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High-performance, long-wave (~10.2 μm) InGaAs/GaAs quantum dot infrared photodetector with quaternary $In_{0.21}Al_{0.21}Ga_{0.58}As$ capping

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A high-performance InGaAs/GaAs vertical quantum dot infrared photodetector (QDIP) with combined barrier of quaternary $In_{0.21}Al_{0.21}Ga_{0.58}As$ and GaAs was investigated in this study. A dominant long wavelength (~10.2 μm) response was observed from the device. The device demonstrates large responsivity (2.16 A/W) with narrow spectral-width ($\Delta\lambda/\lambda \sim 0.14$) and high detectivity ($1.01 \times 10^{11}$ cm $Hz^{1/2}$/W at 0.3 V) at 10.2 μm at 77 K. In addition, the device has also produced a detectivity in the order of 6.4×10^{10} cm $Hz^{1/2}$/W at 100 K at a bias of 0.2 V, indicating its suitability for high-temperature operations. *© 2011 American Institute of Physics.*
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Mid-wavelength infrared (MWIR) ~3–5 μm and long wavelength infrared (LWIR) ~8–14 μm detectors are important in a variety of commercial, military, and space applications.[1–5] Quantum dot infrared photodetectors (QDIPs) have evolved from quantum well infrared photodetector (QWIP) technology and are capable of detecting infrared (IR) wavelengths across a broad range. Due to their long carrier capture and relaxation times, QDIPs with self-organized InAs/GaAs quantum dot (QD) in active regions have the potential for lower dark current and higher photo-response levels than QWIPs. These advantages are believed to arise from the three-dimensional confinement of carriers within the dot. Thus, the bound carriers are sensitive to normal incident light, making QDIPs particularly attractive for focal plane array implementation.

Several studies have been attempted to realize room-temperature operation of normal-incidence QDIPs with high device performance, especially in the far-IR atmospheric window range of 8–14 μm.[1,2,6,7] Dark current at a high temperature is the main hindrance to high-temperature QDIP operation. Several QDIP designs, e.g., utilization of AlGaAs barrier layers within QDIPs,[8] use of InGaAs capping in the active region,[9] dot-in-a-well (DWELL) QDIP structures,[10] introduction of short (typically 10 Å) AlGaAs barriers between DWELL absorbers,[11,12] and tunneling QDIP structures,[13,14] have been proposed as means to minimize the dark current level in a device. However, the device performance levels of the available IR photodetectors are still inadequate. Therefore, QDIP devices with enhanced detectivity that work at high temperatures and within a broad spectral range (8–14 μm) are of interest.

To obtain a QDIP with a dark current level that is as small as possible to enhance detectivity, we developed an uncoupled InGaAs/GaAs QD heterostructure in which the dots were capped with a relatively thick combination barrier comprising a 30-Å layer of quaternary $In_{0.21}Al_{0.21}Ga_{0.58}As$ and a 500-Å layer of GaAs. This thick barrier is incorporated in the QD heterostructure in order to check carrier tunneling in adjacent dot layers at high temperature and a concurrent lowering of the dark current level.[15] It has been reported that by increasing the thickness of the active region with appropriate spacer layers, the thermionic emission and tunneling contributions to the dark current can be reduced.[16] In the present study, the heterostructure was grown by using molecular beam epitaxy (MBE) technology in the n-i(QD)-n configuration on a semi-insulating ⟨001⟩ GaAs substrate. Both the QD layer and the combination capping were repeated 35 times (Fig. 1 inset).

The technological significance of using an InAlGaAs cap in these structures is that it acts as a surface strain-driven phase-separation alloy that is activated by surface-strain modulation across the InAs QD layer.[17–19] As the QDs are covered by the quaternary cap, the In adatoms from the alloy migrate toward the relaxed dots, resulting in a compositional In gradient across the periphery of the islands. This gradient prevents intermixing of the QDs and the barrier material during MBE growth, thereby preserving the shape of the QDs. However, phase separation in the quaternary InAlGaAs cap leads to alloy clustering and compositional modulation in the layers,[20] which may drastically degrade the growth front for subsequent QD layers and lead to homogeneous strain[21] in the structures during the growth process. Overall strain in the structures restricts the possible number of dot layers in a multilayer structure; hence, combination capping was chosen. In such capping, the subsequent overgrowth of the quaternary alloy with a high temperature-grown GaAs layer helps to planarize the growth front for the next QD layer due to increased Ga mobility at elevated temperatures.[22] Note that quaternary cap composition is chosen so that it is perfectly lattice-matched with the GaAs, according to Vegard's law[23,24] and has a similar band-gap energy. Thus, a drawback of the dot-in-a-well approach[9] is avoided with the structure.

