QWIP AND MCT FOR LONG WAVELENGTH AND MULTICOLOR FOCAL PLANE ARRAY APPLICATIONS

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ABSTRACT

Infrared (IR) sensor technology is critical to all phases of ballistic missile defenses. Traditionally, material systems such as indium antimonide (InSb), platinum silicide (PtSi), mercury cadmium telluride (MCT), and arsenic doped silicon (Si: As) have dominated IR detection. Improvement in surveillance sensors and interceptor seekers requires large size, highly uniform and multicolor (or multispectral) IR focal plane arrays involving mid-wave, long-wave and very-long-wave IR regions. Among the competing technologies are the quantum well infrared photodetectors (QWIP) based on lattice-matched GaAs/AlGaAs and strained layer InGaAs/AlGaAs material systems. In this paper, a discussion of cooled IR technology with emphasis on QWIP and MCT will be given. Details will be given concerning device physics, material growth, device fabrication, device performance, and cost effectiveness for long wavelength infrared, very long wavelength infrared, and multicolor applications. The conclusion drawn here is that even though QWIP cannot compete with MCT at the single device level (considering the quantum efficiency and D^*), it has potential advantages over MCT for long wavelength and very long wavelength focal plane array applications in term of the array size, uniformity, operability, yield, reliability, and cost of the systems. QWIPs are especially promising for very-long-wave IR at low temperature operation, and when simultaneous multicolor detection using a single focal plane array is desired. Operating a very-long-wave IR focal plane array at low background is a big challenge to both MCT and QWIP, while QWIP has more potential to be realized due to its good device property at low temperature.

1. Introduction

Infrared (IR) detection has been extensively investigated ever since the discovery of IR radiation in 1800. It has been utilized both in commercial world and military applications. The IR spectrum can be divided into short-wave IR (SWIR, 1 to 3 μm), mid-wave IR (MWIR, 3 to 5 μm), long-wave IR (LWIR, 8 to 12 μm), and very-long-wave IR (VLWIR, >12 μm). MCT is the most extensively investigated semiconductor alloy system for infrared detectors, with special consideration of its potential for LWIR and VLWIR applications. During more than 30 years of research, significant progress has been made in MCT materials, growth, processing, passivation, substrates, and manufacturing capability. In the SWIR, large size focal plane arrays (FPAs) have been demonstrated with pixel format up to 1024×1024.[1] According to Compain and Boch from Sofradir and Leti,[2] two-dimensional arrays in MWIR can be found with up to 320x240 elements for full performance and up to 640x480 elements with limited performance. In LWIR, most of the arrays are limited to 320x240 elements for full performance range in France. In the United States, a 640x480 array using liquid phase epitaxy (LPE) has been reported,[3] but the reliability has been an issue. The progress in the LWIR and VLWIR has been relatively slow until the recent development of molecular beam expitaxy (MBE) growth technology. So far, 128x128 and 256x256 LWIR arrays by MBE using both planar[4] and mesa[5] structures have been demonstrated. A 128x128 MCT array at 15 μm has also been demonstrated using planar structure by MBE[6] which is a significant achievement for MCT technology. MBE technology gives MCT more potential to produce high quality FPAs in LWIR, but the array size, uniformity, reproducibility, and yield are still difficult issues, considering the substrate problems, material properties, and array fabrication, especially for low temperature and low background operation. Extending to VLWIR and multicolor brings more challenges to MCT due to the even narrower band gap and more complicated device structures, especially at low temperatures for strategic applications.

The quantum well infrared photodetector (QWIP) is a relatively new technology that has been developed very quickly in the past 10 years.[7] N-type

GaAs/AlGaAs and InGaAs/AlGaAs systems on GaAs substrates are the most studied and mature systems. Large size GaAs/AlGaAs FPAs with up to 640x480 in LWIR[8,9] and 128x128 at 15 μm[10] have been demonstrated, with excellent uniformity and operability. Among the cooled IR detector systems, PtSi and InSb can be operated only in MWIR with no wavelength tunability and multicolor capabilities. Si:As has a wide band spectrum from 0.8 to 30 μm, but no tunability or multicolor capability has been developed. It can be operated only at temperatures around 12K. Both MCT and QWIP offer wavelength flexibility in MWIR, LWIR and VLWIR, as well as multicolor capabilities. In this paper, the discussion will be concentrated on these two IR systems at LWIR, VLWIR, and multicolor with emphasis on low temperature and low background applications. Fundamental problems of each system and how they affect the device performance and applications will be discussed.

2. Material Properties

Both QWIP and MCT are semiconductor IR devices. High quality semiconductor materials are essential to the device performance and array production. The main requirements of IR materials are low defects, large size of wafers, reliability, uniformity and reproducibility of intrinsic and extrinsic properties.

MCT has been considered the most important, yet most challenging, 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 band gap of MCT from 0 eV (x=0) to 1.45 eV (x=1 at 77K) which, theoretically speaking, could cover IR ranges from 1 to 50 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 around 70% and a relatively small thermally generated dark current at temperature (T) larger than 77K.

However, MCT has very serious technological problems in mass production.[11] The natural band gap of MCT is very narrow at LWIR (0.124eV at 10 μm cutoff, 0.082 eV at 15 μm cutoff) which makes the material system unstable. HgTe is a semimetal in which the bond of Hg-Te is very weak and is destabilized further by alloying it with CdTe. The high mercury vapor pressure and the Hg-Cd-Te phase diagram shape result in serious difficulties in repeatable and uniform growth.[12, 13] The soft, but brittle, nature of the MCT material and substrates makes the device processing difficult. Significant progress has been achieved in material and device qualities, however, difficulties still exist due to lattice, surface, and interface instabilities. Problems remain in material properties, such as the roles of various impurities, dopant behavior, crystal growth, native defect chemistry, surface science, junction formation, passivation, and contact technology. Improved understanding of MCT material properties and how they affect the device performance is still critical to the continued development of MCT technology, especially for LWIR, VLWIR, and multicolor applications.

