Doping effect on dark currents in In 0.5 Ga 0.5 As Ga As quantum dot infrared photodetectors grown by metal-organic chemical vapor deposition

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Doping effect on dark currents in $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$ quantum dot infrared photodetectors grown by metal-organic chemical vapor deposition

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Stacked self-assembled $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$ quantum dot infrared photodetectors grown by low-pressure metal-organic chemical vapor deposition, with and without silicon dopants in the quantum dot layers, are investigated. The increase of dark currents observed at higher doping levels is attributed to higher defect density leading to stronger sequential resonant tunneling and to lowering of the operating temperature of the device. © 2006 American Institute of Physics. [DOI: 10.1063/1.2354432]

Infrared detectors are important for the variety of applications, including night vision, targeting and tracking, medical diagnosis, environmental monitoring, and space science. Quantum dot infrared photodetectors (QDIPs) have attracted intense interest recently, and devices operating at mid-wavelength-infrared ($3\text{--}5\ \mu\text{m}$) and long-wavelength-infrared ($8\text{--}14\ \mu\text{m}$) ranges were demonstrated.^{1–4} QDIP technology promises improved performance compared with the quantum well infrared detectors due to the possibility of normal incidence operation, lower dark currents, expected higher responsivity and detectivity due to suppressed electron-phonon scattering and higher operating temperatures. The models developed by Ryzhii,⁵ Phillips,⁶ and recently adjusted for contributions of field-assisted tunneling currents by Stiff-Roberts *et al.*⁷ can be used to calculate the dark current, photocurrent, responsivity, and detectivity as a function of structural parameters of QDIPs with relatively good experimental agreement. They predict that an increase of electron sheet density (achievable by intentional doping of QDs) increases the QDIP's photoresponse, but at a cost of increased dark current and lower detectivity.

Recently QDIPs with detectivities D^* as high as $3 \times 10^{11}\ \text{cm Hz}^{1/2}/\text{W}$ at 78 K (Ref. 8) and $10^{11}\ \text{cm Hz}^{1/2}/\text{W}$ at 100 K (Ref. 9) were reported. Interestingly such an excellent performance was achieved for both classes of QDIPs: based on undoped multiple QD *n-i-n* (Ref. 8) and intentionally Si-doped QD (Ref. 9) structures, both grown by molecular beam epitaxy. It suggests that satisfactory performance can be expected both for doped and undoped QD based devices provided that accurate control over the size and density of self-assembled QDs and structural and electrical uniformities of barrier layers is maintained. It also requires achieving very low growth defect densities. Very few reports regarding metal-organic chemical vapor deposition (MOCVD) grown QDIPs exist in the literature,^{10,11} and there has been no systematic study of doping effect on dark current characteristics for these detectors. In this letter, such dark current characteristics and their temperature dependence for ten-layer $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$ QDIP structures, at various QD doping levels, grown by low pressure MOCVD at the Australian

National University are presented and discussed.

We examined the following QDIP structures: a *n-i-n* structure^{12,13} with undoped QDs (sample A) and two structures with Si doping in the dot layers of $3.0 \times 10^{17}\ \text{cm}^{-3}$ (sample B) and $6.0 \times 10^{17}\ \text{cm}^{-3}$ (sample C), respectively, grown on a semi-insulating GaAs (001) substrate by MOCVD. Each structure contained ten layers of QDs formed by depositing 5.7 ML of undoped or intentionally Si-doped $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$, as noted previously. The resulted dots had average density of $6 \times 10^{10}\ \text{cm}^{-2}$ and average height and width of 3.1 and 18.9 nm, respectively. QD layers were separated by 50 nm GaAs barriers and sandwiched between two highly Si-doped top (300 nm) and bottom (1000 nm) contact layers. The standard photolithography technique was used to define $250 \times 250\ \mu\text{m}^2$ QDIP mesa structures. The MOCVD growth parameters, mesa fabrication, and some of the performance characteristics of *n-i-n* QDIP structure with detectivity as high as $1.2 \times 10^9\ \text{cm Hz}^{1/2}/\text{W}$ at 77 K were reported previously.¹⁴ The fabrication and growth procedures performed in this work were identical, apart from the doping levels for the QD layers. The devices were mounted on the cold finger of a 10 K CTI-Cryogenics cryostat system and the dark-current-voltage characteristics of the QDIPs were measured using an HP4145A semiconductor parameter analyzer.

Figure 1 shows the dark current of sample A with undoped QD region for various temperatures in the range from 14 K to room temperature, where forward bias denotes that the top contact of the device is biased positively. At a bias of 0.1 V, dark current increased over seven orders of magnitude from $1.7 \times 10^{-11}\ \text{A}$ at 14 K to $1.9 \times 10^{-4}\ \text{A}$ at 296 K. The characteristics for forward and reverse biases are slightly asymmetric up to 50 K and at high temperature ranges. In the high temperature range, this effect is caused by the non-symmetrical carrier injection from the bottom and top contact layers in different current directions due to the asymmetry of the device. Figure 2 shows Arrhenius plots of the dark current for various applied reverse and forward biases in the range of 0–0.5 V for sample A. We found that the current decreased exponentially with temperature and in this voltage range the characteristics show a high level of symmetry and they overlap for positive and negative applied biases. Within

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FIG. 1. I - V dark current characteristic as a function of temperature for ten-stack $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$ QDIPs grown by low pressure MOCVD (sample A).

