Photovoltaic infrared detection with p-type graded barrier heterostructures

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Photovoltaic infrared detectors have significant advantages over photoconductive detectors due to zero bias operation, requiring low power and having reduced low frequency noise. They also exhibit no thermally assisted tunneling currents, leading to higher operating temperatures. p-type emitter/graded barrier GaAs/AlₓGa₁₋ₓAs structures were tested as photovoltaic detectors in the infrared region, operating under uncooled conditions and without an applied bias voltage. A photovoltaic responsivity of 450 mV/W was obtained with a detectivity (D*) of 1.2 × 10⁹ Jones at a peak wavelength 1.8 μm at 300 K. Responsivity and D* increased to ~1.2 V/W and 2.8 × 10⁹ Jones, respectively, at 280 K. A non-linear improvement in responsivity was observed with increased emitter thickness. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4704695]

I. INTRODUCTION

Group III–V semiconductor materials are extremely important for the development of infrared (IR) detectors operating over a wide wavelength range.¹–³ Most photovoltaic devices are based on p-n junction structures. Use of superlattice structures for infrared photovoltaic devices has gained increasing interest in recent years.⁴–⁷ Photovoltaic response has been demonstrated in multi-quantum-well structures, which generate a photovoltage owing to the Schottky junction characteristics.⁸ Furthermore, photovoltaic multi-quantum-well IR detectors with GaAs/AlGaAs superlattice structures, consisting of n-doped GaAs and undoped AlGaAs layers with a graded barrier at one contact end have also been reported at low temperatures.⁹,¹⁰ Here, we demonstrate p-doped GaAs/AlₓGa₁₋ₓAs, emitter/graded barrier structures with different aluminum fractions (x), operating as photovoltaic detector under uncooled condition. The zero bias reduces the Joule heating in the device and will also reduce low frequency noise and dark current.

II. PROCEDURE

Six wafers were tested, each consisting of a single barrier/emitter/barrier structure between two contact layers; a schematic of the valence band structure is shown in Fig. 1(a).⁹ Of these six wafers, five had the barriers graded with a decreasing Al fraction (X2) from the emitter end and to (X1) towards the bottom contact end of the structure. The sixth sample had a flat barrier instead of the graded barrier as the control sample. All wafers had a constant barrier (X3) between the emitter and the top contact. Device parameters are given in Table I, where X₁, X₂, and X₃ represent the aluminum fractions of the barriers at the bottom contact end and the emitter end of the graded barrier, and in the flat barrier, respectively. Out of the five wafers, three of the graded barriers were grown using continuous alloy fraction variation (SP 1005, SP 1006, SP 1007), whilst the other two (V0727, V0728) were formed by digital alloying as described elsewhere.¹¹

The sample has a constant barrier (Al₆₇Ga₃₃As) on the bottom contact side (instead of the graded barrier) and a small constant barrier (Al₅₇Ga₄₃As) at the top contact side, separated by a single GaAs emitter layer. The emitters were p-doped to 1 × 10¹⁹ cm⁻³ in all six wafers. All wafers studied were grown by molecular beam epitaxy and processed into mesas by wet etching followed by deposition of metal contacts. The photoconductive mode response (response with applied bias) of some of these devices (V0727, V0728) is reported elsewhere.¹¹

III. RESULTS

Four dominant photoexcitation and carrier transport mechanism under photovoltaic mode are summarized in Fig. 1(a), using the valence band diagram for the graded barrier structures. In the first path, named h1, the exited carriers (holes) in the bottom contact region scatter from the graded barrier and fall back into the bottom contact layer. In the second path (h2), exited carriers have sufficient energy to overcome the higher end of the graded barrier and are collected at the bottom contact layer even after scattering off the graded barrier. Therefore, a net charge will be accumulated at the bottom contact. This carrier accumulation generates a shift in the energy levels between the two layers (bottom contact and emitter). In the third and fourth paths, h3 and h4, respectively, exited carriers from the emitter (top contact) will pass over the constant barrier and transport to the top contact (emitter) region. The net carrier accumulation at either emitter or top contact will be zero. Therefore, there will be no energy band shift between the top contact and emitter region due to carrier transport between them. Owing to the asymmetry of these carrier transport mechanisms, a photovoltage (Vp) will be generated between the bottom and top contact. For example, a photovoltage of 0.6 mV was
observed in V0728, when illuminated with the full spectrum of the IR source (1 μm to 5 μm) of an FTIR spectrometer. This response was linearly proportional to the light intensity.

