Infrared Detectors Reach New Lengths

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INTRODUCTION

Infrared (IR) detectors operating from mid IR wavelengths to very long wavelength IR (i.e., 3-18 μm) are of great interest for a variety of ground based and space based applications such as night vision, early warning systems, navigation, flight control systems, weather monitoring, and astronomy (IR detectors are used in the focal plane of telescopes). In addition IR detectors in this spectral region can be used for pollution monitoring, as well as monitoring the relative humidity profiles and the distribution of different constituents in the atmosphere (e.g., O₃, CO, N₂O). This is due to the fact that most of the absorption lines of gas molecules lie in this IR spectral region. Some examples are monitoring the global atmospheric temperature profiles to the accuracy of one Kelvin and the depth to one kilometer (by measuring the temperature dependence of the absorption signatures of the carbon dioxide molecules), relative humidity profiles, and the distribution of minor constituents in the atmosphere, studies which are already being planned for NASA’s Earth Observing System¹ (10S). This spectral
region is also 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 great commercial, scientific and academic interest in IR detectors operating in this wavelength region.

It is customary to make IR detectors in this spectral span by utilizing the interband absorption of narrow band gap semiconductors (e.g., InSb, Hg$_{1-x}$Cd$_x$Te). Fig. 1 shows the schematic band diagram of a conventional intrinsic detector which involves interband absorption. If a photon is absorbed by the photosensitive material when an incoming photon has sufficient energy $E$ (e.g., hv, where $h$ is the Planck's constant and $v$ is the frequency of the incoming photon) to photocreate an electron from the valence band to the conduction band. In a detector structure these photocreated carriers are collected by applying an electric field, thereby producing a photocurrent or a photovoltage. Since the absorbed photon energy is greater than the energy of the band gap $E_g$, both electrons and the holes are created, thus, the semiconductor does not need to be doped (these detectors are called intrinsic detectors). Large two dimensional arrays of InSb (512x512 pixels) and Hg$_{1-x}$Cd$_x$Te (128x128 pixels) detectors have already been demonstrated up to cut off wavelengths of 5 $\mu$m and 11 $\mu$m respectively. In InSb, since the band gap is fixed, these detectors cannot be operated at longer wavelengths. On the other hand, Hg$_{1-x}$Cd$_x$Te can be made into narrow band gap materials by varying the alloy composition. However, the long wavelength large 1 Hg$_{1-x}$Cd$_x$Te arrays are highly nonuniform in composition and doping (thus large nonuniformities in spectral response and sensitivity). Furthermore, there are large numbers of trap centers throughout the band gap and charged surface states (thus higher 1/f noise) which produce substantial and detrimental parasitic currents. In addition, such narrow band gap materials are more difficult to grow and process into devices compared to wide
band gap semiconductors (thus low yield and high cost)\textsuperscript{2}. These difficulties motivate the exploration of utilizing the \textit{artificial low effective} band gap structures made of wide band gap semiconductors such as GaAs (see Fig. 2) which are easy to grow and process into devices. The basic advantages of the GaAs based quantum well infrared photodetectors (QWIPs), namely the highly mature GaAs growth and processing technologies, become more important at longer wavelengths where the narrow band gap materials become more difficult to work with.

