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Three-color (λ_{p1}~3.8 μm, λ_{p2}~8.5 μm, and λ_{p3}~23.2 μm) InAs/InGaAs quantum-dots-in-a-well detector

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We report a three-color InAs/InGaAs quantum-dots-in-a-well detector with center wavelengths at ~3.8, ~8.5, and ~23.2 μm. We believe that the shorter wavelength responses (3.8 and 8.5 μm) are due to bound-to-continuum and bound-to-bound transitions between the states in the dot and states in the well, whereas the longer wavelength response (23.2 μm) is due to intersubband transition between dot levels. A bias-dependent activation energy ~100 meV was extracted from the Arrhenius plots of the dark currents, which is a factor of 3 larger than that observed in quantum-well infrared photodetectors operating at comparable wavelengths. *© 2003 American Institute of Physics.* [DOI: 10.1063/1.1615838]

In the past few years, there has been active research to realize mid-infrared (MIR) and far-infrared (FIR) detectors based on intersubband transitions in quantum dots (QDs).[1–4] Owing to the three-dimensional (3D) confinement of carriers, QD detectors are expected to display improved device performance characteristics, such as low dark current and higher operating temperatures.[5,6] Several researchers have also reported the observation of a long excited-state lifetime in QDs,[7] which should translate into higher detectivity and higher operating temperature.[8] However, such a dramatic improvement in the performance of QD detectors has not been demonstrated as yet. One of the possible reasons for this anomaly could be because of the fact that most of the intersubband detectors fabricated so far do *not* operate on the ground state to the first excited dot state transition. This is borne out by the fact that the calculated spacing between the electronic ground state and the first excited state in a pyramidal or lens-shaped (In,Ga)As/GaAs dot with a base dimension of 20 to 25 nm and height of 8 to 10 nm is in the range of 50 to 60 meV (20 to 25 μm),[9] whereas the operating wavelength of the detectors fabricated using these dots is in the range of 6 to 10 μm (120 to 200 meV).[1–3] Thus, most of these detectors operate on a bound-to-quasi-continuum transition, from the ground state in the dot to an excited state close to the GaAs band edge. Since the excited states close to the band edge are expected to be phonon coupled, their lifetimes are not very long. In order to realize the potential of 3D confinement and long carrier lifetimes of excited states, *it is imperative that the detectors operate on a well-confined bound-to-bound transition*. We have recently reported intersubband detectors in which the InAs dots are placed in a thin InGaAs quantum well, which in turn is positioned in a GaAs matrix.[10] Such a heterostructure, known as the dots-in-a-well (DWELL) design, not only reduces the thermionic emission by lowering the ground state of the dot with respect to the GaAs band edge, it also enables us to operate on a bound-to-bound transition from the ground state in the dot to a state in the InGaAs quantum well (QW).[10]

In this letter, we report a three-color (λ_{p1}~3.8 μm, λ_{p2}~8.5 μm, and λ_{p3}~23.2 μm) QD detector. We believe that the peak at ~8.5 μm is probably due to a transition from the ground state in the dot to a state in the InGaAs QW, whereas as the shorter-wavelength peak (~3.8 μm) is to a state above the QW. We believe that the FIR response (λ_{p3} ~23.2 μm) is due to a transition between the electronic states within the QD, since the energy spacing agrees with the theoretically calculated values. The long-wavelength response was observed up to 80 K (peak responsivity ~2 mA/W), which is a very high operating temperature reported for FIR QW or QD detector.

The DWELL detectors were grown in a VG-80 solid-source molecular-beam epitaxy system with a cracked As_2 source. The GaAs layers were grown at a substrate temperature, T_{sub}=580 °C, whereas the 90-Å $In_{0.15}Ga_{0.85}As$ well and the InAs dots were grown at T_{sub}=480 °C, as measured by an optical pyrometer. The details of the growth are described elsewhere.[4] 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. A two-dimensional view of the conduction-band profile is shown in Fig. 1. From photoluminescence 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 two bound states in the dot[9] and one confined state in the QW as shown in the inset to Fig. 1.