The I–V characteristics for V0728 and SP1007 at 300 K at low bias are shown in the Fig. 1(b). The V0728 has the higher resistance (15 KΩ at zero Bias) and lower dark current compared to SP1007 (2.1 KΩ at Zero Bias) throughout the voltage domain. The asymmetry in the I–V is due to the asymmetry in the device structure. The differences in the barrier heights are causing the differences in resistance for the two devices. At negative bias (top contact negative), the slope of the graded barrier becomes less steep; hence the effective barrier height is reduced allowing an increased dark current to flow through the device. Due to the higher resistance, the carrier accumulation in the V0728 will be higher allowing a large photovoltage buildup compared to the SP1007. A photovoltaic response was observed for all the tested devices with a graded barrier (V0727, V0728, SP1005, SP1006, and SP1007) showed at room temperature. As the spectral measurements, open circuit voltage of the device was measured by a voltage amplifier (Stanford Research, SR 560) and a Perkin Elmer system 2000 FTIR. The data were calibrated using responsivity of a bolometer. Out of the tested devices, the highest signal was observed for the device from the wafer V0728, as expected through the analysis of I–V data. The open circuit voltage responsivity spectra of a device from this wafer at 280 K and 300 K are shown in Fig. 2(a). At 300 K, a peak responsivity of 460 mV/W was observed at the wavelength of 1.8 μm and the estimated photocurrent is ~ 40 μA/W. The Johnson noise limited specific detectivity value for the device is calculated as D* = 1.5 × 10^6 Jones using

$$D^* = R_v \sqrt{\frac{A}{4kTR_0}}$$

Here, R_v is the responsivity in volts per watt and, R_0 is the resistance at zero bias, A is the area of the device, k is the Boltzmann constant, and T is the temperature. When the temperature of the device was reduced, an increase in the responsivity and D* values at 300 K, at 1.8 μm, is tabulated in Table I. The quantum efficiency (QE) of the devices is calculated to be 0.03% at the peak response.

The responsivity spectra of SP1005, SP1006, and SP1007 at room temperature are shown in Fig. 2(b). SP1007, having a thicker emitter of 80 nm, shows a higher responsivity compared to the other two wafers (SP1006 and SP1005) which have thinner emitters of 50 nm and 20 nm, respectively.

### TABLE I. Summary of the device parameters, where X1, X2, and X3 represents the aluminum (Al) fraction of the barriers at the bottom contact and the emitter ends of the graded barrier, and at the constant barrier, respectively. The responsivity and specific detectivity (D*) of the devices at 300 K, and a wavelength of 1.8 μm, are also shown.