The possibility of using GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As multi quantum well (MQW) structures to detect IR radiation was first suggested by I. Hisaki \textit{et al.}\textsuperscript{,3} at the IBM Thomas J. Watson Research Center. The idea of using MQW structures to detect IR radiation can be understood by the basic principles of quantum mechanics. The quantum well is equivalent to the well known \textit{particle in a box} problem in quantum mechanics, which can be solved by the time independent Schrödinger equation. The solutions of this problem are the eigenvalues that define the energy levels inside the well in which the particle is confined (see Fig. 2). The positions of the energy levels are primarily determined by the well dimensions (height and width). Therefore, as shown in Fig. 3, by \textit{tailoring} the quantum well structure, the separation between the allowed energy levels can be adjusted so that the IR photons can induce an intersubband transition between the ground state and the first excited state. The lattice matched GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As (where \(x\) is the molar ratio between Al and Ga) materials system is a good candidate in which to create such a potential well, since the band gap of Al\textsubscript{x}Ga\textsubscript{1-x}As is higher than that of the GaAs and can be changed continuously by varying \(x\) (and hence the depth of the well or height of the barrier). Carriers (electrons for n-type material and holes for p-type material) can be introduced by doping, the GaAs well. These carriers will occupy the ground state of the quantum wells at low temperatures.
The first experimental investigation of MQW structure to detect 1 R radiation was carried out by John Smith et al. at the California Institute of Technology, and theoretically analyzed by Larry Coon et al. at the University of Pittsburgh. The first experimental observation of the strong intersubband absorption within the quantum wells in the conduction band was performed by Lawrence West et al. at Stanford University, and the first QWIP was demonstrated by Barry et al. at the AT&T Bell Laboratories. This first QWIP was based on intersubband transition between two bound quantum wells (i.e., ground state and the first excited state are inside the well). The intersubband absorption excites an electron from the ground state to the first excited state, where it can tunnel out to the continuum (continuous energy levels above the quantum well) in the presence of an external electric field, thereby producing a photocurrent as shown in Fig. 4.

In addition to the photocurrent, all detectors including QWIPs produce a parasitic current which is a called dark current. This must be minimized to achieve high performance. In QWIPs, the dark current originates from three different mechanisms as shown in Fig. S. The dark current arising from the first process is due to quantum mechanical tunneling from well to well through the Al$_x$Ga$_{1-x}$As barrier (sequential tunneling). This process is independent of temperature. Sequential tunneling dominates the dark current at very low temperatures (<30 K). The second mechanism is thermally assisted tunneling which involves a thermal excitation and tunneling through the tip of the barrier into the continuum energy levels. This process governs the dark current at medium temperatures. The third mechanism is classical thermionic emission and dominates the dark current at higher temperatures (>45 K). Fig. 6 shows the dark current and the photocurrent of typical 15 μm QWIP at various temperatures.
(photocurrent is independent of temperature). At higher temperatures the last mechanism is the major source of dark current, and the thermal generation rate is determined by the lifetime of the carriers and the well doping density. In this case, the carrier lifetime will determined by the thickness of the Al$_x$Ga$_{1-x}$As barriers as described by Immanuel Rosencher et al. at the Thomson-CS Research Laboratory, France. The dependence of the dark current (and hence the detector performance) on doping density was analyzed by Sarath Gunapala et al. at the AT&T Bell Laboratories. In particular, they have found that the dark current can be reduced by many orders of magnitude by lowering the well doping density, without significantly reducing, the performance of the detectors.

By reducing the quantum well width it is possible to push the second excited state (first excited state) into the continuum resulting in a strong bound-to-continuum intersubband absorption as shown in Fig. 4. The major advantage of the bound-to-continuum QWIP is that the photoexcited electron can escape from the quantum well to the continuum transport states without requiring tunnel through the barrier, as shown in Fig. 4. As a result, the bias required to efficiently collect the photoelectrons can be reduced dramatically, thereby lowering the dark current. Due to the fact that the photoelectrons do not have to tunnel through the barriers, the Al$_x$Ga$_{1-x}$As barrier thickness of bound-to-continuum QWIP can now be increased without reducing the photocelectron collection efficiency. In addition, increasing the barrier width from a few hundred Å to 500 Å can reduce the ground state sequential tunneling, by an order of magnitude. By making use of these improvements, Barry Levine et al. at the AT&T Bell Laboratories successfully demonstrated the first bound-to-continuum QWIP operating at 10 μm with a dramatic improvement in the performance. Due to this high performance and the excellent uniformity of GaAs based QWIPs, several groups have
demonstrated large (two dimensional array of 128x128, 256x256, and 512x512 pixels) imaging arrays-1-lo-11 up to a cut off wavelength of 10 μm.

