Very Long-Wavelength GaAs/Al$_x$Ga$_{1-x}$As Infrared Hot Electron Transistor

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ABSTRACT

We have demonstrated a bound to continuum state GaAs/Al$_x$Ga$_{1-x}$As infrared hot electron transistor which has a peak response at $\lambda_p = 16.3 \mu m$. This device utilizes a bound-to-continuum quantum well infrared photodetector as a photosensitive emitter and a wide Al$_x$Ga$_{1-x}$As barrier between the base and the collector as an energy discriminating filter. An excellent photo-current transfer ratio of $\alpha_p = 0.12$ and very low dark current transfer ratio of $\alpha_d$: $7.2 \times 10^{-5}$ is achieved at a temperature of $T = 60$ K.
Infrared (IR) detectors and imaging systems that operate in the wavelength range 3-18 μm are required in many space applications such as monitoring the global atmospheric temperature profiles, relative humidity profiles, cloud characteristics, and the distribution of minor constituents in the atmosphere which are being planned for the NASA’s Earth Observing System (EOS). These space applications have placed stringent requirements on the performance of the IR detectors and arrays including high defectivity, low dark current, uniformity, radiation hardness and lower power dissipation. Also this spectral region is rich in information vital to the understanding of composition, structure and the energy balance of molecular clouds and star forming regions of our galaxy. Thus, there is a great interest in IR detectors operating both inside and outside the atmospheric windows (3 -5 μm and 8-12 pm).

Since the GaAs based quantum well infrared photodetectors (QWIPs)\textsuperscript{1-13} which utilize the intersubband transitions meet most of the above mentioned requirements, these detectors should be very attractive for the detection of IR radiation in the 6- 18 μm spectral range. However the only problem associated with the very long wavelength QWIPs (k> 12 μm) is the higher dark current which adversely affects detector performance. By analyzing the dark current of shallow quantum wells which were designed for very long wavelength operation, we have realized that at low temperatures (< 60 K) the total tunneling contribution of the dark current (sequential tunneling + thermionic assisted tunneling) is significantly higher than the thermionic contribution of the dark current (Fig. 1). The conduction electrons carrying these two tunneling current components are lower in energy than the photoelectrons 8. Thus, an IR hot electron transistor (IHET)\textsuperscript{14-16}, which has an additional wide Al\textsubscript{x}Ga\textsubscript{1-x}As barrier to filter out sequential tunneling and thermionic assisted tunneling currents will perform better at very long wavelength than QWIP.

In order to analyze the dark current of a QWIP which has a intersubband absorption peak at 16 μm, we first calculated the effective number of electrons \textsuperscript{11,17} n(V) which are thermally excited into the continuum transport states, as a function of bias voltage V, using the following expression.

\[
n(V) = \left(\frac{m^*}{\pi \hbar^2 L_p}\right) \int_{E_o} f(E)T(E,V) dE \tag{1}
\]
The first factor containing the effective mass \( m^* \) represents the average three dimensional density of states. Where \( L_p \) is the **superlattice period**, \( f(E) \) is the Fermi factor \( f(E) = [1 + \exp(E - E_0 - E_F)/KT]^{-1} \), \( E_0 \) is the bound state energy, \( E \) is the two-dimensional Fermi energy, \( E \) is the energy of the electron, and \( T(E,V) \) is the tunneling current transmission factor which is obtained by using WKB approximation to a biased quantum well. In equation 1, the effective number of electrons above the barrier account for **thermionic** contribution and the number of electrons below the barrier account for **thermionic** assisted tunneling and tunneling contribution of the dark current. Then the bias-dependent dark current \( I_d(V) \) was calculated, using \( I_d(V) = eA\bar{v}(V) \), where \( \bar{v}(V) \) is the average transport velocity, \( A \) is the device area, and \( e \) is the electronic charge. The average transport velocity was calculated using \( \bar{v}(V) = \mu F[1 + (\mu F/\nu_s)^2]^{-1/2} \), where \( \mu \) is the mobility, \( F \) is the electric field, and \( \nu_s \) is the saturated drift velocity. In order to obtain \( T = 60\, \text{K} \), bias-dependent dark current \( \mu = 1200 \, \text{cm}^2/\text{Vs} \) and \( \nu_s = 5.5 \times 10^6 \, \text{cm/s} \) was used. Fig. 1 shows the \( T=60\, \text{K} \) dark current due to thermionic emission, total dark current (thermionic + thermionic assisted tunneling + tunneling), and experimental dark current of a QWIP sample which has wavelength cutoff \( \lambda_c = 17.8 \, \text{p.m.} \). According to the calculations tunneling through the barriers dominate the dark current at temperatures below 30K, at temperatures between 30-55 K thermionic assisted tunneling might become important, and at temperatures above 55 K thermionic emission into the continuum transport states dominate the dark current.

