Performance Assessment of Quantum Well Infrared Photodetectors

K. K. Choi, C. Y. Lee,* M. Z. Tidrow,** and W. H. Chang

U. S. Army Research Laboratory, EPSD

Fort Monmouth, NJ 07703-5601

S. D. Gunapala

Jet Propulsion Laboratory, California Institute of Technology

Pasadena, CA 91109

Abstract

The performance of GaAs/AlGaAs quantum well infrared photodetectors (QWIP) specified in terms of background limited temperature T_b and specific detectivity D* has been calculated based on realistic detector parameters. It is found that for a detector with an external quantum efficiency η of 6.970, T_b is 76 K for a 10 μm cutoff wavelength. This value of T_b agrees with the recent experimental result and is significantly higher than the previous estimation by Kinch and Yariv. If η is unity, the projected T_b can be as high as 88 K with a D* of 2.2 x 10^{11} cm√Hz/W. For a lower temperature operation, D* increases to 7.5 x 10^{11} cm√Hz/W at 77 K, comparable to that of a HgCdTe detector.

PACS number: 85.60.Dw, 85.60.Gz, 72.40.+w

*National Science Foundation Grant ECS-9217579, Cornell University, Ithaca, NY 14853

** National Research Council Research Associateship Program

Although quantum well infrared technology is progressing rapidly in recent years,[1] the ultimate performance of a GaAs/AlGaAs quantum well infrared photodetector (QWIP) has been perceived to be much lower than that of a HgCdTe detector. This impression is based on the assumption that, being a majority carrier device, the carrier lifetime of a QWIP is extremely short, which causes the thermal generation rate G_{th} much higher than an intrinsic detector. Combined with its relatively low external quantum efficiency η, the operating temperature of a QWIP would be much lower than that of a HgCdTe detector. In particular, Kinch and Yariv[2] estimated the temperature for background limited performance (BLIP) to be 58 K for a cutoff wavelength λ_c of 10 pm, 50 K lower than that of a good quality HgCdTe detector.

With the advancement of quantum well infrared technology, however, some of the restrictions in the original estimation based on an unoptimized QWIP have been overcome by better detector designs and better light coupling schemes. For example. G_{th} of a QWIP can be substantially reduced by lowering the doping density N_d, by increasing the barrier thickness,[3] or by placing an electron energy filter next to a QWIP to form an infrared hot-electron transistor (IHET).[4] Concurrently, η can be increased significantly using an improved grating coupler.[5,6] Recently, BLIP is achieved by an IHET with λ_c = 9.8 μm without a grating coupler at a temperature of 77 K,’ significantly higher than the previous estimation. Therefore, it is useful to reexamine the performance limitation of a QWIP in light of the recent development and project its potential performance. In this work, we will provide an estimation for the background limited temperature T_b and the dark current limited specific defectivity D^* of a QWIP with different λ_c based on realistic detector characteristics.

It is well known that the thermal generation rate G_{th}, defined as $n_{th}NL/\tau$, plays an important role in determining the sensitivity of a detector,[2] where N is the number of quantum well periods in a QWIP, L is the length of one quantum wcll period, and τ is the lifetime of a *photoelectron.* n_{th} is the volume density of thermally generated clcctrons approximate y given by[2]

$$n_{th} = \frac{1}{L}\frac{m^*}{\pi\hbar^2}kT e^{-(H - E_F - E_1)/kT}, \qquad (1)$$

where T is the operating temperature, H is the barrier height, E_F is the Fermi energy and El is the ground state energy. Here, we assume a QWIP with only onc bound state in the wcll and ignore the presence of thermally assisted tunneling (TAT) process.~'[8] From Eq. (1), in addition to lowering E_F, n_{th} and hence G_{th} can bc reduced by increasing the barrier thickness, provided that the factor NL/τ is independent of L, which is found to bc the casc.[9] The fact that τ is independent on L is consistent with the theoretical consideration[10] that optical phonon emission time is proportional to L duc to normalization of the initial continuum state wavcfunction. Physically, it means that a photoelectron spends more time in the barrier where recombination is not possible. Since NL/τ is independent on L, G_{th} is inversely proportional to L as long as the photoelectrons arc delocalized. One concern of increasing L is that the optical absorption might bc reduced since the oscillator strength is also dependent on the wavcfunction normalization length. However, the increase of the density of the continuum states exactly compensates the oscillator strength reduction, and hence the optical absorption for each quantum wcll is independent on the barrier thickness, [11]

