



# Optical properties of electron beam and $\gamma$ -ray irradiated InGaAs/GaAs quantum well and quantum dot structures

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## HIGHLIGHTS

- ▶ Electron beam and  $\gamma$ -ray irradiation degrade the optical properties of InGaAs based quantum structures.
- ▶ 1-MeV electron beam makes more damage than  $\gamma$ -ray.
- ▶ QD structure is more resistant than QW and bulk structure upon to the irradiation.

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## ABSTRACT

The effects of electron beam and  $\gamma$ -ray irradiation on the optical properties of InGaAs/GaAs quantum dot (QD), quantum well (QW), and bulk structures, which were grown by metal organic vapor phase epitaxy, have been investigated. Optical properties of all the structures were degraded by both kinds of irradiation. Electron beam irradiation caused a larger reduction in the photoluminescence (PL) intensity and carrier lifetime of the samples than  $\gamma$ -ray irradiation. Also, red-shift of the PL peak was observed in almost all the irradiated QD and QW structures. Comparing the different structures, the QD structure showed the best radiation resistance.

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## 1. Introduction

InGaAs/GaAs quantum well (QW) and quantum dot (QD) structures have gathered much research interest due to their tunable spectral window and subsequent huge application potential in optoelectronic devices, such as diode lasers (Chen et al., 1990; Huffaker et al., 1998), photodetectors (Tidrow et al., 1997; Xu et al., 1998), and solar cells (Yang and Yamaguchi, 2000; Aroutiounian et al., 2001). However, when these devices are operated in harsh environment like space, radiation damage by electron, proton and heavy ions can lead to operational failure or the reduction in the device lifetime. The effects induced in nanostructured materials by ion and electron irradiation have been investigated intensively (Krashennnikov and Nordlund, 2010). The displacement damage by irradiation is usually the main concern for optoelectronic devices (Johnston, 2000). It was reported that the maximum power output of InGaAs solar cell degraded by 55% and 70% after 1 MeV electron and 3 MeV proton irradiation, respectively (Yamaguchi, 1995; Dharmarasu et al., 2001). Therefore, it becomes an inevitable task to evaluate the performance

of optoelectronic devices in radiation environment before using them in any space application. Although numerous efforts (Guffarth et al., 2003; Huang et al., 2003; Erchak et al., 2001; Piva et al., 2000; Ribbat et al., 2001; Chen et al., 1996; Walters et al., 2000) have been made to improve the radiation hardness of optoelectronic materials and devices, studying the effects of radiation on basic optoelectronic quantum structures is still essential for understanding the overall performance of the devices in radiation environment.

In this paper, we investigate the optical properties of  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}$  single quantum well and  $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$  quantum dot structures irradiated by electron beam and Co-60  $\gamma$ -ray radiation. The effects of various energies and flux densities of the electron beam have also been studied. Low temperature photoluminescence (PL) and time-resolved photoluminescence (TRPL) have been applied for characterization of the optical properties of the samples.

## 2. Experimental details

QW and QD samples were grown on semi-insulating GaAs (100) substrates in a horizontal metal organic vapor phase epitaxy

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(MOVPE) reactor at atmospheric pressure. Trimethylindium (TMIn), trimethylgallium (TMGa), tertiarybutylarsine (TBAs), and tertiarybutylphosphine (TBP) were used as precursors for indium, gallium, arsenic, and phosphorus, respectively. The structures of the QW and the QD samples are schematically illustrated in Fig. 1(a) and (b). The  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$  QW structure was grown at  $650^\circ\text{C}$  and V/III ratios used for the GaAs and the InGaAs layers were 27 and 23, respectively. In the QD structure, both  $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$  islands and the GaAs capping layer were grown at  $550^\circ\text{C}$  but a V/III ratio of 10 and 18 was used for the islands and the capping layer, respectively. Also, a 150-nm-thick GaAs/GaAs epilayer (Fig. 1(c)) and a 150-nm-thick  $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{InP}$  lattice-matched epilayer (Fig. 1(d)) were grown for reference.

After MOVPE growth, each sample was cut into eight pieces. Seven pieces were used for different types of irradiation experiments, while one piece was kept as a reference. The different irradiation types used in this work are summarized in Table 1 and labels A–G are used to identify the irradiation types in the figures and in the text. Both electron and  $\gamma$ -ray irradiation were carried out at room temperature. Electron beam irradiation was carried out by an ELV-8 vertical electron accelerator. Two kinds of electron beams were chosen, 1.1 MeV electron beam with a flux density of  $2.6 \times 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$  and 1.8 MeV electron beam with a flux density of  $5.0 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ . A Co-60 source was applied for  $\gamma$ -ray irradiation with a dose rate of  $1.22 \text{ Gy}(\text{Si})/\text{s}$ . Gray (Gy) is the unit of absorbed radiation dose of ionizing radiation, and is defined as the absorption of one joule of ionizing radiation by one kilogram of matter. For semiconductor materials, the fluence of the beam is calibrated for absorption in silicon and, therefore, the unit  $\text{Gy}(\text{Si})$  is normally used. The electron flux density and  $\gamma$ -ray dose rate were measured by using Faraday cup beam integration and Fricke dosimetry system, respectively.

