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We demonstrate midinfrared photodetection at $\lambda=4.5$ μm in a multi-quantum well detector using a strained InGaAs/AlGaAs alloy grown on a GaAs substrate. The detector shows very low dark current of a few pA, a peak unpolarized light responsivity $R=12$ mA/W for an external 45° angle of incidence, and a background-limited detectivity $D^*_{BL}=4\times10^{10}$ cm Hz$^{1/2}$/W at temperatures up to 95 K in the same conditions. This opens the way to high performance 3–5 and 8–12 μm GaAs-based multispectral detectors

Quantum well infrared photodetectors (QWIPs) are envisioned as a viable alternative to HgCdTe infrared detectors. Taking advantage of mature GaAs growth technology, large and uniform arrays could be realized, leading to low-cost, monolithically integrated imaging devices.[1,2] In addition, specific features of quantum well (QW) detection would allow new functions to be developed, such as electrical tunability and band switching.[3,4] In view of thermal imaging applications, detectors are needed in both 8–12 and 3–5 μm atmospheric windows. Whereas the lattice-matched GaAs/$Al_xGa_{1-x}As$ alloy, grown on GaAs substrate, can be conveniently exploited for 8–12 μm QWIPs,[1] is not suitable for detection at wavelengths shorter than about 5 μm, due to the (X,Γ) band crossing in $Al_xGa_{1-x}As$ for $x>0.45$.[5] Beyond this band crossing limit, thermal transitions become related to the X band while optical transitions remain related to the Γ one. This implies a thermal activation energy lower than the optical one, leading to poor temperature performance (i.e., high dark current[6,7]). Moreover, the high defect density at those high Al concentrations has detrimental effects on the detector performances, such as carrier freeze-out, high generation-recombination noise,...[8] Thus, the need is seen for a different alloy, with a larger band offset. A lattice-matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ QWIP, based on the less mature InP technology, was reported[9] to have a responsivity spectrum peaked at 4.1 μm. However, for this material system, multispectrality is difficult to obtain, since it is necessary to control either quaternary lattice AlGaInAs alloys or strained-balanced GaInAs/Al(Ga)InAs superlattices. Another group[10] recently demonstrated a two-color QWIP, consisting of two AlGaAs/GaAs and InGaAs/GaAs stacked structure grown on a GaAs substrate. The responses were peaked at 8 and 5.3 μm, missing the 3–5 μm band of interest. In this letter, we show that 4.5 μm detection can indeed be achieved with a similar approach, using strained InGaAs/AlGaAs alloys grown on GaAs substrate.

The sample, grown by molecular beam epitaxy on a semi-insulating GaAs substrate, consists of 100 repetitions of the following single well: 2 Å AlAs, 8 Å GaAs, 25 Å $In_{0.16}Ga_{0.84}As$, 8 Å GaAs, 2 Å AlAs, separated by a 336-Å-thick $Al_{0.37}Ga_{0.63}As$ barrier (see Fig. 1). The period of the structure was confirmed by x-ray diffraction measurements. The $In_{0.16}Ga_{0.84}As$ wells were Si doped to 5×10^{11} cm^{-2}. The multi-quantum well (MQW) structure was clad between two 0.5 μm Si-doped contact layers ($n=2.8\times10^{18}$ cm^{-3}). To counterbalance In segregation and obtain abrupt InGaAs-on-GaAs interfaces, and In-rich prelayer was deposited prior to the growth of the InGaAs well.[11,12] The two ultrathin AlAs barriers have been added to the basic QW structure to raise slightly the second energy level. The absorption spectrum was determined at different temperatures, using a Nicolet 740 Fourier transform infrared spectrometer in a multipass configuration.[13] Figure 1 shows the absorbance spectra at 300 and 5 K, for 25 passes of polarized light in a 45° bevelled sample, absorbance being defined as $-\log_{10}$ (transmission). The two spectra are peaked at $\lambda=4.65$ μm (5 K) and $\lambda=4.8$ μm (300 K). Calculating the corresponding value for single pass and Brewster incidence, we find a quantum efficiency value of $\eta(73°)=2.5\%$ at room temperature and of $\eta(73°)=3\%$ at 5 K. On the other hand, the spectral width (FWHM) decreases from 0.62 μm (300 K) to 0.45 μm (5 K), giving about the same value for the integrated absorption. This shows that no freeze out of electrons takes place. At low temperatures, the usual blueshift of transition energy (7 meV in this case) is observed.[14,15] In the temperature range of 5–100 K, the shape of the absorption spectrum remains substantially unchanged. The high energy tail of the absorption spectra indicates the bound-to-slightly extended behavior of the transition. Nevertheless, the width is smaller than that usually obtained in the bound-resonant extended case, i.e., when the second bound state in the QW is in resonance with