**VERY LONGWAVELENGTH III QWIP**

Most of the QWIP work described in the previous sections has concentrated on the 8-10 μm spectral band, although wavelengths as short as λₚ=2.7 μm have been demonstrated. The design of QWIPs operating in the 8-10 μm atmospheric window typically consists of 40 Å wide GaAs quantum wells and 500 Å thick AlₓGa₁₋ₓAs barriers with x ≈ 0.3. In order to tailor the QWIP response to the very long wavelength spectral region (λₚ> 12 μm) the barrier height should be lowered; however, in addition to lowering the barrier height, the quantum well width must be widened in order to lower the photoexcited continuum state closer to the top of the barrier. By doing this very long wavelength IR (VJWIR) QWIPs up to a cut off wavelength of 19 μm have been demonstrated by Avigdor Zussman et al. at the AT&T Bell Laboratories.

In order to optimize the performance of VJWIR QWIPs Gabby Sarusi et al. at the AT&T Bell Laboratories have utilized the bound-to-quasicontinuum intersubband absorption (occurring when the first excited state is in resonance with the top of the barrier). This transition maximizes the intersubband absorption, while maintaining the excellent electron transport. The device structure of a QWIP operating at λₚ= 15 μm typically consists of 65 - 70 Å wide GaAs quantum wells and 600 Å thick AlₓGa₁₋ₓAs barriers with x ≈ 0.15. These structures are grown by the technique of molecular beam epitaxy (MBE), and consist of 50 periods of quantum wells and barriers, sandwiched between 0.5 μm top and 1 μm bottom Si doped Nᵢ = 1 x 10¹⁸ cm⁻³ contact layers. The quantum well doping of 8-10 μm QWIPs is usually Nᵢ=1x10¹⁸ cm⁻³. However, in
order to lower the Fermi level ($E_F$) of the carriers, in these very long wavelength ($\lambda = 16.5$ pm) QWIPs, so as not to be too large a fraction of the cutoff energy $E_c = \hbar \omega / \lambda$, and to reduce the thermal generation rate, well doping density has been substantially reduced to $N_D = 1.4 \times 10^{17}$ cm$^{-3}$.

**LIGHT COUPLING**

QWIPs do not absorb radiation incident normal to the surface since the light polarization must have a 

electric field component normal to the superlattice (growth direction) to be absorbed by the confined carriers. As shown in Fig. 7, when the incoming light contains no polarization component along the growth direction, the matrix element of the interaction vanishes (i.e., $\vec{E} \cdot \vec{p}_z = 0$) where $\vec{E}$ is the polarization and $\vec{p}_z$ is the momentum along $z$ direction). As a consequence, these detectors have to be illuminated through a 45" polished facet (see Fig. 8(a)). Clearly, this illumination scheme limits the configuration of detectors to linear arrays and single elements. For imaging, it is necessary to be able to couple light uniformly to two dimensional arrays of these detectors. Keith Goosen et al. at Princeton University have demonstrated efficient light coupling to a QWIPs using linear gratings which removed the light coupling limitations and made two dimensional QWIP imaging arrays feasible (see Fig. 8(b)). These line gratings were made of metal on top of each detector or groove etched through a cap layer on top of the quantum well structure. These gratings deflect the incoming light away from the direction normal to the surface, enabling intersubband absorption. The normal incidence light coupling efficiency of line gratings is comparable to the light coupling efficiency of a 45" polished facet illumination scheme and yields an quantum efficiency (the fraction of the incident photons effective in producing the emitted electrons) of about 10%-20% (for QWIPs having 50 periods and
This relatively low quantum efficiency is due to the poor light coupling efficiency and the fact that only one polarization of the light is absorbed. In order to maintain high absorption and thus high quantum efficiency, the quantum well doping density must be kept very high, leading to a higher dark current. In order to further increase the quantum efficiency without increasing the dark current, Jan Anderson et al.\textsuperscript{15} at the industrial Microelectronics Center, Sweden, developed the cross grating (or two dimensional grating) for QWIPs operating at the 8-10\(\mu\)m spectral range. In this case the periodicity of the grating is repeated in both directions, leading to the absorption of both polarizations of incident 1 R light. The addition of an optical cavity results in two optical passes through the MQW structure before the light is diffracted out through the substrate, as shown in Fig. 8(c).