<table>
<thead>
<tr>
<th>Device No.</th>
<th>X1</th>
<th>X2</th>
<th>X3</th>
<th>Emitter thickness (nm)</th>
<th>Peak responsivity (mV/W) at 300 K</th>
<th>D* (Jones) at 300 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>V0727</td>
<td>0.55</td>
<td>1.0</td>
<td>0.57</td>
<td>20</td>
<td>17.1</td>
<td>6.0 × 10^4</td>
</tr>
<tr>
<td>V0728</td>
<td>0.55</td>
<td>1.0</td>
<td>0.57</td>
<td>80</td>
<td>450</td>
<td>1.2 × 10^6</td>
</tr>
<tr>
<td>SP1001</td>
<td>0.75</td>
<td>0.75</td>
<td>0.57</td>
<td>80</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>SP1005</td>
<td>0.45</td>
<td>0.75</td>
<td>0.57</td>
<td>20</td>
<td>1.1</td>
<td>9.9 × 10^3</td>
</tr>
<tr>
<td>SP1006</td>
<td>0.45</td>
<td>0.75</td>
<td>0.57</td>
<td>50</td>
<td>3.9</td>
<td>3.3 × 10^4</td>
</tr>
<tr>
<td>SP1007</td>
<td>0.45</td>
<td>0.75</td>
<td>0.57</td>
<td>80</td>
<td>20.8</td>
<td>1.4 × 10^5</td>
</tr>
</tbody>
</table>
is showing an exponential behavior. This phenomenon has
responsivity shown in inset of Fig.2(a)); the response is
photovoltaic response shows a peak at a wavelength of 1.8
FIG. 2. (a) The photovoltaic response of V0728 at 280 K and 300 K; the
emitter thicknesses (80 nm, 50 nm, and 20 nm, respectively). A peak response was seen at
V0727 is lower owing to the smaller emitter, 20 nm compared to 80 nm in
emitter thickness. The photovoltaic response decreased with decreasing emitter thick-
threshold at 2.6 \( \mu m \). The photovoltaic responsivity increases with the decreasing
temperature. Inset: Responsivity of wafer V0727 at 300 K. The responsivity of
V0727 is lower owing to the smaller emitter, 20 nm compared to 80 nm in
V0728. (b) The photovoltaic response of SP1007, SP1006, and SP1005 at
300 K. The photovoltaic response decreased with decreasing emitter thick-
nesses (80 nm, 50 nm, and 20 nm, respectively). A peak response was seen at
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V0727 is lower owing to the smaller emitter, 20 nm compared to 80 nm in
V0728. Inset: Responsivity of wafer V0727 at 300 K. The responsivity
Photovoltaic response was observed for V0728 and V0727
(responsivity shown in inset of Fig. 2(a)); the response is
higher in V0728 with an 80 nm emitter. Since each wafer has
the same doping density in the emitter, the device with a
thicker emitter is thus likely to have an increased charge accu-
mulation. The higher photovoltage is a result of a higher num-
calorid in the contact region. Wafer
SP1001, which did not have a graded barrier, did not show a
photovoltaic response when operated close to room tempera-
tures. Without the graded barrier, there will be no net carrier
transport in either direction, and hence no photovoltage should
be observed.
A similar behavior was observed for V0728 and V0727
(responsivity shown in inset of Fig. 2(a)): the response is
higher in V0728 with an 80 nm emitter. Since each wafer has
the same doping density in the emitter, the device with a
thicker emitter is thus likely to have an increased charge accu-
mulation. The higher photovoltage is a result of a higher num-
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tures. Without the graded barrier, there will be no net carrier
transport in either direction, and hence no photovoltage should
be observed.

The ratio of the peak responsivity (1.8 \( \mu m \)) for V0728 to
V0727 is ~26, whilst for SP1007 to SP 1005 it is ~19. This
responsivity increment is much greater than the ratio in emitter
thickness. The responsivity increase in the SP devices with emitter thickness is shown in the inset of Fig. 2(b) and
is showing an exponential behavior. This phenomenon has
not yet been fully understood. The difference in the responsivity ratios between V07 and SP wafers may, however, be a
result of the differences in the rate of scattering at the barriers, owing both to the two different methods used in growth
and also to the difference in the aluminum fractions in the graded barriers (the gradient in the barrier). Additionally due
to the differences in the device resistance, the accumulated
carriers may discharge quickly in the SP series devices com-
pared to the V07 series.

