effects as well?

Slight increase in QD integrated PL (from ~ 10% to 70%) with low to intermediate proton doses (from $7x10^{11}$ to $7x10^{12}/cm^2$)

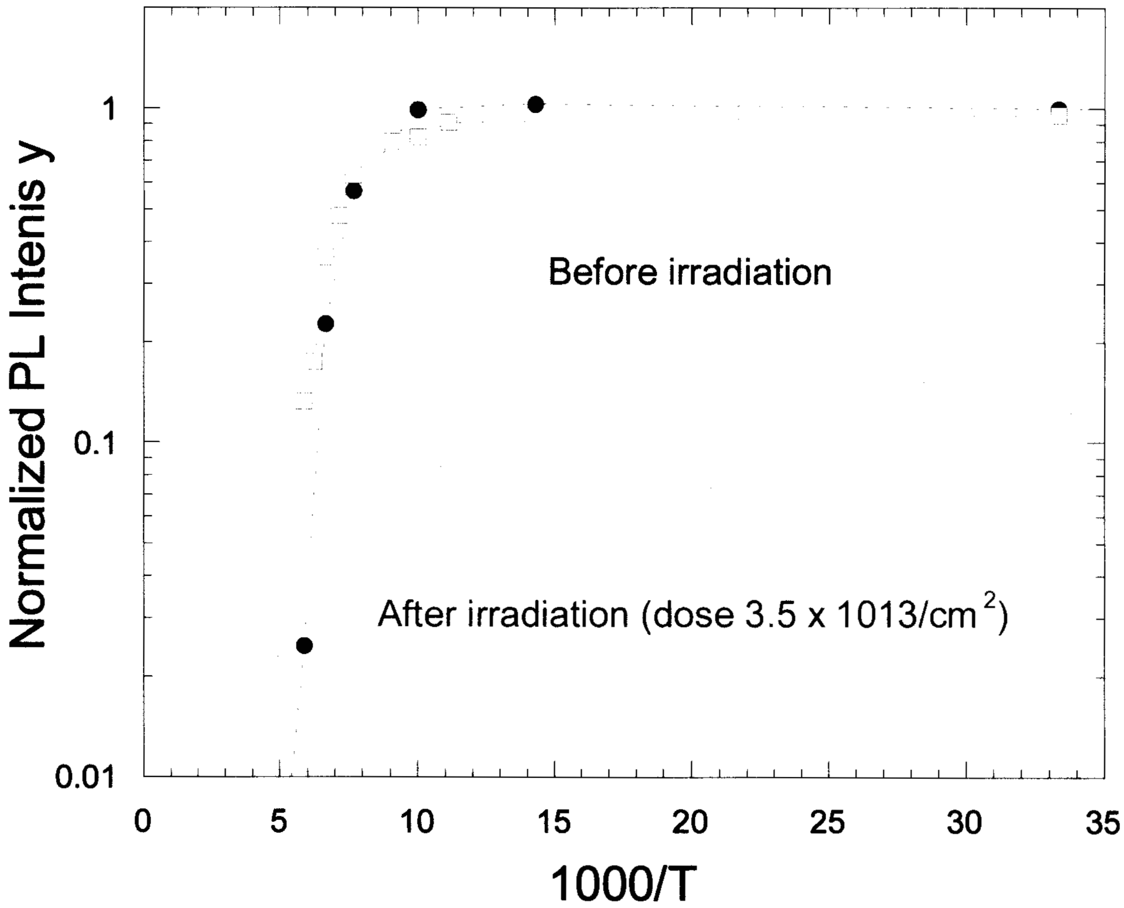
No such increase is observed in the QW structures:
PL enhancement is an effect of three-dimensional confinement

Reduction of the phonon bottleneck by defect assisted phonon emission has been proposed as a mechanism to explain the bright PL emission in QDs [P. C. Sercel, *Phys. Rev. B* **51**, 14532 (1995)]

In quantum dots with defect free interfaces, introduction of deep level defects as those originated from displacement damage might provide additional relaxation paths for thermalization of carriers and therefore increase the luminescence emission [H. Benisty, C. M. Sotomayor-Torres, and C. Weisbuch, *Phys. Rev. B* **44**, 10945 (1991)]

