GaAs/AlGaAs quantum well photodetectors with a cutoff wavelength at 28 μm

A. G. U. Perera,[a] W. Z. Shen, and S. G. Matsik
Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia 30303

H. C. Liu and M. Buchanan
Institute for Microstructural Sciences, National Research Council, Ottawa K1A 0R6, Canada

W. J. Schaff
School of Electrical Engineering, Cornell University, Ithaca, New York 14853

(Received 6 October 1997; accepted for publication 31 January 1998)

We demonstrate the longest (λ_c=28.6 μm) far-infrared quantum well photodetectors (QWIPs) based on a bound-to-bound intersubband transition in GaAs/AlGaAs. The responsivity is comparable with that of mid-infrared GaAs/AlGaAs and InGaAs/GaAs QWIPs. A peak responsivity of 0.265 A/W and detectivity of 2.5×10^9 cm$\sqrt{\text{Hz}}$/W at a wavelength of 26.9 μm and 4.2 K have been achieved. Based on the temperature dependent dark current and responsivity results, it is expected that similar performance can be obtained at least up to 20 K. [S0003-6951(98)00813-4]

GaAs/AlGaAs quantum well infrared photodetectors (QWIPs) have attracted much attention[1] and been demonstrated with a detection cutoff of 19 μm.[2] QWIP detectors with longer wavelengths would be of interest for space applications such as infrared astronomy and satellite mapping where high detectivity, low dark current, high uniformity, radiation hardness and low power consumption are important. For these uses, arrays of QWIPs would provide a useful alternative to the Si and Ge detectors currently available in this wavelength range[3] with detectivities ranging from 10^9 to 10^{14} cm$\sqrt{\text{Hz}}$/W. In this letter we present the first far-infrared results on a GaAs/AlGaAs QWIP with peak response at 27.2 μm.

The detector design is shown in Fig. 1. The structure consisted of 20 periods of 118 Å GaAs wells and 400 Å $Al_{0.07}Ga_{0.93}As$ barriers. The first 0.02 μm of the contact regions adjacent to the barriers were doped with Si to 1.5×10^{17} cm^{-3}, while a thicker layer doped to 1×10^{18} cm^{-3} was grown on each contact to facilitate the formation of connections to the device, and the wells were doped with Si to 4.0×10^{16} cm^{-3}. Including the exchange interaction this produced energy bands at 10.5 and 53.5 meV with a designed peak response at 28.8 μm for a bound-to-bound transition. The bound-to-bound operation was adopted for the following reason. Due to the presence of numerous multiphonon absorption features in the wavelength range of interest, it was decided that a single narrow and strong response feature would offer the best chance of measuring a signal whose peak response location could be confirmed.

The GaAs/AlGaAs far-infrared (FIR) QWIPs were fabricated by etching mesas of 240 μm$\times$240 μm (conventional wet chemical etching techniques) and Ni/Ge/Au ohmic contacts were evaporated onto the top and bottom layers. The dark current–voltage curves measured at different temperatures are shown in Fig. 2. The low level of well doping (4.0 $\pm 0.4\times 10^{16}$ cm^{-3}) produces a reduced asymmetry in the dark current of this device structure, since higher doping increases the Si dopant migration in the growth direction,[4] and hence high asymmetry in the band structure. At low bias where tunneling is negligible, the dark current is expected to increase exponentially with the temperature and at high temperatures (>30 K) is dominated by the thermionic emission current (I_{TE}) of bound-to-bound transitions in QWIPs:[1]

$$I_{TE}=\frac{e^2m^*}{\pi\hbar^2}\frac{Av}{L_w}\Delta_1 e^{-(E_b-e\Delta_2-E_F-E_1)/k_BT}, \tag{1}$$

where m^* is the effective electron mass of GaAs, A is the mesa area, E_b is the barrier height, v is the effective drift velocity over the barrier, E_F is the Fermi energy, E_1 is the first energy level in the wells and $\Delta_{1(2)}$ is the potential drop across one barrier (well). The dark current versus inverse temperature follows an excellent straight line of the log plot and yields a thermal activation energy of 36.0 $\pm$ 0.5 meV, which is in reasonable agreement with $E_b-e\Delta_2-E_F-E_1$ of 41.7 meV obtained from energy calculations. Equation (1) gives a good fit to the low bias dark current curve over 3-4 orders of magnitude in current, as shown in the bias dependent case of inset (i) and temperature dependent case of inset (ii) in Fig. 2, with an effective drift velocity v of 7.5×10^7 cm/s. The low temperature (<25 K) dark current is due to