Here, we demonstrate that a device with a thick combination barrier has a substantially higher performance in terms of responsivity (2.16 A/W) and detectivity (1.01×10^{11} cm $Hz^{1/2}$/W at 0.3 V) around 10 μm and has a low dark current

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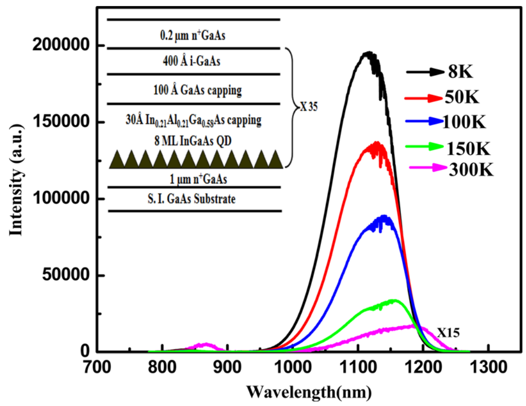

FIG. 1. (Color online) Photoluminescence spectra of the heterostructure (inset shows the schematic) recorded at temperatures ranging from 8 to 300 K.

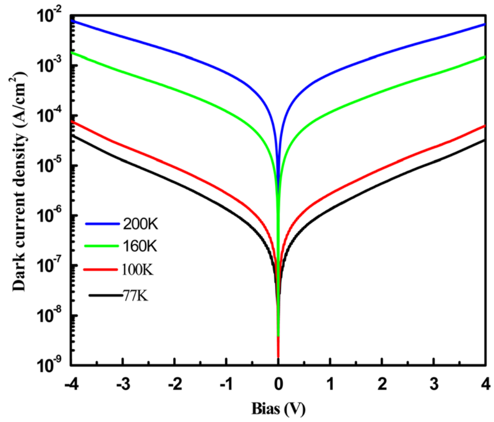

FIG. 3. (Color online) Variation of dark current density as a function of bias at temperatures ranging from 77 to 200 K.

density in the order of 1.36×10^{-6} A/cm^2 at 77 K and at 1 V bias. Further, the combination capping helps to maintain the structural parameters of QDs.[18] In existing QDIPs consisting of self-organized QDs, the structural parameters are believed to be less than optimum due to intermixing during the growth of the barrier layers, thus leading to low detectivity.

The QD profile of our heterostructure was confirmed by using cross-sectional transmission electron microscopy (XTEM); an example image is presented in Fig. 2. There was no evidence of defects or dislocations in the heterostructure. The results indicate that our process for producing a heterostructure with a thick combination cap allows the stacking of 35 layers of uncoupled active QDs without producing defects; the absence of defects helps to enhance responsivity. To determine the optical quality of the material, temperature-dependent photoluminescence (PL) measurement was performed by using a 405-nm excitation wavelength under 40 mW of power. The signal was dispersed by a 0.75-nm monochromator and detected using liquid nitrogen-cooled InGaAs array detectors. In Fig. 1, an intense PL peak from the sample is observed in the 1.12 μm range at 8 K. The persistence of PL emission from the sample until $\sim$150 K indicates the low density of defects in the heterostructure. The full width half maximum (FWHM) of the emission peak at 150 K is $\sim$40 nm. A room temperature (300 K) emission peak from the heterostructure is also shown in Fig. 1.

To test QDIP performance, 0.4×0.4 mm detector test mesas were fabricated. A typical Au/Ge/Ni/Au stack was used for creating an ohmic contact. The fabricated device was then bonded to a leadless chip carrier and mounted on the cold head of a liquid nitrogen cooled cryostat for performance measurement.

The QDIP dark current level determines the maximum operating temperature of the device because thermal effects create a large increase in dark current. The dark current voltage at different temperatures (77 K to 200 K) was measured by using a semiconductor parameter analyzer (HP 4145). The device's current density as a function of bias is shown in Fig. 3. The symmetry in the current-voltage curve, for both positive and negative bias, indicates the uniformities in the structural parameters of the QDs. The symmetry in the dark current characteristic also indicates that the effect of the asymmetric position of the InAlGaAs barrier in the device structure is minimal, confirming our claim that the specific composition of the quaternary alloy has a similar band-gap energy as that of GaAs. Usually, the major contributor to dark current is the tunneling current rather than the thermionic emission current, at temperatures below 200 K. Current tunneling has been minimized in our heterostructures by the use of uncoupled QDs with a thick combination cap. Hence, the dark current density is significantly low (1.36×10^{-6} A/cm^2 at 77 K and 6.92×10^{-4} A/cm^2 at 200 K, both at 1 V) in our heterostructures.

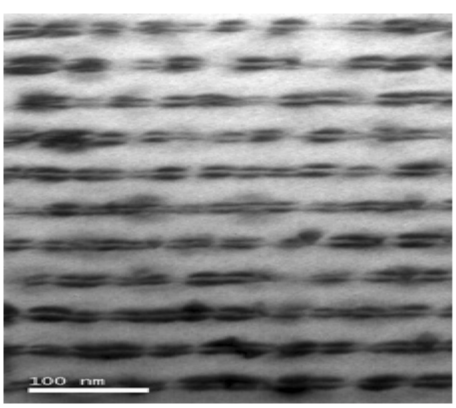

FIG. 2. XTEM image of the 35-layer InGaAs/GaAs QDs showing a defect-free structure.

