InGaAs BASE INFRARED HOT-ELECTRON TRANSISTORS


U. S. Army Electronics Technology and Devices Laboratory
Fort Monmouth, New Jersey 07703-5601

ABSTRACT

An infrared hot-electron transistor with a thin (300 Å) InGaAs base layer is constructed. The transistor structure increases the detectivity of a state-of-the-art quantum well infrared photoconductor (QWIP) by a factor of two at 77 K, provides a photovoltage gain of 9.7 and a power gain of 3.2, reduces the noise equivalent temperature difference of a detector array by a factor of 36, and can be used for quasi-photovoltaic operation. Using the transistor structure as an analytical tool, the photoelectron transport properties of a QWIP can be extracted, based on which a quantitative theory for the photoconductive gain can be established.

INTRODUCTION

Long wavelength infrared detection using intersubband absorption has been progressing rapidly in the last several years. However, the operating principle of the detectors is still not well established. In order to better understand the optical and transport properties of the quantum well infrared photoconductor (QWIP) and further improve its performance, we included a thick quantum barrier adjacent to the QWIP structure. The resultant device constitutes an infrared hot-electron transistor (IHET). The additional barrier serves dual purposes. It functions as an hot-electron energy analyzer in the study of the properties of the QWIP structures, and as an electron energy filter in improving the detector sensitivity. The new structure also facilitates the readout coupling and reduces system noise by providing a photovoltage amplification and quasi-photovoltaic operation.

DETECTOR STRUCTURE

The infrared sensitive QWIP structure adopted in this study consists of 50 periods of GaAs wells and A10.25Ga0.75 As barriers. The well width and the barrier width are 40 Å and 200 Å respectively. The QWIP structure is sandwiched between a 6000-Å-thick n⁺-GaAs layer which is served as the emitter, and a 300-Å-thick In0.13Ga0.87As layer as the base. On the top of the base, a 2000-Å-thick A10.25Ga0.75 As barrier is grown as the analyzer and the filter, followed by a 1000-Å-thick GaAs collector. The structure is grown by molecular beam epitaxy on a (100) semi-insulating substrate. All the layers except the barriers are doped to 1.2×10¹⁸ cm⁻³. The band structure under emitter and collector biases is shown in Fig. 1.

Fig. 1. The band structure of the detector under an emitter bias Vₑ and a collector bias Vₓ. M₁ and M₂ are the minibands above the barriers.

INFRARED ABSORPTION OF QWIP

Infrared absorption of QWIP is initiated by electronic intersubband transitions from the ground state E₁ to the first excited state E₂. The absorption coefficient αₗ can be shown to be

\[ \alphaₗ = \frac{\rhoₑ}{L_p} \frac{e^2}{2\hbar m^* c^2} \sin^2 \theta \frac{\Gamma/2}{\Delta \omega^2 + (\Gamma/2)^2} \]  

where ρₑ is the 2-dimensional electron density per well, L_p is the length per period, f is the oscillator strength, θ is the angle between the direction of light propagation and the superlattice axis, n is the refractive index, and Γ is the absorption width.

With the present device parameters, α at the peak is calculated to be 1020 cm⁻¹, assuming f = 0.96, θ = 45°, hω₀ = 124 meV, Δλ/λ = 20%. If infrared radiation is allowed to make a double pass through the sample, the internal quantum efficiency η for unpolarized light is then equal to 11%. By using proper diffraction gratings for light coupling, η can be made close to unity (1). Fig. 2 (a) shows the absorbance of the mentioned QWIP structures at Brewster’s angle. From the peak absorption, we estimated η at 45° to be 5%, half of the estimated value. On the other hand, the measured

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\( \eta = 10\% \) of a similar structure is consistent with the calculated value. The second sample has the same nominal well width and doping density but different barrier parameters (width = 300 Å, and Al molar ratio = 0.22), the absorption curve is shown in Fig. 2 (b). The difference of \( \eta \) is most likely due to the uncertainty in the background subtraction. Note that the position of the absorption peak at \( E_2 \) is unrelated to the miniband structures of the samples, which are denoted by \( M_n \) in Fig. 2.

![Fig. 2](image)

**Fig. 2.** (a) The absorption spectrum and the photocurrent spectrum of a QWIP with well width 40 Å, barrier width 200 Å and Al molar ratio of 0.25. (b) The absorption spectrum of a QWIP with well width 40 Å, barrier width 300 Å and Al molar ratio of 0.22.