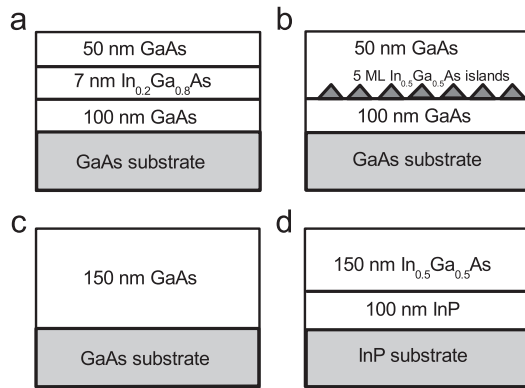
Low-temperature (10 K) continuous-wave PL measurements were conducted by utilizing a diode-pumped frequency-doubled

Nd:YVO4 laser emitting at 532 nm for excitation. A liquid-nitrogen-cooled germanium detector and standard lock-in techniques were used to record the PL spectra. The low-temperature TRPL measurements were performed by exciting the samples with 150 fs pulses at 780 nm from a mode locked Ti:sapphire laser and by detecting the signal using a Peltier-cooled micro-channel plate multiplier and time-correlated single photon counting electronics.

### 3. Results and discussion

#### 3.1. Irradiation effects on the QW structure

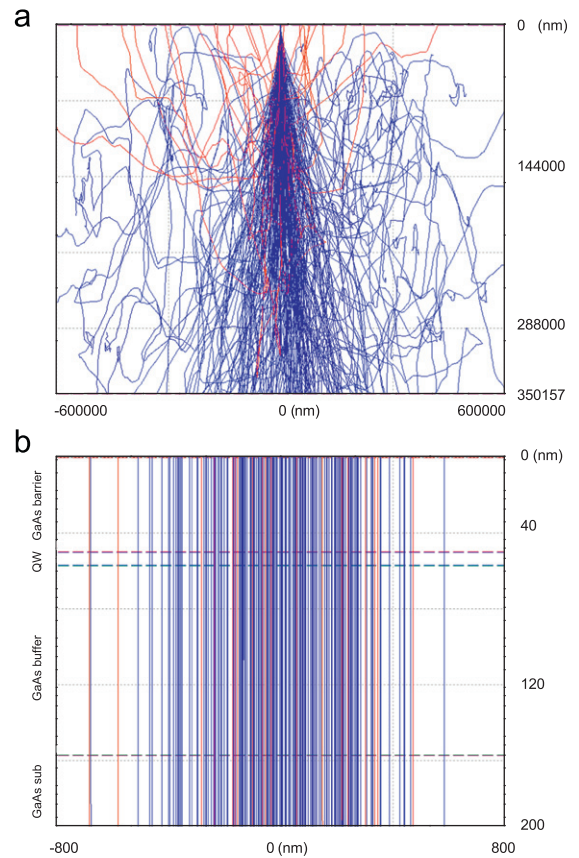
First, a Monte-Carlo simulation of electron beam-sample interactions was carried out on the  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}$  QW structure (Fig. 1(a)) by the simulation software CASINO V2.42 (Drouin et al., 2007). Fig. 2(a) shows the simulated 1 MeV electron beam trajectories in the whole sample thickness, from which it can be seen that most of the electrons penetrate the sample and the rest are mainly stopped in the substrate bulk layer. Fig. 2(b) shows the electron trajectories in the QW active area, in which the electron beam goes straight through. Therefore, it can be concluded that 1 MeV electron beam irradiation can make displacement damage not only in the QW active layer but also in the barrier, buffer and substrate layers as well. The damage in the substrate might be even more severe.



**Fig. 1.** Schematic diagrams of the sample structures: (a)  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}$  quantum well, (b)  $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$  quantum dot, (c) GaAs/GaAs epilayer, and (d)  $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{InP}$  epilayer.

**Table 1**  
Different irradiation types used in this article and their corresponding labels.

| Irradiation type | Dose rate<br>$e^-: \text{cm}^{-2} \text{ s}^{-1}$<br>$\gamma: \text{Gy}(\text{Si})/\text{s}$ | Total dose<br>$e^-: \text{cm}^{-2}$<br>$\gamma: \text{Gy}(\text{Si})$ | Label |
|------------------|----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|-------|
| 1.1 MeV electron | $2.6 \times 10^{11}$                                                                         | $1 \times 10^{15}$                                                    | A     |
| 1.1 MeV electron | $2.6 \times 10^{11}$                                                                         | $2 \times 10^{15}$                                                    | B     |
| 1.8 MeV electron | $5.0 \times 10^{10}$                                                                         | $5 \times 10^{14}$                                                    | C     |
| 1.8 MeV electron | $5.0 \times 10^{10}$                                                                         | $1 \times 10^{15}$                                                    | D     |
| 1.8 MeV electron | $5.0 \times 10^{10}$                                                                         | $2 \times 10^{15}$                                                    | E     |
| $\gamma$ -Ray    | 1.22                                                                                         | $5.4 \times 10^5$                                                     | F     |
| $\gamma$ -Ray    | 1.22                                                                                         | $1.1 \times 10^6$                                                     | G     |



**Fig. 2.** Computer simulation showing the electron trajectories of 1 MeV electron beam in the  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}$  QW sample (a) in the whole sample thickness, and (b) within 200 nm from the surface. Electron beam direction is from top to bottom. The blue lines represent forward electrons and the red lines represent backscattered electrons. The figures show the trajectories of 200 electrons entering in an area with a radius of 500 nm. The thickness of the substrate was set at 350  $\mu\text{m}$ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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