

# Fabrication and Characterization of 640x486 GaAs Based Quantum Well Infrared Photodetector (QWIP) Snapshot Camera

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## ABSTRACT

A 9  $\mu\text{m}$  cutoff 640x484 hand-held quantum well infrared photodetector (QWIP) camera has been demonstrated. Excellent imagery, with a noise equivalent differential temperature (NE $\Delta$ T) of 43 mK has been achieved. In this paper, we discuss the development of this very sensitive long wavelength infrared (LWIR) camera based on a GaAs/AlGaAs QWIP focal plane array (FPA) and its performance in quantum efficiency, NE $\Delta$ T, uniformity, and operability.

**KEY WORDS:** Intersubband Transitions, Infrared (IR), Long-wavelength Infrared (LWIR), Gallium Arsenide (GaAs), Quantum Well Infrared Photodetector (QWIP), Focal Plane Arrays, Noise Equivalent Temperature Difference (NE $\Delta$ T), Infrared Imaging Cameras

## INTRODUCTION

Fabricated entirely from large bandgap materials which are easy to grow and process, it is now possible to obtain large uniform focal plane arrays (FPAs) of QWIPs tuned to detect light at wavelengths from 6 to 25  $\mu\text{m}$  in the GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As material system [4]. Improving QWIP performance depends largely on minimizing the parasitic current that plagues all light detectors, the dark current (the current that flows through a biased detector in the dark, i.e., with no photons impinging on it). As we have discussed elsewhere [5,6], at temperatures above 45 K, the dark current of the QWIPs having cutoff wavelengths in the 8-12  $\mu\text{m}$  spectral region are entirely dominated by classic thermionic emission of ground state electrons into the energy continuum. Minimizing this dark current component is critical to the commercial success of the QWIP as it allows the highly-desirable high-temperature camera operation.

Therefore, we have designed the bound-to-quasi bound quantum well by placing the first excited state exactly at the well top. The previous QWIPs were called the bound-to-continuum, because the first excited state was a continuum energy band above the well top (typically 10 meV). Dropping the first excited state to the well top causes the barrier to thermionic emission (roughly the energy height from the ground state to the well top) to be ~10 meV more in our bound-to-quasi bound QWIP than in the bound-to-continuum one, theoretically causing the dark current to drop by a factor of ~6 at a temperature of 70 K [5-7]. The dark current-voltage curve of the 8.3  $\mu\text{m}$  peaked bound-to-quasi bound QWIP is shown in Figure 1. This compares well with the factor of ~6 drop we have expected from the theoretical estimations.

## TEST STRUCTURE RESULTS

Each period of the multi-quantum well (MQW) structure consists of a 45 Å well of GaAs (doped

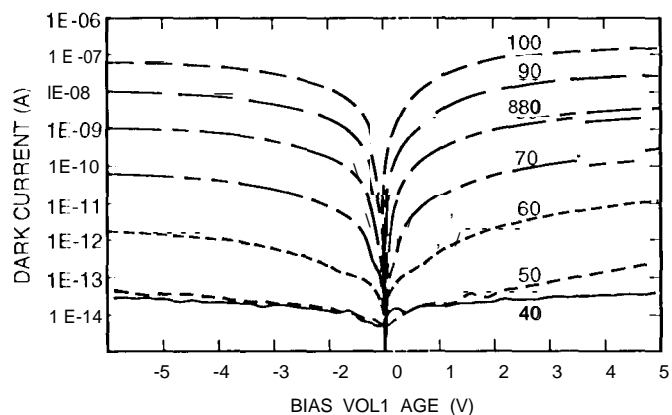


Figure 1. Dark current-voltage curves of 8.3  $\mu\text{m}$  peaked bound-to-quasi bound at temperatures from  $T = 40-100$  K. Data were taken with a 200  $\mu\text{m}$  diameter test structure and normalized to 18 x 18  $\mu\text{m}^2$  pixel.

