Two-color InGaAs/GaAs quantum dot infrared photodetectors by selective area interdiffusion

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(Received 6 May 2008; accepted 13 June 2008; published online 8 July 2008)

We report the postgrowth fabrication of two-color InGaAs/GaAs quantum dot infrared photodetectors (QDIPs). By capping half of the as-grown QDIP structure with titanium dioxide (TiO_2) and performing rapid thermal annealing under the optimized condition, a blueshifted photoluminescence from the uncapped region was obtained compared with the TiO_2 covered region. The corresponding device spectral photoresponse from the two adjacent regions exhibited a shift of 0.8 μm around the wavelength of 6 μm. This is a result of the simultaneous promotion and suppression of thermal interdiffusion during rapid thermal annealing. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2955517]

Two-color or multicolor infrared (IR) photodetector is highly desirable for high performance IR systems for applications such as remote temperature sensing, chemical analysis, target identification, and spectrometers. With recent development of quantum dot IR photodetectors (QDIPs), which have demonstrated normal incidence operation and higher operating temperature than their quantum well (QW) counterparts,[1] multiwavelength photon detection has also been investigated by varying QDIP designs and use of dots-in-a-well (DWELL) structures.[2–6] However, these methods require highly accurate and reproducible growth conditions. It is well known that simple interdiffusion technique such as thermal annealing causes a big wavelength shift in the band to band photoluminescence (PL) in QD structures due to a large thermal interdiffusion effect.[7,8] Redshift in wavelength of QDIPs after thermal interdiffusion has also been reported recently.[9,10] However, in order to further realize the multicolor detection, selected regions of the sample have to be protected from interdiffusion (such that the wavelength remains unchanged from the as-grown structure) to create a differential wavelength shift across the same wafer after thermal treatment. Our previous study on QD intermixing has shown that thermal interdiffusion can be suppressed by using dielectric capping layer such as titanium dioxide (TiO_2) due to the thermal stress effect.[11] In this work, by employing a layer of TiO_2 film to suppress thermal interdiffusion, a two-color InGaAs/GaAs QDIP was demonstrated with two distinct photoresponse peaks.

The QDIP structure used in this work was an *n-i-n* structure grown on a semi-insulating GaAs (001) substrate by metal-organic chemical vapor deposition (MOCVD). It contained ten layers of 5.7 ML undoped $In_{0.5}Ga_{0.5}As$ QDs separated with 50 nm of GaAs barrier layers and sandwiched between two highly Si-doped top (300 nm) and bottom (1000 nm) GaAs contact layers. The MOCVD growth details can be found in Ref. 12. One piece of as-grown sample was cleaved from the wafer and masked to allow half of the sample to be deposited with 180 nm of TiO_2 film by e-beam evaporation. Rapid thermal annealing was performed on the whole sample at 750 °C for 30 s. The TiO_2 layer was then removed using reactive ion etching under the CHF_3/Ar flow at a rf power of 200 W. The etching conditions have been optimized such that with all the TiO_2 fully etched, minimal GaAs (<0.1 μm) was removed from the uncapped region. The two different regions of the samples were measured by PL at room temperature using a diode-pumped solid-state frequency-doubled green laser at 532 nm through an 0.5 m monochromator and a cooled InGaAs photodetector. The sample was then fabricated into QDIP devices with 250 $\times$ 250 μm mesa structures using standard QDIP fabrication processes and the QDIPs were mounted in a liquid nitrogen cooled Dewar for device characterization.[12]

Figure 1 shows the room temperature PL spectra taken from the two-color QDIP. Compared with the as-grown sample, QD luminescence peak from the uncapped region of the two-color QDIP has been blueshifted from 1151 nm (1.101 eV) to 1126 nm (1.077 eV), whereas the spectrum from the TiO_2 capped region remains unchanged. The uncapped region exhibits blueshifted PL wavelength resulting from the atomic thermal interdiffusion of the InGaAs QDs and their surrounding GaAs barriers, due to the presence of grown-in defects formed during the low temperature growth of QDs and large strain that are associated with the dots.[7,8] Interdiffusion will modify the shape of the QD

