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Effect of high energy proton irradiation on InAs/GaAs quantum dots: Enhancement of photoluminescence efficiency (up to ~7 times) with minimum spectral signature shift

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ABSTRACT

We demonstrate 7-fold increase of photoluminescence efficiency in GaAs/(InAs/GaAs) quantum dot hetero-structure, employing high energy proton irradiation, without any post-annealing treatment. Protons of energy 3–5 MeV with fluence in the range $(1.2–7.04) \times 10^{12}$ ions/cm^2 were used for irradiation. X-ray diffraction analysis revealed crystalline quality of the GaAs cap layer improves on proton irradiation. Photoluminescence study conducted at low temperature and low laser excitation density proved the presence of non-radiative recombination centers in the system which gets eliminated on proton irradiation. Shift in photoluminescence emission towards higher wavelength upon irradiation substantiated the reduction in strain field existed between GaAs cap layer and InAs/GaAs quantum dots. The enhancement in PL efficiency is thus attributed to the annihilation of defects/non-radiative recombination centers present in GaAs cap layer as well as in InAs/GaAs quantum dots induced by proton irradiation.

1. Introduction

Quantum dot (QD) based devices are emerging as an alternate platform for quantum well (QW) based devices. High efficient InAs/GaAs QD lasers, photo-detectors that can show better yield than QW devices have been demonstrated recently [1–3]. The advantage of these group III–V compound semiconductor based QD devices is its low threshold current density [4] and the ability to tune the emission wavelength from 1500 nm to 1100 nm [1,5,6]. Therefore it finds applications in infrared detectors [3], focal plane arrays [7] and in telecom/datacom [8] sectors. Lots of research is being carried out to improve the characteristics of QDs to reach the theoretically expected device efficiency [9]. One of the major characteristics of InAs/GaAs or III–V based QDs, that is being worked on is the photoluminescence (PL) efficiency to realize highly efficient low-threshold QD lasers. To improve the PL efficiency in InAs/GaAs QDs, different techniques such as deuteration [10], nitrogen treatment on the QDs before capping [11], stacking of multi-layers of QDs [12], QDs grown in a DWELL (dot-in-the-well) structure [13] and rapid thermal annealing [14] are used. Most of the techniques described above results in undesirable spectral emission shift due to the intermixing of atoms between the QDs and the barrier material (cap layer). Hence a unique technique that could not promote the inter diffusion and undesirable spectral shift will definitely benefit quantum dot resonant microcavity vertical cavity surface emitting lasers (VCSELs) and resonant cavity light emitting diodes which have less QDs in the active region, that require high yield PL and less spectral emission tolerance. Leon et al. demonstrated PL efficiency of InAs/GaAs QDs could be enhanced using 1.5 MeV proton irradiation with fluence of 7×10^{12} ions/cm^2 [15]. In their study they obtained only a marginal increase in PL efficiency with a fluence of 7×10^{12} ions/cm^2, and further increase in fluence resulted in degradation in PL. This is what motivated us to carry out a systematic investigation using protons irradiation (3–5 MeV) in the low fluence range of $(1.2–7.04) \times 10^{12}$ ions/cm^2 on GaAs/(InAs/GaAs) QD hetero-structure.

Ion beam irradiation is one of the tools to manipulate the structural, electrical and optoelectronic property of materials [16–18]. Due to its precision control over size and depth-wise damage creation/modification in materials, ion beam irradiation technique is acceptable equally in research as well as in semiconductor industry. Ion beam synthesis of buried layers in single crystal silicon started about 30 years ago [19]. The SIMOX (separation by implantation of oxygen) technology, which is widely used in industry allowed the fabrication of high performance devices [20]. Ion beams are employed to create buried/embedded quantum dots

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[21], fabricating buried epitaxial layer with Schottky barriers [22], electrical isolations in chips/to make buried electrical isolation of surface device from conducting substrate [23], increasing surface hardness, etc. In 2003, Lu et al. [24] and Yalin et al. [25] reported enhancement of PL efficiency in InAs/GaAs QDs using 50–70 keV proton irradiation. But these studies were carried out in multi-layer QDs samples followed by rapid thermal annealing treatment at temperatures in the range 600–700 °C. In the present work we exploited ion beam irradiation to tailor the optoelectronic property of InAs/GaAs QDs to enhance PL efficiency without any post-annealing treatment and considerable shift in spectral emission.

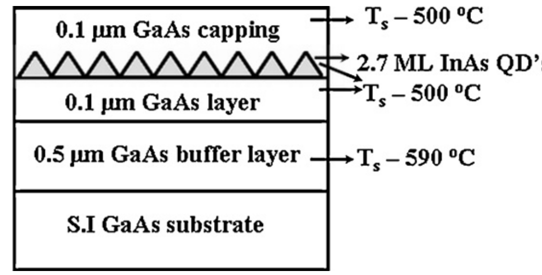

Fig. 1. Schematic of GaAs/(InAs/GaAs) hetero-structure under study.

