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Device physics and focal plane array applications of QWIP and MCT

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Infrared (IR) sensor technology is critical to many commercial and military defense applications. Traditionally, cooled infrared material systems such as indium antimonide, platinum silicide, mercury cadmium telluride (MCT), and arsenic doped silicon (Si:As) have dominated infrared detection. Improvement in surveillance sensors and interceptor seekers requires large size, highly uniform, and multicolor IR focal plane arrays involving medium wave, long wave, and very long wave IR (VLWIR) regions. Among the competing technologies are the quantum well infrared photodetectors (QWIPs) based on lattice matched or strained III–V material systems. This paper discusses cooled IR technology with emphasis on QWIP and MCT. Details will be given concerning device physics, material growth, device fabrication, device performance, and cost effectiveness for LWIR, VLWIR, and multicolor focal plane array applications.

Keywords: IR detectors, HgCdTe, QWIP, focal plane arrays, multicolor IR detection, low background.

1. Introduction

Infrared (IR) detection has been extensively investigated since the discovery of IR radiation in 1800. The IR spectrum can be divided into short wave IR (SWIR) (1–3 μm), medium wave IR (MWIR) (3–5 μm), long wave IR (LWIR) (8–12 μm), and very long wave IR (VLWIR) (12 μm). IR focal plane array (FPA) technology is very important to both commercial and military applications. It also has important applications to ballistic missile defense. Commercial applications of IR FPA could cover medical, fire control, surveillance and driver's vision enhancement. The military applications could include night vision, rifle sight, surveillance, missile guidance, tracking, and interceptors. Endoatmospheric interceptors and airborne surveillance sensors used for tactical applications typically observe warm targets with high background irradiance from heated windows, scattered sunlight, and the earth's surface. Such applications require accurate measurement and subtraction of background irradiance to detect the target's signal. In contrast, exoatmospheric interceptors and space based surveillance sensors used for strategic applications typically engage cool targets with low background irradiance levels. The targets are often far away and unresolved at the early stage of detection. For strategic applications where the scene is a space background and the targets are at relatively low temperatures, LWIR and VLWIR are appropriate wavelength bands. For tactical applications, the most important wavelength bands are determined by the atmospheric transmission windows of SWIR, MWIR, and LWIR. Therefore, IR FPAs with high sensitivity, high uniformity, large format, and flexible wavelength are needed from SWIR to VLWIR. Multicolor capabilities are highly desirable for advance IR sensor systems. The stability, reproducibility, yield, cost, maintenance, and manufacturability are also very important issues.

Most commercial market probably will be dominated by uncooled IR detector FPAs operating at room temperature, except for medical applications

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where high resolution and accuracy are needed. Uncooled IR detector FPAs have been developed very quickly in recent years with large format array developed. They include both microbolometer and ferroelectric detector arrays. The thin film microbolometer structures directly built on Si readout circuitry are more matured then the thin film ferroelectric detector arrays at present time. Uncooled IR detector arrays have the potential to beat cooled IR detectors at VLWIR. However, uncooled detectors developed so far are less sensitive than the cooled detectors discussed here. It also has no intrinsic multicolor capability. Current cooled IR sensor systems use material systems, such as InSb, PtSi, HgCdTe (MCT), and Si:As. Quantum well infrared photodetector (QWIP) is a relatively new technology to IR sensor applications. Among these cooled IR detector systems, PtSi FPAs are highly uniform and manufacturable. But it has very low quantum efficiency and can only operate in the MWIR range. InSb FPA technology is mature with very high sensitivity, but it can also only be operated in the MWIR range. Neither PtSi nor InSb has wavelength tunability or multicolor capabilities. Si:As has a wide band spectrum (0.8 to 30 μm), with no tunability or multicolor capability, and it can only be operated at very low temperatures around 12 K. MCT and QWIP offer high sensitivity with wavelength flexibility in MWIR, LWIR, and VLWIR regions, as well as multicolor capabilities. MCT can also work at SWIR, while QWIP has to go to direct band gap scheme for SWIR. In this paper, the discussion is concentrated on QWIP and MCT with emphasis on LWIR, VLWIR, and multicolor applications, especially those at low temperature and low background. The fundamental properties of each system and how they affect the device performance and applications are also discussed.

2. Material properties and device processing

Both QWIP and MCT are semiconductor devices, and high quality materials are essential to the device performance and array production yield. In addition to good sensitivity in single detectors, FPAs require demanding spatial uniformity. To achieve this with high yield and low cost in production requires low defect densities, large wafers, and reliability, uniformity, and reproducibility of intrinsic and extrinsic material properties.

2.1. Material properties

MCT has been considered the most important material for IR detection. The fundamental advantage of MCT is its direct interband transition with adjustable band gap. By properly controlling the composition x and operation temperature in $Hg_{1-x}Cd_xTe$, one can vary the bandgap of MCT from 0 eV to 1.45 eV, theoretically corresponding to all wavelengths above 1 μm. Other advantages of MCT include small effective mass, high electron mobility, and long minority carrier lifetime. All these advantages contribute to a very high quantum efficiency of around 80% and a relatively high operating temperature. However, MCT is also a very challenging material for IR detection. HgTe is a semimetal, in which the Hg–Te bond is very weak and is further destabilized by being alloyed with CdTe. The high mercury vapor pressure and the Hg–Cd–Te phase diagram shape result in serious difficulties in repeatable and uniform growth [1,2]. The soft but brittle nature of the MCT material and substrates makes the device processing difficult. The quality of the material and available large area substrate affects large format MCT FPAs at LWIR and VLWIR. With the development of alternative substrates and passivation technology in MCT, the stability and the quality of MCT materials at LWIR has been greatly improved.

QWIPs use intersubband transitions instead of direct interband transitions. III–V materials are used that have a relatively wide bandgap (1.43 eV for GaAs). The advantages of the GaAs/AlGaAs material system is that it has superior bond strength and material stability, well behaved dopants, and thermal stability. No surface passivation is needed in QWIP, which simplifies processing and makes it relatively easy to build radiation hard detectors. The mechanical hardness of the material and substrate makes device processing and array fabrication easier than for MCT; this should lead to higher yield for FPAs. However, the intersubband transition used in this wide bandgap material gives some fundamental difficulties as discussed in Section 3.