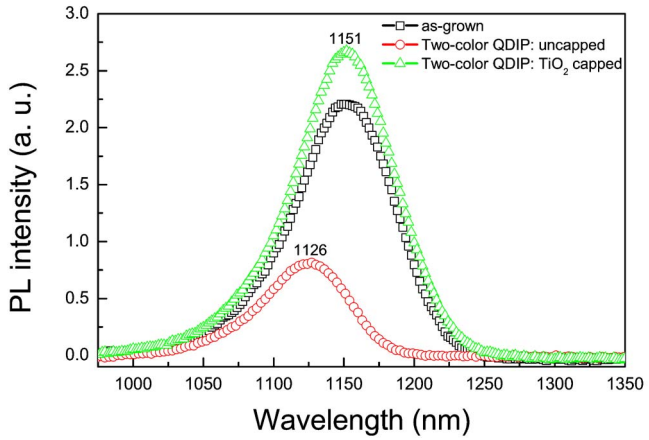

FIG. 1. (Color online) Room temperature PL spectra of the two-color QDIPs. The spectrum for the as-grown sample is also shown for comparison.

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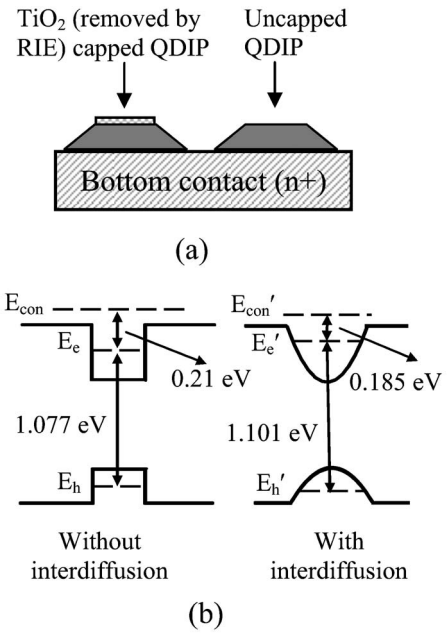

FIG. 2. (a) The schematic diagram of the two-color detector sample and (b) the band gap diagram showing various transitions within the two QDIPs.

potential, leading to an increased ground state and thus a blueshifted interband (band-to-band) transition energy $[E'_e - E'_h\ (1.101\ \text{eV}) > E_e - E_h\ (1.077\ \text{eV})]$ and a redshifted intersubband transition energy (will be discussed later), as shown schematically from Fig. 2. For the region that has been capped with TiO_2 layer, due to the large thermal expansion coefficient of TiO_2 (compared with GaAs), a tensile stress will be imposed to the QD structure during annealing. This tensile stress field is sufficiently strong to inhibit the diffusion of the grown-in defects within the whole QDIP structure and thus greatly suppress the thermal interdiffusion. This is consistent with the results obtained in our earlier study of a single layer QD structure,[11] demonstrating that deposition of TiO_2 layer is also able to effectively suppress interdiffusion in QDIP structures with at least ten QD layers. Some reduction of PL intensity from the uncapped region of the sample can also be observed in Fig. 1, which could be due to the formation of nonradiative recombination centers on the bare (uncapped) surface (despite the use of GaAs proximity capping layer) and/or by partial strain relaxation of the multistacked QD layers after annealing. Deposition of TiO_2 is able to not only protect the sample surface but also reduce the system strain (as will be discussed later) during annealing, leading to improved PL efficiency as exhibited in Fig. 1.