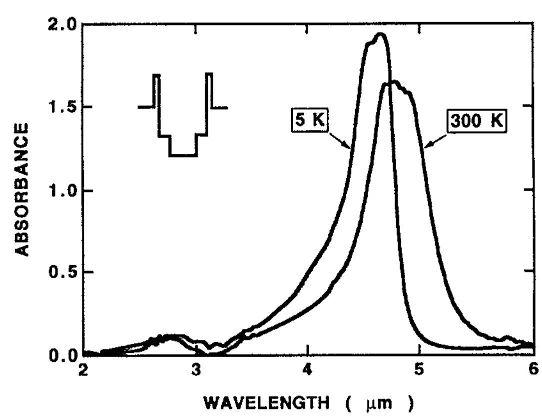

FIG. 1. Absorbance spectra of 100 InGaAs/AlGaAs QWs for 25 passes of TM polarized light for a 45° internal angle, at 5 and 300 K.

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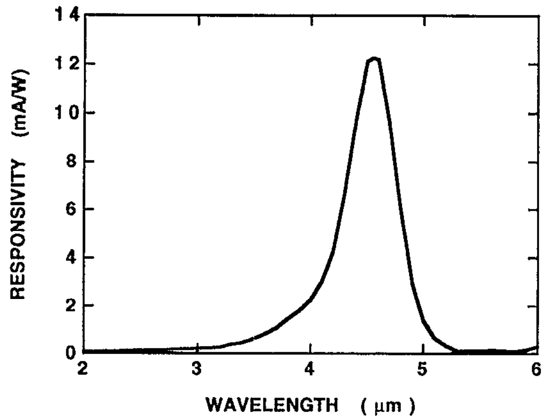

FIG. 2. Responsivity of the InGaAs/AlGaAs QWIPs to TM polarized light, for 45° external angle of incidence, at 80 K and 10 V applied bias.

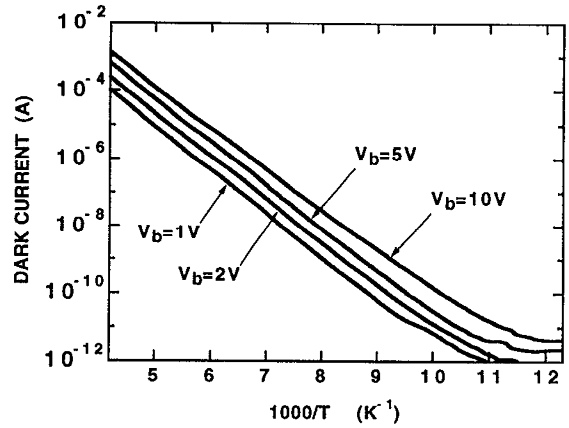

FIG. 3. Arrhenius plot of InGaAs/AlGaAs QWIPs dark current for various applied biases.

the barrier energy. We attribute this unusual spectral width to the presence of the two additional thin AlAs barriers: indeed, the final state is resonant with the $Al_{0.37}Ga_{0.63}As$ barrier continuum through the AlAs tunnel barrier, which leads to a spectral width intermediate between those of the bound-to-extended and the bound-to-bound cases.[16]