For example, considering a QWIP with N = 30, N_d = 5 x 101^7 cm^{-3}, well width W = 50 A, barrier thickness B = 500 Å, Al molar ratio x = 0.25, the barrier height H and the Fermi energy E_F are equal to 187 and 8.9 meV, respectively. Using Eq. (l), n_{th} is calculated m bc 2.1

x 10^9 cm^{-3} at 77 K. Note that at this doping level and the assumed L, n_{th} is about three orders of magnitude lower than the minority carrier concentration (= 1.5 x 10^{12} cm^{-3}) of a good quality HgCdTe detector, which had been ignored in the previous estimation. To determine the lifetime τ, the opto-electronic properties of an IHET having the specified QWIP as the emitter are characterized.' At the emitter voltage V_e = - 1 V, the emitter dark current density J_{de} is 6.5 x 10^{-4} A/cm^2, from which the transit time (=NL/v_d) is calculated to be 88 ps. At the same time, from the photocurrent measurement, g is determined to be 1.0 at this bias, which gives τ a value of 88 ps. This value of τ is significantly larger than the previous estimation of 8.5 ps,[2] but is closer to the recent experimental result of 50 ps for a higher doping sample.[9] The larger τ is due to the larger L for the present QWIP (550 Å vs 330 Å assumed in ref. 2), a higher measured gain (1.0 instead of an assumed value of 0.5) and a lower measured v_d (= $J_{de}/n_{th}e$ = 1.9 x 10^6 cm/s instead of an assumed value of 1 x 10^7 cm/s) at the stated V_e. Combined with the calculated n_{th}, G_{th} is estimated to be 4.1 x 10^{15} $e^-/cm^2/s$, only a factor of 10 larger than a good quality HgCdTe detector, rather than five orders of magnitude larger as estimated previously.[2] The discrepancy of the two estimations is mainly due to the fact that the shorter lifetime 01' a QWIP (104 shorter) as emphasized previously is largely compensated by the smaller carrier concentration (10^3 smaller), leading to a comparable thermal generation rate. Here, wc note that although G_{th} determines the sensitivity of individual detectors, it does not contain all the information regarding to system performance. For a given G_{th}, a detector with a smaller n_{th} and a shorter τ will have the advantages of a smaller power consumption, a larger R_oA value and a higher speed.

In order to determine whether the estimated G_{th} is low enough for detector applications. it needs to be compared with the optical generation rate GOP (= $\eta\Phi$), where η is the external quantum efficiency and Φ is the optical flux. From the photocurrent measurement of the specified QWIP, λ_c is measured to be at 9.8 μm with an absorption width of 1.7 μm, from which Φ is calculated to be 2.3 x 10^{16} ph/cm^2/s for a 300 K background and a field of view FOV of 36°. From the optical absorption measurement, η is determined to be 6.9 % at the absorption peak using a 45° light coupling angle at the mesa edge without an antireflection coating. Hence, G_{op} is equal to 1.6 x 10^{15} e^-/cm^2/s, a factor of 2.6 lower than G_{th}. Therefore, the specified QWIP is not BLIP at 77 K under the present experimental condition. This estimation is close m the measured ratio of dark current to window photocurrent of 3.0 at the stated V_e.[7]

However, G_{th} can be further reduced by using an IHET structure. With an electron energy high pass filter,[4,7] the dark current with energy up to EC can be totally suppressed, where E_c is the electron energy corresponding to λ_c. For the electrons with E > EC, a fraction of electrons, which is referred as the collection efficiency f,[12] will be collected at the collector. The value of f depends on a number of factors. For example, it depends on the hot-electron population in the ballistic peak and in the phonon replicas after the lmt-electrons travel across the base,[12] the relative position between the filter barrier height and the hot-electron distribution, and the impurity scattering rate. Since the value of f is not the focus of this work, wc content here with the fact that the absolute value of f does not affect T_b because the filter suppresses both the dark current and the photocurrent equally for E > EC. In the present case, EC is 7.5 meV higher than H, so that n_{th} is reduced by another factor of 3.1 at 77 K, and G_{th} is equal to 1.3 x 10^{15} e^-/cm^2/s, only about a factor of 3 larger than that of HgCdTe detector. The reduced n_{th} allows the IHET operated in BLIP condition at V_e = -1 V, which is confirmed experimentally.[7] At lower V_e, T_b increases to 80 K.