The detectors were wire bonded to a chip carrier and the normal incidence responsivity spectra were obtained using a Perkin-Elmer system 2000 Fourier transform infrared spectrometer. Data were taken with two sets of beamsplitters and windows, and were corrected by background spectra. The resulting three-color response is shown in Fig. 2. Let us first

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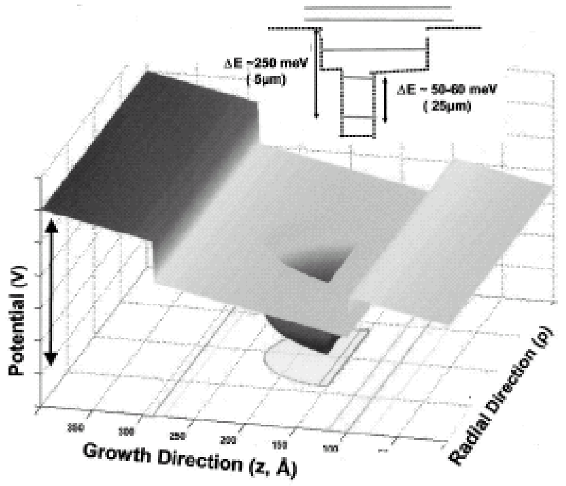

FIG. 1. Conduction-band profile and energy-level spacing for the InAs/InGaAs dots in a well heterostructure.

discuss the two MIR peaks: 8.5 and 3.8 μm. These peaks have previously been observed by the authors on similar detector structures.[10] We believe that the peak at 8.5 μm (145 meV$<\Delta E_c$) is probably a transition from a bound state in the dot to a bound state in the QW whereas the broad shoulder around 3.8 μm (326 meV$>\Delta E_c$) is possibly a transition from a state in the dot to a quasi-bound state close to the top of the well, as shown in the inset to Fig. 2. Moreover, the 3.8-μm peak has a larger linewidth ($\Delta\lambda/\lambda\sim42\%$) than does the 8.5-$\mu$m peak ($\Delta\lambda/\lambda\sim28\%$). This is consistent with the analyses of Levine[11] and Gunapala[12] who showed that the linewidth of a QW detector operating on bound-to-bound transition is narrower than that of a detector operating on a bound-to-continuum transition.

Using elementary principles of quantum mechanics, the polarization dependence of the MIR transition can be obtained. It can be shown that a transition between a state in the dot and a state in the well would be sensitive to normal incidence or s-polarized radiation. It must be mentioned that in the DWELL structure the state in the well is no longer a purely z-confined state with an $\exp(-i\mathbf{k}\cdot\boldsymbol{\rho})$ dependence for the radial (ρ) wave function. If we erroneously assume that the QW state is only z-polarized, then the matrix element for this transition can be written as

$$M_{\mathrm{WD}}\propto\int\psi_{\mathrm{well}}(z)[\mathbf{A}(\boldsymbol{\rho})\hat{\mathbf{e}}(\boldsymbol{\rho})\cdot\mathbf{p})]\psi_{dot}(z,\boldsymbol{\rho})d\mathbf{r}_{\|}dz, \qquad (1)$$

where z denotes the growth direction and $\boldsymbol{\rho}$ denotes the vector in the plane of the QW (Fig. 1) and $[\mathbf{A}(\boldsymbol{\rho})\hat{\mathbf{e}}\cdot\mathbf{p})]$ denotes the operator for s-polarized light. Since $[\mathbf{A}(\boldsymbol{\rho})\hat{\mathbf{e}}\cdot\mathbf{p})]$ is a hermitian operator, we know that $M_{\mathrm{WD}}=M^{*}_{\mathrm{WD}}$. However Eq. (1) gives us a nonzero value if the operator acts on the right wave function and gives us zero if it acts on the left wave function, thus giving $M_{\mathrm{WD}}\neq0$ and $M^{*}_{\mathrm{WD}}=0$, which is a mathematical absurdity. The only way to resolve this anomaly is to modify our initial assumption and to include a radial component for the QW state, that is, $\psi_{\mathrm{well}}=\psi_{\mathrm{well}}(\boldsymbol{\rho},z)$. The physical explanation of this statement is that the presence of the dots breaks the symmetry of the QW and introduces some degree of localization in the wave function at the points in the plane where the dots are present. Thus normal incidence absorption that is forbidden in QW infrared photodetectors (QWIPs) is allowed in these DWELL structures. This is a very important property of these detectors since it eliminates the need for gratings and optocouplers, thereby leading to a simplified fabrication process for the QD detector.

