Transverse-electric-field-enhanced response in InAs/AlGaAs/GaAs quantum-dot infrared photodetectors

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By introducing a 2-nm- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ capping layer on the InAs quantum dots, a transverse-electric- (TE) field-enhanced multicolor quantum-dot (QD) infrared photodetector has been achieved. The TE-enhanced peaks are due to the transition from the *S*-like ground state to the *P*-like first excited states induced by the strain field effects on the quantum dot. After rapid thermal annealing, the TE dominant peaks can be changed to transverse-magnetic- (TM) field-enhanced and vice versa. This is because the rapid thermal annealing creates defects at the boundary of QDs and their surrounding material, which release the compressive strain within the QDs. © 2005 American Institute of Physics. [DOI: 10.1063/1.1929881]

Self-assembled InAs quantum dots (QD) on GaAs substrate prepared by molecular beam epitaxy (MBE) have attracted much attention in recent years.^{1–5} Due to its long capture and relaxation times,⁶ the QD structure is suitable for the optoelectronic applications of the infrared photodetector,^{7–10} lasers,^{11,12} and optical memories.¹³ Because of the three-dimensional (3D) confinement of carriers, the quantum-dot infrared photodetector (QDIP) exhibits improved device performance, such as low dark current and higher operating temperature.^{7,9,10} Also, compared to the quantum-well infrared photodetector (QWIP) or the superlattice-infrared photodetector (SLIP), the 3D confinement can increase the transverse-electric (TE) response resulting from the intersubband transition.¹⁴ Thus, the QDIP has the advantage over the QWIP or the SLIP when applying in the focal plane array, i.e., the normal incident absorption without grating coupling. The interesting thing is that there is still a TE-mode response in the SLIP.¹⁴ In the early years during the development of the QWIP, i.e., GaAs/AlGaAs, InGaAs/InAlAs, and InGaAs/AlAs,^{15–19} many researchers observed the TE absorption as well as the transverse-magnetic (TM) absorption and this was attributed to the formation of a strain-induced energy level that favors TE absorption. Several different explanations, such as spin-flip intersubband transitions induced by the spin-orbit coupling¹⁹ and the D_{2d} tetragonal perturbation of the local (crystal and strain) field effects on the quantum well,¹⁷ were also proposed in their reports.

In this letter, the polarization-resolved responses of multicolor InAs/AlGaAs/GaAs QDIPs are reported, and the observed peaks are due to bound-to-bound and bound-to-continuum transitions. The responses are TE or TM mode enhanced, depending on the detection wavelength, device structure, and postgrowth annealing. Possible mechanisms are also proposed.

The InAs/AlGaAs/GaAs QDIP, as shown in Fig. 1, was grown by a VG V80 solid-source molecular beam epitaxy (MBE) on (100) semi-insulating GaAs substrate. The ten-stacked active region was grown at 510 °C. Every stack consisted of 3 (2.2) monolayer (ML) Si-doped InAs QDs, which

were covered with a 2-nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer and a 30-nm GaAs spacer. After the growth of InAs QDs, all shutters were closed for 5 s to allow atoms to migrate on the surface. The active region was sandwiched by two 15-nm-thick $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ blocking layers grown at 510 °C in order to block the dark current and *n*-GaAs contact layers grown at 580 °C. The dopant concentrations in both InAs QDs and contact layers are $1 \times 10^{18} \text{ cm}^{-3}$. After growth, the samples were processed with or without rapid thermal annealing (RTA) at 650 °C for 30 s as a comparison. Finally, the $100 \times 100 \mu\text{m}^2$ device was fabricated by a standard lithography process. The responsivity of the device was measured under a 45°-edge-coupling scheme with closed-cycle cryogenics

FIG. 1. (a) Schematic device structure of the InAs/AlGaAs/GaAs QDIP. (b) The 45°-edge-coupling scheme and the definition of polarizations.

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FIG. 2. Spectral response of the 3-ML InAs/AlGaAs/GaAs QDIP measured at 20 K in terms of polarization (a) without and (b) with RTA.

and Perkin–Elmer S2000 Fourier transform infrared spectroscopy. The absolute value of the spectral responsivity is calibrated with a standard blackbody radiation source operated at 1080 K. For photoluminescence (PL) measurements, the samples were excited by an Ar⁺ laser with a 514.5-nm wavelength and an excitation density of about 100 W/cm².

Figure 2 shows the polarization-resolved spectral responses of the 3-ML InAs/AlGaAs/GaAs QDIPs under the same bias (a) before and (b) after RTA, respectively. The measurement temperature is 20 K. The TE and TM polarizations of incident light are defined in Fig. 1(b). Notice that the TM polarization can be decomposed into the electric field components parallel and perpendicular to the growth direction with equal intensities. The two shorter-wavelength peaks at 6 and 10 μm are due to the bound-to-continuum transitions from InAs QDs with different size distributions, while the three peaks located around 16 μm are assigned to be the ground-state-to-first-excited-state transitions within QDs of different sizes. The detail arguments about the origins of these peaks were reported elsewhere.²⁰

Considering the peak positions first, as shown in the figure, all the peak positions almost stay the same or just slightly shift while changing the polarizations. This indicates that the anisotropic strain inside the QD comes from both the lateral and vertical confinements, which mix the wave functions and create a single broad peak whose position is independent of polarization. On the other hand, the energy separations between the TE and TM mode absorptions exist both in strained and unstrained quantum wells.^{17–19}

But we can still observe different trends in terms of different polarizations for different peaks. For the two shorter-

FIG. 3. Spectral response of the 2.2-ML InAs/AlGaAs/GaAs QDIP measured at 20 K in terms of polarization (a) without and (b) with RTA.

wavelength peaks at 6 and 10 μm , the responsivities of the TM mode are larger than those of the TE mode both with (b) and without (a) RTA. This result is in good agreement with the previous reports of conventional InAs/GaAs QDIPs.^{14,21} The nonzero responsivities of the TE mode are usually suggested as resulting from the nonplanar-shaped dots. Another minor factor is the breaking of symmetry/asymmetry of wave functions due to the Si dopants in the QDs.

