Quantum well infrared photodetectors for long wavelength infrared applications

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ABSTRACT

Quantum Well Infrared Photodetectors (QWIPs) offer greater flexibility than usual extrinsically doped semiconductor IR detectors because the wavelength of the peak response and cutoff can be continuously tailored by varying layer thickness (well width), barrier composition (barrier height), and carrier density (well doping density). The $GaAs/Al_xGa_{1-x}As$ material system allows the quantum well parameters to be varied over a range wide enough to enable light detection at any wavelength range between 6-20 μm [Ref 1,2] . The spectral band width of these detectors can be tuned from narrow ($\Delta\lambda/\lambda \sim 10\%$) to wide ($\Delta\lambda/\lambda \sim 40\%$), allowing various applications [Ref 3]. Also, QWIP device parameters can be optimized to achieve extremely high performance at lower operating temperatures (~ 40 K) for low background, long-wavelength, infrared applications in the strategic arena as well as in Astronomy. Furthermore, QWIPs offer low cost per pixel and highly uniform, large format, focal plane arrays (FPAs) mainly due to mature GaAs/AlGaAs growth and processing technologies.

1. INTRODUCTION

The detection mechanism of the Quantum Well Infrared Photodetector (QWIP) involves photoexcitation of electrons between ground and first excited state subbands of multi-quantum wells (MQWs), which are artificially fabricated by placing thin layers of two different, high-bandgap semiconductor materials alternately [1,2]. The bandgap discontinuity of the two materials creates quantized subbands in the potential wells associated with conduction bands or valence bands. The structure parameters are designed so that the photo excited carriers can escape from the potential wells and be collected as photocurrent. In addition to larger intersubband oscillator strength, these detectors offer greater flexibility than the usual extrinsically doped semiconductor IR detectors because the wavelength of the peak response and cutoff can be continuously tailored by varying layer thickness (well width) and barrier composition (barrier height) [1,2].

2. WAVELENGTH TENABILITY & SPECTRAL BANDWIDTH

The lattice matched $GaAs/Al_xGa_{1-x}As$ material system is commonly used to create such a QWIP structure. Highly uniform and pure crystal layers of such semiconductors can be grown on large substrate wafers [3,4], with control of each layer thickness down to a fraction of a molecular layer, using modern crystal-growth methods like molecular beam epitaxy (MBE). Thus, by changing the quantum well width and the barrier height (Al molar ratio of $Al_xGa_{1-x}As$ alloy), this intersubband transition energy can be varied over a wide enough range to enable light detection at any narrow wavelength range between 6-20 μm [1,2]. See Fig. 1. Unlike the responsivity spectrums of intrinsic infrared detectors, the responsivity spectrums of QWIPs are much narrower due to their resonance intersubband absorption [1,2]. The normalized responsivity spectra $R(\lambda)$ are given in Fig. 2, where we see that the *bound* and *quasibound* excited state QWIPs are much narrower $\Delta\lambda/\lambda \sim 10\%$ than the *continuum* QWIPs $\Delta\lambda/\lambda = 24\%$. This is due to the fact that, when the excited state is placed in the continuum band above the barrier, the energy width associated with the state becomes wider [1,2].

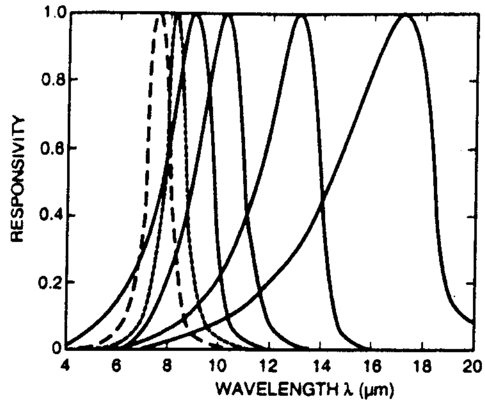


Fig. 1. Experimental measurements of the responsivity GaAs/AlxGa1-xAs QWIPs optimized to respond at different wavelength ranges.

