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Enhancement in multicolor photoresponse for quaternary capped $In_{0.5}Ga_{0.5}As/GaAs$ quantum dot infrared photodetectors implanted with hydrogen ions

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ABSTRACT

In(Ga)As/GaAs-based quantum dot infrared photodetectors (QDIPs) are among the most efficient devices in the mid-wavelength infrared and long-wavelength infrared regions for various defense and space application purposes. Considering the importance of the results reported so far on In(Ga)As/GaAs QDIPs, here we had tried to develop a post-growth method for enhancing QDIP characteristics using both low energy and high energy light ion (hydrogen) implantations. The field-assisted tunneling process of dark current generation was suppressed due to the hydrogen ion implantation, even at a very high operational bias. A stronger multicolor photo-response was obtained for devices implanted with low energy hydrogen ions. From experimental results, we proposed a device model which explains the improved QDIPs performance caused by hydrogen ion implantation.

1. Introduction

Despite the low fill factor of quantum dot infrared photodetectors (QDIPs) [1,2], they were proven superior to quantum well infrared photodetectors (QWIPs) due to their comparatively low dark current [3] and high responsivity and detectivity [4,5]. A three-dimensional carrier confinement and phonon bottleneck are responsible for the better performances of QDIPs [4,5]. Their intrinsic sensitivity to the normal incidence of infrared light [4] made their use ideal for high-resolution, multicolor photodetection in mid-wavelength infrared (MWIR) and long-wavelength infrared (LWIR) regions [6–10]. Moreover, QDIPs offer a narrower spectrum width at the detection wavelength compared to QWIPs [7].

To date, many studies have been reported on InAs/GaAs-based QDIPs with GaAs or InGaAs capping or dot-in-a-well structures [11–15]. However, the electrical and spectral properties of In(Ga)As/GaAs-based QDIPs using combination capping of the quaternary alloy InAlGaAs and GaAs layers have not been extensively studied [16,17]. The quaternary InAlGaAs capping acts as a strain-driven phase separation alloy and prevents out-diffusion of the In atoms from the dots by forming an indium gradient along the dot periphery [18,19]. The quaternary composition of $In_{0.21}Al_{0.21}Ga_{0.58}As$ and GaAs are almost lattice-matched [18,19].

With this growth engineering technique of using quaternary alloy capping, we carried out a simultaneous post-growth method to improve the QDIP characteristics using low and high energy light ion (hydrogen) implantations. The main purpose of this effort is to overcome the effects of the low fill factor (~20–25%) of the QDs in the active region. The current study examined the effect of hydrogen ion implantation on the electrical and spectral properties of quaternary alloy-capped InGaAs/GaAs QDIPs.

2. Experimental

Quaternary alloy-capped $In_{0.5}Ga_{0.5}As/GaAs$-based n-i-n QDIPs (Fig. 1) were grown over semi-insulating GaAs (100) substrates using solid-source molecular beam epitaxy (Riber SYS14020 Epineat III–V). A growth rate of approximately 0.22 monolayers (ML)/s was maintained to grow 7 ML InGaAs/GaAs dots throughout this 10-layer heterostructure. An immediate 30 Å quaternary ($In_{0.21}Al_{0.21}Ga_{0.58}As$) capping was performed, followed by 500 Å intrinsic GaAs capping after each layer of dots was grown. At room

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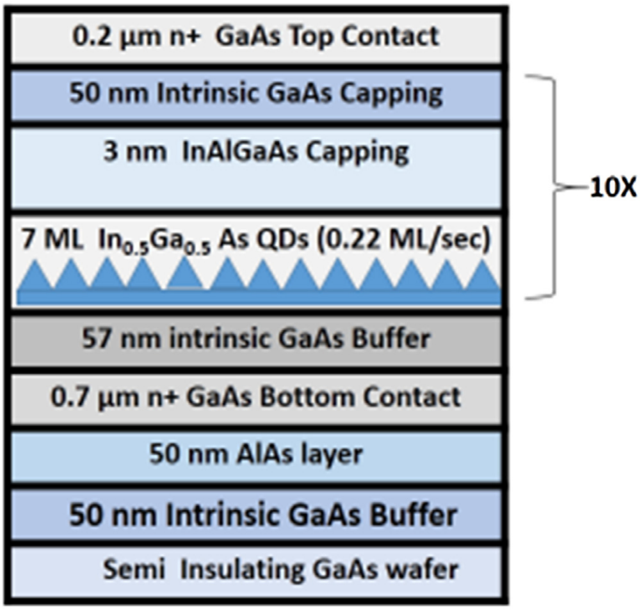

Fig. 1. Ten-layer quaternary alloy (InAlGaAs)-capped $In_{0.5}Ga_{0.5}As$/GaAs quantum dot infrared photodetector heterostructure.

temperature, for low energy hydrogen ion implantation, using a low energy ion beam accelerator, 50 KeV hydrogen ions were implanted over these heterostructures by varying the dose between 8×10^{11} and 2×10^{13} ions/cm^2 whereas high energy 3 MeV hydrogen ions were implanted over the same heterostructure with dose varying in the range from 2×10^{12} to 1×10^{13} ions/cm^2.