$n \sim 5 \times 10^{17} \text{ cm}^{-3}$ ) and a  $500 \text{ \AA}$  barrier of  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ . Stacking identical quantum wells (typically 50) together increases photon absorption. Ground state electrons are provided in the detector by doping the GaAs well layers with Si. This photosensitive MQW structure is sandwiched between  $0.5 \mu\text{m}$  GaAs top and bottom contact layers doped  $n = 5 \times 10^{17} \text{ cm}^{-3}$ , grown on a semi-insulating GaAs substrate by molecular beam epitaxy (MBE). Then a  $0.7 \mu\text{m}$  thick GaAs cap layer on top of a  $300 \text{ \AA}$   $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  stop-etch layer was grown *in situ* on top of the device structure to fabricate the light coupling optical cavity. The MBE grown QWIP structure was processed into  $200 \mu\text{m}$  diameter mesa test structures (area =  $3.14 \times 10^{-4} \text{ cm}^2$ ) using wet chemical etching, and Au/Ge ohmic contacts were evaporated onto the top and bottom contact layers.

The detectors were back illuminated through a  $45^\circ$  polished facet [5] and a responsivity spectrum is shown in Figure 2. The responsivity of the detector peaks at  $8.3 \mu\text{m}$  and the peak responsivity ( $R_p$ ) of the detector is  $124 \text{ mA/W}$  at bias  $V_B = -2 \text{ V}$ . The spectral width and the cutoff wavelength are  $\Delta\lambda/\lambda = 10\%$  and  $\lambda_C = 8.8 \mu\text{m}$  respectively. The bias dependent peak responsivity of the detector was measured, and it is small, up to about  $V_B = -0.5 \text{ V}$ . Beyond that it increases nearly linearly with bias reaching  $R_p = 179 \text{ mA/W}$  at  $V_B = -5 \text{ V}$ . This type of behavior of responsivity versus bias is typical for a bound-to-quasi bound QWIP. The peak quantum efficiency was  $17.5\%$  at bias  $V_B = -2 \text{ V}$  for a  $45^\circ$  double pass. The lower quantum efficiency is due to the lower well doping density ( $5 \times 10^{17} \text{ cm}^{-3}$ ) as it is necessary to suppress the dark current at the highest possible operating temperature. A peak quantum efficiency as high as  $25\%$  has already been achieved with regular well doping density (i.e.,  $1 \times 10^{18} \text{ cm}^{-3}$ ). Due to lower readout multiplexer well depth (i.e.,  $9 \times 10^6$  electrons) a lower dark current is mandatory to achieve a higher operating temperature. In this case, the highest operating temperature of  $70 \text{ K}$  was determined by the cooling capacity of the liquid nitrogen laboratory dewar. The operating temperature of  $70 \text{ K}$  has been achieved by pumping on liquid nitrogen.

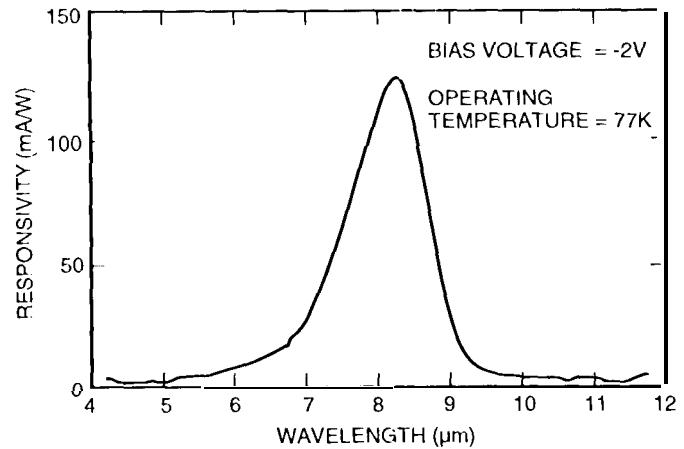


Figure 2. Responsivity spectrum of a bound-to-quasibound LWIR QWIP test structure at temperature  $T = 77 \text{ K}$ . The spectral response peak is at  $8.3 \mu\text{m}$  and the long wavelength cutoff is at  $8.8 \mu\text{m}$ .