Encouraged by the agreement between the present estimation and the experiment, we extend our estimation on T_b to detectors with different λ_c. In order to determine G_{op}, we obtained λ_c and the absorption linewidth for different well width W and Al molar ratio x based on our previous calculations.[11] The theoretical result together with our experimental data is shown in Fig. 1. The theory predicts accurately the optical properties of a QWIP. in order to simplify the discussion, wc will assume a constant W of 50 A in the estimation of T_b. For a fixed W, η will be fixed under the same experimental conditions since the oscillator strength is independent on x.[11] From the optical properties of the QWIP and the assumed η = 6.9 %, G_{op} can be calculated under the specified experimental conditions.

On the other hand, with τ and L assumed to be constant, G_{th} can be obtained from Eq. (1) for different x. The background limited temperature as a function of λ_c at which $G_{op} = G_{th}$ for both the QWIP (labeled as T_{be}) and the IHET (labeled as T_{bc}) is shown in Fig. 2. The theory shows that T_{bc} is generally higher than T_{bc} except for short λ_c where the resonant state becomes quasi-bound. In such case, an absorption width of 1.2 μm due to impurity broadening is assumed in the theory. Fig. 2 also shows the experimental data for detectors with optimized structures at the respective λ_c. For detecter A labeled in Fig. 2, W is equal to 50 Å, N_d = 1.2 x 10^{18} cm^{-3}, B = 500 Å and the quantum well barrier is equally divided into three layers of different x: 0.28, 0.305 and 0.3310 suppress the TAT current at the QWIP. The absorption width of [his structure is relatively wide (2 μm) because of the lack of parity symmetry, and the λ_c of this detector measured at the emitter (9.4 pm) is slightly longer than that measured at the collector (8.8 μm). Detector B is the same detector discussed above as an example. For detector C, W = 66 Å, N_d = 5 x 10^{17} cm^{-3}, B = 500 Å, and x = 0.15, and for the detector D, w = 60 Å, N_d = 8 x 10^{17} ~m-

3.B = 500 A, and x=0.15. The larger W adopted for longer λ_c is to improve η at the absorption peak through the increase of the oscillator strength.[1] However, the integrated absorption strength will remain the same due to the decrease of the absorption width as shown in Fig, 1, therefore, the present estimation is still applicable. Fig. 2 indicates that the present simple calculation provides a good estimation for both T_{bc} and T_{bc}. Nevertheless, the gap between T_{bc} and T_{bc} is usually larger than the theory predicted due to the presence of TAT current, which is not included in the theory.

With a grating coupler, η is expected to be enhanced. In Fig. 2, we provide an estimation for T_b if η can be increased to unity. Note that even for a 36° FOV, T_{bc} can be as high as 88 K for a 10 μm cutoff, 30 K higher than the previous estimation and is closer to a value of 82 K estimated by Liu based on a model calculation. 13 Compared with HgCdTe detectors, the G_{op} of an IHET is usually lower because of the narrower absorption width, leading to a lower T_b. But for any given bandwidth required by an application, one can usually design an IHET that can match this bandwidth, and hence having a T_b similar to HgCdTe detectors.