Many more passes of 1 R light, and significantly higher absorption, can be achieved with a randomly roughened reflecting surface, as shown in Fig. 9(a). Gabby Sarusi et al. at the AT&T Bell Laboratories have shown experimentally that by careful design of surface texturing and randomization, efficient light trapping can be obtained. They demonstrated nearly an order of magnitude enhancement in responsivity compared to 45\(^\circ\) illumination geometry. The random structure on top of the detector prevents the light from being diffracted normally backward after the second bounce as happens in the case of cross-grating (see Fig. 8(c)). After each bounce, light is scattered at a different random angle and the only chance for light to escape out of the detector is when it is reflected towards the surface within the critical angle of the normal. For the \{La As/air interface this angle is about 17\(^\circ\), defining a very narrow escape cone for the trapped light. Some considerations have been taken into account when designing such random scatters to reduce the probability of light being diffracted into the escape cone. The reflector was designed with three levels of scattering sLa-faces located at quarter...
wavelength separations, as shown in Figs. 9(b) and 9(d). As shown in Fig. 9(b) and 9(c), these scattering centers were arranged in cells to prevent clustering of the scattering centers, having the same dimension as the light wavelength in GaAs. The combined area of the top unetched level and the bottom level (l/2 deep) are $U^2/2$ (where $U^2$ is the area of a unit cell as shown in Fig. 9(b)). The area of the intermediate level (l/4 deep) is also $U^2/2$. These reflecting areas and depths were chosen such that the normally reflected light intensities from two adjacent surfaces are equal and 180° out of phase, thus maximizing the destructive interference at normal reflection (and hence lower the light leakage through the escape cone). These scattering centers were organized randomly inside the cell as shown in Fig. 9(c). This random structure was fabricated on the detectors by using standard photolithography and selective dry etching. The advantage of the photolithographic process over a completely random process is the ability to accurately control the feature size at the pixel to pixel uniformity, which is a prerequisite for high sensitivity imaging focal plane arrays. It is clearly evident from the experiments that maximum responsivity is obtained when the unit cell size is equal to the wavelength of the QW11 maximum response. When this condition is met, light scattering becomes very efficient. If the unit cell is larger than the wavelength of the IR radiation (in GaAs), the number of scattering centers on the detector surface will decrease and the light is scattered less efficiently. On the other hand, if the unit cell size is smaller than the wavelength (in GaAs), the scattering surface becomes effectively smoother, and as a consequence scattering efficiency again decreases. Naturally, thinning down the substrate enables more bounces of light and therefore higher responsivity. One of the main differences between the effect of the cross grating and the random reflector is the shape of the responsivity curve; unlike the cross grating, the random reflector has little impact on the bandwidth of the response curve since the scattering efficiency of the random reflector is significantly less wavelength dependent.
than for the regular grating. Therefore, for the QWIPs with random reflectors, the integrated responsivity is enhanced by nearly the same amount as the peak responsivity.

DETECTOR AND ARRAY PERFORMANCE

Figures of merit such as responsivity and detectivity are commonly used to compare the performance of detectors. Responsivity is the ratio of the signal current to the incident radiation power on the detector. Fig. 10 shows typical photoresponse curves of very long wavelength bound-to-continuum QWIPs at temperature $T = 55$ K. The absorption and photoresponse curves of bound-to-continuum QWIPs are much broader than those of the bound-to-bound QWIPs. Detectivity ($D^*$) is the signal to noise ratio normalized to unit area and unit bandwidth. The primary noise source in QWIPs is the shot noise produced by the dark current. Therefore, unlike the narrow band gap detectors, in which the noise is dominated by temperature independent processes at low temperatures, QWIP performance can be further improved by cooling to cryogenic temperatures, as shown in Fig. 11.

