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

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We demonstrate the longest (λc~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 2.5×109 cm 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. © 1998 American Institute of Physics. [S0003-6951(98)00813-4]

GaAs/AlGaAs quantum well infrared photodetectors (QWIPs) have attracted much attention1 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 range3 with detectivities ranging from 109 to 1011 cm 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 Al0.07Ga0.93As barriers. The first 0.02 μm of the contact regions adjacent to the barriers were doped with Si to 1.5×1017 cm−3, while a thicker layer doped to 1×1018 cm−3 was grown on each contact to facilitate the formation of connections to the device, and the wells were doped with Si to 4.0×1016 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×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 (4.0×1016 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 (ITe) of bound-to-bound transitions in QWIPs:1

\[
I_{\text{TE}} = \frac{e^2 m^* A_v}{\pi \hbar^2} \frac{E_F}{k_B T} \Delta_1 e^{-(E_b - E_F - E_1)/k_B T},
\]

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 ± 0.5 meV, which is in reasonable agreement with \(E_b - E_F - E_1\) 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 7.5×107 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 4×1016 cm−3 with Si. Buffer regions 0.2 μm thick adjacent to the first and last barriers were doped to 1.5×1017 cm−3 and the contacts were doped to 1×1018 cm−3. The energy bands were at \(E_1 = 10.5\) meV and \(E_2 = 53.5\) meV.

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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. 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. 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.

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 $\Delta \lambda/\lambda_p = 9.0\%$. 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 812 meV (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 $\lambda_c = 28.6 \mu m$, which is about 10 μm longer than the previously reported longest wavelength of QWIPs. 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 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 well. 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 well.

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 line-width 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 \(D^* = \frac{R}{\sqrt{2\pi f_i d}}\), where the dark current shot noise is given by \(i_n = \sqrt{4qI_d\Delta f}\), \(\Delta f\) 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 \(D^*_n = 2.5 \times 10^9\) cm 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 \(\mu\)m, 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 \(\sim 20\) \(\mu\)m 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 (\(\lambda_c = 28.6\) \(\mu\)m) 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 \(2.5 \times 10^9\) cm 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.

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\(^8\)H. C. Liu, Appl. Phys. Lett. 60, 1507 (1992)