In order to perform electro-optical measurements, 100 μm$\times$200 μm mesas were chemically etched using standard lithography techniques. 80 μm$\times$80 μm AuGeNi ohmic contacts were evaporated onto the top and bottom contact layers, leaving an optical window of 1.36×10^{-4} cm^2. The photocurrent spectrum was then measured at $T=80$ K, with 10 V applied bias (mesa top positive) and for external 45° angle of incidence, using a glowbar source and a double prism spectrometer. We normalized the spectrum using a photon flux measured with a pyroelectric detector and we calculated the corresponding responsivity (Fig. 2). The peak unpolarized light responsivity is $R=0.012$ A/W at $\lambda=4.5$ μm, with a FWHM of 0.5 μm. We recall that the responsivity is given by

$$R=\eta ge/h\nu \tag{1}$$

where η is the unpolarized light quantum efficiency for 45° incidence and g the photoconductive gain. From the measured value of quantum efficiency at Brewster angle, we deduce the corresponding value for 45° incidence of unpolarized light: $\eta(45°)=6.5\times10^{-3}$, so we find $g=0.5$. Moreover, using[17]

$$g=\tau_{\text{life}}/\tau_{\text{transit}}, \tag{2}$$

a value $\mu\tau_{\text{life}}=7\times10^{-9}$ cm^2/V is obtained. Estimating an electron mobility of $\mu=400$ cm^2/V s, we get an order of magnitude for the lifetime: $\tau_{\text{life}}\approx15$ ps. This compares well with the values obtained in the GaAs/AlGaAs system.[1]

We then studied the dark current as a function of temperature, for various bias voltages. Figure 3 shows an Arrhenius plot of dark current, for temperature ranging from 80 to 240 K and for applied bias $V_b=1$, 2, 5, 10 V (nearly symmetrical curves were obtained for negative biases). At low temperature, the current attains very low values (below 5 pA), being limited by tunneling or defect-assisted transport through the barriers. As temperature rises, thermal current prevails, giving rise to the typical exponential behavior of thermally activated current, with an activation energy $E_{\text{act}}=230\pm10$ meV for the 150–250 K temperature range. We observed persistent photoconductivity:[18] after short exposure to visible light, the dark current is increased with respect to that measured before illumination, and it slowly decreases towards it original value. This behavior is possibly due to *DX* centers in the high Al concentration $Al_{0.37}Ga_{0.63}As$ barriers, originating from partial redistribution of the Si dopant in the barriers.

To deduce the maximum temperature for background-limited infrared performance (BLIP), we measured the photocurrent at 77 K, exposing the detector to background-room-temperature radiation: $I_{\text{opt}}=5\times10^{-11}$ A, with a 10 V bias and for an $f/1.6$ field of view. This temperature is sufficiently low so that the dark current is negligible compared to the background photocurrent. As the dark current reaches the same value for $T=95$ K, we deduce a $T_{\text{BLIP}}=95$ K at 10 V bias with 45° incidence angle. Since the noise in MQW detectors, at $T<T_{\text{BLIP}}$, corresponds to the generation-recombination noise related to the background current: $I_n^2=4egI_{\text{opt}}\Delta f$,[19] we may derive the detectivity D^*_{BL} of our detector: $D^*_{\text{BL}}=4\times10^{10}$ cm Hz$^{1/2}$/W, at 10 V bias, at $T<95$ K, and for an $f/1.6$ field of view. This value is comparable to those obtained by others with InGaAs/InAlAs on a less favorable InP substrate,[9] or with indirect AlGaAs barriers,[6] while our detector is based on more promising direct-gap AlGaAs/InGaAs technology.

In conclusion, we have demonstrated a 4.5 μm MQW detector, based on strained AlGaAs/InGaAs alloy grown on a GaAs substrate. Very low dark current results in good detectivity $D^*_{\text{BL}}=4\times10^{10}$ cm Hz$^{1/2}$/W, with a detection spectral window $\Delta\lambda=0.5$ μm. Optical coupling by gratings will strongly enhance the performance,[20] with a typical enhancement of the detectivity by a factor of 10 and leading to BLIP temperatures in the 120 K range, thus opening the way to high performance GaAs-based multispectral MQW detection.

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