2.2. Substrates

Epitaxial crystal growth techniques are used to achieve large area layered structures with abrupt interfaces, complex compositions, good doping uniformity, and well controlled layer thickness. Low cost production epitaxial techniques require affordable, large area substrates that are structurally, chemically, optically, and mechanically matched to the device material. The quality of the substrates is very important because defects and crystalline imperfections in the substrates often propagate into the epitaxial layers.

CdZnTe is the most frequently used substrate for MCT. It has the metallurgical compatibility and lattice match with MCT that permit the growth of relatively higher quality epitaxial layers of MCT. However, the available CdZnTe substrates are relatively small, soft, fragile, and expensive (about $4000 for 16 cm^2 polished). The typical dislocation concentration of CdZnTe is $10^4/cm^2$ to $10^5/cm^2$ which allows the growth of good quality MCT for MWIR and LWIR [3]. However, defects become more important at longer wavelengths, and this defect concentration may cause problems for low background, low temperature, and VLWIR applications. Alternative substrates for MCT can potentially reduce substrate cost, facilitate large area arrays, and in the case of Si, thermally match the readout. The most studied alternative substrates for MCT are Si, GaAs, and sapphire. Si is the most desirable substrate and is being extensively pursued. For example, MWIR devices up to 1024×1024 have been grown on silicon with CdTe as a buffer layer [4]. For LWIR MCT, CdZnTe buffer layers are needed, which are more difficult to develop and not yet available. The major problem is the large lattice mismatch between the substrate and MCT material, which produces dislocations in the devices.

For QWIPs, the GaAs/AlGaAs and strained InGaAs/AlGaAs material systems are the most mature systems and cover from MWIR to VLWIR. GaAs substrates are used which are nearly lattice matched with all Al concentrations. Large are (6 inch diameter) and high quality GaAs substrates are available at a moderately low cost (about $150 for a 3 inch diameter wafer). For the MWIR InGaAs/GaAs system on GaAs, there is a limit on the indium concentration and layer thickness because of the lattice mismatch. Highly strained layers with 35 percent indium concentration have been grown, and the devices show very high quality material [5,6].

The thermal expansion coefficients of both GaAs and CdZnTe are poorly matched with the Si readout. Different thermal expansion of the detector array and the ROIC causes strain and stress when the FPA is cooling down. GaAs can sustain more strain and stress due to its strong chemical bonds and durable mechanical properties. Substrate thinning or removal is also a standard practice in QWIP FPA fabrication that somewhat relieves the strain and stress caused by thermal expansion. Either substrate thinning, or using an engineered shimmer on the ROIC is sometimes used for MCT FPAs [7].

2.3. Material growth

For an MCT photodiode, the active and capping layers can be grown with either liquid phase epitary (LPE) [8], metalorganic vapour phase epitaxy (MOVPE) [9], or molecular beam epitary (MBE) [10]. The high mercury vapour pressure, low sticking coefficient, and the shape of the MCT phase diagram make the control of composition, doping, and interface profiles challenging in MCT material growth, especially for reproducible LWIR, VLWIR, and multicolour devices. LPE, the maturest technology for MCT growth, has been used routinely for large volume production in SWIR, MWIR, and LWIR linear arrays. One difficulty with LPE is its variation of x across the $Hg_{1-x}Cd_xTe$ wafer, which causes spectral nonuniformity, especially at VLWIR. Another difficulty is to precisely control x in depth in LPE growth, which makes it difficult to grow multilayer structures, such as in multicolour arrays. MBE technology may be necessary to produce the next generation of MCT detectors because they require low temperature growth of multilayer heterojunction structures with precise control over the alloy composition and doping levels. However, the layer qualities, compositions, and doping efficiencies are extremely sensitive to growth conditions such as substrate temperatures and effusion cell fluxes, in MBE growth.

The junctions of an epilayer MCT diode can be formed by ion implantation or *in situ* doping during the active and cap layer growth. Ion implantation has the advantage that it is a planar process and requires only a simple surface passivation. The advantage of the *in situ* doping approach is that it is a simple layer by layer growth process, so it is relatively easy to build a multilayer structure. The challenge of the *in situ* doping approach is tight control of growth temperature and fluxes and a rather narrow window for the optimal growth. p–type doping is very difficult in MCT and growing p-n junction *in situ* using MBE is even more difficult. In addition, *in situ* doped mesa structures require passivation of a larger junction area [10]. So far, the device performance of MBE growth and LPE growth is comparable [10] in the LWIR. In the VLWIR, 15 to 18 μm MCT detector test arrays have been grown using LPE by Lockheed Martin (LM) [11], while MBE has demonstrated 128×128 pixel arrays at 15 μm [12].

To date, most of the QWIP material is grown by MBE. GaAs MBE is a very mature and proven technology in III–V electronic industry and monolithic microwave integrated circuit (MMIC) applications. Large and high quality GaAs substrates and mature GaAs growth and processing technology facilitate highly uniform, large format QWIP FPAs with high yield and reproducibility. The GaAs MBE technology permits precise control of layer thickness, chemical concentration, and doping profile. To produce the detection wavelength for MWIR, InGaAs/AlGaAs is usually used to increase the well depth. Highly strained InGaAs/AlGaAs material grown by MBE has shown very high quality material growth [5,6].

2.4. Device processing

The soft, but brittle, nature of MCT material and substrates makes device processing more difficult than that of GaAs materials. Because of the weak bond of MCT, chemical etching is very sensitive to the etching solution and the process. Dry etching has proven to be more successful than wet etching. Furthermore, band bending at the surface can result in surface leakage, so surface passivation is required to control surface leakage current and the device's thermal stability. Passivation of photodiodes is challenging because the same coating must simultaneously stabilize regions of n– and p–type materials. Although these problems have been largely overcome for MWIR and LWIR devices, they remain important issues for VLWIR and multicolor devices, especially where multiple p–n junctions are exposed to surface.

Device processing and array fabrication for QWIPs use standard III–V processing technology, which is more mature and repeatable. GaAs substrate is easier to handle and remove. No surface passivation is needed. On the other hand, since n–type GaAs/AlGaAs and InGaAs/AlGaAs systems require an optical coupling structure such as a diffraction grating to effectively couple IR light into the detectors, the processing steps needed to form the optical coupling structure partially offset the processing advantages of the QWIP. However, initial concerns about spatial uniformity of the gratings have proven unwarranted; large format QWIP FPAs have been demonstrated with excellent response and spectral uniformity.