As shown in Fig. 2 the device structure consisted of a multi-quantum well region of 50 periods of 500 \( \text{Å} \) undoped \( \text{Al}_{0.11}\text{Ga}_{0.89}\text{As} \) barrier and 65 \( \text{Å} \) doped GaAs well. The quantum wells were doped to \( n = 5 \times 10^{17} \, \text{cm}^{-3} \), and sandwiched between a heavily doped (\( n = 1 \times 10^{18} \, \text{cm}^{-3} \)) \( 1 \, \mu\text{m} \) GaAs contact layer at the bottom as the emitter contact and a doped (\( n = 3 \times 10^{17} \, \text{cm}^{-3} \)) 500 \( \text{Å} \) GaAs layer on the top as the base contact. On top of the base a 2000 \( \text{Å} \) undoped \( \text{Al}_{0.11}\text{Ga}_{0.89}\text{As} \) layer and a doped (\( n = 3 \times 10^{17} \, \text{cm}^{-3} \)) 0.5 \( \mu\text{m} \) GaAs layer were grown. The 2000 \( \text{Å} \) undoped \( \text{Al}_{0.11}\text{Ga}_{0.89}\text{As} \) As layer acted as a discriminator between the **tunnel-electrons** and photo-electrons, and the top 0.5 \( \mu\text{m} \) GaAs layer served as the collector. This device structure was grown on a semi-insulating GaAs substrate using molecular beam epitaxy. The inset of the Fig. 2 shows the diagram of the device. QWIP operation can be obtained between the emitter and the base and all the terminals (three) are required for the IHET operation. The IHET currents were measured at the collector (low energy tunneled electrons drain through the base).
To facilitate the application of bias to the quantum well structure, the following processing steps were carried out. First arrays of $200 \times 200 \ \mu\text{m}^2$ square collectors were chemically etched. In the next processing step the $6.25 \times 10^{-4} \ \text{cm}^2$ QWIP mesas which overlap with collector mesas were etched. Finally, Au/Ge ohmic contacts were evaporated onto the emitter, base and collector contact layers. The emitter and collector dark currents versus base-collector bias voltage are shown in Fig. 3. This figure also shows the excellent dark current filtration capability of the quantum filter. The dark current transfer ratio $\left( \alpha_d = \frac{I_{C(dark)}}{I_{E(dark)}} \right)$ is $7.2 \times 10^{-5}$ at operating base-collector bias voltage $V_{CB} = -42 \ \text{mV}$ (Fig. 3).

The intersubband absorption was measured on a 45" polished multipass waveguide at $T = 60K$ and absorption coefficient $\alpha_p = 694 \ \text{cm}^{-1}$ at $\lambda_p = 17.1 \ \mu\text{m}$ was obtained. This $\alpha_p$ corresponds to an unpolarized absorption quantum efficiency $\eta = \frac{1 - e^{-2\alpha_p}}{2} = 16.5\%$. Also these $200 \times 200 \ \mu\text{m}^2$ square detectors were back illuminated through a 45" polished facet as previously described in detail and the responsivity spectrums were measured with a tunable source consisting of a 1000K blackbody and a grating monochromator. The emitter and collector responsivity spectrums measured at $T = 60K$ are shown in Fig. 4. These two spectrums are similar in shape and peak at $\lambda_p = 16.3 \ \mu\text{m}$. The values of the cutoff wavelength $\lambda_c$ and the spectral width ($\Delta \lambda / \lambda_c$) (full width at half maximum) are $17.3 \ \mu\text{m}$ and $20\%$ respectively. The absolute responsivity was measured by two different methods: by comparing the detector photo-response with the photo-response of a calibrated pyroelectric detector, and by using a calibrated blackbody source. The peak responsivity $R_p$ of the detector was $400 \ \text{mA/W}$. Fig. 5 shows the IHET emitter and collector photo-currents versus base-collector voltage at $T = 60K$. The emitter was kept at -1V bias relative to the base potential. Due to the hot electron relaxation in the wide base region, the photo-current at the collector is smaller relative to the emitter photo-current. The photo-current transfer ratio $\left( \alpha_{ph} = \frac{I_{C(\text{photo})}}{I_{E(\text{photo})}} \right)$ is $1.2 \times 10^{-1}$ at $V_{CB} = -42 \ \text{mV}$. Note that the $\alpha_d$ is more than three orders of magnitude smaller than $\alpha_p$, which clearly indicates that the dark current of IHET is four orders of magnitude smaller than the dark current of QWIP, while the photo current is reduced by an order of magnitude only. This four orders of magnitude reduction in dark current reduces the noise current by two orders of magnitude (and hence results in higher defectivity).
The optical gain \( g \) of the detector determined from \( R = \frac{e}{h \nu} \eta g \) is given by \( g = 0.2 \). The noise current \( i_n \) was calculated using \( i_n = \sqrt{4eI_g A \Delta f} \), where \( A \Delta f \) is the bandwidth. The calculated noise current of the detector is \( i_n = 17 \) pA at \( T = 60K \). The peak \( D^* \) can now be calculated from \( D^* = R \sqrt{A \Delta f / i_n} \). The calculated \( D^* \) between the emitter and the base (QWIP) at \( V_{EB} = -1V, V_{CB} = -42 \) mV and \( T = 60K \) is \( 5.8 \times 10^8 \) cm\( ^2 \)Hz/W. The detectivity \( D^* \) at the collector (IHET) is determined from \( D^*(IHET) = \frac{\alpha_p}{\sqrt{\alpha_d}} D^*(QWIP) \). Table 1 shows the QWIP and IHET defectivity \( D^* \) at temperature \( T = 60K \) for several base-collector bias voltages. The defectivity of IHET increases dramatically with decreasing temperature reaching \( D^* = 1 \times 10^{12} \) cm\( ^2 \)Hz/W at \( T = 25 \) K and is even larger at lower temperatures.