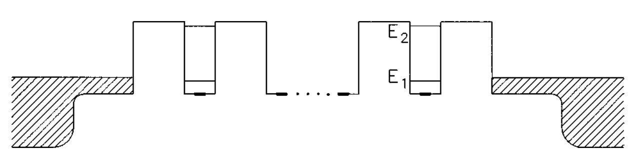

FIG. 1. Structure designed for the bound-to-bound GaAs/AlGaAs QWIP with a predicted peak response of 28.8 μm. The observed peak was 27.2 μm. The 400 Å thick barriers had an Al fraction of 0.07 and the wells were 118 Å thick and doped to 4×10^{16} cm^{-3} with Si. Buffer regions 0.2 μm thick adjacent to the first and last barriers were doped to 1.5×10^{17} cm^{-3} and the contacts were doped to 1×10^{18} cm^{-3}. The energy bands were at E_1=10.5 meV and E_2=53.5 meV.

[a]Electronic mail: uperera@gsu.edu

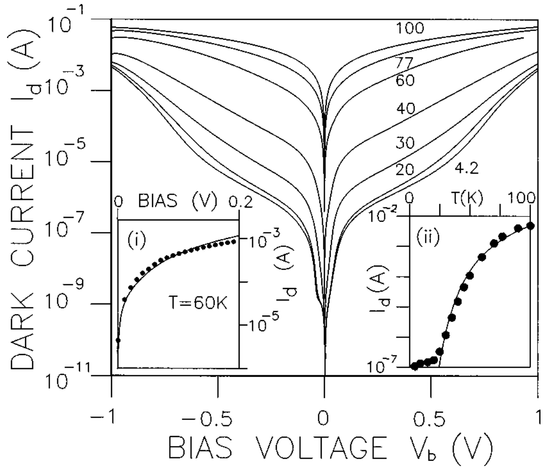

FIG. 2. Dark current I_d vs bias voltage V_b curves as a function of temperature for the FIR GaAs/AlGaAs quantum well photodetector. Shown in inset (i) is the bias dependence of dark current at 60 K (solid line) and the theoretical results from Eq. (1) (filled circles). Inset (ii) shows the temperature dependence of the dark current at low bias of 0.1 V (filled circles), and the solid line is the theoretical current contribution from thermionic emission. Positive bias means top positive.

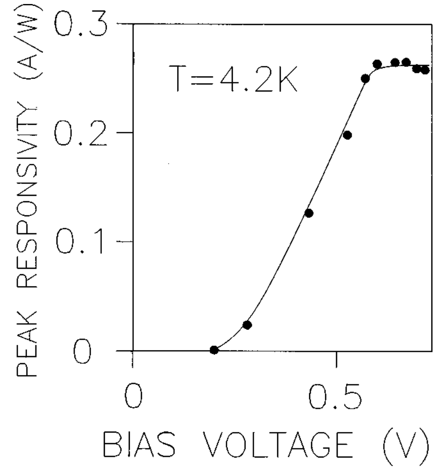

FIG. 4. Bias dependence of the measured absolute peak responsivity, showing a saturation at a bias of 0.6 V.

the contribution of sequential resonant tunneling, which increases rapidly at higher bias (>0.50 V) due to the field-assisted tunneling (see 4.2 K and 20 K dark current curves in Fig. 2).