A FIR peak centered around 23.2 μm was also observed in these detectors, and is shown in Fig. 3. We believe that this peak could possibly be due to transitions between two states in the QD since the calculated energy spacing between the dot levels is about 50–60 meV (20–25 μm). Aslan *et al.*[13] have recently reported a FIR response close to 50 meV ($\lambda_p\sim24$ μm) at $T=6$ K due to intersubband transitions in modulation-doped InAs/GaAs QDs. In our structures, the FIR response is visible up to temperatures as high as 80 K. Perera *et al.*[14] have previously measured the spectral response for a 28-μm QWIP at 4.2 K with the signal disappearing beyond 15 K. The dramatic improvement in the temperature performance of the FIR response for the DWELL detector is probably due to the 3D confinement for the states in the dot. Moreover, at high temperatures, the

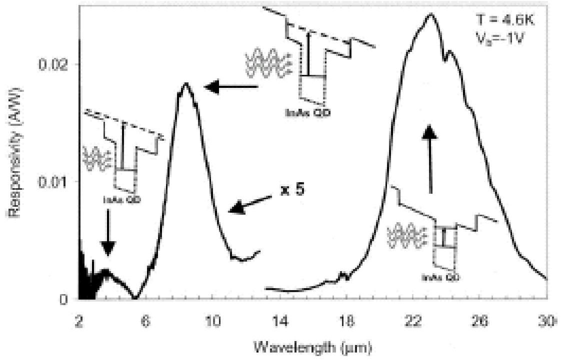

FIG. 2. Three-color response from the 10-layer InAs/In$_{0.15}$Ga$_{0.85}$As DWELL detector. The participating transitions are shown in the inset.

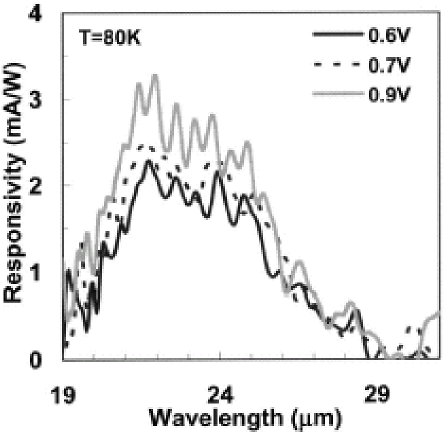

FIG. 3. FIR response of the 10-layer InAs/In$_{0.15}$Ga$_{0.85}$As DWELL detector (a) as a function of temperature at $V_b=0.8$ V and (b) as a function of bias at $T=80$ K.

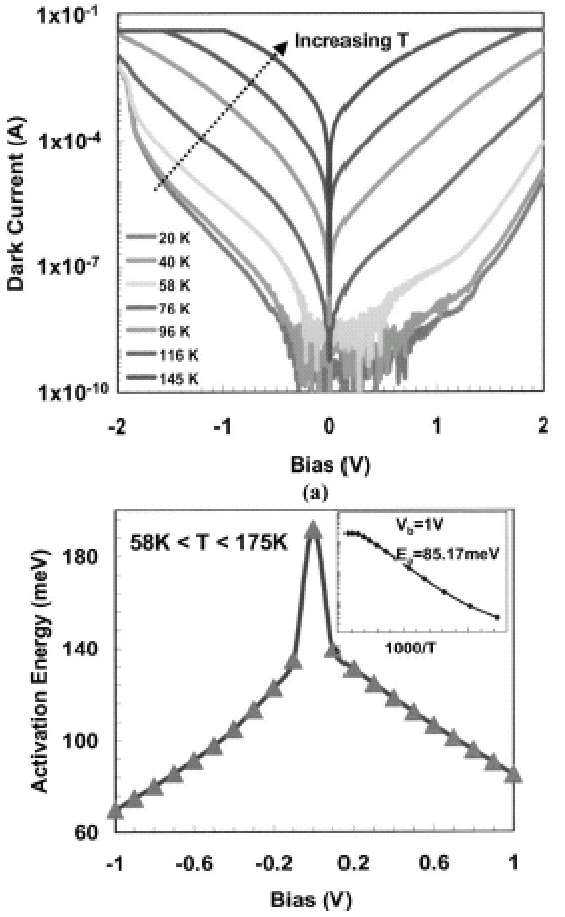

FIG. 4. (a) Dark current density characteristics of the two-color DWELL detector in the range of 20 to 175 K and (b) the activation energy extracted from the Arrhenius plots (shown in inset) as a function of the applied bias.

