Effect of Well Width on Three-Color Quantum Dots-in-a-Well Infrared Detectors

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***Abstract*—Three-color InAs–InGaAs quantum dots-in-a-well (DWELL) detectors having different well sizes are presented. Three DWELL detectors (1388, 1373, and 1299) with different quantum well (QW) widths (120, 110, and 90 Å, respectively) have been characterized showing response peaks at three distinct wavelengths. The detector 1388 has peak wavelengths at ∼6.25, ∼10.5, and ∼23.3 μm. The two peaks at 6.25 and 10.5 μm are believed to be due to bound-to-bound transitions from the ground state in the dot to a state in the well, whereas the longer wavelength peak (∼23.3 μm) which has a detectivity of 7.9×10^{10} cm $\cdot \sqrt{\mathrm{Hz}}/\mathrm{W}$ at 4.6 K under -2.2-V bias is due to an intersubband transition between the dot levels. The operating wavelength of these detectors in the short wavelength region can be tailored by changing the width of the QW. Spectral responsivity curves of 1373 and 1299 show a shift of the short wavelength peaks toward decreasing wavelength while the long wavelength peak remains around ∼23.3 μm confirming that the particular transition is due to the quantum dot.**

***Index Terms*—Infrared detectors, quantum dot (QD), quantum well (QW), three color.**

I. Introduction

QUANTUM dot infrared photodetector (QDIP) research has attracted much attention for midwave and long-wave infrared applications [1]–[4] during past few years. Several research groups have already demonstrated the intersubband transitions in midinfrared (MIR) and far-infrared (FIR) QDIPs [5]. Recently, we have reported a three-color quantum dots-in-a-well (DWELL) infrared photodetector [6] with peak wavelengths at 3.8, 8.5, and 23.3 μm. Owing to the three-dimensional confinement of carriers, QDIPs are sensitive to normal-incidence infrared radiation, which is forbidden in n-type quantum well infrared photodetectors (QWIPs). In addition, QDIPs are expected to show improved performance characteristics such as low dark current and higher operating temperatures [7].

The authors of [6] have recently reported intersubband detectors in which the InAs dots are placed in a thin InGaAs quantum well (QW), which in turn is positioned in a GaAs matrix [4]. Such a heterostructure is known as the DWELL design. DWELL heterostructure provides a better confinement for carriers trapped in the quantum dot (QD) by lowering the ground state of the dot with respect to the GaAs band edge resulting in low thermionic emission. In this letter, the experimental results on three-color detector structures with different QW widths are reported discussing the transitions leading to each peak.

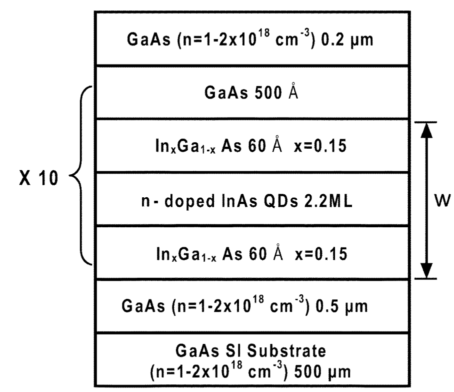

Fig. 1. Schematics of the DWELL detector structure. The width of the QW, i.e., the width of $In_xGa_{1-x}As$ with $x = 0.15$ layer (indicated as w in the figure), is different for each detector.

II. Device Structure and Experiment

The structures were grown by molecular beam epitaxy with the details of the growth described elsewhere [8]. Using standard lithography, metal evaporation, and wet etching, n-i-n detectors were fabricated for top-side illumination with the diameter of the illuminated area ranging from 25 to 300 μm. The detector structure of 1388 is shown in Fig. 1. The other two detectors have the same structure but different thickness of InGaAs well in order to have different well widths. There are ten layers of n-doped InAs–$In_{0.15}Ga_{0.85}As$ in each of the detector structures. The QDs are directly doped n-type using silicon as the dopant to a sheet density of 5×10^{11} cm^{-2}, which translates to about one electron per dot, while the QW is unintentionally doped. A window is opened on top of the structure and mesa with 300-μm diameter was used for spectral measurements. From photoluminescence (PL) measurements of the ground state transition of the dot (1.25 μm at $T = 300$ K) and using a $60:40$ conduction band : valence band ratio, it is estimated that the ground state of the dot is about 250 meV below the GaAs band edge. We believe that there are at least two bound states in the dot and one confined state in the QW [6].

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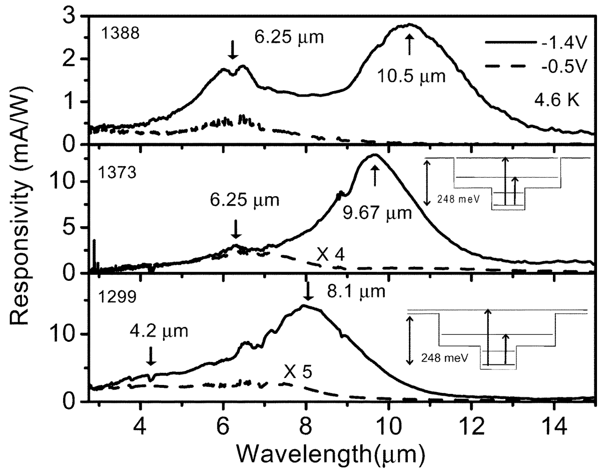

Fig. 2. First two peaks of the three detectors biased with −1.4 and −0.5 V at 4.6 K. The band diagram showing the transitions leading to each peak is given in the inset and the transition states for 1388 are same as 1373. Arrows indicate the peak positions and × sign implies that the curve has been multiplied by the number indicated.