The photoconductive gain  $g$  was experimentally determined using  $g = i_n^2 / 4eI_pB + 1/2N$ , where  $B$  is the measurement bandwidth,  $N$  is the number of quantum wells, and  $i_n$  is the current noise, which was measured using a spectrum analyzer. The photoconductive gain of the detector reached  $0.98$  at  $V_B = -5 \text{ V}$ . Since the gain of QWIP is inversely proportional to the number of quantum wells  $N$ , the better comparison would be the well capture probability  $P_c$ , which is directly related to the  $g$  by  $g = 1/Np_c$ . The calculated well capture probabilities are  $25\%$  at low bias (i.e.,  $V_B = -1 \text{ V}$ ) and  $2\%$  at high bias (i.e.,  $V_B = -5 \text{ V}$ ) which indicate the excellent hot-electron transport in this device structure. The peak detectivity is defined as  $D_p^* = R_p \sqrt{AB} / i_n$ , where  $R_p$  is the peak responsivity. The measured peak detectivity at bias  $V_B = -3.0 \text{ V}$  and temperature  $T = 70 \text{ K}$  is  $1.8 \times 10^{11} \text{ cm}^2/\text{Hz/W}$ . These detectors show background limited performance (BLIP) at bias  $V_B = -2 \text{ V}$  and temperature  $T = 73 \text{ K}$  for  $300 \text{ K}$  background with  $f/2$  optics.

## QWIP IMAGING FOCAL PLANE ARRAYS

It is well known that QWIPs do not absorb radiation incident normal to the surface unless the IR radiation has an electric field component normal to the layers of superlattice (growth direction) [5]. As we have discussed before [5,9] more IR light can be coupled to the QWIP detector structure by incorporating a two dimensional grating surface on top of the detectors which also removes the light coupling limitations and makes two dimensional QWIP imaging arrays feasible. This two dimensional grating structure was fabricated on the detectors by using standard photolithography and  $\text{CCl}_2\text{F}_2$  selective dry etching.

After the 2-D grating array was defined by the photolithography and dry etching, the photoconductive QWIPs of the  $640 \times 484$  FPAs were fabricated by wet chemical etching through the photosensitive GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  multi-quantum well layers into the  $0.5 \mu\text{m}$  thick doped GaAs bottom contact layer. The pitch of the FPA is  $25 \mu\text{m}$  and the actual pixel size is

18x18 $\mu\text{m}^2$ . The cross g[-stings on top of the detectors were then covered with Au/Ge and Au for Ohmic contact and reflection. Figure 3 shows twelve processed QWIP FPA on a 3 inch GaAs wafer. Indium bumps were then evaporated on top of the detectors for Si readout circuit (ROC) hybridization. A single QWIP FPA was chosen and hybridized (via indium bump-bonding process) to a 640X4X4 CMOS multiplexer (Amber Ali- 18 I) and biased at  $V_B = -2.0$  V. Figure 4 shows a size comparison of this large area long-wavelength QWIP FPA to a quarter. At temperatures below 70 K, the signal to noise ratio