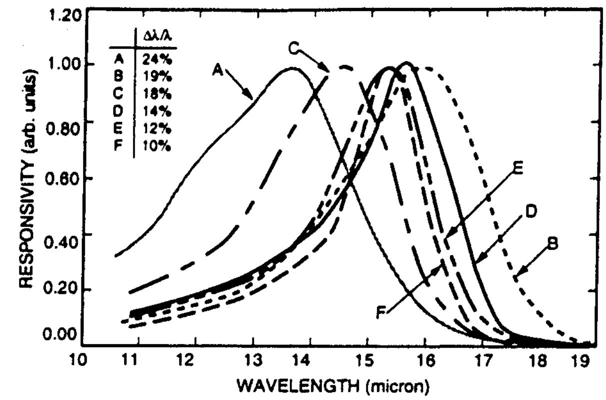


Fig. 2. Spectral band width variation of QWIPs with bound-to-bound, bound-to-quasibound and bound-to-continuum transitions.

Spectral bandwidth can be further increased by repeating a unit of several quantum wells with slightly different parameters, such as well width and barrier height [3]. Since each single set of parameters for a bound-to-quasibound quantum well corresponds to a spectral band pass of about 1.5 μm, three different sets of values are sufficient to cover a 12-16 μm spectral region. See Fig. 3. The device structure reported here involved 33 repeated layers of GaAs three-quantum-well units separated by thick $Al_xGa_{1-x}As$ barriers. The well thickness of the three-quantum-well units are designed to respond at peak wavelengths around 13, 14, and 15μm respectively and are separated by thin $Al_xGa_{1-x}As$ barriers [3]. The Al mole fraction (x), of barriers throughout the structure, was chosen such that the 13 μm peak quantum well operates under bound-to-quasibound conditions. The excited state energy level broadening has been further enhanced due to the overlap of the wavefunctions associated with excited states of quantum wells separated by thin barriers. Energy band calculations based on a two band model show excited state energy levels spreading about 28 meV. Responsivity spectra in Fig. 3 shows broadning up to $\Delta\lambda \sim 5.5$ μm, i.e. the full width at half maximum from 10.5 - 16μm. This broadening, $\Delta\lambda/\lambda_p \sim 42\%$, is about a 400% increase compared to a typical bound-to-quasibound QWIP [1-3].

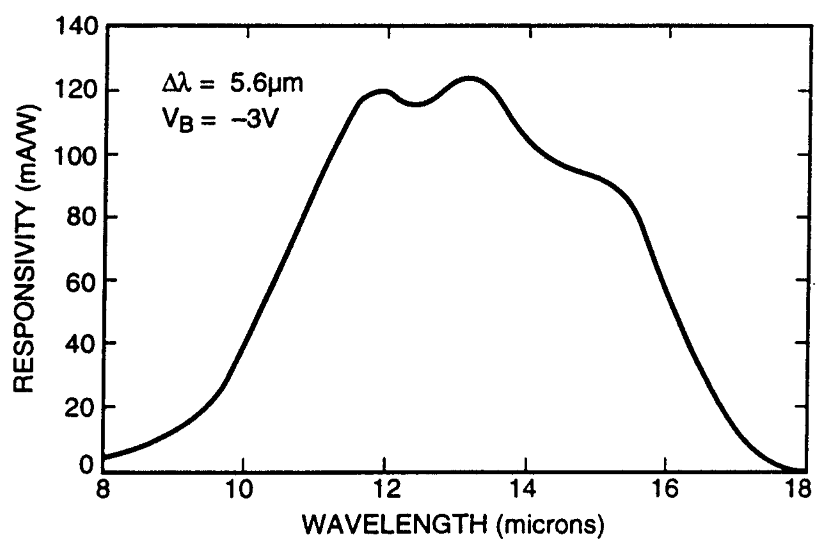


Fig. 3. Experimental measurements of the Responsivity spectrum of broad-band QWIP measured at the bias voltage VB = - 4 V.