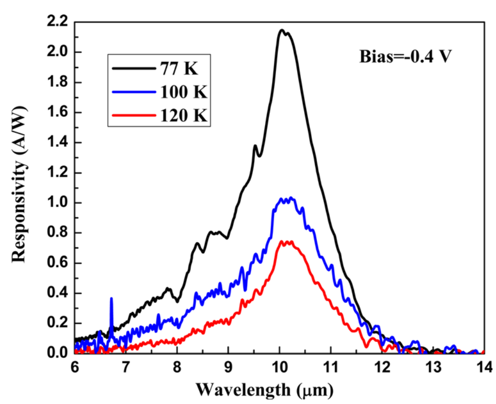

FIG. 4. (Color online) Temperature-dependent response of the 35-layer InGaAs/GaAs QDIP with quaternary capping.

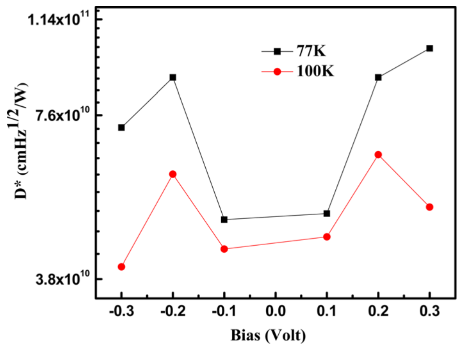

FIG. 5. (Color online) Specific detectivity of the quaternary capped QDIP as a function of bias.

The spectral responses at several temperatures and applied biases were measured with a Fourier transform infrared spectrometer using a glow bar source. Peak responsivity and detectivity measurements were conducted by using a 900 K calibrated black body source. The peak response at $\sim$10.2 μm, a desirable wavelength for advanced IR detectors, for our quaternary capped QD device can be seen in the photo-response spectra in Fig. 4. The high-intensity response observed at 10.2 μm is probably due to the bound-to-bound transition of carriers in the QDs.[25] Interestingly, the FWHM is narrow, corresponding to the 10.2-μm peak. The spectral width ($\Delta\lambda/\lambda$) value is 0.14 for this peak (where $\Delta\lambda$ is the FWHM of the peak). The narrow spectral width clarify bound-to-bound transition within the QDs. It also suggests uniformity in the QD structural parameters, as discussed above. We believe the weaker photo-response at 8.5 μm is due to the transition of electrons from the ground state of the InGaAs QDs to the wetting layer of the QDs.[25] Further, the responsivity at 10.2 μm decreases with increasing temperature. This is because the excited states become more populated. In addition, the intra-band transition rate decreases with increasing temperature. It can also be attributed to the short carrier lifetimes at high temperatures. The peak responsivity at 10.2 μm is comparably high (2.16 A/W at a -0.40 V bias). Moreover, the results shown in Fig. 5 indicate that the responsivities of the 8.5 and 10.2 μm peaks are sufficiently high for efficient application in focal plane arrays.

The highest specific detectivity (D*) value for the QDIP structure, which indicates the signal-to-noise ratio of the device, is 1.01×10^{11} cm Hz$^{1/2}$/W at 77 K at a 0.3 V bias (Fig. 5). Fig. 5 also shows that the 100 K detectivity of the device at a 0.20 V bias is quite high (6.4×10^{10} cm Hz$^{1/2}$/W), indicating the significance of the device structure for operation at high temperatures. Low detectivity values in QDIPs are mainly due to the high dark current, which in our heterostructure is alleviated by introducing a thick barrier layer.

In summary, we report a 35-layer InGaAs/GaAs QDIP with a combined quaternary $In_{0.21}Al_{0.21}Ga_{0.58}As$ and GaAs capping that responds in the LWIR (8–14 μm) region and that has state-of-the-art responsivity (2.16 A/W) and detectivity (1.01×10^{11} cm Hz$^{1/2}$/W). By using thick combination capping, we designed a defect-free heterostructure of uncoupled QDs, a structure in which the tunneling contribution to the dark current is minimal. We presume that strain-driven phase separation of In from the quaternary InAlGaAs cap helps to maintain the uniform structural parameters of the QDs in the QDIP, by stopping barrier material diffusion across the dots. Photo-response results showed two-color (8.5 and 10.2 μm) performance of the QDIP heterostructure, justifying its use in advanced sensing and imaging applications. Hence, a combination of quaternary and GaAs layer barrier for the InGaAs QD layer in the active region of QDIPs can be effective for suppression of the dark current, allowing high-temperature operation and enhancement of both photo-response and detectivity.

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