III. Results and Discussion

The main goal of this letter is to identify and confirm the transitions leading to each of the peaks of DWELL detectors reported. The spectral response of the three detectors in the range 3–15 μm is shown in Fig. 2. The two curves for each detector in the figure are for two different bias values (−0.5 and −1.4 V). The two distinct peaks in MIR region are believed to be due to transitions from the ground state in the dot to a state in the well. The sample 1299 exhibits its first peak at ∼4.2 μm and the second peak at ∼8.1 μm. A semiempirical estimate, based on the PL spectra with a 60 : 40 split of the bandgap difference, gives the energy separation between the ground state of the dot and conduction band edge of GaAs to be 225–250 meV (∼4.9–5.5 μm). Hence, the 4.2-μm peak is probably due to transitions from the ground state of the dot to the continuum state of the well and the second peak should be due to transitions from the ground state of the dot to a bound state in the well as shown in the inset to Fig. 2. Moreover, it has been shown [9] that the line width $(\triangle\lambda/\lambda)$ of a QW detector transitions from bound-to-bound states is narrower than that of transitions from bound-to-continuum states. The line width of 4.2-μm peak is about 42%, whereas, the line width of 8.1-μm peak is about 28%, and this observation is consistent with the above description. The photocurrent is proportional to the product of the oscillator strength and the escape probability. For the bound-to-bound peak, the oscillator strength is larger, whereas, the escape probability is smaller, and for the bound-to-continuum peak, the oscillator strength is smaller, whereas, the escape probability is larger. Hence, the bound-to-continuum peak is seen even at lower biases, whereas, the bound-to-bound peak dominates at larger biases, where field assisted tunneling increases the escape probability.

When the width of the QW is increased, the energy spacing between the levels in the well decreases causing the second MIR peak to red-shift since it is connected to transitions from the dot to well bound state. The results of 1388 detector agrees well with this idea. In addition to that, the continuum state in 1299 could become quasi-bound state in 1388 since the 1388 detector is made by stretching the well of 1299. Then the first peak of 1388 is due to transitions from the ground state of the dot to a quasi-bound state in the well. This can be confirmed by the red-shift of the first peak of 1388 and the narrower line width compared with 1299. As designed, the first peak of 1373 is expected in between the first peak of 1299 and 1388. However, it is almost at the same position of the first peak of 1388 and the second peak of 1373 is closer to that of 1388 than expected. This could be explained if the size of the QD was unintentionally changed during the growth process. Based on doping concentration and sheet density of dots, it has been found that a single dot consists of one electron [4]. Multiple electrons within a dot could lead to a splitting of photoresponse peaks due to intralevel and interlevel Coulomb interactions [10]. Therefore, the tiny peaks upon the major peaks may be due to either different dot sizes in the same DWELL structure or Coulomb interactions due to multiple electrons in the dot. The expected red-shift due to Coulomb interaction with applied electric field could be compensated by the blue-shift due to Stark effect [10].

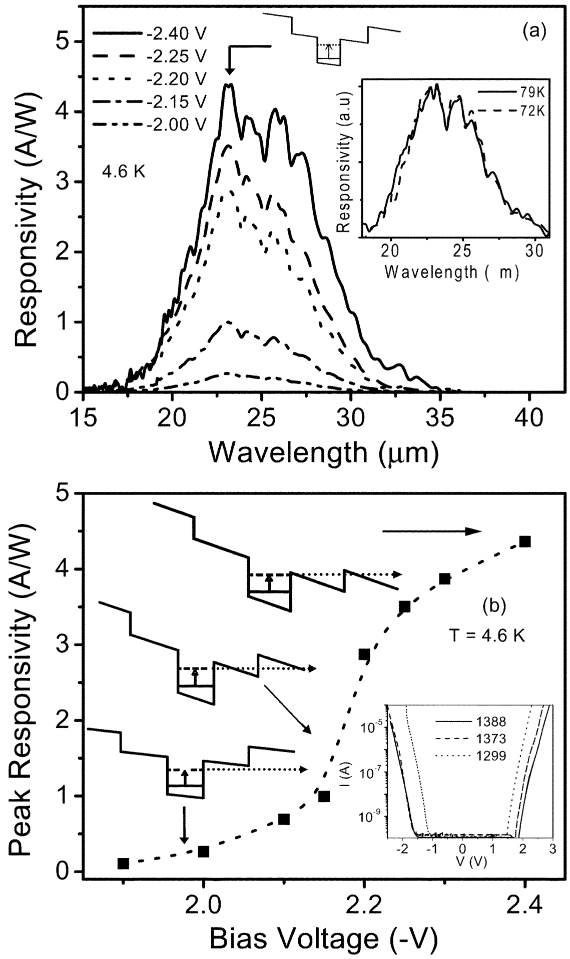

Fig. 3. (a) FIR response of 1388 at different bias values (negative indicates that the top contact is negative). The band diagram represents the transition leading to the response. The inset shows the responsivity at high temperature (72 K, 79 K). (b) Variation of the peak responsivity of 1388 detector with applied bias and the corresponding transition between the states in the dot with bias. The inset represents the current–voltage at 4.6 K.

