n-Type GaAs/AlGaAs heterostructure detector with a 3.2 THz threshold frequency

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Terahertz detection using the free-carrier absorption requires a small internal work function of the order of a few millielectron volts. A threshold frequency of 3.2 THz (93 μm or ~13 meV work function) is demonstrated by using a 1×10^{18} cm^{-3} Si-doped GaAs emitter and an undoped $Al_{0.04}Ga_{0.96}As$ barrier structure. The peak responsivity of 6.5 A/W, detectivity of 5.5×10^{8} Jones, and quantum efficiency of 19% were obtained at 7.1 THz under a bias field of 0.7 kV/cm at 6 K, while the detector spectral response range spans from 3.2 to 30 THz. © 2007 Optical Society of America

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The terahertz region (0.1–10 THz) is the least explored region in the electromagnetic spectrum. Recent demonstration of terahertz emitters has sparked a huge interest in terahertz detectors and applications.[1,2] Most applications are still limited by the lack of fast response terahertz detectors. Investigating and developing photon detectors such as free-carrier detectors will be beneficial to terahertz applications. Far-infrared (>50 μm) detection has been successfully demonstrated by using the free-carrier absorption mechanism in homojunction interfacial work-function internal photoemission (HIWIP)[3] and heterojunction interfacial work-function internal photoemission (HEIWIP) detectors[4–6] in recent years. Extending the threshold frequency (f_0) into the terahertz region (<3 THz) requires an internal work function (Δ) of no more than 12 meV. Engineering such a small Δ is not trivial and requires careful designing, growth, and processing.

In HEIWIP detectors, an undoped alloy semiconductor material is used as the barrier region, and a doped semiconductor is used as the emitter. The f_0 of the detector can be tailored[5] by changing the alloy fraction (x) in the barrier and the doping concentration in the emitter.[7] The Δ is given by $\Delta=\Delta_x+\Delta_d$, and $\Delta_d=\Delta_{narr}-E_F$, where Δ_x is the conduction band offset between the emitter and the barrier (the valence band offset in p type), Δ_{narr} is the bandgap narrowing in the emitter layer due to doping, and E_F is the Fermi energy measured with reference to the bottom of the conduction band (with reference to the top of the valance band in p type). In $GaAs/Al_xGa_{1-x}As$ structures, a change in the band offset with x is given by $\Delta_x=790\times$(in meV) for n type and $\Delta_x=530\times$(in meV) for p type. The f_0 is determined by $f_0=\Delta/4.133$ in terahertz, where Δ is in millielectron volts.

The reported results on HEIWIP detectors are limited to p-type structures[4,5] because of the lower sensitivity of the E_F to the emitter doping. The Fermi energy can be given[8] by $E_F=1/2m^*(h/2\pi)^2(3\pi^2N/N_m)^{2/3}$, where m^* is the effective mass of carriers (electron or holes), h is the Planck constant, N is the carrier concentration, and N_m is the number of conduction-band minima. Since the hole effective mass is much higher than the electron effective mass, E_F changes more rapidly with carrier concentration in the n-type material. For an example, when the free-carrier concentration increases from 1×10^{18} cm^{-3} to 2×10^{18} cm^{-3}, the corresponding E_F shift in the p-type material is ~6 meV while it is 32 meV in the n type. When designing detectors with smaller Δ, the larger E_F shift in the n type is an advantage since $\Delta=\Delta_x+\Delta_{narr}-E_F$. According to theoretical calculations, to achieve f_0s of 3.75, 3.00, and 2.50 THz in p-type structures with 1×10^{18} cm^{-3} doped GaAs emitters, the x values required in the $Al_xGa_{1-x}As$ layer are 0.014, 0.008, and 0.003, respectively. The required x values in n-type structures to obtain the same f_0s with the same doping concentration are 0.043, 0.039, and 0.037, respectively. It is clear that the required x values for smaller f_0 (<3 THz) in p-type structures are very small and are not practical to achieve using any growth method at present. Theoretically, Δ reaches the limit of a 2 THz threshold (~8.3 meV) as x reaches zero in p-type $GaAs/Al_xGa_{1-x}As$ HEIWIP with 1×10^{18} cm^{-3} doped GaAs emitters, whereas it is theoretically possible to design an n-type