In summary, we have demonstrated a very long wavelength (\( \lambda_c = 17.3 \mu m \)) IHET. Even though the QWIP emitters we have used were not optimized for 16 \mu m operation, this device clearly shows the dark current filtration capability of the energy filter. Thus, by incorporating an energy discriminating filter to an optimized QWIP which operate at 16 \mu m (\( D^* = 2 \times 10^{10} \) cm\( ^2 \)Hz/W at \( T = 60K \)), it is possible to achieve defectivity \( 1 \times 10^{11} \) cm\( ^2 \)Hz/W at \( T = 60K \). This \( D^* \) is adequate for most of the applications we have mentioned before. In addition, these detectors show absolutely no change in dark current and responsivity after an exposure of 6.5 Mrad of 1 MeV proton radiation which is equal to 5 years of radiation damage in space. Due to excellent uniformity, radiation hardness, lower power dissipation and lower 1/f noise these GaAs based QWIPS and IHETs should be extremely attractive to space born applications such as EOS missions and IR astronomy.

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REFERENCES

TABLE I. Comparison of QWIP and IHET defectivity $D^*$ at temperature $T = 60$ K for several base-collector bias voltages.

<table>
<thead>
<tr>
<th>$V_{BC}$ (mV)</th>
<th>$\alpha_p/\sqrt{\alpha_d}$</th>
<th>$D^*$ QWIP (cm$^2$/Hz/W)</th>
<th>$D^*$ IHET (cm$^2$/Hz/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>0.72</td>
<td>6.0 x 10$^8$</td>
<td>4.3 x 10$^8$</td>
</tr>
<tr>
<td>-35</td>
<td>1.17</td>
<td>5.9 x 10$^8$</td>
<td>6.9 x 10$^8$</td>
</tr>
<tr>
<td>-40</td>
<td>3.98</td>
<td>5.9 x 10$^8$</td>
<td>2.3 x 10$^8$</td>
</tr>
<tr>
<td>-42</td>
<td>14.14</td>
<td>5.8 x 10$^8$</td>
<td>8.2 x 10$^8$</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

FIG. 1 Theoretical and experimental (solid) dark current-voltage curves at T = 60K. Dotted curve shows the dark current (theoretical) due to thermionic emission only. Dashed curve shows the total dark current (thermionic + tunneling + thermionic assisted) versus bias voltage.

FIG.2 Conduction-band diagram of an infrared hot electron transistor, which utilizes bound to continuum intersubband transition. The inset shows the schematic diagram of IHET.

FIG.3 IHET emitter and collector dark currents versus base-collector voltage at T = 60K. Emitter bias was kept at -1V relative to the base potential. This figure also shows the lower energy dark current filtration capability of the quantum filter.

FIG.4 Emitter and collector responsivity spectra at temperature T = 60K. Emitter was kept at -IV bias relative to the base and collector.

FIG.5 IHET emitter and collector photo-currents versus base-collector voltage at T = 60K. Emitter was kept at -IV bias relative to the base potential.
T = 60K

- DARK CURRENT
  (TN + TAT + TH)
- DARK CURRENT
  (TH)
- EXPERIMENTAL

BIAS VOLTAGE $V_B$ (V)

DARK CURRENT $I_d$ (A)
A QWIP (Quantum Well Infrared Photodetector) is depicted in the diagram. It consists of multiple periods of a quantum well, with electrons being photoexcited from the emitter through the quantum well layers. The electrons then tunnel through a barrier and are collected in the collector. The diagram labels the electron flow from the emitter to the collector, passing through the quantum periods and the tunneling regions. The text indicates that there are 50 periods of 65 Å with a tunneling width of 500 Å. The current flows from the emitter to the collector, illustrating the concept of quantum tunneling in infrared detection.
T = 60K
V_{EB} = I_{V}

OPERATING VOLTAGE

COLLECTOR

'EMITTER'

BASE COLLECTOR VOLTAGE V_{CB} (mV)

DARK CURRENT I (A)
RESPONSIVITY $R$ (A/W)

- QWIP
- IHET

$T = 60 \, K$
$V_{EB} = -1 \, V$
$V_B = V_C = 0 \, V$

WAVELENGTH $\lambda$ (μm)
\[ T = 60K \]

\[ E_B = -I_v \]

EMITTER PHOTOCURRENT \( I_p \) vs BASE COLLECTOR VOLTAGE \( V_{CB} \) (mV)