3. Basic device physics

MCT IR detectors could be operated either as a photoconductor or a photodiode. In the second generation staring FPA applications, MCT photodiodes using photovoltaic (PV) effect are preferred over photoconductors. The advantages of a MCT photodiode are their relatively high R_0A product and lower power consumption compared with MCT photoconductors. The major difficulties with a MCT photodiode is its involvement with p–type materials, and its requirement of controlled doping of both n– and p–type regions. MCT photodiodes have been made using either p–on–n or n–on–p homo- or heterojunctions. p–on–n material is relatively easier to grow due to its lower and controllable doping in the n–type base. Heterojunctions usually exhibit higher R_0A products than homojunctions [13] because they suppress currents associated with contacts and, to some degree, currents from the depletion region. Most American companies are now using p–on–n heterojunctions. The devices can be made in either planar or mesa formats. In a MCT photodiode, IR photons with energy larger than the band gap are absorbed by the photodiode, thereby exciting electrons from the valence band to the conduction band. If the absorption occurs within the depletion region, the electron-hole pairs are immediately separated by the strong built-in electric field and contribute to photocurrent in the external circuit. If the absorption occurs outside, but near, the depletion region, the excited electron-hole pairs may diffuse to the depletion region, where they are separated by the electric field and contribute photocurrent.

The fundamental difference between a QWIP and MCT is that a QWIP uses intersubband transitions within the conduction band (n–type) or valence band (p–type). A typical QWIP consists of GaAs/AlGaAs 30 to 50 quantum well periods. Using GaAs as the well region and AlGaAs as the barrier region, confined quantum well structures can be formed when the well width is small. The thickness of the GaAs layer determines the well width and the x value in $Al_xGa_{1-x}As$ determines the barrier height. The well region has one bound ground state and one or more excited states, depending on the barrier structure. n–type QWIPs are donor doped, resulting in a Fermi energy above the ground state. Electrons in the ground state can absorb IR photons with energy coinciding with the energy difference between the excited and ground states. Using either InGasAs or GaAs as well region, the detection wavelength of QWIPs can vary from 4 μm to larger than 20 μm. With different combinations of barriers and well structures, different detection wavelengths, detection bandwidths, and multicolor combinations can be achieved. QWIPs are usually operated in the photoconductive (PC) mode, and bias voltage (typically around 2 V) is applied to sweep the excited electron out of the well region. However, because of the unique properties of the QWIP structure, the bias currents are much lower than in most conventional photoconductors. For example, the power dissipation in a QWIP array operated at 2 V bias is comparable to the dissipation in MCT photodiode arrays (that are operated at much lower bias).

One major disadvantage of the intersubband transition used in n–type QWIPs is that optical absorption is anisotropic; the absorption cross section is proportional to the square of the component of electric polarization perpendicular to the quantum well layers. This implies that a simple QWIP does not directly absorb normally incident light. Therefore, all n–type QWIP pixels for two-dimensional (2-D) arrays include a metalized diffraction grating or other similar structure to couple normally incident light into directions that are strongly absorbed by the quantum wells. The absorption quantum efficiency of the detectors is therefore a function of both the absorption strength of the quantum wells and the effectiveness of the coupling structure. Another characteristics of intersubband transition is the short carrier lifetime. A short carrier lifetime gives an intrinsically fast device speed, however, it also forces QWIP to operate at a lower temperature due to the higher dark current.

4. Device performance

This section focuses on single detector performance. Since MCT devices are typically photodiodes, and QWIPs are typically photoconductors, care must be used in selecting a set of performance metrics for comparison.

4.1. Quantum efficiency and conversion efficiency

Quantum efficiency (QE) is determined by the amount of absorption a detector structure absorbing IR light. Since MCT is an intrinsic detector that uses band to band transitions, it has a large IR absorption and a wide absorption band. The QE of MCT is very high, typically greater than 70 percent at wavelengths below the cutoff wavelength. When operated in the PV mode, the gain is one.

At typical doping densities, the QE of a QWIP is much smaller than that of MCT. With simple 2-D, square gratings, the spectral QE is quasi-Gaussian with peak QE of 10-25 percent and spectral bandwidth of 1-1.5 μm. The spectral bandwidth can be adjusted (through modifications to the QW and coupling structure) from ~ 0.5 μm to 4 μm, but the integrated absorption tends to remain constant for a fixed number of quantum wells and fixed doping density. Different designs have been used with 1-D, 2-D, ring, checkerboard [14–16], and random gratings [17]. However, the QWIP QE is not fundamentally limited to the current values. New grating designs that improve the quantum efficiency are being studied, such as the E-QWIP [18], antenna grating [19], and corrugated grating (C-QWIP) [20]. Simulations [21] indicate that QE greater than 50 percent for unpolarized light should be achievable in FPA sized pixels through control of grating metal conductivity and pixel geometry. The claim that QE is fundamentally limited to QE below 50 percent is certainly not true.

QWIP is a photoconductor. The photocurrent of a QWIP is determined by the product of the QE, which is the fraction of incident photons that are absorbed (and escape from the well) to yield mobile photoelectrons, and the photoconductive gain g, which is the number of electrons that flow through the contacts for each generated photoelectron. Although the physical interpretation of photoconductive gain is somewhat different in a QWIP than in a continuous media photoconductor [22], the gain is approximately the ratio of the excited carrier lifetime to the device transit time. A parameter called conversion efficiency (CE) is sometimes defined as QE×g. On the other hand, a photodiode has a gain of unity, so the QE is the same as the CE. A small gain is desired when a QWIP is working under the ROIC charge well capacity limited situation, either due to a very high background or a heated window, or due to high dark current at high operation temperature. A higher gain (and consequently higher CE) is often desirable for low background applications, where it often takes too long to fill the charge wells in the ROIC. If a QWIP is operated at low temperature under background limited photodetection (BLIP) condition, the gain for photocurrent is often much larger than the gain for dark current [23]. In this situation, the photocurrent gain should be large, filling the charge wells in a reasonable time.