3. QWIP CAMERAS

Long wavelength infrared QWIP cameras developed at the Jet Propulsion Laboratory, in collaboration with Raytheon Systems, demonstrate the potential of $GaAs/Al_xGa_{1-x}As$ QWIP technology for highly sensitive, low power, low cost, and highly uniform large format FPA imaging systems. These cameras utilize FPAs as large as

640x486 based on optimized GaAs/Al_xGa_{1-x}As multi-quantum-well structures (MQWs) coupled with random or two dimensional periodic grating reflectors. Reported uniformity of these FPAs is better than 99.95% after two point correction has been reported [4,5]. Other advantages of GaAs/AlGaAs based QWIPs are higher yield, durability, radiation hardness, and no 1/f noise till 30 mHz. In addition, QWIP FPAs do not show any performance degradation with age. One of the JPL/Raytheon 256x256 QWIP cameras developed in 1995, shows no performance degradation over a three year period after going through more than 2000 temperature cycles and over 4000 operational hours. Unlike narrow bandgap semiconductor detectors, high radiation tolerance is expected in QWIPs due to the use of larger bandgap material. Experimental study shows that the operability of GaAs based QWIPs is nearly 100% under low proton fluence ~ 10^{12} to 10^{13} cm^{-3} [6].

Figure 4 shows 640x486, 8-9 μm, QWIPcamera in which hybrid was mounted onto an 84-pin lead-less chip carrier and installed into a laboratory dewar which is cooled by liquid nitrogen to demonstrate the LWIR imaging camera. The FPA was cooled to 70K by pumping on liquid nitrogen and the temperature was stabilized by regulating the pressure of gaseous nitrogen. This hybridized FPA gave excellent images with operability 99.97%, demonstrating the large format array capability of GaAs QWIP technology. A commercially available Amber ProView™ image processing system was used to obtain clock signals for the readout multiplexer and to perform digital data acquisition and non-uniformity corrections. The resolution of digital data acquisition 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 NEΔT of this QWIP camera is 36 mK at an operating temperature of T = 70 K and bias V_B = -2 V, at 300 K background with f/2 optics [5]. This is in good agreement with expected focal plane array sensitivity due to the practical limitations on charge handling capacity of the multiplexer, read noise, bias voltage and operating temperature. The uncorrected NEΔT 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 311,040 pixels in the 640 x 486 FPA is about 5.6% (= sigma/ mean). The non-uniformity after two-point (17^0 and 27^0 Celsius) correction improves to an impressive 0.04%.

(a) (b)

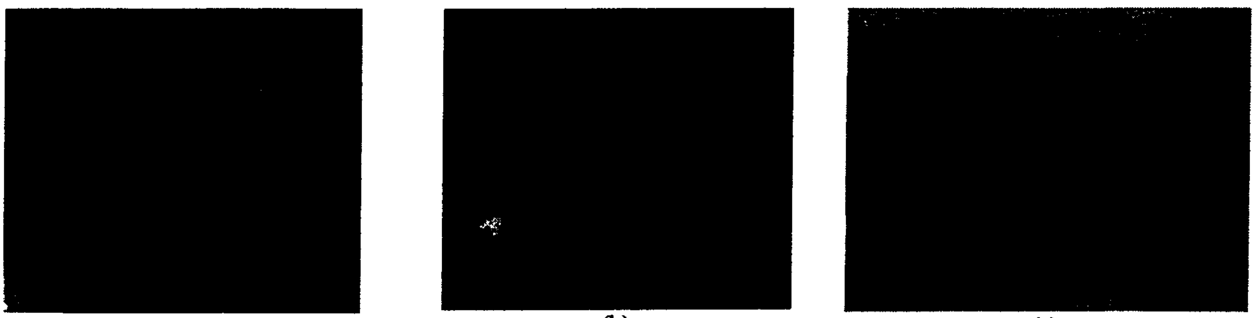
Fig. 4. Picture of the JPL developed (a) 640 x 486 and (b) 256x256 hand-held long-wavelengths QWIP camera.