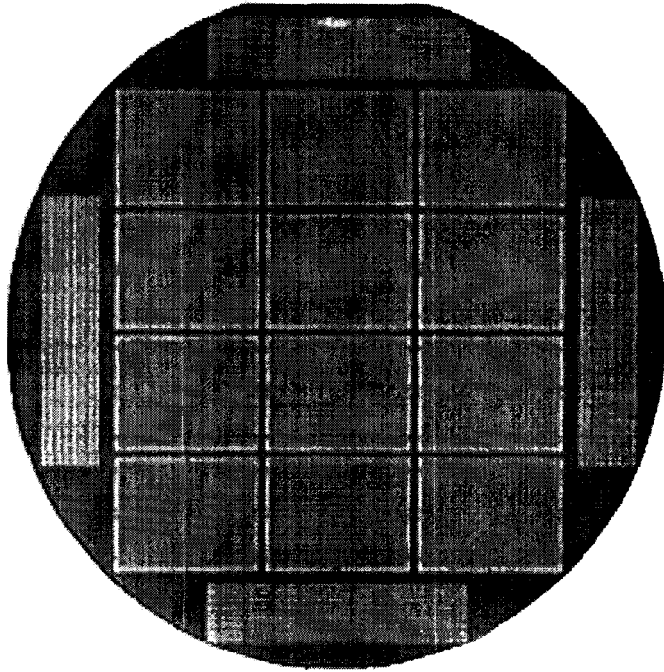


Figure 3. Twelve 640 x 484 QWIP focal plane arrays on a 3 in. GaAs wafer.

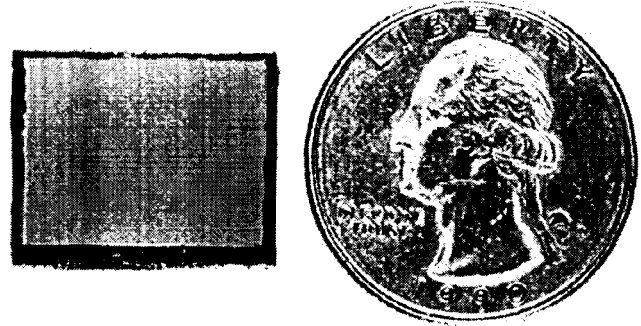


Figure 4. A size comparison of the 640 x 484 long-wavelength QWIP FPA to a quarter.

of the system is limited by array non-uniformity,, multiplexer readout noise, and photo current (photon flux) noise. At temperatures above 70 K, temporal noise due to the QWIP's higher dark current becomes the limitation. As mentioned earlier this higher dark current is due to thermionic emission and thus causes the charge storage capacitors of the readout circuitry to saturate. Since the QWIP is a high impedance device, it should yield a very high charge injection coupling efficiency into the integration capacitor of the multiplexer. In fact Bethea *et al.* [2] have demonstrated charge injection efficiencies approaching 90%. Charge injection efficiency can be obtained from [3]

$$\eta_{inj} = \frac{g_m R_{Det}}{1 + g_m R_{Det}} \left[ \frac{1}{1 + \frac{j\omega C_{Det} R_{Det}}{1 + g_m R_{Det}}} \right] \quad (1)$$

where  $g_m$  is the transconductance of the MOSFET and it is given by  $g_m = eI_{Det}/kT$ . The differential resistance  $R_{Det}$  of the pixels at -2 V bias is  $5.4 \times 10^{10}$  Ohms at  $T=70$  K and detector capacitance  $C_{Det}$  is  $1.4 \times 10^{-14}$  F. The detector dark current  $I_{Det} = 24$  pA under the same operating conditions. According to equation (1) the charge injection efficiency  $\eta_{inj} = 99.5\%$  at a frame rate of 30 Hz. The FPA was back-illuminated through the hat thinned substrate membrane (thickness  $\approx 1300$  Å). This thinned GaAs FPA membrane has completely eliminated the thermal mismatch between the silicon CMOS readout multiplexer and the GaAs based QWIP FPA. Basically, the thinned GaAs based QWIP FPA membrane adapts the thermal expansion and contraction coefficients of the silicon readout multiplexer. Therefore, this thinning has played an extremely important role in the fabrication of large area FPA hybrids. In addition, this thinning has completely eliminated the pixel-to-pixel cross talk of the FPA. This initial array gave excellent images with 99% of the pixels working, demonstrating the high yield of GaAs technology. The operability was defined as the percentage of pixels having noise equivalent differential temperature less than 100 mK at 300 K background and in this case operability happens to be equal to the pixel yield.