In a bound-to-miniband QWIP designed for high background applications, the photoconductive gain is around 0.2 with 50 wells, and is inversely proportional to the number of wells. The conversion efficiency is around 6 percent. Other QWIP structures have demonstrated gain values from 0.2 to greater than 1. For example, use of a smaller number of quantum wells and use of the bound-to-continuum structure can increase the gain and improve the detector performance for low temperature applications. With slightly increased doping density, a three-well simplified-QWIP (S-QWIP) has been demonstrated with high performance and a 29 percent conversion efficiency [24]. By optimizing the device structure, the number of wells, the doping density, and new grating schemes, further improvement in QWIP conversion efficiency and dark noise is expected.

4.2. Dark current and R_0A

Two important figures of merit in evaluating device performance are R_0A product (for MCT photodiodes) and dark current (for QWIPs). They reflect the quality of the material and device design. R_0A is defined as the product of dynamic resistance at zero bias voltage with detector area. When a photodiode FPA is under operation, a small negative bias is needed.

The dark current in a photodiode may consist of diffusion current, generation-recombination (g-r) current, tunneling current, and surface leakage current. Piotrowski [25] (Fig. 11.44 and Table 11.4) shows the main sources of the dark current from a photodiode. Diffusion current is the fundamental current mechanism in a p–n junction photodiode. It arises from the random thermal generation of electron-hole pairs within roughly a minority carrier diffusion length on either side of the depletion region. g-r current is associated with thermal generation within the deletion region. The Auger process is the only fundamental lifetime limit for these processes. Other mechanisms, such as Shockley-Reed-Hall (SRH), are not intrinsic and should be reduced with progress toward purer and higher quality materials. Tunneling current is caused by direct tunneling of electrons across the junction from the valence band to the conduction band (band-to-band tunneling) or indirect tunneling through interband states (trap assisted tunneling). Finally, actual p-n junctions often have additional dark current and noise, which is related to the surface. The surface of devices is passivated in order to stabilize the surface against chemical and heat induced changes as well as to control surface recombination, leakage, and related noise. Near zero bias, the noise components from nearly equal currents flowing in opposite directions add incoherently such that the total noise is determined by the area normalized diode impedance R_0A.

In MCT diodes specifically, dark current can come from the base and cap layers, depletion layers, surfaces, and contact regions. Generally, the Auger mechanism governs the high temperature lifetime, and the SRH mechanism is responsible for low temperature lifetimes. The g-r current varies with T as n_i, and is less rapid than diffusion current, which varies as n_i^2, where n_i is the intrinsic carrier density. Thus, a temperature is finally reached at which the two currents are comparable, and below this temperature the g-r current dominates [8]. The longer the cutoff wavelength, the lower this temperature is, in general. At low temperature for LWIR, such as 40 K, tunneling current dominates, and large spreads in R_0A distributions are typically observed that are associated with localized defects [26]. The tunneling mechanism is still not well understood, and it usually varies from diode to diode.

R_0A is commonly used for MCT diode as the figure of merit for the device quality. Top quality MCT diodes have shown R_0A products close to the theoretical limit. For example, a 10 μm cutoff MCT diode at 77 K has shown $R_0A = 665\ \Omega\,\mathrm{cm}^2$ [27], which is within a factor of two of that predicted for the Auger 7 limit. In practice, nonfundamental sources often dominate the dark current of present MCT photodiodes, with the exception of specific cases of near room temperature devices and highest quality 80 K LWIR and 200 K MWIR devices [28]. Typical values of R_0A at 77 K as a function of cutoff are given by Wu's [10] Fig. 1, including both LPE and MBE growth. From the figure, one can see that the average R_0A at 10 μm is around 300 $\Omega\,\mathrm{cm}^2$ and drops to 30 $\Omega\,\mathrm{cm}^2$ at 12 μm. At 40 K, R_0A varies between 10^5 and $10^8\ \Omega\,\mathrm{cm}^2$ with 90 percent above the $10^5\ \Omega\,\mathrm{cm}^2$ at 11.3 μm [26]. A good quality 128×128 pixel FPA grown by MBE from Hughes Research Center gives an R_0A of 220 $\Omega\,\mathrm{cm}^2$ at 80 K with 9.92 μm cutoff [29]. Santa Barbara Research Center's LPE growth shows similar values [8]. The LWIR 128×128 pixel FPA grown by MBE at Rockwell International has an R_0A of 83 $\Omega\,\mathrm{cm}^2$ at 80 K with 10.1 μm cutoff [30]. One should notice, however, even though R_0A is often used as a figure of merit for MCT diode, the FPA is often operated under small negative bias (–10 to –50 mV). A small negative bias usually increases the R_DA, but decreases the array uniformity. For example, when a 15 μm MCT test array shows very good R_0A uniformity down to 60 K, the R_DA at –20 mV and –40 mV show large variation at 60 K [31].

QWIP is a photoconductor and dark current is usually used to measure device quality and performance. The major effects of dark current in a QWIP are; first, it causes g-r noise and therefore reduces the SNR, and second, it fills the charge well of the readout capacitor.

The behaviour of the dark current of a QWIP is well understood. It has three mechanisms with one mechanism usually dominates at one temperature range, even though all three mechanisms contribute at all temperatures. At low temperatures (T < 40 K for 10 μm cutoff), the dark current is mostly caused by defect related direct tunneling (DT). With high quality III–V material growth and processing, this dark current is very small. In the medium operating temperature range (40 to 70 K for 10 μm cutoff), thermally assisted tunneling (TAT) dominates. Electrons are thermally excited and tunnel through the barriers, with possible assistance from defects in the triangle part of the barrier that forms under bias. At high temperature (70 K for 10 μm cutoff), thermally excited electrons are thermionically emitted (TE) above the barriers. One can adjust the device structures, doping densities, and bias conditions to get optimum dark current and photoresponse for specific applications. However, when the device is TE dominated, which means the dark electrons have energy and transport mechanisms similar to photoelectrons, it is very hard to reduce the dark current without sacrificing the photoelectrons. A typical LWIR QWIP dark current density at 77 K is about 5×10^{-4} A/cm^2 for $\lambda_c = 9$ μm and bias voltage of –2V. It usually reduces exponentially with inverse temperature with a reduction of three to five orders of magnitude between 77 K and 40 K. A dark current of 5×10^{-4} A/cm^2 is in the nanoampere for a 24×24 μm^2 pixel. Certain techniques, such as the E-QWIP [18] and C-QWIP [20], use coupling structures that are etched right through the QW stack. These schemes can maintain the detector optical area, while reducing the dark current by a factor up to 5. The fact that this can be done without introducing significant surface currents is further evidence of the low surface leakage along the unpassivated GaAs/AlGaAs surface.