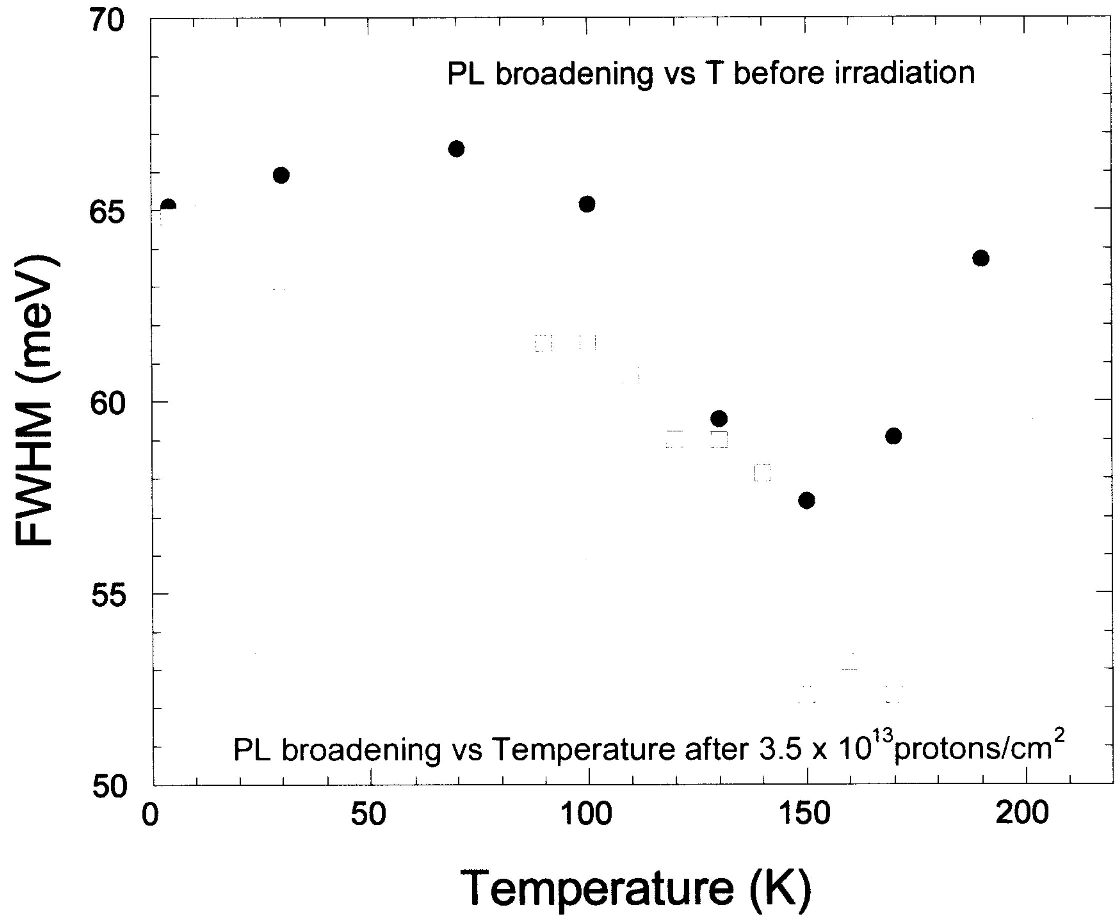
What are the mechanisms responsible for the small degradation observed in the optical emission from QD structures (> $10^{13}/cm^2$) ??

The degradation in minority carrier diffusion lengths expected in the barrier and wetting layer materials is the most probable cause for the initial degradation observed in QD PL at higher proton doses and will contribute to any observed degradation in QD PL emission, by limiting carrier capture into the dots. This is most likely to take place before effects from direct damage in the dots becomes a significant mechanism for optical degradation.



Slightly lower activation energy

Lower normalized PL at temperatures ~ 100 K.



More pronounced decrease in the inhomogenous PL broadening (Or full width at half maxima FWHM) with temperature after radiation damage

Conclusions/Summary of Results

[redacted]