We have used the following equation to calculate the noise equivalent temperature difference (NETD) of the FPA.

$$NETD = \frac{\sqrt{AB}}{D_B^* (dP_B / dT) \sin^2(\theta / 2)} \quad (2)$$

where  $D_B^*$  is the blackbody detectivity,  $dP_B/dT$  is the derivative of the integrated blackbody power with respect to temperature, and  $\Theta$  is the field of view angle [i.e.,  $\sin^2(\Theta/2) = (4f^2 + 1)^{-1}$ , where  $f$  is the  $f$  number of the optical system]. The background temperature  $T_B = 300$  K, the area of the pixel  $A = (18 \mu\text{m})^2$ , the  $f$  number of the optical system is 2.3, and the frame rate is 30 Hz. Figure 5 shows the experimentally measured NE $\Delta T$  of the FPA at an operating temperature of  $T = 70$  K, bias  $V_B = -2$  V for 300 K background and the mean value is 43 mK. This agrees reasonably with our estimated value of 25 mK based on test structure data. The experimentally measured peak quantum efficiency of the FPA was 2.3% (lower focal plane array quantum efficiency is attributed to 51% fill factor and 30% reflection loss from the GaAs back surface). Therefore, the corrected quantum efficiency of a focal plane detector is 6.5% and this corresponds to an average of one pass of IR radiation (equivalent to a single 45° pass) through the photosensitive multi-quantum well region.

## FOCAL PLANE ARRAY CAMERA

A 640x484 QWIP FPA hybrid was mounted onto a 84-pin lead-less chip carrier and installed into laboratory dewar which can be cooled by liquid nitrogen, to demonstrate a LWIR imaging camera. The other element of the camera is a 100 mm focal length AR coated germanium lens, which gives a  $9.2^\circ \times 6.9^\circ$  field of view. It is designed to be transparent in the 8-12  $\mu\text{m}$  wavelength range, to be compatible with the QWIP's 8-9  $\mu\text{m}$  operation. The digital acquisition resolution of the camera is 12-bits, which determines the instantaneous dynamic range of the camera (i.e., 4096). However, the dynamic range of QWIP is 85 Decibels.

The measured mean NE $\Delta T$  of the QWIP camera is 43 mK at an operating temperature of  $T = 70$  K and bias  $V_B = -2$  V, for a 300 K background. The uncorrected NE $\Delta T$  non-uniformity (which includes a 1% non-uniformity of the ROC and a 1.4% non-uniformity due to the cold-stop in front of the FPA not yielding the same field of view to all the pixels) of the 309,760 pixels of the 640x484 FPA is about 10% (=  $\text{sigma}/\text{mean}$ ). Figure 6 shows the noise histogram of this first unoptimized 640x484 QWIP FPA. The non-uniformity after two-point (17° and 27° Celsius) correction improves to an impressive 0.1%. As mentioned earlier, this high yield is due to the excellent GaAs growth uniformity and the mature GaAs processing technology.