4.3. D*

D* is an important figure of merit for comparing IR detectors operated with the same noise bandwidth. It reflects the SNR at a certain temperature with unit noise bandwidth and detector area. Under BLIP conditions, QE is the key for determining the SNR in photocurrent, since the fluctuations in photocurrent are determined entirely by statistical fluctuations in the number of absorbed photons. The gain simply acts as a linear multiplier that does not affect the SNR of the photocurrent. Therefore, with a 300 K background under BLIP operations and the charge well on the ROIC is unlimited, the D* of a single MCT device is usually much higher than that of a QWIP due to its higher quantum efficiency. If the detector/readout is charge well capacity limited, i.e., if the integration time is being truncated to avoid overfilling the charge well, which is often the case with present ROIC at high background, then we can not only use QE as a measure. For example, with an in band detector photon flux of Φ, photoconductive gain g, quantum efficiency η, and electronic charge e, the detector photocurrent will be

$$I_p = e\Phi\eta f \tag{1}$$

With an integration bandwidth Δf, the BLIP g-r noise current corresponding to this BLIP current is approximately [22]

$$I_n = \sqrt{4eIg\Delta f} \xrightarrow{BLIP} 2eg\sqrt{\Phi\eta\Delta f}. \tag{2}$$

Then, if the integration time, τ, is selected to fill a charge well of capacity N_w electrons, τ and the SNR are

$$\tau = \frac{N_w}{\Phi\eta g} \tag{3}$$

$$SNR = \sqrt{\frac{N_w}{2g}}. \tag{4}$$

The corresponding SNR for an MCT photodiode is $\sqrt{N_w}$. When g = 1, the SNR for MCT is higher than QWIP by a factor of $\sqrt{2}$, which is the well known ratio for PV versus photoconductive (PC) detectors. However, when g < 0.5, the integrated SNR is higher for the QWIP. If under BLIP and g becomes so low that the QWIP cannot fill the charge well in the available integration time, the SNR will be reduced. Thus, the only way to meaningfully determine whether the QWIP or MCT is better in a particular case is to evaluate the integrated SNR with a specified well capacity and background flux level, i.e., use a system level comparison. But in general, when there is a sufficiently low signal, high frame rate, or hyperspectral applications, the higher QE of MCT generally dominates, yielding a higher SNR than QWIP.

4.4. BLIP temperature

The BLIP temperature of a detector is the temperature at which the dark noise of the detector equals the background noise, and is specified for a given field of view (FOV) and background temperature. BLIP operation is very desirable, but it becomes more difficult under low background conditions. MCT generally achieves higher BLIP temperature than QWIP at high backgrounds due to its higher QE and longer carrier lifetime. The main disadvantage of QWIPs versus MCT is the shorter carrier lifetime, which usually forces the QWIP to operate at a lower temperature. For example, QWIPs with cutoff wavelength near 10 μm are usually operated at 60 to 70 K, while MCT photodiodes with similar cutoff can be operated at 80 to 90 K. The lifetime in GaAs/AlGaAs QWIPs is dominated by longitudinal optical (LO) phonon transitions that are a fundamental process for that QW structure. Therefore, while several techniques have been demonstrated to achieve 80 K operation of GaAs/AlGaAs QWIPs, it is unlikely that they will ever operate at as high a temperature as comparable MCT devices. However, detectors based on quantum dots may eventually work at higher operating temperature since the carrier lifetime is roughly 10 times longer than in quantum wells and is not limited by LO phonons [32].

As the background flux is lowered, the dark current must also be reduced to maintain BLIP. QWIP performance generally improves more reliably and uniformly with cooling, so the QWIP often performs better than MCT at lower temperatures (~40 K). Even at higher backgrounds, the difference between the BLIP temperature for QWIP and MCT is not as large as once proposed. An estimate by Kinch and Yariv in 1989 [33] gave a thermal generation rate of a QWIP that was five orders of magnitude higher than that of MCT at 77 K. Improved QWIP material growth, device design, and optimised doping have produced a much smaller thermal generation rate for QWIPs, so that now it is only 10 times larger than MCT at 77 K [34].

4.5. Uniformity

FPA evaluations show that fixed pattern noise associated with array nonuniformity is one of the main factors limiting array performance [35]. The nonuniformity (and operability) directly affects the noise equivalent differential temperature (NEDT) or noise equivalent irradiance (NEI), and is particularly important for applications involving accurate temperature measurements, background subtraction, threshold testing, or tracking and discrimination of multiple unresolved targets. Nonuniformity also increases the false alarm rate in automatic target recognition systems. Dead pixels are an extreme form of nonuniformity that can result in missing unresolved targets during tracking. Fixed pattern noise is a spatial nonuniformity in apparent temperature (while looking at a uniform scene) that does not vary with time. It reflects the intrinsic nonuniformities of the FPA. For thermal imaging applications, since almost all cooled FPAs are operated with gain and offset correction, purely linear variations in both detector and readout response with signal flux are fully corrected and do not result in fixed pattern noise in the corrected image. Rather, corrected fixed pattern noise results from nonlinearities in the detector or readout. Moreover, even linear variation in detector response can increase fixed pattern noise when combined with a nonlinear readout characteristic. Therefore, the so-called uncorrected response uniformity of the detector array is usually important, even if the variation is fully linear.