the investigated temperature range, the curves exhibit three different regions suggesting that the dark current in each of these regions is governed by different mechanisms. Similar behavior has been experimentally observed in InAs/GaAs QDIPs (Ref. 15) and explained by the model proposed by Stiff-Roberts *et al.*⁷ In their model the high temperature range (>125 K) is ascribed to the thermally limited region through thermionic emission and field assisted tunneling and the lower temperature region (<125 K) to a defect-limited region through sequential resonant tunneling (SRT). The third, low temperature region (<50 K) shows very weak temperature dependence, with dark current limited by reduced conductivity due to impurity scattering. Activation energies in the region dominated by SRT of sample A as a function of applied bias are shown in Fig. 3. The activation energy at zero bias is about 170 meV and very slightly increases to a maximum of 173.4 meV at 0.4 V, and then almost linearly decreases to about 55 meV at 2.9 V. The origin of the SRT in QDIPs is not clear, and various mechanisms have been proposed. In the insert of this graph a schematic of the current flow mechanism discussed by Duboz *et al.*¹⁵ (a) and Stiff-Roberts *et al.*⁷ (b) are shown. According to the first mechanism electrons are thermally excited to a QD level at the same energy as the wetting layer of the next period and

FIG. 2. Arrhenius plots at various applied biases for undoped QDIPs (sample A).

FIG. 3. Calculated activation energies as a function of applied bias for sample A at 70 K. The insert shows graphs of tunneling current mechanisms discussed in text.

then tunnel out. As the density of QD levels is discrete, the activation energy should vary with bias in a steplike fashion, but the QD nonuniformity smoothes this variation. Other mechanisms, such as direct tunneling from QD states to QD states of the next period, are probably in this case negligible as with relatively thick 50 nm barrier layers the vertical alignment is not observed, but defect-assisted tunneling¹⁶ [shown as insert (b)] is expected to be dominant, especially for the MOCVD growth method. Figure 4 shows a comparison of dark currents at 70 K (a), Arrhenius plots (b), and calculated activation energy values (c) for samples A, B, and C. Both doped QDIP structures (samples B and C) show a dramatic increase in dark current in comparison with undoped QD sample (sample A). At 70 K and applied bias of 0.1 V, dark current increases from 7.6×10^{-11} A for sample A to 1.4×10^{-5} and 7.4×10^{-5} A for samples B and C, respectively. The I - V characteristics for sample A are almost symmetric, but for both doped samples B and C the dark currents at forward bias are about 40% higher than at reverse bias. The same effect has been observed in Refs. 15 and 17 and interpreted by the asymmetry of the device discussed previously, which for doped samples becomes apparent at much lower temperatures than for undoped samples. Only in Ref. 18 the QDIP structures with higher doping levels and at negative biases have shown lower dark currents than their undoped counterparts. To explain this asymmetry the authors noted that the Si dopants in the InAs wetting layer of intentionally doped QDs provide free carriers to fill the InAs QDs, where the Si dopants in the QDs are mostly neutral because the second energy levels of QDs were ~ 30 meV below the Fermi level. This assumption was based on the observed higher activation energy for doped QD samples. Thus the ionized donor source in the wetting layer created a slightly asymmetric potential in the QDIP, which favored the negative bias. As a result higher responsivity was observed for reverse than forward biases, which is in contradiction to our results.

The onset of SRT region, discussed previously, shifts to lower temperatures with an increase in intentional doping level of QDs, as seen in Arrhenius plots of Fig. 4(b), and its contribution to dark current is dominant in the temperature range of ~ 70 – 130 K for sample A, ~ 40 – 90 K for sample B, and ~ 30 – 80 K for sample C, respectively. Figure 4(c)

FIG. 4. Comparison of dark current characteristics and activation energies for samples A (undoped QDs), B (QDs with Si-doping level of $3.0 \times 10^{17} \text{ cm}^{-3}$), and C (QDs with Si-doping level of $6.0 \times 10^{17} \text{ cm}^{-3}$) all taken at 70 K. (a) I - V characteristics, (b) Arrhenius plots for 0.1 V applied bias voltage, and (c) calculated activation energies as a function of applied bias voltage.

shows activation energies as a function of applied bias calculated for linear range of Arrhenius plots shown in Fig. 4(b). For all the samples the activation energy decreases with the applied bias. As the doping level in QDs increases the activation energy decreases, which is in contradiction with the previously discussed Ref. 18 but in agreement with Ref. 15. Its value is changing from 173 to 55 meV for sample A, and for samples B and C from 70 and 62 meV to almost zero, respectively, as the applied bias is changing from 0 to 3 V. Interestingly the activation energy of undoped QDIP sample (sample A) shows a maximum at $\pm 0.4 \text{ V}$ applied bias, which is in agreement with the optimum applied voltage for the highest measured detectivity for this structure,¹⁴ as expected. The activation energy curve for sample A is mostly symmetric for forward and reverse bi-

ases, but for samples B and C slightly higher activation energies are maintained for reverse biases in the entire measurement range [see insert Fig. 4(c)]. We believe that this asymmetry is caused by the differences in carrier injection from the bottom and contact layers in different current directions. With the depletion of electrons from QDs, the electrons from contact layer become a dominant factor to influence the dark current. Under positive bias, more electrons are injected from the bottom contact layer to the top contact layer because of the higher sheet electron density of the bottom contact layer, and thus the activation energy is lower for the forward than reverse biases.

In conclusion, we have examined dark current characteristics and their temperature dependence for ten-layer $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$ QDIP structures, at various QD doping levels, up to $6.0 \times 10^{17} \text{ cm}^{-3}$, grown by low pressure MOCVD. Lower, symmetric dark currents and higher activation energies for undoped, MOCVD grown QDIP structures are observed. Defect-induced sequential resonant tunneling due to significant level of growth defects in Si-doped QD samples is shown to dominate their behavior leading to limited operational temperature range of these detectors.

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