Accordingly, for the normal incidence spectral photoresponse from the two-color QDIP measured at a positive bias of 0.8 V (on the top contact layer with respect to the bottom contact layer), similar behavior has been observed, as shown in Fig. 3. Compared with the spectrum from the as-grown QDIP, deposition of TiO_2 did not cause any change in the spectral response of the device with a peak at 5.9 μm [0.21 eV that corresponding to $(E_{\text{con}} - E_e)$ in Fig. 2(b)]; whereas after annealing at 750 °C for 30 s, a wavelength redshift in the peak photoresponse to 6.7 μm [0.185 eV corresponding to $(E'_{\text{con}} - E'_e)$ in Fig. 2(b)] can be observed from the uncapped region of the sample. Interestingly the differential intersubband transition energy of $[(E_{\text{con}} - E_e) - (E'_{\text{con}} - E'_e) = 0.025\ \text{eV}]$ between the two different regions of the

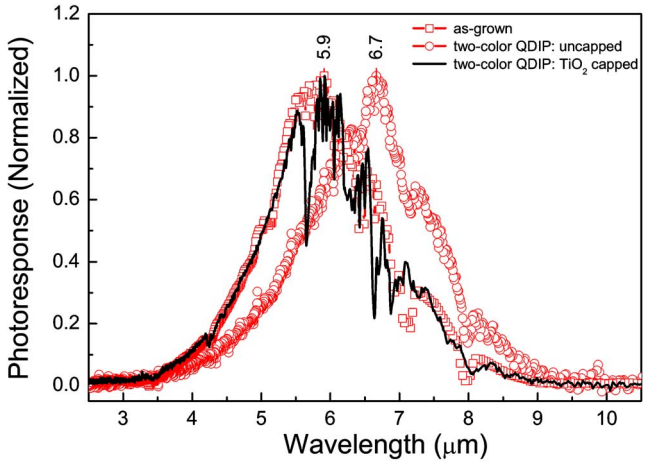

FIG. 3. (Color online) The 77 K spectral photoresponses of the two-color QDIPs, in comparison with the spectrum for the as-grown.

two-color device is very similar to their interband PL energy difference $[(E'_e - E'_h) - (E_e - E_h) = 0.024\ \text{eV}]$. This implies that the position of the delocalized continuum state with the strongest optical absorption has moved closer to the GaAs barrier as a result of the shape modification of the QD confining potential after thermal interdiffusion for the uncapped sample, as schematically shown in Fig. 2(b). Similar behavior has been observed and discussed in more detail in interdiffused QW IR photodetectors (QWIPs) in previous theoretical[13] and experimental[14] studies. Another possibility in this case could also be that QD hole ground state energy is much less sensitive to the confinement potential profile change than electron ground state. Thus the PL energy shift caused by interdiffusion is mainly due to the change of the electron ground state energy, making it similar to the amount of energy shift obtained from intersubband transition (photoresponse). On the other hand, under the same annealing conditions, with the suppression of interdiffusion, the QD band structure remained unchanged for the TiO_2 capped detector exhibiting the same spectral properties as the as-grown devices.

Figure 4 shows the 77 K dark current-voltage (I-V) characteristics of the two-color detectors. In comparison, the

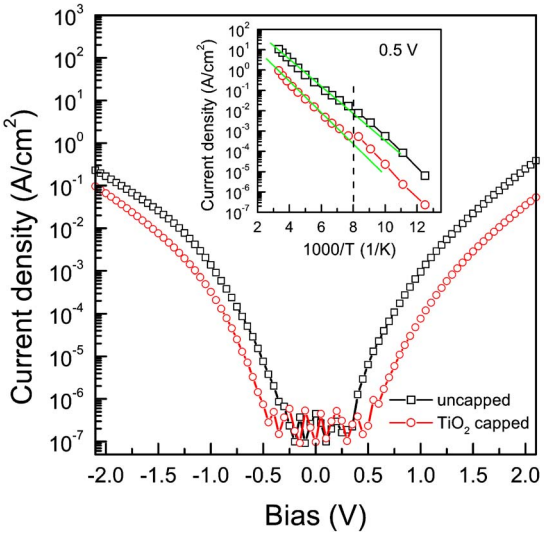

FIG. 4. (Color online) The 77 K I-V characteristics of the two-color QDIPs. Inset plots the dark current density vs inverse temperature (1000/T) at the bias of 0.5 V for both QDIPs.