Response nonuniformity is usually calculated as the standard deviation over mean of either uncorrected or corrected response, evaluated over the operable pixels in an array. For the same array, the calculated nonuniformity therefore depends on the specification of operability. A higher requirement for the operability usually leads to a lower uniformity and vice versa. Beck et al. [36] gives a good example, where the corrected response nonuniformity is given as a function of the number of bad pixels. The corrected responsivity nonuniformity of the center 64×64 pixels in a 256×256 pixel QWIP array is 0.04 percent with 10 pixels excluded (an operability of 99.75 percent). If only 4 pixels are excluded (a 99.90 percent operability), the nonuniformity increases to 0.045 percent. These values are considered very good for a 20°C calibration interval. The uncorrected response nonuniformity for the entire 256×256 pixel array was 1 to 3 percent with an operability greater than 99.5 percent [36]. Similarly good uniformity has been demonstrated in a 128×128 pixel 15 μm array by the NASA Jet Propulsion Laboratory [37], which had an uncorrected response nonuniformity of 2.4 percent and a corrected nonuniformity of 0.1 percent with a 30°C calibration interval. This high uniformity and operability is associated with the relatively mature GaAs growth and processing technology. It is also a direct consequence of the excellent spectral uniformity generally seen in QWIP FPAs [38].

Nonuniformity and operability have historically been more of an issue for MCT. One of the major problems is the nonuniformity of the dark current and spectral response related to the material properties and device quality, especially at LWIR and VLWIR. MBE technology has helped to improve the uniformity in MCT arrays. For example, a 128×128 pixel LWIR array by Rockwell [30] has achieved 97.7 percent operability and 0.017 percent corrected nonuniformity (with 10°C calibration interval). (This value is lower than the value of 0.04 percent quoted above for QWIP, but for different calibration intervals. Since the corrected nonuniformity increases roughly as the square of the calibration interval, the measured value of 0.017 percent over 10°C would increase to roughly 4×0.017 = 0.068 percent over 20°C.) This value is also considered very good; however, uniformity remains an issue for MCT , especially at low temperature and VLWIR.

4.6. NEDT and NEI

Noise equivalent temperature difference (NEDT) is the temperature change of a scene required to produce a signal equal to the rms noise. It is a system level parameter that depends on parameters such as the f number of the optics used, and is often used to characterize the sensitivity of FPAs. When NEDT is defined to include both spatial and temporal noise, FPA corrected response uniformity becomes a limiting factor. For example, when the temporal noise of the detectors is reduced below the fixed pattern spatial noise, increasing D^* will no longer decrease NEDT. In such cases, an improvement of corrected nonuniformity from 0.1 percent to 0.01 percent could lower NEDT from 63 to 6.3 mK. At 77 K, the peak D^* of a LWIR QWIP is about 10^{10} $\mathrm{cmHz^{1/2}W^{-1}}$, which is sufficient for very good thermal imaging with NEDT of 15 mK [39] at video frame rate. The higher D^* of MCT can, and in some cases does, yield lower NEDT than QWIP, but the performance of many MCT FPAs is limited by nonuniformity, so that the lower NEDT is not realized. Further decreases in NEDT will require further improvements in uniformity. For low background applications, NEI is commonly used as a figure of merit. It is the radiant flux density necessary to produce a signal equal to the rms noise. The relationship between the NEI and NEDT is very simple: $\mathrm{NEDT} = \mathrm{NEI}\times(dP_b/dT)^{-1}$, where P_b is the background photon flux in the spectral band of measurement. When the array is nonuniformity limited, NEI is proportional to the nonuniformity. When nonuniformity is reduced, a lower NEI is obtained. At very low background, NEI is limited by the temporal noise in which the dark current nonuniformity plays an important role [40].

5. Low background applications

For low background applications, we are usually dealing with a faint target that is far away. An increased QE and reduced dark current are desired at the same time to bring the signal above the detector noise level. MCT has high QE but needs to reduce the dark current at low temperatures. QWIP needs to improve both for low background applications. Several grating schemes under study, in combination with S-QWIP structures, have the potential to increase the conversion efficiency and reduce the dark current at the same time [18]. However, the only way to reduce dark current in either MCT or QWIP to the levels required is to decrease the operating temperature. At low temperature in MCT, the dark current does not usually continue decreasing at the same exponential rate seen at higher temperature. The defect and impurity related tunneling dominates and the dark current becomes very nonuniform [8]. The lateral collection scheme used by Rockwell improves the R_0A at 40 K to some extent, but the distribution of the R_0A is still spread out over three orders of magnitude [26]. A recent report by Rockwell [41] shows that a 128×128 LWIR MCT array has 99 percent operability at 77 K. However, while operating at 40 K, orders of magnitude variation in R_0A are found. This nonuniformity of R_0A is related to the excess tunneling currents induced by nonuniformly distributed localized defects. Therefore, under low background conditions, the dark current nonuniformity limited fixed pattern noise limits the array performance. The purification of the substrate, source material, growth, and processing conditions might improve the MCT device quality at low temperature. Therefore, until such improvements are achieved, QWIP devices typically yield more uniform and predictable performance under low temperature, low background conditions.

6. VLWIR

VLWIR sensors are very important in strategic missile defenses and space applications. FPAs of 12–18 μm are very useful for the detection of cold objects such as ballistic missiles in midcourse [42]. For VLWIR, the band gap of the detector must be made even narrower than for LWIR, and the operating temperature has to be made lower to suppress the thermally excited dark current. Both of these requirements aggravate the problems associated with current MCT material. Direct and defect assisted tunneling current are increased with a decreased band gap and lower operating temperature. The variation of x across the MCT wafer can be a more serious problem and cause a much larger spectral nonuniformity. For example, at 77 K, a variation of $\Delta x = 0.2$ percent gives a cutoff wavelength variation of $\Delta\lambda_c = 0.063$ μm at MWIR ($\lambda_c = 5$ μm), while the same Δx can cause cutoff wavelength variations of $\Delta\lambda_c = 0.25$ μm for LWIR (10 μm), and $\Delta\lambda_c = 0.56$ μm for VLWIR (15 μm). Therefore, the required composition control is much more stringent for LWIR and VLWIR than for MWIR. This spectral response nonuniformity due to compositional inhomogeneity cannot be fully corrected by two- or three-point corrections. A spectral filter can be used to eliminate the spectral nonuniformity but this increases the system complexity and reduces optical throughput somewhat. Despite these difficulties, a 15 μm 128×128 MCT array has been demonstrated by Rockwell [12]. The operability is 98.85 percent at 8.1×10^{15} cm^{-2}s^{-1} background flux, and the uncorrected response nonuniformity is 9.8 percent at 40 K. Lockheed Martin also demonstrated uniform and well controlled composition of 15–18 μm MCT detector material using LPE technology [11].