Devices V0728 and V0727 shows a photoresponse threshold at ~2.6 \( \pm 0.2 \) \( \mu m \), while SP1005, SP1006, and
SP1007 show a broader response region with a threshold around 3.5 \( \pm 0.2 \) \( \mu m \). The Arrhenius plot of dark current ver-
sus temperature gives the barrier height as ~490 \( \pm 15 \) meV
(2.55 \( \pm 0.1 \) \( \mu m \)) and ~360 \( \pm 10 \) meV (3.44 \( \pm 0.1 \) \( \mu m \)) in agreement with the photovoltaic response threshold. The
barrier height calculated using the Anderson rule, conduction
band to valance band ratio (CB:VB) of 60:40 gives a VB barrier
height ~610 meV for AlAs/GaAs interface in V07 series
(barrier due to difference in aluminum fractions x = 1 and x
= 0) and a barrier height of ~430 meV for Al0.75Ga0.25As/
GaAs interface (x = 0.75 and x = 0) in the SP series. The
constant barrier height is ~300 meV (x = 0.57 and x = 0)
for both the sets of devices. Therefore, the barrier offset for
V07 and SP samples is ~310 meV (x = 0.57 and x = 1) and
~130 meV (x = 0.57 and x = 0.75), respectively. None of
the barrier heights calculated by the Arrhenius data are equivalent to any of the barriers or barrier offsets calculated
by the Anderson Rule. The difference in the values obtained
by Arrhenius data and Anderson rule can be due to the tun-
neling effects through thinner region of the graded barrier.
Another reason can be the Anderson rule of CB:VB ratio of
60:40 may not be valid for aluminum fraction, x > 0.45, as
the X-valley becomes lower than the \( \Gamma \)-valley for AlGaAs
under this condition and the band gap becomes indirect and
lower than the energy difference between VB and \( \Gamma \)-val-
ley.\(^{12}\) Additionally, CB:VB ratios from 55:45 to 65:35 can be
found in literature for GaAs/AlGaAs interface, and 67:32
(66:34) ratio gives the band offset of 488 meV (365 meV)
for V07 (SP) devices in agreement with the values calculated
by Arrhenius data (490 \( \pm 15 \) meV and ~360 \( \pm 10 \) meV).

The variation in D* for V0728 with wavelength in both
the photoconductive mode (with a bias of ~0.1 V) and pho-
tovoltaic mode (0 V bias) is shown in the Fig. 3. The noise
generated by the measuring instruments is negligible com-
pared to the device noise. The inset of Fig. 3 shows the noise
current density \( (S(f) \) of V0728 at ~0.1V bias voltage and at 0 V bias. At high frequency (f > 10 kHz), the measured
noise density is closer to the Johnson noise limit. D* calcu-
lated with the measured noise at 10 kHz is 1.2 \( \times 10^6 \) Jones.
As a comparison between the photovoltaic and photoconduc-
tive modes of operation, sample V0728 was then operated in
photoconductive mode under the negative bias (bottom con-
tact positive) for which it was designed. The D* value of
1.5 \( \times 10^6 \) Jones for photovoltaic operation was significantly
higher than the photoconductive value of 3.5 \( \times 10^4 \) Jones.
This indicates the potential for better performances of devi-
ces, in the photovoltaic mode of operation using graded bar-
riers at room temperature.
Noise current density ($S(f)$) of V0728 at K. Photovoltaic mode has a higher detectivity due to low noise. Inset: The shot noise caused by dark current in biased device. Shows a low noise level in the device with $0$ V bias due to the absence of shot noise caused by dark current in biased device.

IV. DISCUSSION

The $D^*$ obtained for this device is comparatively low compared to other infrared detectors working at room temperature and responding in shorter wavelength ($< 2$ $\mu$m), such as the p-i-n InGaAs detector with $D^*$ of the order of $10^{11}$ Jones. However, these results shown in this paper are not from a device designed for optimized photovoltaic mode operation. However unlike other detectors, graded barrier detectors are intra-band devices, providing wavelength tunability by adjusting the barrier height. Therefore, implementation of the design can lead to uncooled IR detectors for long wavelength detection. Further improvements to the $D^*$ is possible by modifying the structure parameters of the graded barrier device; such as having thicker emitters, adjusting the barrier thicknesses, the aluminum composition in the barriers, multiple layers, emitter doping, and substituting the emitter layer with different materials with higher absorption coefficient. Possible modifications and expected improvement factors summarized in Table II and are briefly discussed below.