As can be seen from Fig. 12 rapid progress has been made in the performance (detectivity) of very long wavelength QWIPs, starting with bound-to-bound QWIPs which had relatively poor sensitivity, and culminating in high performance, bound-to-quasicontinuum QWIPs with random reflectors. The achieved detectivities are more than sufficient to demonstrate large two dimensional imaging arrays (128x128 or larger) at very long wavelength, which is presently not possible with intrinsic narrow band gap detectors. Fig. 13 shows a picture of a 128x128 QWIP two dimensional imaging array produced by the Jet Propulsion Laboratory, which has a peak responsivity at 15 $\mu$m. Fig. 14 presents an expanded image showing the random
reflectors on the pixels (single elements) of this imaging array. Due to the pixel-to-pixel nonuniformities, the detectivity of a single pixel is not sufficient to describe the performance of a large imaging array. Noise, induced by nonuniformity, has to be taken into account for a complete evaluation. This point has been discussed in detail by Freeman Shepherd et al.,\(^\text{17}\) at the U.S. Air Force Rome Laboratories for the case of PtSi infrared focal plane arrays which have low response, but very high uniformity. The general figure of merit to describe the performance of a large imaging array is the noise equivalent temperature difference \(\text{NET} = T\), which includes the spatial mist originating from pixel-to-pixel nonuniformities. \(\text{NET}\) is the minimum temperature difference across the target that would produce a signal-to-noise ratio of unity. Due to superior material quality and the high uniformity associated with the GaAs/Al\(_x\)Ga\(_{1-x}\)As materials system, arrays of very long wavelength QWIPs with very low \(\text{NET}\) will be a reality in the near future.

**NEWMATERIA1 Al.S SYSTEM**

All the VI.WIR QWIPs which have been discussed thus far are based on the lattice-matched GaAs/Al\(_x\)Ga\(_{1-x}\)As materials system. However, it is interesting to consider GaAs as the barrier material since the transport in binary GaAs is expected to be superior to that of a ternary alloy such as Al\(_x\)Ga\(_{1-x}\)As, as was previously found to be the case in the \(\text{In}_{0.53}\text{Ga}_{0.47}\)As/InP binary barrier structures.\(^\text{18}\). To achieve this, Sarath Gunapala et al.,\(^\text{19}\) at the Jet Propulsion Laboratory have used the lower band gap non-lattice matched alloy \(\text{In}_{x}\text{Ga}_{1-x}\)As as well material together with GaAs barriers. This heterobarrier system is also well suited for very long-wavelength (\(\lambda > 14\) pm) QWIPs.

These non-lattice-matched GaAs/\(\text{In}_{0.5}\text{Ga}_{0.5}\)As QWIPs were grown by MBE on a semi-insulating GaAs substrate. The detector structure consisted of 0.5 \(\mu\)m GaAs top
and 1 μm bottom contact layers Si doped with \(1 \times 10^{17} \text{ cm}^{-3}\), and 10 sets of doped (doping density \(N_D = 5 \times 10^{17} \text{ cm}^{-3}\)) \(\text{In}_{0.2}\text{Ga}_{0.8}\text{As}\) quantum wells of well width \(1_n\), separated by nine 60 nm undoped GaAs barriers. In addition, all of these structures contain 60 nm thick GaAs spacer layers between the quantum wells and the top and bottom contact layers. Despite the 1.2% lattice mismatch between \(\text{In}_{0.2}\text{Ga}_{0.8}\text{As}\) and GaAs, excellent quality non-lattice matched \(\text{GaAs/In}_{0.2}\text{Ga}_{0.8}\text{As QWIP}\) structure have been grown. 