The extension of QWIP to VLWIR is relatively easy because there is very little change in material properties, growth, and processing. At VLWIR, the intersubband spacing of a QWIP is relatively smaller than at LWIR. Due to the lower quantum well barriers, the dark current of thermionic emission dominates at a lower temperature. In order to achieve equivalent performance of a 10 μm cutoff QWIP at 77 K, the temperature needs to be cooled to 55 K for a 15 μm cutoff [37] and 40 K for an 18 μm cutoff [43]. An unoptimized 128×128 pixel QWIP FPA at a 15 μm cutoff wavelength has been demonstrated by JPL [37] with an NEDT of 30 mK at 45 K with 300 K background and f/2.3 optics. This initial array gives excellent images with 99.9 percent operability and uncorrected responsivity nonuniformity of 2.4 percent. Comparing the array results from MCT and QWIP at 15 μm, QWIP has higher operability and uniformity, presumably because of the high material quality of GaAs technology.

It is also important to note that the data from the MCT and QWIP arrays were taken at high background, so that the nonuniformity reflects mainly spatial variations in spectral response and responsivity. At low backgrounds where dark current nonuniformity dominates, the difference between QWIP and MCT is expected to be larger. It is a big challenge for both QWIPs and MCT to meet requirements of VLWIR and low background at the same time. The major challenge for QWIP is to increase the conversion efficiency, while for MCT it is to improve the nonuniformity of both dark current and responsivity.

7. Multicolor detectors

As IR technology continues to advance, the demand for multicolor IR detectors for advanced IR systems will grow. For military applications, multicolor detectors are needed for better target temperature estimation, and target discrimination and identification. So far, the multiple waveband measurements have been achieved with separate FPAs that have a dichroic filter, a mechanical filter wheel, or a dithering system with a striped filter. Each of these approaches is expensive in terms of size, complexity, and cooling requirements. A single FPA with multicolor capability is desirable to eliminate the spatial alignment and temporal registration problems that exist whenever separate arrays are used. A single FPA also has the advantages of simpler optical design and reduced size, weight, and power consumption.

Both QWIP and MCT detectors offer wavelength flexibility from MWIR to VLWIR and multicolor capability in these regions. The main challenges facing all multicolor devices are more complicated device structures, thicker and multilayer material growth, and more difficult device fabrication, especially when the array size gets larger and pixel size gets smaller. For MCT, the multilayer structure and multiple p–n junctions required in a multicolor device mean more difficult in material growth, device fabrication and passivation. And problems are further compounded when multicolor involves VLWIR compared with single VLWIR. Since MCT layers absorb all radiation with wavelength below the layer's cutoff, the shorter wavelength layer (the MW layer in an LW/MW detector) must be thick enough to absorb nearly all radiation or the residual signal will appear as spectral crosstalk in the longer wavelength layer. The active region of current single color MCT is usually thicker than 10 μm, while that of QWIP is usually less than 3 μm. Cooled filters might have to be used with MCT LW/LW two color FPAs. For multicolor arrays, QWIP's narrow band spectrum is an advantage, resulting in low spectral crosstalk without the requirement of full absorption (and therefore thick layers) in the shorter wavelength section and without cooled filters. The major challenge for QWIP is developing broadband or multicolor optical coupling structures that permit efficient absorption of all required spectral bands. Most QWIP arrays use 2-D grating, which is very wavelength dependent, and the efficiency gets lower when the pixel size gets smaller. Lockheed Martin has used rectangular and rotated rectangular 2-D gratings for their two color LW/LW FPAs and the FPAs show very good imaging. But the grating only couples half of the IR radiation for each color compared to the square 2-D gratings for single color FPAs. Other gratings have been developed for broad band coupling, such as the previously mentioned C-QWIP, antenna coupler, and random reflector. However, they require more development before they can be inserted into a wafer level process [44]. The quantum efficiency becomes a more difficult issue for QWIP multicolor FPA than for single color.

8. State of the art

Both MCT and QWIP have been developed into large format FPAs. MCT FPAs have been developed in SWIR [45], MWIR [46], LWIR, and VLWIR, while QWIP FPAs are mostly in LWIR and VLWIR, with MWIR only in two color FPAs. In the LWIR regime, MCT staring arrays have been demonstrated up to 480×640 elements [47]. The progress of MCT in the LWIR and VLWIR has benefited from the recent development of II–VI MBE growth technology. 128×128 and 256×256 LWIR arrays grown by MBE for both planar [30] and mesa [48] structures are also demonstrated. Rockwell also demonstrated a 128× 128 MCT array at 15 μm wavelength [12]. LWIR QWIP FPAs with up to 640×480 pixels have been demonstrated by Lockheed Martin and JPL [49,50]. JPL also demonstrated a 128×128 QWIP FPA at 15 μm [37]. Table 1 gives some recent data of single color FPA performance of MCT and QWIP provided by Rockwell, Lockheed Martin and JPL.

For multicolor FPAs, a MW/MW two-color MCT 128×128 FPA has been demonstrated by Raytheon at Santa Barbara Research Center [51]. Typical FPA performance at 78 K and f/1.9 include pixel operability greater than 98 percent for both bands; NEDT < 24 mK for the 3.87 μm cutoff and NEDT < 12 mK for the 4.5 μm cutoff; and uncorrected responsivity nonuniformity 5 percent for the 3.87 μm cutoff, and 2 percent for the 4.5 μm cutoff. An MW/LW two-color MCT FPA at wavelengths of 4.67 μm and 8.76 μm has been demonstrated by Rockwell [52]. The array size is 64×63, cleverly using a 128×128 readout. The NEDT is 6 mK for the MW and 10 mK for the LW up to 100 K operating temperature with f/2.5 illumination. The operability for one array is 95.2 percent for the MW and 93.0 percent for the LW. At 77 K, median R_0A is 10^7 $\Omega\,cm^2$ for the MW, and ~5000 $\Omega\,cm^2$ for the LW. Both values compare favorably with published single color results. Similar efforts are also being pursued at Lockheed Martin and Texas Instruments using different architectures. For QWIP, two-color 256×256 MW/LW and near infrared (NIR)/LW FPAs with sequential imaging were demonstrated by Lockheed Martin in 1993 and 1994, respectively. The most recent development in multicolor QWIP FPAs are two color MW/LW and LW/LW FPAs with simultaneous imaging capability at Lockheed Martin. The results of the LW/LW are presented by Tom Faska at the 1998 IRIS/Detector conference [44]. The FPA has NEDT of 24 mK for the 8.6 μm and 35 mK for the