The hand-held long-wavelength IR camera features a JPL-developed 256x256 pixel, 8-9 μm QWIP FPA mounted into a 450 mW Stirling closed-cycle cooler assembly and installed into an Amber Radiance-I camera body [4]. See Fig. 4. The camera has 12-bit data resolution, weight less than 10 lb, consumes less than 50 W, and features push-button control of all imaging parameters. A 32-bit floating-point digital signal processor combined with multitasking software executes image-processing and analysis functions within the camera body. The other element of the camera is a 100 mm focal length germanium lens, with a 5.5 degree field of view. It is designed for transparence in the 8-12 μm wavelength range, to be compatible with the QWIP's 8.5 μm operation.

The pitch of the FPA is 38 μm and the actual pixel size is 28x28 μm^2. The FPA was back-illuminated through the flat thinned substrate membrane (thickness ≈ 1300 Å). This initial array gave excellent images with 99.98% of the pixels working (number of dead pixels ≈ 10), demonstrating the high yield of GaAs technology [4]. The measured mean value NEΔT of the FPA at an operating temperature of T = 70 K, bias V_B = -1 V, and 300 K background is 26 mK. This agrees reasonably with our estimated value of 8 mK based on test structure data. The peak quantum efficiency of the FPA was 3.3% (lower focal plane array quantum efficiency is attributed to 54% fill factor and 90% charge injection efficiency) and this corresponds to an average of three passes of IR radiation (equivalent to a single 45° pass) through the photosensitive multi-quantum well region [4].

4. QWIP CAMERA APPLICATIONS

Such a portable LWIR camera can be used not only in classical night-vision applications but for medical imaging such as thermal mapping human skin (see Fig. 5). JPL QWIP Radiance camera has been used by a group of researchers from the State University of New York in Buffalo and Walter Reed Army Institute of Research in Washington DC in the Dynamic Area Telethermometry (DAT) [7,8] DAT has been used to study the physiology and patho-physiology of cutaneous perfusion, which has many clinical applications. DAT involves accumulation of hundreds of consecutive IR images and fast Fourier transform (FFT) analysis of the biomodulation of skin temperature, and of the microhomogeneity of skin temperature (HST, which measures the perfusion of the skin's capillaries). The FFT analysis yields the thermoregulatory frequencies and amplitudes of temperature and HST modulation. Their preliminary study demonstrates significant potential advantages of DAT over static thermal imaging as a diagnostic tool for breast cancer. To obtain reliable DAT data, one needs an IR camera in the >8 μm wavelength range with a repetition rate of 30 Hz (allowing accumulation of a maximal number of images during the observation period, frame to frame instrumental stability (to avoid artifact stemming from instrument modulation) and sensitivity of less than 50 mK (3-5 μm cameras may not be suitable for quantitative clinical applications because of the reflectivity of the human skin in this wavelength range). According to these researchers the longer wavelength operation, higher spatial resolution, higher sensitivity and greater stability of the QWIP RADIANCE made it the best choice of all IR cameras.



(a) (b) (c)

Fig. 5. (a), (b) A 8 -9 μm image of a hand taken by 640x486 snap-shot long-wavelengths QWIP camera. (c) A 8 -9 μm image of a face taken by 256x256 hand-held long-wavelengths QWIP camera. These images demonstrate the high sensitivity of the long-wavelength QWIP staring array cameras.

Figure 6 shows the infrared images of a just burned area right after the fires that raced through the Southern California seaside community of Malibu in October, 1996. These video images are taken as seen by a Los Angeles TV news crew in nighttime using JPL developed QWIP RADIANCE camera sensitive in the 8-9 μm wavelength range. This allows the camera to see through smoke and pinpoint lingering hotspots which are not normally visible. This enabled the TV station to transmit live images of hotspots in areas which appeared innocuous to the naked eye. These hotspots were a source of concern and difficult for firefighters, because they could flare up even after the fire appeared to have subsided.