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Based on the results and calculations published elsewhere, increasing the emitter doping from $1 \times 10^{19}$ $\text{cm}^{-3}$ up to $3 \times 10^{19}$ $\text{cm}^{-3}$, an improvement factor of $\sim 3$ is expected by increasing the number of excited carriers. Similarly, analyzing the improvement in the responsivity with increasing gradient in the barrier, shown in Figs. 2(a) and 2(b), an improvement by factor of $\sim 3$ is expected by lowering the aluminum fractions from $X_1 = 0.55$ to 0.05 at the lower end of the barrier. Lowering the aluminum fraction at the lower end of the graded barrier will allow the VB in the bottom contact to shift further, generating a higher response voltage. And with addition of 30 emitter/barrier layers will improve the photon absorption; hence an improvement factor of 25 is expected. Multilayer structure will increase the photon absorption in the device; hence more carriers will be excited and accumulated in the contact region. Additionally, multilayer device can act as a series connection of individual units, therefore increase the response voltage. Furthermore, keeping the resistance of the device to an optimum value by adjusting the barrier thicknesses, that maintains the low noise as well as a high responsivity, will improve the $D^*$ by an additional factor of 3 or more improving the $D^*$ to about $10^9$ Jones, make this device competitive with the reported photovoltaic devices operates under low applied bias voltage. Additionally an improvement factor of $\sim 15$ can be expected via enhancing the absorption using surface plasmon effects; theoretical models have predictions of around 20 times enhancement of absorption via plasmon effects. The result is a total enhancement with a factor of $10^6$. Furthermore by adopting different materials with high absorption coefficient (e.g., at $\lambda \sim 1$ $\mu$m, $T \sim 295$ K and p-doped ) than GaAs ($\sim 20$ $\text{cm}^{-1}$) such as InN ($\sim 10^3$ $\text{cm}^{-1}$) and InP ($\sim 200$ $\text{cm}^{-1}$) shall enhance the absorption, hence the performance of the device by a factor of 10 or more. This offers the prospect of the detectivity to be greater than $10^{11}$ Jones which is a competitive with commercially available detectors, such as the p-i-n InGaAs detector with $D^*$ of the order of $10^{11}$ Jones.

V. CONCLUSION

In conclusion, single emitter barrier structures with p-doped GaAs emitters and undoped AlGaAs graded barriers were tested for their photovoltaic response. We found that structures with a graded barrier had a photovoltaic response at room temperature and without any applied bias voltage. A device with a higher aluminum fraction in the graded barrier ($x = 1$ to 0.55), and with an emitter thickness of 80 nm, showed the highest responsivity of $\sim 450$ mV/W at 300 K. This responsivity was shown to increase as temperature decreased. Furthermore, increasing the emitter region thickness by a factor of four led to an increase in the peak responsivity by factor of $\sim 26$. Devices also showed better $D^*$ values when operated in a photovoltaic mode rather than in a

### Table II. Summary of expected enhancement factors due to modifications proposed for the present structure.

<table>
<thead>
<tr>
<th>Description</th>
<th>Present value</th>
<th>Proposed value</th>
<th>Expected improvement factor in $D^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase doping</td>
<td>$1 \times 10^{19}$</td>
<td>$3 \times 10^{19}$</td>
<td>3</td>
</tr>
<tr>
<td>Gradient in the barrier ($X_1$)</td>
<td>0.55</td>
<td>0.05</td>
<td>3</td>
</tr>
<tr>
<td>Number of layers ($30$)</td>
<td>1</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Impedance (Johnson noise)</td>
<td>$15 \text{k}\Omega$</td>
<td>$2 \text{k}\Omega$</td>
<td>3</td>
</tr>
<tr>
<td>Plasmon effect</td>
<td>—</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>High absorbing material</td>
<td>GaAs ($\sim 20$ $\text{cm}^{-1}$)</td>
<td>InN ($\sim 10^3$ $\text{cm}^{-1}$)</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>InP ($\sim 200$ $\text{cm}^{-1}$)</td>
<td>10</td>
</tr>
</tbody>
</table>
photoconductive mode. Possibility of further enhancing the responsivity and detectivity is discussed. Additionally, the concepts presented in this paper can be extended to long wavelength IR radiation in the 8–14 μm range, as well as the terahertz frequency range, using phosphide and nitride based materials. Use of a photovoltaic mode of operation thus offers considerable potential advantages for long wavelength detection.

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