In addition to T_b, one can also estimate the dark current limited D* for the collector at the operating temperature equal to T_{bc}. In evaluating D*, we need to know the collection efficiency f for a particular detector. Here, we assume f = 1, which may be achieved by using a very narrow base to confine the photoelectrons in the ballistic peak[4] together with a graded high pass filter.[7] Fig. 3 shows the theoretical D* for different η. If η = 1, D* is equal to 2,2 x 10^{11} cm√Hz/W at 88 K and 7.5 x IO" cm√Hz/W at 77 K, comparable to a D* of 2 x 10^{12} cm√Hz/W for a HgCdTe detector at 77 K.[14] Fig 3 also shows the experimental data at T_{bc} with η = 6.9 %. The data arc lower than the theoretical curve since f is designed to be less than 1 in these detectors. As noted previously,[7] a large D* may not translate to a better focal plane array performance since a detector with f = 1 will generate too large the current level for signal integration. Instead, the present detectors are optimized for the lowest noise equivalent temperature difference for the currently available readout circuits.

In summary, wc have refuted the notion that the performance of a QWIP is necessarily inferior to a HgCdTc detector. In fact, the thermal generation rate and the quantum efficienc y of a QWIP can be made close to that of a HgCdTe detector, and hence a QWIP offers comparable performance for infrared detection even on the individual detector level, as demonstrated by Lundqvist et al. recently.[5] At longer wavelength regime, the preparation of HgCdTe detector arrays becomes increasingly difficult because of material nonuniformity. In this case, the higher GaAs material quality of QWW arrays becomes critical. For a cutoff of 15.4 μm, the present calculation shows that with a quantum efficiency of 0.5, the detectivity of an IHET operated at 59 K is 1.2 x 10^{11} cm$\sqrt{Hz}$/W, sufficient for most space applications.

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Captions

FIG. 1 A plot of cutoff wavelength λ_c and absorption width of a QWIP as a function of barrier Al molar ratio x for different well widths. The figure also shows the experimental optical properties of four QWIPs with W = 66 Å (diamonds), 60 Å (circles), 50 Å (squares), and 44 Å (triangles).

FIG. 2 A plot of background limited temperature for the emitter T_{be} and the collector T_{bc} as a function of cutoff wavelength λ_c for two values of quantum efficiency 0.069 and 1.0. The plot also shows the *experimental* T_{bc} (circles) and T_{bc} (triangles) using 45° light coupling angle with a field of view of 36°.

FIG. 3 The theoretical dark current limited detectivity D* as a function of cutoff wavelength λ_c at the operating temperature equal to T_{bc} for different values of quantum efficiency. In this plot, the collection efficiency f is assumed to be unity. The plot also shows the measured collector defectivity using 45° light coupling angle.