Recently, the camera has been used to observe volcanoes, mineral formations, weather and atmospheric conditions. This QWIP camera was taken to the Kilauea Volcano in, Hawaii. The objective of this trip was to map geothermal features. The wide dynamic range enabled us to image volcanic features at temperatures much higher (300 - 1000 C) than can be imaged with conventional thermal imaging systems in the 3 - 5 μm range or in visible. Figure 7 shows an infrared image of the Mount Kilauea Volcano in, Hawaii. The infrared image of the volcano clearly shows a hot lava tube running underground which is not visible to the naked eye.

Since most of the absorption lines of gas molecules lie in the same spectral range, these LWIR cameras can be used to monitor and measure pollution, and determine relative humidity and gas distribution in the atmosphere. Large format LWIR FPAs are required in integrated in-situ science instruments and compact thermal infrared spectrometers planed in NASA's space science missions and in Earth observation missions. These instruments can be used in a variety of applications such as global thermal-mapping, sea surface temperature measurements, volcanic plume mapping (which are important for climatology, meteorogy, oceanography) and environmental studies. QWIP FPAs are ideal for these instruments due to higher uniformity, larger FPA formats, stability (no lower 1/f noise till

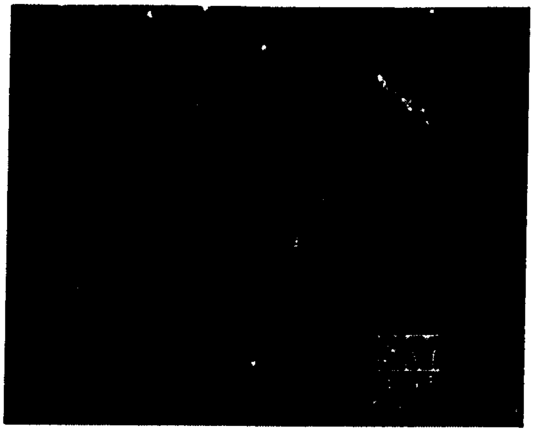


Fig. 6. Infrared image from the 256x256 portable QWIP camera. This portable camera features infrared detectors covers longer wavelengths than previous portable cameras could. This allows the camera to see through smoke and pinpoint lingering hotspots which are not normally visible. This enables firefighters to locate the hotspots in areas which appeared innocuous to the naked eye. These hotspots are a source of concern and difficulty for firefighters, because fire can flare up even after it appears to have subsided.

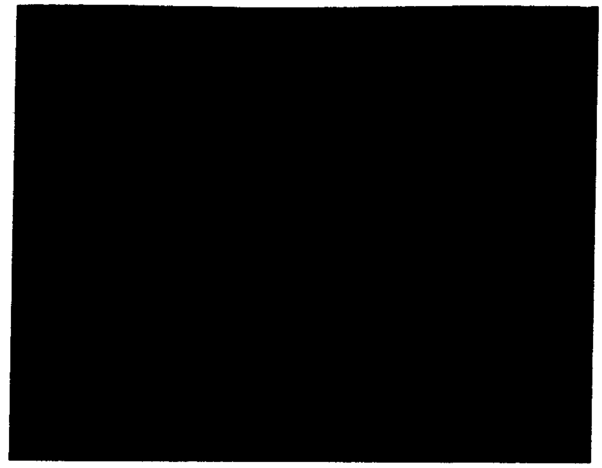


Fig. 7. Infrared image from the 256x256 portable QWIP camera. The wide dynamic range enabled us to image volcanic features at temperatures much higher (300 - 1000 C) than can be imaged with conventional thermal imaging systems in the 3 - 5 μm range or in visible. The infrared image of the volcano clearly show a hot lava tube running underground which is not visible to the naked eye. This demonstrates the advantages of long wavelength infrared in geothermal mapping.

30 mHz), and lower cost than any other LWIR detector. Perhaps most importantly, the spectral response of QWIP detector can be directly tuned to any specific narrow or broad bandpass within the 6-20 μm wavelength range.

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