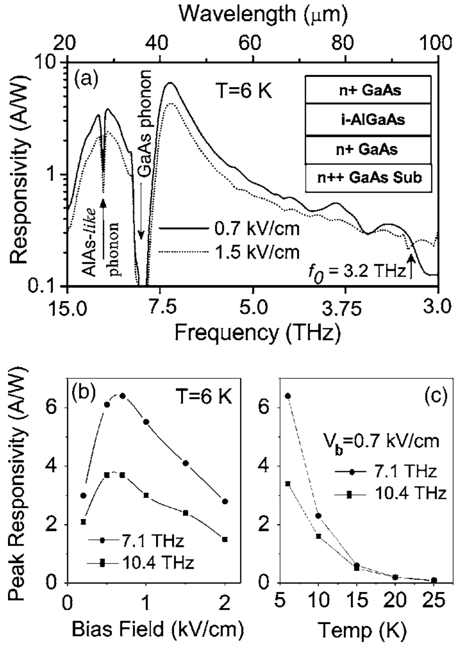

Fig. 1. (a) Responsivity variation for 0.7 and 1.5 kV/cm is shown. The highest R_{peak} is 6.5 A/W at 0.7 kV/cm at 6 K. The f_0 is 3.2 THz. The f_0 that is 3.2 THz was determined by the instrument noise level. The inset shows the device structure. Top and bottom contacts are 100 and 700 nm thick n-doped GaAs, respectively. The barrier is 1 μm thick undoped GaAs/$Al_{0.04}Ga_{0.96}As$. (b) Variation of R_{peak}s at 7.1 and 10.4 THz under different bias fields. (c) R_{peak} variation with a temperature at the bias field of 0.7 kV/cm, and responsivity vanishes after 25 K.

GaAs/$Al_xGa_{1-x}As$ HEIWIP even with $f_0=1$ THz. Lowering the Δ by increasing the doping concentration in p-type emitters does not work effectively due to light-hole–heavy-hole transition.[9] Hence, an alternative to this is changing from the p to the n type. Controlling the Δ can effectively be done by changing the doping concentration in the n-type detectors while keeping the x in an achievable range. Therefore, n-type detectors have an advantage over the p-type detectors when designing far-infrared/terahertz detectors (small Δ). The other alternative is to use an inverted HEIWIP structure.[6] However, the reported lowest f_0 with an inverted structure is 2.3 THz (128 μm) for an x value of 0.005. In this Letter, the capability of extending the f_0 to the 3 THz limit by using an n-type single barrier HEIWIP is demonstrated.

The device structure consists of an undoped 1 μm thick $Al_xGa_{1-x}As$ ($x=0.04$) barrier layer sandwiched between two 1×10^{18} cm^{-3} Si-doped GaAs contact layers with the top contact being 100 nm and the bottom contact being 700 nm in thickness as shown in the inset in Fig. 1(a). A 5×10^{18} cm^{-3} Si-doped GaAs was used as the substrate, which is electrically isolated from the active layers. The doping concentration and the x value were verified by secondary ion-mass spectrometry (SIMS). The top and bottom contact layers work as emitter layers in the reverse and forward bias operations, respectively. The thickness of the top contact layer was kept at 100 nm to allow a substantial amount of light to pass through to the bottom contact layer. Mesas were processed by wet etching. NiGeAu was deposited on the bottom and top layers as ohmic ring contacts. The Δ was estimated to be 13–14 meV by Arrhenius analysis. The calculated E_F in the emitter is 56 meV, while the Δ_x in the GaAs/AlGaAs interface is 32 meV for $x=0.04$. Considering bandgap narrowing[10] of 35–45 meV in the GaAs emitter layer due to 1×10^{18} cm^{-3} Si doping, the calculated Δ should be between ~10 and 20 meV, corresponding to a 2.4–5.0 THz (125–60 μm) threshold frequency. The calculated f_0 from the Arrhenius analysis is 3.1–3.4 THz.

Spectral measurements were performed by using a Fourier transform infrared (FTIR) spectrometer. A silicon composite bolometer was used to calibrate the raw spectra obtained with the detector. The maximum peak response (R_{peak}) of 6.5 A/W at 7.1 THz (42 μm) was obtained at a bias field of 0.7 kV/cm in the forward bias operation (top-emitter positive) as shown in Fig. 1(a). The R_{peak} obtained in the reversed bias is 1.7 A/W at 0.25 kV/cm. At a bias field of 0.5 kV/cm, the R_{peak} in the forward bias is 6.1 A/W, while the R_{peak} in reverse bias is 1.1 A/W. The responsivity ratio in forward and reverse bias operations follows the thickness ratio of the bottom and the top contact layers. The variations of the responsivity values at 7.1 and 10.4 THz with different bias fields are shown in Fig. 1(b). The R_{peak} under the 0.7 kV/cm bias field decreases from 6.5 to 0.1 A/W when the operating temperature increases from 6 to 25 K. The variation of the responsivity values at 7.1 and 10.4 THz with operating temperature is shown in Fig. 1(c). Under the reverse bias, R_{peak} of 1.7, 1.1, and 0.7 A/W at 10 THz (30 μm) was obtained at −0.25, −0.5, and −0.75 kV/cm, respectively. The experimental f_0 of 3.2 THz (93 μm) was estimated with respect to the instrument noise level. As expected, f_0 did not change with the applied bias implying that there is little space charge buildup on the interface. Two minima in the responsivity curve can be seen at approximately 11 THz (27 μm) and 8.3 THz (36 μm) due to AlAs-like and GaAs optical phonons in the AlGaAs layer. The R_{peak}, peak quantum efficiency (η_{peak}), and peak detectivity (D^*_{peak}) at different bias fields are given in Table 1 for forward bias operation.