On the absorption curve, besides the \( E_2 \) peak, there are modulation structures. These modulation peaks, absent in the normal incidence, match the oscillatory structures in the responsivity curve shown in Fig. 2 (a) measured at temperature equal to 10 K and 45° light coupling angle. This result indicates that the absorption modulations are due to electron transitions. However, more studies are needed to identify their origin.

**DARK CURRENT CHARACTERISTICS**

The dark current characteristics of the detector at 77 K are shown in Fig. 3 for the collector to base bias \( V_c \) equal to 0 V. For this device, the emitter area is 7.92x10^{-4} cm², and the collector area is 2.25x10^{-4} cm². The device configuration is shown in the insert of Fig. 3. The emitter current \( I_e \) has been normalized according to the ratio of the emitter area to the collector area. The electron current injected to the base is separated into two branches according to the energy of the electrons by the barrier located between the base and the collector. The lower energy electrons are blocked by the barrier and drained through the base, while the higher energy electrons overcome the barrier and are collected at the collector as collector current \( I_c \). At the emitter to base bias \( V_e \) equal to -0.85 V, the dark current transfer ratio \( \alpha_d \), defined as \( I_e/I_c \), is 9.1x10^{-3}.

**PHOTOCURRENT TRANSPORT CHARACTERISTICS**

The photoresponse of the detector is characterized by using either a CO₂ laser or a glowbar-monochromator. Fig. 4 shows the current responsivity \( R \) as a function of \( V_e \). At low \( V_e \), \( R \) is directly proportional to \( V_e \). As \( V_e \) becomes more negative, \( R \) becomes constant. After \( V_e = -4 \) V, \( R \) increases again. In order to understand the voltage dependence of \( R \), it is important to know the photoelectron transport properties. In the following experiment, the collector photocurrent \( I_{pc} \) at the wavelength \( \lambda = 9.25 \) μm is measured as a function of \( V_e \) at different constant \( V_c \). As \( V_e \) becomes more negative, the barrier height of the energy analyzer becomes higher as shown in Fig. 1, and less photocurrent will be collected. The rate of

![Fig. 3](image)

**Fig. 3.** The emitter dark current \( I_e \) and the collector \( I_c \) as a function of the emitter bias \( V_e \) at 77 K. The insert shows the schematic device configuration.

![Fig. 4](image)

**Fig. 4.** A plot of experimental (solid curve) and theoretical (dotted curve) dc current responsivity \( R \) at photon energy equal to 150 meV as a function of emitter bias \( V_e \). The diamonds are the position of the photoelectron peak \( \epsilon V_m \) above the analyzer barrier shown in Fig. 5.
change of $I_{ph}$ as a function of $V_c$, $dI_{ph}/dV_c$, is then a measure of the photoelectron energy distribution $\rho$. The result is shown in Fig. 5. The width of the distribution $\Gamma_\rho$ is found to be insensitive to $V_c$ and the mean value is 76 meV. However, this apparent $\Gamma_\rho$ is not the intrinsic width of the photoelectron distribution since additional broadening occurs in the thick energy analyzer. Nevertheless, it does show that the distribution is Lorentzian and the energy of the photoelectrons

\[ \text{Fig. 5. A plot of } dI_{ph}/dV_c \text{ as a function of } V_c \text{ at different } V_e \text{ at } T = 10 \text{ K.} \]

increases with $V_c$ when $V_c$ becomes large. If we fix the values of $V_c (= -1.2 \text{ V})$ and $V_e (= 0 \text{ V})$ but change the incident photon energy, the photoelectron distribution can be analyzed at the front boundary of the analyzer. In this case, $\Gamma_\rho$ is found to be 17 meV.

PHOTOCONDUCTIVE GAIN OF QWIP

The above results show that the photoelectron distribution is very narrow, indicative of the diffusive transport of the photoelectrons; if the transport is ballistic or quasi-ballistic, the expected energy distribution would be much broader. Hence, the standard theory for photoconductor applies for the QWIP devices:

\[ R = \frac{e}{\hbar} \frac{\eta(V_c)g(V_c)}{\eta(V_e)} \]

where $R$ is the current responsivity, $\eta$ is the quantum efficiency, $g$ is the photoconductive gain, $v_e$ and $v_d$ are the contact recombination velocity and the drift velocity respectively, $\tau_\text{re}$ and $\tau_\text{tr}$ are the transit time and the hot-electron lifetime respectively. Eq. 2 is valid if $v_e << v_d$, i.e. hot-electron energy relaxation is small at the contacts.