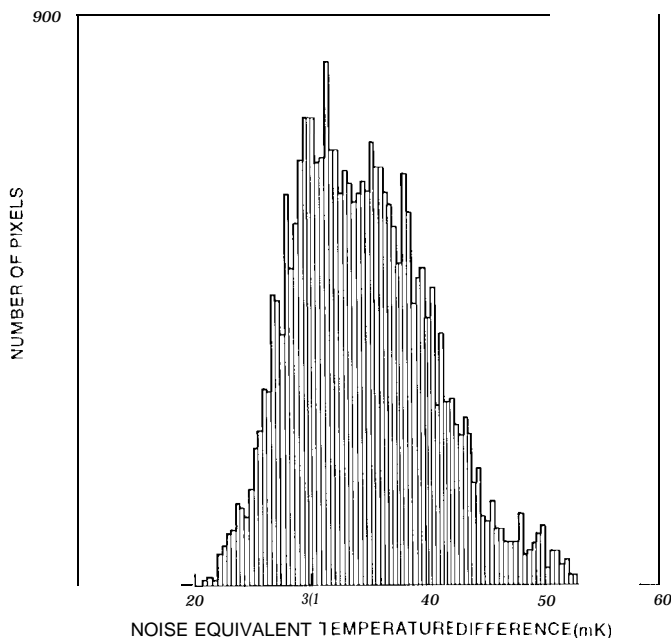


Figure 5. Noise equivalent temperature difference (NEAT) histogram of the 309,760 pixels of the 640 x 484 array showing a high uniformity of the FPA. The uncorrected non-uniformity (= standard deviation/mean) of this unoptimized FPA is only 10% including 1% non-uniformity of ROC and 1.4% non-uniformity due to the cold-stop not being able to give the same field of view to all the pixels in the FPA.

Video images were taken at a frame rate of 30 Hz at temperatures as high as  $T = 70$  K, using a ROC capacitor having a charge capacity of  $9 \times 10^6$  electrons (the maximum number of photoelectrons and dark electrons that can be counted in the integration time of each detector pixel). Figure 7 (a) and (b) show two frames of video image taken with this long-wavelength 640x484 QWIP camera. Figure 7(a) shows a man's face with a warm mustache which was heated by a hot air-blower. It also shows the hot air emanating from the air blower. Figure 7(b) shows a cold hand of a person who momentarily touched a cold soda can. These images demonstrate the high sensitivity of the 640x484 long-wavelength QWIP staring array camera.

It should be noted that these initial unoptimized FPA results are far from optimum. The light coupling gratings were not optimized (as described earlier) for maximum light coupling efficiency; no anti-reflection coatings were used on the backside of the FPA; and finally the multiplexer used was not optimized to supply the proper bias required by photoconductive QWIPs (i.e., AF-181 was optimized for photovoltaic InSb FPAs). Implementation of these improvements should significantly enhance the QWIP FPA operating temperature (i.e., 77 K for 9  $\mu\text{m}$ ).

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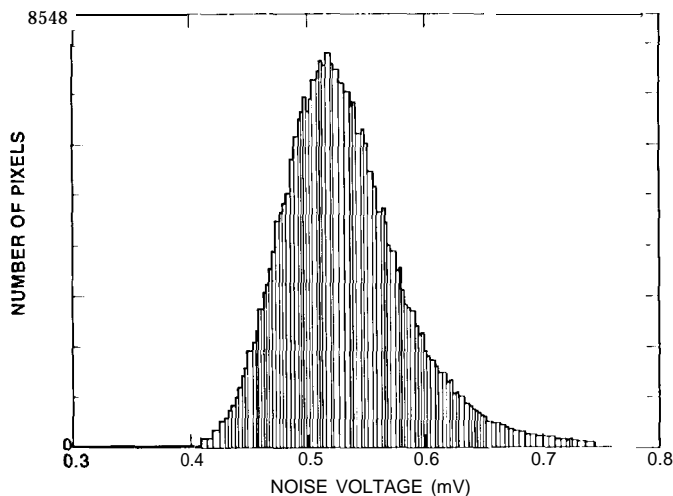


Figure 6. Noise histogram of the 640 x 484 long-wavelength QWIP FPA. The noise uniformity of this first unoptimized FPA is about 11% before corrections.

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Figure 7(a). A man's face with a warm mustache which was heated by a hot air blower. It also shows the hot air emanating from the air blower. Figure 7(b) shows a cold hand of a person who momentarily held a cold soda can. These images demonstrate the high sensitivity of the 640 x 484 long-wavelength QWIP staring array camera.

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