The spectral responsivity of the third peak of 1388 in FIR region under different applied bias fields is shown in Fig. 3(a). From eight-band k.p. modeling [11], it is found that the energy separation between the states in the QDs with base diameter of

TABLE I
RESPONSIVITY AND DETECTIVITY OF EACH PEAK OF SAMPLE 1299, 1373, AND 1388 AT 4.6 K WITH −1.4-V BIAS (∼−22.5 kVcm^{-1} FIELD)

Sample Number	Well Width (Å)	λ_{peak} (μm)	Responsivity (mA/W)	Detectivity ($cm\sqrt{Hz}/W$)
1299	90	4.2	3.9	1.1×10^9
		8.1	14.0	3.9×10^9
		23.3	60.2	1.9×10^{10}
1373	110	6.25	3.0	5.4×10^9
		9.7	12.9	2.3×10^{10}
		25.5	3.8	6.9×10^9
1388	120	6.25	1.8	6.2×10^9
		10.5	2.8	1.7×10^{10}
		23.3	25.6	6.6×10^{10}

20 nm and 7–8 nm of height is about 50–60 meV. Hence, it is believed that the FIR peak at ∼23.3 μm is due to transitions between two bound states in the dot. The variation of the peak responsivity of 23.3-μm peak with the bias voltage is given in Fig. 3(b). As shown in energy band diagrams, at high fields, the barrier is pulled strongly down so that excited carriers have to tunnel through only a thin region. This would increase the escape probability. As a result, the experimental response curves show a drastic increase in the response when the bias is increased from −1.0 to −2.4 V. Moreover, the FIR peak is broader than a peak leading to bound-to-bound transitions possibly due to the 10% size fluctuations of the dots in the self assembly process. This is also reflected in the broader PL line width of QDs compared to that of the QWs.

Detector results for the three peaks of three detectors at 4.6 K with −1.4-V bias and the well width for each are given in Table I. The bias and temperature were chosen to report the optimum detectivity for all three samples. All but the FIR peak of 1373 were observed up to 80 K while the FIR peak of 1373 could be obtained up to 60 K. Among all these detectors, the highest detectivity of $\sim 7.9 \times 10^{10}$ cm $\cdot \sqrt{\text{Hz}}$/W at 4.6 K under −2.2-V bias and 3.2×10^8 cm $\cdot \sqrt{\text{Hz}}$/W at 80 K under −1.4-V bias was reported for 1388 at 23.3- μm wavelength. The detector 1388 shows higher detectivity compared to 1299 at 25 μm even with lower responsivity due to lower noise current than 1299 detector, under the given conditions (dark current curves at 4.6 K are given in the inset to Fig. 3(b) and the variation at 80 K is same as at 4.6 K). The improvement in the operating temperature of FIR response (up to 80 K), compared with a typical FIR QWIP [12] operating at ∼10–20 K, provides the benefit of the quasi-zero dimensional confinement.

As shown in Fig. 4, the FIR peak stays almost at the same position (23.3 μm) for 1299 and 1388 detectors. Changing width of the QW does not affect states in the QD and this confirms that the FIR peak is due to transitions between dot states. Due to the fact that the dot size of 1373 has been changed causing the energy space between dot states to decrease, the FIR peak of 1373 has shifted to ∼25.5 μm.

IV. CONCLUSION

All the peaks of the three-color infrared detector presented are based on transitions in InAs–InGaAs DWELL heterostructure. Each peak obtained for each detector emphasize the corresponding transition between states in the structure. Operating wavelength in MIR range can be tailored by varying the applied bias. Detectors can be designed by changing the well width or the size of the dot so that they can be operated at different wavelengths depending on the application. Normal incidence and high temperature operation in FIR region are advantages of DWELL detectors over typical n-type QW detectors.

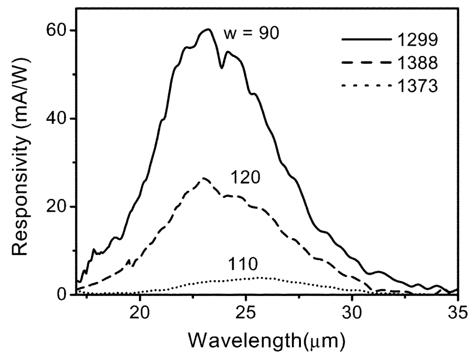

Fig. 4. Spectral response of the FIR peak for all three detectors at 4.6 K under −1.4-V bias (−23.7, −22.9, and −22.5 kVcm^{-1} field for 1299, 1373, and 1388, respectively).

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