Table 1. Recent data on MCT and QWIP FPA measurement provided by Rockwell, Lockheed Martin and JPL

Parameter	MCT (Rockwell)	QWIP (JPL)	QWIP (LM)	MCT (Rockwell)	QWIP (JPL)
Array size	256×256	256×256	640×480	128×128	128×128
λ (μm)	~1–10.5	8.0–9.0	8.5–9.5	~1–13.8	13.2–15
FPA T (K)	77	72	60	60	45
F/#	3.8	2.0	2.3	3.8	2.3
NEDT (mK)	20	15	15–25	44	15
τ_{int} (ms)	0.468	10	4	0.067	15
Operability (%)	99.65	99.99	99.8–99.99	99.33	99.99
Pitch (μm)	40	38	24	40	50
Fill factor (%)	100	54	84	100	54
Raw non-U (%)	4.9	2.0	5	9.2	2.0
Corrected non-U (%)	0.019	0.01	0.1	not measured	0.01
Bkgd flux (ph/cm^{2}s)	4.1E15	7E15	6.3E15	8.2E15	9E15
D^* (Jones)	2.8E11	2.4E11	2E10 at 80 K	2.9E11	2.4E11

11.2 μm at 40 K with f/2 optics. The pixel operability in each color is > 97 percent and has now improved to > 99 percent.

Currently, both QWIP and MCT FPAs in LWIR and multicolor are in the development stage. The results reviewed here have demonstrated some of the capability of each technology, but may not represent the optimum performance. In each cited reference, methods of improvement are suggested and are expected to yield better performance.

9. Cost

So far, all QWIP and MCT large format LWIR and VLWIR FPAs have been developed in research and development laboratories without mass production experience. The cost of an FPA is a function of the fabrication yield, which depends strongly on the maturity of the technology. The production cost varies with production quantity, and the production learning curve varies with different companies. The substrate, manufacturing equipment, and the available potential vendors also affect the price. Another major cost issue is in the process of developing IR detector arrays that are reliable with high performance capability and fast cycle times. Affordability, prompt delivery, and low maintenance are also important factors.

MCT detectors have been the center of a major industry with a worldwide turnover of billions of dollars [53]. Major efforts have been directed toward solving the material related problems. The potential improvements in MCT FPAs rely heavily on the advancement of the MCT material growth and processing technologies. Development of LWIR, VLWIR, and multicolor MCT for low background, low temperature performance requires the development of high purity material growth and device processing, and minimization of crystalline defects. Development of VLWIR and more than two colors in MCT are challenging, especially for low background applications. The main challenge in producing large MCT arrays at LWIR, VLWIR, and multicolor will probably be reproducibility and yield associated with material issues.

QWIP is grounded on a commercial III–V material technology that is the basis of a multibillion dollar electronics industry. Because of the maturity of GaAs growth technology and stability of the material system, no investment is needed for developing QWIP substrates, MBE growth, and processing technology. Investment will concentrate on device and grating design improvements to increase quantum efficiency and operating temperature. The rapid development of QWIP over the past 10 years and flexible sharing of facilities with other III–V devices will likely result in lower production costs compared with MCT. In tactical systems, these production advantages are somewhat offset by the need for lower operating temperature and therefore a more powerful cooler. However, the operating temperature advantage of MCT tends to disappear at the lower temperatures used for VLWIR and space applications, so the cooler costs would be the same in these systems. Perhaps the most significant long range advantage of QWIPs is the fact that the material growth and processing facilities are shared with other higher volume III–V devices such as lasers, light emitting diodes, and millimeter wave circuits. This means that a large amount of expensive capital equipment and experienced processing personnel are maintained by these other applications, but available for the production of infrared focal plane arrays on an as needed basis. By contrast, infrared detectors are the only major application of MCT, so the entire processing and personnel infrastructure must be continuously maintained by that application alone. In an era in which fewer military infrared systems are being funded, this may be increasingly important.

10. Conclusions

A discussion of MCT and QWIP has been given, with emphasis on the material properties, device physics, device structures, and their impact on FPA performance and applications. From the discussion, one can see that both MCT and QWIP are suitable materials for IR detection and have wavelength flexibility and multicolor capability. Both technologies demonstrated large format FPAs. The main advantages of MCT are its high quantum efficiency and wide spectral bandwidth, and its relatively low thermally generated dark current at T > 77 K compared with that for QWIPs. Further work is needed on material related issues that affect low temperature performance as well as manufacturability. MCT has the potential to be improved at LWIR and VLWIR with low backgrounds if the low temperature dark current anomaly can be solved.

Even though QWIP is a photoconductor, it has high impedance and low power consumption, and is easy to match with the cryogenic readout circuit. The main advantages of QWIP are uniform, reproducible performance associated with the mature III–V material technology, consistent increase of performance with reduced operating temperature for low background applications, and potentially lower long term cost associated with flexible facility sharing with other III–V devices. The main problems in QWIP are its relatively low QE and/or conversion efficiency and a relatively high thermal generation rate at T 70 K. Improved optical coupling methods are needed to increase QE. Improved device structures and readout circuits could push QWIP to T > 80 K operation, but it will be hard to compete with MCT in this temperature range. However, due to the high material quality at low temperature and in the VLWIR region, QWIP has the potential to fulfill the system requirements for many low-background, low-temperature applications. Further study is needed to optimize the device design, improve the device performance, and extend to VLWIR and multicolor FPAs.

In summary, current QWIP technology cannot compete effectively with MCT at high operating temperature due to the fundamental lifetime limit associated with the intersubband transitions. MCT presently also has a clear advantage for high frame rate or hyperspectral applications where maximum QE and wide band spectrum are necessary. However, QWIP has advantages for some LWIR and VLWIR FPA applications in terms of array size, uniformity, and cost. QWIPs are especially promising for VLWIR at low temperature operation. However, achieving the required VLWIR performance at low background is a challenge for both QWIP and MCT.

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