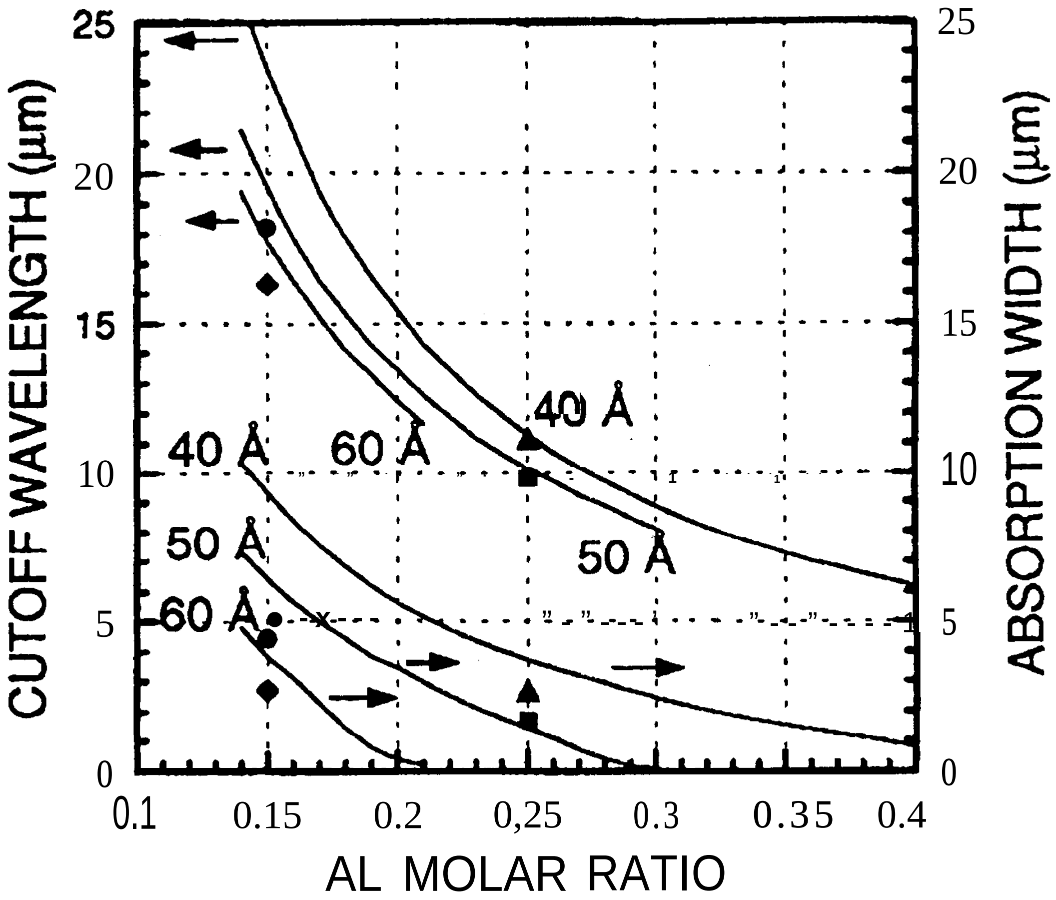
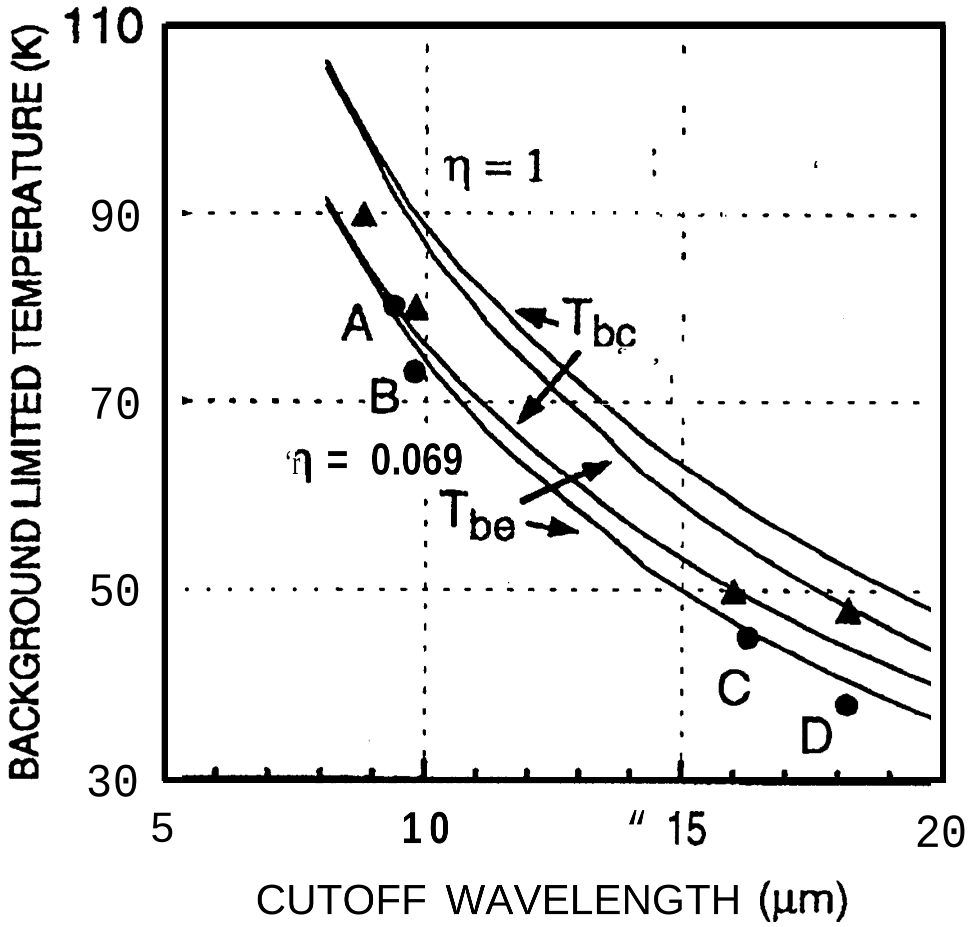