TiO_2 capped detector has exhibited an order of magnitude lower dark current than the uncapped detector. It is known that for QWIPs, the major source for dark current above 50 K is from the thermionic emission of electrons from the QWs to the barrier conduction bandedge.[15] However in QDIPs, due to the large strain of QDs, the effects of which can accumulate over a large stacked structure, and the lower temperature required for their growth, defects have the potential to play a more significant role by increasing the rate at which electrons can tunnel from the QD ground and excited states. Therefore, the temperature region in which dark current is defect-limited may be extended.[16] The thermal activation energies for the electrons to escape to form the dark current (at a given bias and temperature region) are reflected in the slope of the Arrhenius plot shown in the inset of Fig. 4. The presence of the nonlinearities up to ~125 K in both curves indicate the possible role of defects[16] as well as the QD size and energy distribution.[17] For QDIP structures consisting of multistacked QD layers, annealing is able to remove some background defects formed during low temperature growth, however, simultaneously it could also cause partial relaxation of compressive strain within the large number of QD stacks, leading to the formation of extended defects. Thus, for the two-color detectors that were annealed under the same condition, similar amount of grown-in defects may be annihilated by annealing. However, as mentioned earlier, since the TiO_2 film was able to induce a large tensile stress field upon the QDIP structure, it may compensate the compressive strain within the QD layers during annealing thereby reduce the formation of extended defects leading to a reduction of dark current. Furthermore, since the ground state energy was increased for the uncapped device of the two-color detectors after thermal interdiffusion [see Fig. 2(b)], the thermal activation energy of its dark current is also decreased, causing a further increase of dark current at higher temperatures. Thus, as indicated in the inset of Fig. 4, its temperature dependent dark current curve exhibits a slightly smaller slope (guided by the straight line) than that of the TiO_2 capped device. Nevertheless, the rather similar linear nature of both curves suggests that their dark currents were still mainly thermally limited and the intermixing process did not significantly alter the mechanisms responsible for the dark current.

The 77 K peak responsivity and detectivity for the two-color QDIPs are plotted in Fig. 5. A maximum detectivity of 0.7×10^9 cm $Hz^{1/2}/W$ and the corresponding responsivity of 2.6 mA/W are obtained from the TiO_2 capped region and a peak detectivity of 0.7×10^9 cm $Hz^{1/2}/W$ and the corresponding responsivity of 3.9 mA/W are obtained from the uncapped region at an external bias of 0.8 V. These values are comparable to those measured from the as-grown device with the detectivity of 1×10^9 cm $Hz^{1/2}/W$ and corresponding responsivity of 5.1 mA/W. The similar device characteristics obtained at both wavelengths of the two-color QDIPs suggest that this device may be suitable for readout integration in a focal plane array (FPA) production.[18]

In summary, a two-color InGaAs/GaAs QDIP has been fabricated by employing a simple scheme of selective area interdiffusion. It indicates that through proper mask design and optimized fabrication processes, a two-dimensional QDIP FPA with alternate two-color pixels can be realized for a variety of future applications such as thermal imaging.

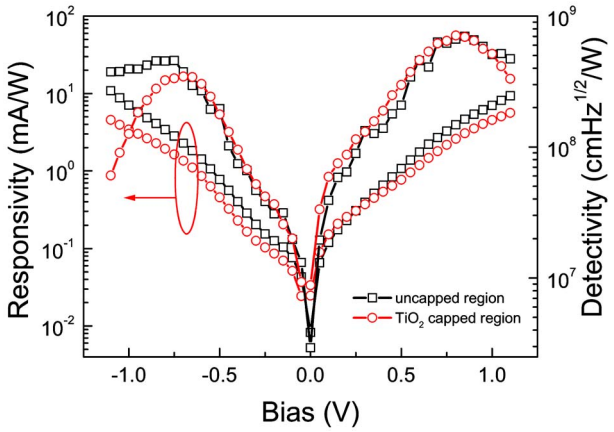

FIG. 5. (Color online) The 77 K bias dependence of peak responsivity and detectivity of the two-color QDIPs.

The authors would like to thank M. Aggett, T. Halstead, and D. Gibson for their excellent technical assistance. The financial support from Australian Research Council is also acknowledged.

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