The photoresponse of HEIWIP detectors depends mainly on photoabsorption in the emitter and photo-

Table 1. R_{peak}, η_{peak}, and D^*_{peak} at Different Bias Fields for the n-Type GaAs/$Al_{0.04}Ga_{0.96}As$ Single Barrier Detector[a]

Bias Field (kV/cm)	R_{peak} (A/W)	η_{peak} (%)	D^*_{peak} ($\times10^8$ Jones)
0.2	3.0	8.9	5.5
0.5	6.1	18.2	6.4
0.7	6.5	18.9	5.5
1.0	5.5	16.5	3.4
1.5	4.1	12.3	2.1

[a] The maximum peak responsivity occurs at 0.7 kV/cm.

emission over the barrier.[8] In HEIWIP, the main photoabsorption mechanism is the free-carrier absorption and can be calculated[7] by $\eta_a = 2I_{ave}(\omega/c)\mathrm{Im}[\varepsilon(\omega)]W$, where $\mathrm{Im}[\varepsilon(\omega)]$ is the imaginary part of the dielectric function of the emitter layer, I_{ave} is the normalized average light intensity in the emitter, W is the emitter thickness, ω is incident light frequency, and c is the speed of light. GaAs and AlAs-like phonons were included in the dielectric function. The photoemission efficiency can be calculated using the escape cone model[11] and the hot carrier transport mechanism.[12] The energy losses due to phonon–electron scattering and the energy dependence of the scattering lengths were ignored in the calculation for simplicity. The responsivity of the detector can be calculated by combining photoabsorption efficiency and photoemission efficiency as shown in Ref. 7. Collection efficiency was taken as 100%. Finally, the responsivity is given by $R = q\eta/hf$, where q is the unit charge, η is the total quantum efficiency, and f is the frequency. The calculated responsivity for forward bias is shown in Fig. 2. The model and the experimental results agree well in the low-frequency region (<8 THz), while the model response is much higher than the experimental response in high-frequency region (>8 THz). This could be due to phonon emission by higher-energy photoexcited carriers and energy-dependent scattering lengths.

Recently, p-type $GaAs/Al_xGa_{1-x}As$ terahertz detectors with f_0 of 4.6, 3.6, and 3.2 THz were reported for $x = 0.02$, 0.01, and 0.005, respectively.[5] An x value of 0.005, which is near the lowest limit for molecular beam epitaxy, has been used to obtain $f_0 = 3.2$ THz while the same f_0 can be obtained with $x = 0.04$ in the n-type detectors as shown in this Letter. The highest responsivity in the n type is at 7.1 THz whereas it was at ~10 THz in all three p-type detectors. The peak responsivity of the above-mentioned 30 layer p-type 3.2 THz threshold detector is 5.6 A/W whereas this single-emitter n-type detector has a R_{peak} of 6.5 A/W. This indicates that the responsivity of n-type detectors is higher than for a similar p-type detector. It is possible to increase the responsivity of the n-type HEIWIP detector further by adding more emitter layers. According to the calculations, the peak responsivity can be optimized up to 10 A/W by adding ten emitters 200 nm thick.

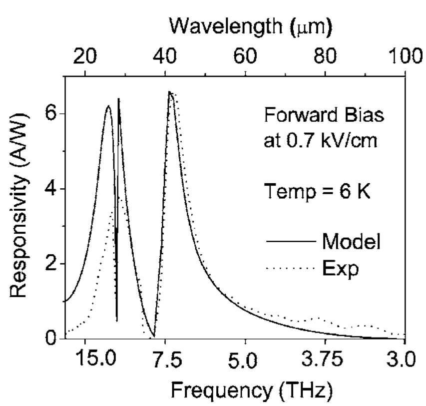

Fig. 2. Experimental and model responsivities for forward bias. In the high-frequency region (>8 THz), the experimental responsivity is less than the calculated responsivity. This may be due to phonon emission by high-energy photocarriers and energy-dependent scattering lengths.

Threshold extension up to 3 THz has been achieved in n-type HEIWIP detectors whereas a very low x-value requirement hinders the extension of the threshold frequency beyond 3 THz in p-type HEIWIP (but not in inverted HEIWIP structures). Here in the n-type HEIWIP, a threshold frequency of 3.2 THz was obtained with a much higher Al fraction compared with the p-type GaAs/AlGaAs HEIWIP.

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