The structural and material characteristics of the devices were studied using cross-sectional transmission electron microscopy (XTEM) and low-temperature photoluminescence (PL) at 8 K. The PL experiments were carried out using a 532-nm excitation source, monochromator, and a nitrogen-cooled InGaAs array detector. Mechanical polishing and ion milling techniques were used to prepare the samples for the XTEM study. Conventional photolithography, wet etching, and metal evaporation techniques were used to fabricate mesa-shaped devices with 200-µm diameters, and temperature-dependent *I–V* measurements were then taken. Low-temperature photoresponses were measured for the as-grown and implanted devices using a Fourier transform infrared spectrometer with a glow bar source. The four devices in the current study are shown in Table 1.

Table 1
Nomenclature for the as-grown and implanted devices. The as-grown device was implanted with 50 keV and 3 MeV hydrogen ions of dose varying between 8×10^{11} and 2×10^{13} ions/cm^2.

Devices	Energy of hydrogen	Implanted Dose (ions/cm^2)
D1	As-grown	As-grown
D2	50 KeV	8×10^{11}
D3	50 KeV	2×10^{12}
D4	50 KeV	2×10^{13}
D5	3 MeV	2×10^{12}
D6	3 MeV	5×10^{12}
D7	3 MeV	1×10^{13}

3. Results and discussion

3.1. Structural and material properties

The XTEM images show the formation of high-density dislocation-free uncoupled dots in all 10 layers of the as-grown sample (Fig. 2). With low energy hydrogen ion implantation up to a dose of 8×10^{11} ions/cm^2, enhancement was noted for device D2 in the low temperature PL emission (Fig. 3). We assumed that the non-radiative recombination centers (NRCs) within the dots, wetting layer and the GaAs capping layer [20,21] of the as-grown sample absorbed most of the carriers that were responsible for radiative recombination. Upon hydrogen ion implantation, these NRCs were annihilated from the dots and their capping layers or near around capping layers. Thus, more carriers from the capping layer could then become lodged in the excited and ground states of dots before they could participate in the PL emission or radiative recombination processes [20,21]. With further dose increases, the PL intensity decreased rather drastically as for devices D3 and D4 (Fig. 3). Further increase of hydrogen ion dose created additional structural defects both in the GaAs barrier layer and also in the QDs [22] for device D3 and D4. These structural defects might have acted as the sinks for the photo excited carriers from the barrier layer and QDs. Thus, the rate of non-radiative recombination had been enhanced for device D3 and D4 and there were degradations in their PL intensities.

Fig. 3 depicts very little red shift in ground state PL peak positions with increasing dose. TRIM calculations [23] showed that during implantation, the electronic and nuclear energy losses of 50 KeV hydrogen ions in In(Ga)As/GaAs systems are ~13.67 eV/Å and 0.05 eV/Å respectively up to a depth of ~3600 Å. These lost energies might have generated local heat within the QD system. The sticking probability of indium atoms in quaternary layer decreased due to this heat generation [24]. Thus, due to less mobility of indium atoms, they might have diffused into the dots from InAlGaAs capping and the dot size was increased. Decrease in dark current density for the implanted devices at higher bias of operation, also proved the fact, described in next section. But there was no out-diffusion of In atoms from dots. As reported earlier, quaternary alloy $In_{0.21}Al_{0.21}Ga_{0.58}As$ acts as a phase separation alloy, and an In concentration gradient is assembled over the dot periphery [19]. This In concentration gradient prevented both out-diffusion of dots and In–Ga intermixing within the dots [19]; no blue shift in PL emissions. There is always a high probability of In-Ga intermixing in the dots due to ex-situ annealing and that was the sole reason for avoiding further annealing treatment on the implanted devices under study.

Fig. 3 also shows that when the QD heterostructures were implanted with high energy hydrogen ions of 3 MeV, for devices D5, D6 and D7, there was an initial enhancement in PL emission as compared to D1. This enhancement might be also due to the eradication of as-grown defects and non-radiative recombination centers at capping layers and near around dots [20,21]. But their PL enhancement was not as high as that of devices implanted with low energy hydrogen ions. TRIM calculations show that, 3 MeV hydrogen ions can penetrate up to a depth of ~55 µm within In(Ga)As/GaAs QD system [23]. Thus there was a high probability that high energy hydrogen ion implantation might caused structural damages within the QDIP heterostructure under study attributed to less enhancement of PL emissions for D5, D6 and D7.

3.2. Electrical properties

Fig. 4 indicates that at low temperature (77 K) and at a bias of −1.5 V, the dark current density was reduced up to almost five orders from ~1.4×10^{-2} A/cm^2 for device D1 to ~2.3×10^{-7} A/cm^2