In(Ga)As Quantum Rings for Terahertz Detectors

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The In(Ga)As quantum ring infrared photodetector (QRIP) were investigated. The quantum ring (QR) is transformed from 500 °C grown 2.2 ML quantum dot (QD) with QD annealing time ~30 s. The QRs show the broad PL spectrum which is blue shifted from QD about 100 meV. The resultant QRIP is a broadband terahertz detector. The response extends from 3 to 100 THz with peak responsivity of 127 mA/W at 23 μm which has a spectral detectivity of $2.3 \times 10^{11} \text{ cm Hz}^{1/2}/\text{W}$ at 10 K under 1.2 V bias. [DOI: 10.1143/JJAP.47.2924]

KEYWORDS: terahertz detector, quantum dots, quantum rings, far-infrared

Terahertz (THz) radiation covers a broad frequency range from 100 GHz to 40 THz. It can be applied in the areas of imaging, communication, medical diagnosis, environmental control, health monitoring and biochemical identification.^{1–4)} There are few suitable detectors operating in this frequency range. Typical quantum well (QW) detectors using AlGaAs/GaAs heterojunction structures with critical Al fractions are not suitable for normal-incidence and high-temperature operations.^{5–7)} Recently, the InAs/GaAs quantum dot infrared photodetector (QDIP) has demonstrated its operability in the far-infrared (FIR) region.^{8,9)} However, the cutoff frequency is limited to less than 40 μm . During the growth of an InAs/GaAs quantum dot (QD), it is difficult to control the InAs dot size to a small value uniformly; hence, it is difficult to achieve a small confined-to-conduction band transition. The growth of an InAs/GaAs quantum ring (QR) is similar to that of QD.^{10–13)} The small confined QR structure is suitable for the requirement. A 2 nm GaAs-capped layer was deposited, surrounding the InAs QDs, and the sample was annealed at a higher temperature to evaporate the central uncovered InAs dot, as shown in Fig. 1. Finally, the edge of the embedded InAs dot and the GaAs capped layer are mixed together to form an In(Ga)As ring structure. The confinement of QR is limited by the capped layer thickness. Therefore, In(Ga)As provides smaller confined-to-conduction band transitions that can be applied to detectors in the FIR range. This structure combines the advantages of QWs and QDs in terms of size controllability and normal incidence availability. In this work, we fabricated a broadband QR terahertz detector. The response was extended from 3 to 100 THz which has a peak spectral responsivity of 127 mA/W at 13 THz under 1.2 V bias.

In(Ga)As QRs were grown by molecular beam epitaxy (MBE) using the Stranski–Krastanov growth mode. Self-assembled 2.2 ML InAs QDs were first grown on a GaAs substrate and covered by a 2 nm GaAs partial capping layer and then annealed for 30 s at 500 °C.^{14–16)} The original QDs had an average height of 8 nm. The 2 nm GaAs layer was insufficient to cover entire dot only the hillside of the dot, hence the central dot was exposed to As₂ vapor. This satisfies the conditions for transformation into QR.¹⁷⁾ The atomic force microscopy (AFM) image of the QR is shown in Fig. 2(a). It has a depth of 1.1 nm and an inner diameter of 10 nm. The cross-sectional transmission electron microscopy

Fig. 1. (Color online) Schematic band structure of QR showing the lower energy transition as compared to that of a precursor QD.

(XTEM) shows the In(Ga)As QR region [Fig. 2(b)]. It demonstrates that the ring region between the outer and inner diameters is narrower than normal QD that provides a smaller confined region than QD does. The center has exuded and the In(Ga)As region surround it remains small. It has been proved that the longer QD annealing time leads to larger strain relief in the higher aspect ratio QDs.¹⁸⁾ The same 2 nm thick GaAs capped layer on QDs results in different InAs buried regions. The small QD has the larger buried region and the high aspect ratio QD has the less. After out diffusion of InAs from central part of QD, the QR is formed. The In(Ga)As ring is smaller in size when QD has high aspect ratio. The higher aspect ratio dot results in a smaller confined ring. The PL spectra of QR and its precursor QD were measured. The PL peak wavelengths show a large blue-shifted from QD to QR, hence, the bandgap of QR is larger and the band discontinuity Δ_{QR} is smaller as shown in Fig. 1. Our device is applied to the quantum structure to replace the intrinsic layer of the typical QDIP n–i–n structure. The ten periods of QR are embedded in the 50 nm undoped GaAs barrier within the 500 nm top and 1 μm bottom contact layers sandwiching it. The schematic of the detector structure is shown in Fig. 2(c).

The detector with an area of $150 \times 150 \mu\text{m}^2$ is fabricated after the above two-step process. The device is measured under an edge coupling scheme with a cryostat. The temperature-dependent dark and ambient background irradiation current–voltage characteristics are measured using by HP 4156B precision semiconductor parameter analyzer. At a lower temperature of 20 K, dark current is restrained

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Fig. 2. (Color online) (a) Three-dimensional AFM image of a single QR. (b) XTEM image of QR. (c) Schematic device structure with self-organized In(Ga)As quantum rings.

Fig. 3. Dark current as functions of applied voltage of the detector from 10 to 80 K. The bold curve represents photocurrents measured at 10 K when the device is illuminated from ambient background radiation through the cryostat window.

Fig. 4. Experimental responsivity spectra obtained under a bias of 1.2 V at 10 K. The inset is the MIR responsivity.

under 2.3×10^{-10} A. The BLIP temperature of the detector is 40 K, as shown in Fig. 3. The real operating temperature can reach 80 K.

Detectivity is the signal-to-noise ratio (SNR). A more useful figure of merit is the normalized detectivity D^* , which normalizes the detector area and band width.

$$D^* = \frac{R_p \sqrt{A_d \Delta f}}{i_n}, \quad (1)$$

where R_p is the responsivity of the detector, A_d is the area of the detector, Δf is the bandwidth of the measurement, and i_n is the noise current which is supposed to be the shot noise and can be expressed as

$$i_n = \sqrt{4eI_d g_n \Delta f}, \quad (2)$$

where I_d is the average dark current and g_n is the noise gain, which is proportional to the photoconductive gain g .

The advantage of D^* as a figure of merit is that it is normalized to an active detector area of 1 cm^2 and a noise

bandwidth of 1 Hz. The responsivity of the device was measured under a 45° -edge-coupling scheme with closed-cycle cryogenics and Bruker IFS 66v/s Fourier transform infrared spectroscopy (FTIR). The detector was attached to the closed-cycle cryostat system with a copper adhesive tape. The mid-infrared (MIR) and FIR radiations were illuminated on the detector to excite photoelectrons. Current was then transferred to voltage using a SRS Model SR-570 current preamplifier. Finally, the voltage signal was transported back to FTIR. The spectral responsivity of the QR detector was measured from 100 to 3 THz and a high detectivity of $2.3 \times 10^{11} \text{ cm Hz}^{1/2}/\text{W}$ was obtained at a peak wavelength of $21 \mu\text{m}$, 10 K and 1.2 V bias. The peak responsivity is observed at 127 mA/W, as shown in Fig. 4. Therefore, a prototype of terahertz photodetector is demonstrated by In(Ga)As QR with band gap tailorable property, this is a promising structure to replace the QD and the photoresponse of the detector can be extended to THz range.

The normal incidence and broadband terahertz detector was fabricated using In(Ga)As quantum rings. The cutoff response can be operated up to 3 THz (100 μ m) at 10 K. Moreover, the quantum ring THz detector has the potential for tailoring its cutoff frequency by adjusting the thin GaAs capped layer.

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