25
20
15
10
5
0
CUTOFF WAVELENGTH (μm)
25
20
15
10
5
0
ABSORPTION WIDTH (μm)
0.1
0.15
0.2
0,25
0.3
0.35
0.4
AL MOLAR RATIO
40 Å
60 Å
40 Å
50 Å
50 Å
60 Å
40 Å
50 Å

FIG. 1



BACKGROUND LIMITED TEMPERATURE (K)
110
90
70
50
30
5
10
15
20
CUTOFF WAVELENGTH (μm)
η = 1
η = 0.069
T_{bc}
T_{be}
A
B
C
D

FIG. 2

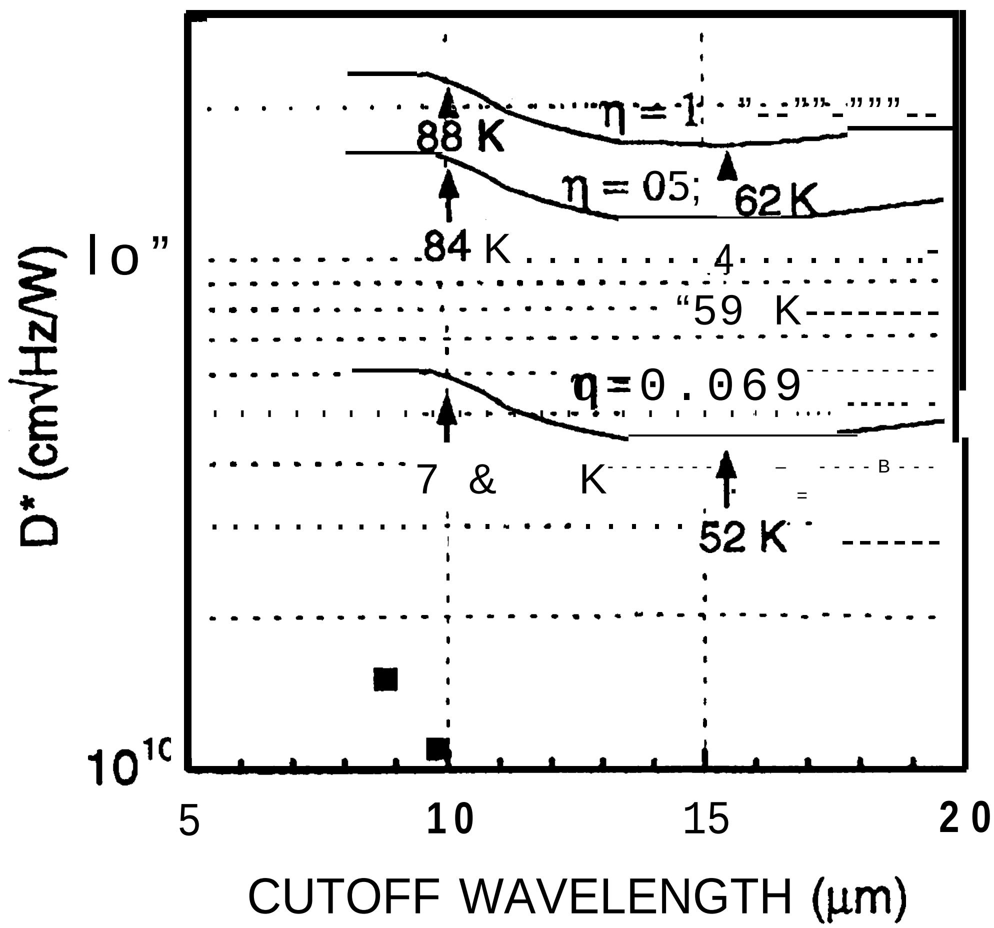

η = 1
88 K
η = 05;
62 K
84 K
59 K
η = 0.069
7 & K
52 K
D* (cm√Hz/W)
10^10
5
10
15
20
CUTOFF WAVELENGTH (μm)

FIG. 3