responsivity of the FIR response is about a factor of 5–10 lower that the MIR response, which could be due to the long-lived carriers in the excited state that make it difficult for photogenerated carriers to escape out of the QD.

Bias-dependent dark current densities for the two-color detector normalized with respect to the contact area (for a 400-μm$\times$400-μm device with a 100-μm-diameter circular opening), is shown in Fig. 4(a). The current density is much lower than that observed in the 28-μm QWIP detector. The activation energy extracted from the Arrhenius plot of the dark current [Fig. 4(b) shows a bias-dependent variation in the range of 70 to 140 meV ($|V_b|<1$), in comparison to 36 meV extracted for the 28-μm QWIP.[14] This further corroborates our premise that the FIR response originates from transitions between QD states.

In summary, we report a three-color infrared ($\lambda_{p1}\sim 3.8$ μm, $\lambda_{p2}\sim 8.5$ μm, and $\lambda_{p3}\sim 23.2$ μm) based on transitions in an InAs/InGaAs dots-in-a-well heterostructure. The mid-infrared peaks are due to bound-to-continuum and bound-to-bound transitions between the states in the dot and states in the well, whereas the far-infrared peak is possibly due to transitions between dot levels. The long-wavelength response was observed up to 80 K, which is a very high temperature in an intersubband detector of comparable operating wavelength.

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[1] B. Kochman, A. D. Stiff-Roberts, S. Chakrabarti, J. D. Phillips, S. Krishna, J. Singh, and P. Bhattacharya, IEEE J. Quantum Electron. **39**, 459 (2003), (and references therein).
[2] H. C. Liu, M. Gao, J. McCaffrey, Z. R. Wasilewski, and S. Fafard, Appl. Phys. Lett. **78**, 79 (2001).
[3] L. Jiang, S. S. Li, N.-T. Yeh, J.-I. Chyi, C. E. Ross, and K. S. Jones, Appl. Phys. Lett. **82**, 1986 (2003).
[4] S. Raghavan, P. Rotella, A. Stintz, B. Fuchs, S. Krishna, C. Morath, D. A. Cardimona, and S. W. Kennerly, Appl. Phys. Lett. **81**, 1369 (2002).
[5] J. D. Phillips, J. Appl. Phys. **91**, 4590 (2002).
[6] V. Ryzhii, I. Khmyrova, V. Mitin, M. Stroscio, and M. Willander, Appl. Phys. Lett. **78**, 3523 (2001).
[7] J. Urayama, T. B. Norris, H. Jiang, J. Singh, and P. Bhattacharya, Appl. Phys. Lett. **80**, 2162 (2002).
[8] P. Bhattacharya, S. Krishna, J. Phillips, P. J. McCann, and K. Namjou, J. Cryst. Growth **227**, 27 (2001).
[9] H. Jiang and J. Singh, Phys. Rev. B **56**, 4696 (1996).
[10] S. Krishna, S. Raghavan, G. von Winckel, P. Rotella, A. Stintz, D. Le, C. Morath, and S. W. Kennerly, Appl. Phys. Lett. **82**, 2574 (2003).
[11] B. F. Levine, J. Appl. Phys. **74**, R1 (1993).
[12] S. D. Gunapala and S. V. Bandara, *Physics of Thin Films*, edited by M. H. Francombe and J. L. Vossen (Academic, New York, 1995), Vol. 21, pp. 113–237.
[13] B. Aslan, H. C. Liu, M. Korkusinski, S. J. Cheng, and P. Hawrylak, Appl. Phys. Lett. **82**, 639 (2003).
[14] A. G. U. Perera, W. Z. Shen, S. G. Matsik, H. C. Liu, M. Buchanan, and W. J. Schaff, Appl. Phys. Lett. **72**, 1596 (1998).