Applying Eq. 2 to the present device, it is necessary to know the specific characteristics of the device. For the present device, high field domain (HFD) formation is observed up to 77 K. Below a critical emitter voltage ($V_e$) equal to -3 V, an increase in $V_e$ results in an increase in the number of HFDs, but keeping the electric field in the low field regime and the high field regime constant (2). Since the major contribution of the photocurrent is from the HFDs, the effective $\eta$ is then proportional to $V_e$ below $V_e$ and constant above $V_e$. Under a constant electric field below $V_e$, $\eta$ is also constant and actually equal to the saturated drift velocity since the electric field ($= 60 \text{ mV per period}$) is much larger than the critical ($7 \text{ mV per period}$) for maximum drift velocity to occur. Since $\eta$ is constant, $\tau_\text{tr}$, being the time to travel across the high field regime, is proportional to the $V_e$ below $V_e$ and constant above $V_e$. If we further assume $v_e$ and $\tau_\text{tr}$ to be constant, the dc current responsivity can be fitted as shown in Fig. 4 for $|V_e| < 4 \text{ V}$ with $v_e/v_d = 0.13$, consistent with the assumption, and $\tau_\text{re}/\tau_\text{tr} = 2.5$ at $V_e$.

For $|V_e| > 4 \text{ V}$, $R$ is larger than the fitting predicted, which indicates that $\tau_\text{tr}$ increases at large $V_e$. This hypothesis is consistent with the increasing photoelectron peak position at large $V_e$ shown in Fig. 5. As the average energy of the photoelectrons above the quantum barriers is increased, $\tau_\text{tr}$ is also expected to increase. In Fig. 4, we plot the peak position of $eV_m$ above the analyzer barrier, which show strong correlation with $R$.

DETECTIVITY OF QWIP AND IHET

The detectivity $D^*$ is defined as $R/\alpha/\eta$, where $\alpha$ is the area, $R$ is the current responsivity of unpolarized light at a particular wavelength and $\eta$ is the dark current induced noise current. At 77 K and $V_e$ equal to -0.85 V, $\eta$ at the emitter is measured to be 2.2 P/A/W (normalized by the square root of the detector area ratio). Combined with the $R$ measured in Fig. 4, $D^*$ is evaluated to be $4.0 \times 10^{10}$ cm$^2$/Hz/W at 8.2 $\mu$m. At $V_e = -1.8 \text{ V}$, $D^*$ is increased to $6.0 \times 10^{10}$ cm$^2$/Hz/W.

For the $D^*$ of an IHET, the current responsivity $R$ is reduced by a factor of $\alpha_D$ compared with the QWIP, but at the same time, the dark current is also reduced by a factor of $\alpha_D$, where $\alpha_D$ and $\alpha_D$ are the photocurrent transfer ratio and the dark current transfer ratio respectively. As a result, the $D^*$ of an IHET is increased by a factor of $\alpha_D/\sigma_D$ in comparison with the original QWIP. Experimentally, we found $\alpha_D$ equal to 0.33 at -0.85 V, 36 time larger than $\alpha_D$ at the same voltage, due to the fact that the energy of the photoelectrons is higher than the dark electrons at 77 K. Hence, the $D^*$ is increased by 3.5 times at this bias, and is equal to $1.4 \times 10^{11}$ cm$^2$/Hz/W. At 60 K, it is $1.1 \times 10^{11}$ cm$^2$/Hz/W.

Note that the $D^*$ of an IHET can exceed the estimation given by Kinch and Yariv (3) for the QWIPs. In their analysis, the thermal electrons include all the electrons with energy higher than the barrier height ($= 190 \text{ meV}$ in the present case), while an IHET is capable of discriminating all the dark electrons to the energy ($= 215 \text{ meV}$) corresponding to the cutoff wavelength. This difference alone reduces the dark current by a factor of 43, and hence increases the estimated $D^*$ by a factor of 6.6 at 77 K.