The responsivity of this \(\text{In}_{0.2}\text{Ga}_{0.8}\text{As/GaAs}\) detector peaks at 16.7 μm and the peak responsivity is 790 mA/W at bias \(V_B = 300 \text{ mV}\). These results also indicate excellent electron transport in this device structure due to the high mobility binary GaAs barriers. This very long-wavelength (\(λ_c = 18 \mu\text{m}\)) \(\text{In}_x\text{Ga}_{1-x}\text{As/GaAs QWIP}\) had a detectivity \(D^*\) of \(1.8 \times 10^{10} \text{cm}^2\text{Hz}^{1/2}\) at \(λ_p = 16.7 \mu\text{m}\) operating at \(T = 40 \text{ K}\). The large responsivity anti detectivity \(D^*\) values are comparable to those achieved with the lattice matched \(\text{GaAs/Al}_x\text{Ga}_{1-x}\text{As}\) materials system, and hence further study seems warranted.

**SUMMARY**

Exceptionally rapid progress has been made in the development of very long wavelength QWIPs, since they were first experimentally demonstrated only a few years ago. Now it is possible for \(\text{VIWIR QWIPs}\) to achieve excellent performance (e.g., detectivities as high as \(D^*\) of \(8 \times 10^{10} \text{cm}^2\text{Hz}^{1/2}\) at \(55 \text{ K}\) for 15 μm QWIP). This operating temperature can be easily achieved by single stage Stirling coolers. Fig. 12 shows the evolution of high sensitivity very long wavelength QWIPs. A mission currently under development at the Jet Propulsion Laboratory is the Atmospheric Infrared Sounder (AIRS). This mission will monitor the 3-15 μm infrared region to obtain the
atmospheric temperature profile and other atmospheric properties. Due to the high internal impedance, low 1/f noise, high radiation hardness, low cost (see Fig. 15), easy hybridization to readout electronics, and high uniformity of QWIP, it is a potential candidate for the VI.WIR focal plane. Arrays of AIRS where the fabrication of Hg$_{1-x}$Cd$_x$Te detector arrays becomes increasingly difficult.

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REFERENCES


FIGURE CAPTIONS

1Fig. 1Band diagram of conventional intrinsic infrared photodetector.
Fig. 2. Schematic band diagram of a quantum well. Intersubband absorption can take place between the energy levels of a quantum well associated with the conduction band or the valence band.

Fig. 3 Calculated peak wavelength ($\lambda_p$) of bound-to-continuum QWIP as a function of Al$_x$Ga$_{1-x}$As barrier composition (x) for various quantum well widths.

Fig. 4 A typical conduction-band diagram of very long wavelength bound-to-continuum quantum well infrared photodetector.

Fig. 5 Dark current mechanisms of QWIP.

Fig. 6 Dark current and the 300 K window photocurrent of a VI.WIR QWIP ($\lambda_p$=15 $\mu$m) at various temperatures. Photocurrent is independent of the temperature.

Fig. 7 QWIPs (with no light coupling scheme) do not absorb normal incident IR light since there is no light polarization component along the quantum well direction (growth direction).

Fig. 8 Different light coupling mechanisms used in QWIPs. (a) 45° polished facet, (b) linear or two dimensional gratings on each detector, and (c) gratings with optical cavity.

Fig. 9 (a) Schematic side view of a thin QWIP pixel with a random reflector. Ideally all the radiation is trapped except for a small fraction which escape through the escape
cone (defined by critical angle $\Theta_C$), (b) top view of the unit cell of the scattering surface (arrows indicate the 16 random possibilities), (c) top view of the one of the 16 possibilities, (d) side view of the unit cell.

Fig. 10 Typical photoresponse curves of bound-to-continuum V.I. W1 R QWIPs at temperature $T = 55$ K.

Fig. 11 Detectivity of V.I. W1 R QWIP as a function of temperature. Unlike the narrow band gap detectors, detectivity increases with decreasing temperature.

Fig. 12 Evolution of the performance of very long wavelength QWIP.

Fig. 13 Picture of the first $15 \mu m \times 128 \times 128$ QWIP focal plane array.

Fig. 14 Random reflectors on pixels ($38 \times 38 \mu m^2$) of QWIP focal plane army. The random reflectors increase the light coupling efficiency by a factor of eight when the substrate thins down to $25 \mu m$.

Fig. 15 Thirty five $128 \times 128$ QWIP focal plane arrays on $3$ in. GaAs wafer.