Surprisingly, the 15.6- μm peak exhibits an unexpected TE-dominant response and the ratio of TE/TM increases after RTA, while the 16.8- and 17.8- μm peaks are still TM-mode enhanced. Although Maimon *et al.*²² have reported almost equal responsivities in both *S* (TE) and *P* (TM) polarizations, we report strongly TE-dominant responses and their changes with respect to polarizations. Peng *et al.*¹⁷ have shown that, at the Brillouin zone center $k=0$, the ground state, corresponding to $l=0$, will be *S*-like, while the excited states, corresponding to $l=1$, are *P*-like triply degenerate states that will split into a (P_x, P_y) doublet ($m_l = \pm 1$, TE active) and a P_z singlet ($m_l = 0$, TM active) under a tetragonal perturbation. Their work proved that both TE- and TM-mode absorptions from ground to first excited states are possible and the observed splitting between the TE and TM absorption peaks is due to the D_{2d} tetragonal perturbation of the local (crystal and strain) field effects on the quantum well. For our QDIPs, the strain inside the InAs QD is anisotropic,²³ which is unlike the in-plane stress in the quantum well. This anisotropic strain couples the doublet and singlet and makes the splitting between the (P_x, P_y) doublet and P_z singlet less. Also, the in-plane confinement contrib-

FIG. 4. Room temperature (~ 300 K) PL spectra of 2.2-ML InAs/AlGaAs/GaAs QDIPs without or with 30, 60, and 90 s RTA.

utes to the TE-mode response. Finally, with the unmissable large fluctuation of dot size, in-plane quantum confinement, and anisotropic strain, the nonzero TE-dominant responses represented in Fig. 2 without an energy shift could be explained as the (P_x, P_y) doublet contributions.

However, the 20-K responses of the 2.2-ML InAs/AlGaAs/GaAs QDIP shown in Fig. 3 changed with respect to the electric field polarization after RTA. Without RTA, the three peaks from a short to long wavelength around $17\ \mu\text{m}$ exhibit TM-, TE-, and TE-dominant responses, respectively. After RTA, they become TE-, TE-, and TM-dominant, respectively. We have examined several devices with the same structure and this changing behavior is assured. To reveal the mechanism behind it, the PL spectra of the same structure with different RTA times, i.e., 30, 60, 90 s, are also measured at room temperature as shown in Fig. 4. It is clear from the figure that the PL peak position redshifted and the intensity decreases while increasing the annealing time from 0 to 90 s. The PL spectrum exhibits a 7.4-meV redshift from 1174 to 1182 nm after the 650°C RTA for 30 s. It is suggested that the RTA process breaks the bonds and creates defects at the interface of QDs and their surrounding material. These defects relax the compressive strain within QDs. Thus, the PL intensity decreases and the peak position redshifts. Of course, In/Ga interdiffusion could play an important role in the spectra. Kosogov *et al.* reported the influence of RTA on the InAs/GaAs QDs with different annealing temperatures and times.²⁴ The results guarantee the blueshifts of the PL spectra due to Ga/In interdiffusion after RTA, and the degree of Ga/In interdiffusion depends on the annealing temperature and time. The 7.4-meV redshift in our experiment indicates that the 2-nm-thick $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ cap layer on InAs QDs reduces the Ga/In interdiffusion due to its higher melting temperature. Thus, it is reasonable to suggest that the strain relaxation due to bond breaking rather than the In/Ga interdiffusion is the main cause of the slight redshift of the PL peak.

Yet the spectral responses of the 3-ML InAs/AlGaAs/GaAs QDIP did not change as dramatically as those of the 2.2-ML one after RTA. This can be explained as that the 3-ML QDs originally have less compressive strain than the 2.2-ML one because the stress gradually relaxes when growing more monolayers of InAs QDs. Then the RTA process makes less influence on the strain of the 3-ML sample.

Another noticeable difference between the PL spectra and responsivities is that the RTA results in a 7.4-meV redshift in PL, yet there is little or no shift in the QDIP response. This is because that the QDIP response is due to the electronic intersubband transitions while the PL energy is the sum of band gap, electronic ground-state to conduction band minimum, and hole ground state to valence band maximum. Only part of the band gap change resulting from the strain relaxation reflects on the electronic subband.

In summary, we have fabricated the InAs/AlGaAs/GaAs QDIPs with enhanced TE-mode responses which can be engineered by RTA. Three peaks were observed in the long-wavelength infrared region around $17\ \mu\text{m}$. They exhibit different polarization-selective responses and can be changed by RTA. It is due to the transition from the S-like ground state to the strain-induced splitting of P-like first excited states.

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