The responsivity spectra of the detector were measured using a Perkin–Elmer, system 2000, Fourier transform infrared spectrometer (FTIR). The detector was back illuminated through a 45° polished facet and a Si composite bolometer was used as the reference detector to obtain the background spectrum and the responsivity. Figure 3 shows bias dependent responsivity spectra of the detector at 4.2 K. The measured responsivity curves were mainly located in the range of 25–30 μm. To our knowledge, this is the longest reported wavelength response in GaAs/AlGaAs QWIPs in the literature. It is noted that the spectral response exhibits a deep valley at 27.8 μm and a shallow valley at 29.8 μm. In such a long wavelength region, the GaAs substrate has multiphonon absorption, which obscures the intersubband transition of the detectors.[1] It is this multiphonon absorption that results in the valleys observed in the responsivity spectra. Similarly, strong TO phonon absorption was also observed in the responsivity curves of p-GaAs homojunction interfacial workfunction internal photoemission (HIWIP) detectors operated at 20–100 μm.[5] The energies of the two valleys correspond well with the two phonon absorption (TO+TA) peaks of 44.0 meV (28.1 μm) and 41.0 meV (30.2 μm) in GaAs (see Table XI in Ref. 6). The two-phonon absorption is weak in p-GaAs HIWIP detectors with normal incidence illumination, however, it is enhanced in QWIPs due to absorption in the back illuminated geometry.

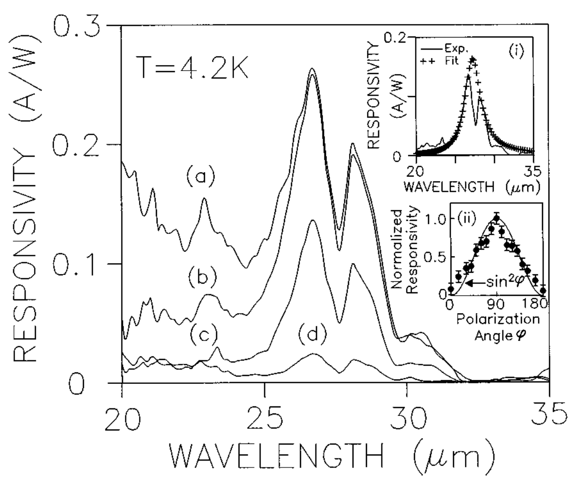

FIG. 3. Spectral response of GaAs/AlGaAs FIR detector measured at 4.2 K under different forward bias values (a) V_b=0.670 V, (b) V_b=0.570 V, (c) V_b=0.432 V, and (d) V_b=0.281 V. The deep valley at 27.8 μm and a small valley at 29.8 μm are due to two phonon absorption of GaAs substrate. Inset (i) shows a Lorentzian fit (+) with spectral width of 2.45 μm to the response at a bias of 0.432 V. Inset (ii) shows the polarization dependence of the QWIP photosignal at a bias of 0.432 V.

The responsivity spectrum is dominated by an intersubband transition between the first and the second electron levels in GaAs wells. This can be clearly seen in inset (i) of Fig. 3, where the responsivity curve can be fitted by a Lorentzian line shape with the half width at half maximum Γ=16.5 cm^{-1} and peak responsivity λ_p=27.2 μm, which give the spectral width $\Delta\lambda/\lambda_p$=9.0%. The peak wavelength and the spectral width are in good agreement with theoretical estimates of bound-to-bound intersubband transitions based on the GaAs/AlGaAs conduction band offset of 812x (meV). We have measured the polarization-dependent photoconductivity signal, and found, as expected, that the photosignal was determined to be highly polarized with the optical transition dipole moment aligned normal to the quantum well structure, which is indicative of intersubband transition [see inset (ii) of Fig. 3]. The cutoff wavelength observed is λ_c=28.6 μm, which is about 10 μm longer than the previously reported longest wavelength of QWIPs.[2,7] The measured highest responsivity of the detector is 0.265 A/W at a bias of 0.67 V. The real values of peak responsivity (R_p) have been hidden by the phonon-induced deep valley, resulting in a reduced value for R_p, however, this value is comparable to that of 8–12 μm and 12–20 μm GaAs/AlGaAs[1,2] and 12–20 μm InGaAs/GaAs[7] bound-to-continuum QWIPs.