Besides improving the $D^*$, when the IHETs are used in a detector array with CCD readout circuit, the integration time per frame can be made longer by a factor of $1/\sigma_D$ due to the reduced dark current. As a result, the noise equivalent temperature difference (NEAT) can be improved by a factor of $\alpha_D/\sigma_D$ ($= 36$ in the present case) due to the increased $D^*$.
PHOTOVOLTAIC AMPLIFICATION AND QUASI-PHOTOVOLTAIC OPERATION OF AN IHET

In this section, we will show the advantages of an IHET in voltage coupled readout circuit. Specifically, an IHET provides an internal photovoltage gain which increases the voltage responsivity of a QWIP, and the IHET can be dc coupled to a high gain amplifier, thereby eliminating the requirement of light intensity modulation.

For a QWIP device, the photovoltage $V_{pc}$ measured with a loading resistance $R_L$ is given by

$$V_{pc} = j_P \left( \frac{1}{r} + \frac{1}{R_L} \right)^{-1}$$

(3)

where $j_P$ is the emitter photocurrent, $r$ is the internal dynamic resistance of the QWIP. On the other hand, if the same QWIP is incorporated into the IHET structure, the photovoltage $V_{pf}$ is given by

$$V_{pf} = \alpha_P j_P \left( \frac{1}{R} + \frac{1}{R_L} \right)^{-1}$$

(4)

where $1/R$ is the output admittance with the input open. In the present case, $R = 4.6 \text{M} \Omega$ is much larger than $r = 69 \text{k} \Omega$ (which has been normalized to the same area) at 77 K and $V_{ce} = -0.85 \text{V}$. If we assume $R_L$ in both the QWIP and IHET is equal to $r$ and $R$ respectively, then the voltage gain is equal to $\alpha_P R/r$ which is 22, and the power gain is equal to $\alpha_P^2 R/r$ which is 7.3. In the actual measurement, we used 2M$\Omega$ instead of 4.6 M$\Omega$ as the loading resistor in the IHET case. The voltage responsivity is measured to be 130 kV/W, and the photovoltage gain is measured to be 9.7, consistent with the theoretical value of 13 because of the smaller loading resistance. The power gain is then equal to 3.2 in this case.

Note that in order to obtain a large voltage gain, a positive bias $V_{cc}$ is needed to keep the quiescent point Q in the active region where $V_c$ is larger than -100 mV. On the other hand, when $R_L$ is small, the resultant $V_c$ can be very small when $V_{cc}$ is zero. For example, if $R_L$ is 100 k$\Omega$, $V_c$ will be only -8 mV, two orders of magnitude less than the applied emitter voltage. This small $V_c$ is easily offset by a positive $V_{cc}$ so that $V_c$ is zero when there is no photosignal, similar to the photovoltaic operation. The IHET can then be directly coupled to a high gain voltage amplifier without saturating the amplifier output. Fig. 6 (a) shows an amplifier circuit with a voltage gain of 1000. Fig. 6 (b) shows the output voltage of the circuit with $R_L = 100 \text{k} \Omega$ and $V_{cc} = 3 \text{mV}$ at $T = 10 \text{K}$ and $8 \text{mV}$ at 77 K. Note that the ambient output voltage without light is very close to zero volts, showing the flexibility of the transistor structure in dc coupling. Finally, it is interesting to note that the schematic diagram in Fig. 6 (a) may be viewed as a two stage amplifier, since the light detected at the emitter is first amplified by the transistor and subsequently by the operational amplifier.

Fig. 6. (a) The schematic diagram of an IHET dc coupled to a voltage amplifier. (b) the dc output voltage of the amplifier at 10 K (lower curve) and at 77 K (upper curve). The 77 K data have been shifted up by 10 V.

CONCLUSION

In summary, we have elucidated the basic operating principle of QWIP and IHET devices. In general, the IHET improves the characteristics of a QWIP significantly. For the present IHET, it increases the $D^*$ by a factor of two, increases the voltage responsivity by a factor of 9.7, provides power gain of 3.2, improves the noise equivalent temperature difference of an detector array by a factor of 36, and can be used for quasi-photovoltaic operation. With further device optimization, a broadband 10 $\mu$m IHET with $D^*$ close to 10$^{12}$ cm$^2$/Hz/W should be achievable.

REFERENCES