2. Experimental

Single layer InAs/GaAs quantum dots were grown by Stranski–Krastanov method over semi-insulating GaAs substrate by solid source molecular beam epitaxy. On the 'EPI' ready semi-insulating GaAs substrate, after desorbing the protective oxide layer, a 0.5 µm intrinsic GaAs buffer layer was grown at 590 °C. Subsequently the temperature was brought down to 500 °C and a thin intrinsic GaAs layer of 0.1 µm was deposited. Thereafter 2.7 ML of InAs was deposited which forms the wetting layer and gives rise to self-assembled quantum dots (500 °C). These quantum dots were further capped by 0.1 µm of intrinsic GaAs layer. The rate of deposition of GaAs was kept at ~0.72 µm/h and InAs around ~0.0323 ML/s, respectively. Fig. 1 shows the schematic of epitaxial grown InAs/GaAs QD hetero-structure on semi-insulating GaAs substrate. The GaAs/(InAs/GaAs) QD hetero-structure were irradiated using protons of energy 3–5 MeV with a fluence ranging from 1.2 to 7.04×10^{12} ions/cm^2 (at room temperature). Stable beam of protons from Folded Tandem Ion Accelerator facility installed at Bhabha Atomic Research Centre, Bombay, India was used for irradiation. Samples were irradiated with protons at normal incidence. Structural characterization was done using X-ray diffraction analysis (Philips PANalytical X'pert Pro. X-ray diffractometer) and cross-sectional transmission electron microscopy (XTEM). For XTEM measurements samples were prepared using conventional mechanical polishing and ion milling techniques, and TEM micrographs were recorded under an acceleration voltage of 200 kV using Philips EM420, with a lattice resolution of 0.3 nm. PL measurements were taken in a temperature range 8 K to room temperature by exciting the samples with a diode pump solid state laser of wavelength 405 nm with excitation density 51.6 W/cm^2. The PL emission was dispersed by a 0.75 mm triple grating monochromatic (SpectroPro-2750) and detected by a liquid nitrogen cooled 0.2 µm InGaAs detector array (Princeton Instruments; OMA 100 V). Power dependent PL spectra were recorded by varying the excitation density in the range 10.7–51.6 W/cm^2. Electronic energy loss, nuclear energy loss and range of protons in InAs/GaAs systems were determined using TRIM calculations [26]. The electronic energy loss of 5, 4 and 3 MeV protons in InAs/GaAs system is about ~24.8, 28.6 and 34.3 eV/nm, whereas nuclear energy loss is about ~14, 17 and 21 meV/nm, respectively. The range of protons in InAs/GaAs is found to be ~55 and 124 µm for 3 MeV and 5 MeV, respectively, and hence all the ions are embedded deep into the substrate.

3. Results and discussion

Fig. 2(a) depicts the PL spectra recorded at 8 K from as-prepared and GaAs/(InAs/GaAs) QD hetero-structure irradiated using protons of energy ranging from 3 to 5 MeV (fluence: 4.22×10^{12} ions/cm^2). As-prepared sample exhibited emission centered at 1163 nm and 1095 nm corresponding to the ground state and first excited state recombination. On proton irradiation, PL efficiency of the system increases with a marginal shift in emission wavelength of about 17 nm towards higher wavelength (red shift). Fig. 2(b) depicts the plot of integrated PL intensity (ground state emission) versus the energy loss of protons in InAs/GaAs system. It clearly exhibits a trend of increase in PL efficiency with increase in energy loss of protons in the system. Interestingly one could notice an anomalous increase in first excited emission upon 4 MeV proton irradiation [Fig. 2(a)]. To further prove the observed effect, power dependent PL spectra were recorded in the range of 10.7–51.6 W/cm^2 at 8 K. Fig. 3(a) and (b) depicts the excitation density

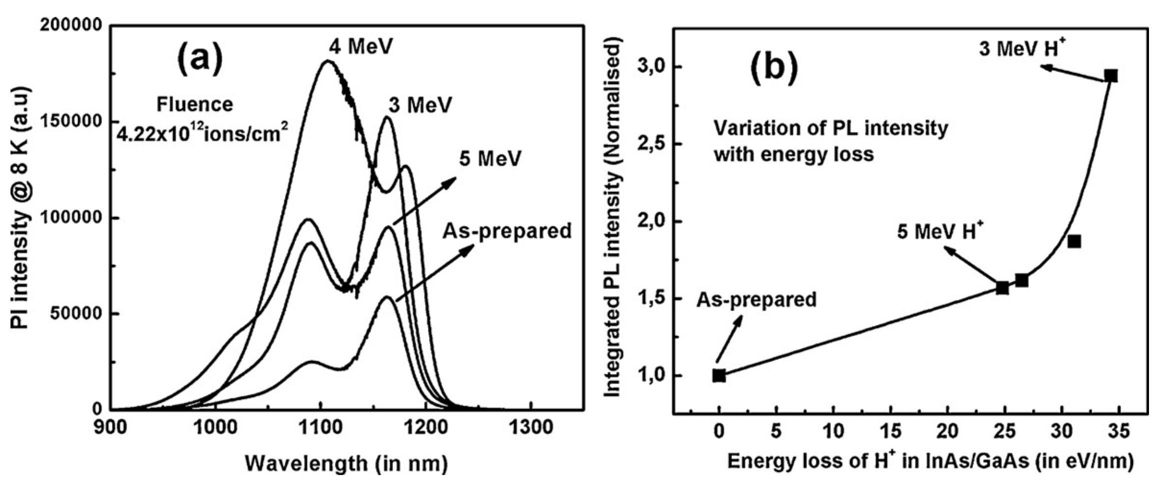

Fig. 2. (a) Photoluminescence spectra recorded at 8 K from InAs/GaAs QDs irradiated with different proton energies and (b) variation of integrated photoluminescence intensity (ground state emission) with increase in energy loss of protons in InAs/GaAs (fluence, 4.22×10^{12} ions/cm^2). PL intensity is normalized with respect to the PL intensity of as-prepared sample.