Figure 4 shows the bias dependence of the measured absolute peak responsivity. The responsivity does not vary linearly with the bias initially, being essentially zero for finite bias (up to 0.20 V). This is due to the necessity of field-assisted tunneling for the photoexcited carriers to escape from the fully bound subbands in the wells. This is also consistent with the dark current results discussed above. Since the bound excited state is closer to the top of the well in the present detector, only a low bias is required to achieve efficient tunneling of photoexcited carriers out of the wells. The responsivity increases superlinearly with the bias reaching 0.20 V and then saturates at a bias of 0.60 V. This type of behavior is typical for a bound-to-bound QWIP.[1]

Further evidence of the bound-to-bound transition QWIP comes from its bias dependent responsivity spectra. Note that as the bias increases the spectral shape changes. The linewidth broadens at higher bias. As is known, the tunneling time out of the wells decreases with increasing bias, resulting in a large escape probability into the continuum. This short tunneling time is expected to broaden the excited bound-state linewidth due to the uncertainty principle. The increase in escape probability into the continuum, together with the strong decrease in tunneling time out of well, is the reason for the broadening and the asymmetrical line shape of the spectrum.

From the responsivities and dark currents, the peak detectivities were calculated using $D_\lambda^* = R\sqrt{A}/i_n$ where the dark current shot noise is given by $i_n = \sqrt{4qI_d g \Delta f}$, Δf is the bandwidth and g is the optical gain, where g is taken to be 1, consistent with the measured values of other QWIPs with a similar number of wells.[8] For the present detector, the highest detectivity is $D_\lambda^* = 2.5\times10^9$ cm$\sqrt{\text{Hz}}$/W at $V_b = 0.6$ V.

To try to address the BLIP (background-limited performance) temperature, we have measured the photocurrent viewing a 300 K background. The 300 K photocurrent of the QWIP at 4.2 K gives the same result as the dark current at 4.2 K, which may be due to two reasons: (i) the weak background in the spectral range 20–30 μm, where the detector responds (see below), and (ii) the leakage current due to other imperfections of material, which is higher than the true dark current. The temperature-dependent response measurements show that the responsivity is almost independent of temperature. Also, there is not much difference in dark current between 4.2 K and 20 K (see Fig. 2). Based on this, it is expected that a similar performance can be obtained up to at least 20 K. At wavelengths longer than ~20 μm multiphonon absorption in the substrate under back illumination starts to increase causing a decrease in the detector response. However, the use of front illumination techniques based on gratings to couple the incident radiation with the quantum well should significantly reduce the absorption problem in GaAs.

In summary, we have demonstrated the longest ($\lambda_c = 28.6$ μm) far-infrared QWIP, which is based on the bound-to-bound intersubband transitions of GaAs/AlGaAs. A peak responsivity of 0.265 A/W and detectivity of 2.5×10^9 cm$\sqrt{\text{Hz}}$/W at 4.2 K have been achieved, with similar performance expected up to 20 K. The responsivity is comparable to that of mid-infrared and long wavelength GaAs/AlGaAs and InGaAs/GaAs QWIPs. Further work is needed to optimize the FIR QWIP response, reduce dark current and improve detectivity.

This work was supported in part by the NSF under Grant No. ECS-94-12248. The work at NRC was supported in part by the Defense Research Establishment Valcartier of the Department of National Defense (Canada).

[1] B. F. Levine, J. Appl. Phys. **74**, R1 (1993).
[2] B. F. Levine, A. Zussman, J. M. Kuo, and J. de Jong, J. Appl. Phys. **71**, 5130 (1992).
[3] P. W. Pellegrini and J. R. Jimenez, in *Thin Films, Advances in Research and Development*, edited by M. H. Francombe and J. L. Vossen (Academic, New York, 1998) Vol. **23**, p. 116, and references therein.
[4] L. Pfeiffer, E. F. Schubert, and K. W. West, Appl. Phys. Lett. **58**, 2258 (1991).
[5] A. G. U. Perera, H. X. Yuan, S. K. Gamage, W. Z. Shen, M. H. Francombe, H. C. Liu, M. Buchanan, and W. J. Schaff, J. Appl. Phys. **81**, 3316 (1997).
[6] J. S. Blakemore, J. Appl. Phys. **53**, R123 (1982).
[7] S. D. Gunapala, K. M. S. V. Bandara, B. F. Levine, G. Sarusi, D. L. Sivco, and A. Y. Cho, Appl. Phys. Lett. **64**, 2288 (1994).
[8] H. C. Liu, Appl. Phys. Lett. **60**, 1507 (1992)