QWIPs use intersubband transition instead of direct interband transition. III-V materials are used which have a relatively wide bandgap (1.43 eV for GaAs). The advantages of a wider band gap material are that it gives superior bond strengths and material stability, well-behaved dopants, thermal stability, and intrinsic radiation hardness. Large size and high quality GaAs substrates and mature GaAs growth and processing technology guarantee highly uniform, large size FPAs with well controlled molar compositions. No passivation is needed in QWIP. The hardness of the material and substrate makes device processing and array fabrication easy to handle, which leads to a high yield of the FPAs. The disadvantage of this wider band gap material is that the energy band gap does not fall in the IR regime, and direct band gap transition cannot be used for IR detection. Intersubband transition is used which sets certain fundamental limits on the device performance at T>80K. Fig. 1 shows the energy band gaps of MCT and QWIP materials.

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 are their relatively high R_oA product and lower power consumption compared with MCT photo-conductors. The major problem with a photo-diode is its involvement with p-type materials. Basic MCT photodiodes consist of either p-on-n or n-on-p, homo- or hetero- junctions. For wavelengths from 2 to 20 μm at 77K, n-type bases are favorable due to the lower and controllable doping. Hetero-junctions usually exhibit higher R_oA products than do homo-junctions.[14] The devices could be either in planar or mesa formats. The operation of a basic p-n junction photodiode with the band gap diagram is illustrated in Fig. 2. An internal potential barrier is built due to the carrier diffusion. IR photons with energy larger than the band gap are absorbed by the photodiode and excite electrons in 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 within one diffusion length of the depletion edge, the excited electron-hole pairs will diffuse to the depletion region first, where they are then separated by the electric field and contribute to photocurrent.

QWIP takes advantage of band gap engineering so that wider band gap materials can be used. The fundamental difference between QWIP and MCT is that QWIP uses intersubband transitions with energy bands either in the conduction band (n-type) or in the valence band (p-type). A typical QWIP usually consists of 30 to 50 quantum well periods. In an n-type GaAs/AlGaAs system, the intersubband transition happens only in the conduction band involving electrons. By changing the Al concentration x, the bandgap of $Al_xGa_{1-x}As$ can vary from 1.43 eV (x=0) to 2.16 eV (x=1) at 300K. 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 d and the Al x value determines the barrier height H. QWIP devices are all in a mesa format. Fig. 3 gives the device structure and band gap diagram of a n-type GaAs/AlGaAs QWIP under bias. The well region has one bound state as ground state and one or more excited states depending on the barrier structure. The quantum wells are doped with electrons with Fermi energy above the ground state. IR photons with energy coinciding with the energy difference between the excited and ground states can be absorbed by electrons. QWIPs usually operate in the photoconductive mode and bias voltage is applied to sweep the excited electron out of the well region. Depending on the position of the excited states in the well region, the intersubband transitions can be defined as bound to bound, bound to quasi-bound, and bound to continuum states. Fig. 4 shows the three most commonly used QWIP structures, bound to quasi-bound,[15] bound to continuum,[16] and bound to mini-band[17] transitions. By designing different well widths and barrier heights, one can achieve QWIP detection from 3 to 20 μm or even longer. With different combinations of barriers and well structures, different detection wavelengths, detection band widths and multicolor can be achieved.

4. Device Fabrication

4. 1 Substrates

Using epitaxial techniques for crystal growth is absolutely necessary for FPA applications when large area epilayers and sophisticated layered structures are required with abrupt interfaces, complex compositions, good doping uniformity, and well-controlled layer thickness. One problem with epitaxial techniques is the need of an affordable, large area substrate which is 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 could propagate into the epitaxy layers.

For MCT, there is no one substrate that satisfies all requirements.[18] CdZnTe is presently the most frequently used substrate for MCT at present time. It has the metallurgical compatibility and lattice match to MCT that permits the growth of relatively higher quality epitaxial layers of MCT. But, the available substrates are relatively small, soft, fragile and expensive (about $700 for 1 in^2 polished). The typical dislocation concentration of CdZnTe[19] is $10^4/cm^2$ to $10^5/cm^2$ which allows the growth of good quality MCT at MWIR and LWIR for tactic applications. But it may not be pure enough for low background, low temperature and VLWIR applications.

For the GaAs/AlGaAs material system used in QWIPs, GaAs substrates have a perfect lattice match to all Al concentrations. Large area (6 in. diameter) and high quality GaAs substrates are available at a much lower cost than CdZnTe (about $150 for 3 in. wafer). For the InGaAs/GaAs system on GaAs, there is a limit on the indium concentration and layer thickness because of the lattice mismatch. High strained layers with 35%

indium concentration have been grown, and the devices show very high quality material.[20,21]

Both thermal expansion coefficients of GaAs and CdZnTe are poorly matched to Si readout. Substrate thinning or total removal has been a standard practice in FPA fabrication which relieves, to certain extent, the strain and stress caused by the thermal expansion. GaAs can sustain a larger strain and stress due to its strong chemical bonds and durable mechanical properties, besides the thinner layer thickness of QWIP compared to MCT. Using alternative substrates for MCT has the potential to reduce the substrate cost, make large size arrays, and match to the readout. Most studied alternative substrates for MCT are Si, GaAs, and Sapphire. Si is the most desirable substrate, and is heavily pursued. Sapphire substrate has the most success with 1024x1024 FPA demonstrated at 3.2 μm cutoff.[1] The limitation of the sapphire substrate is its cutoff wavelength in MWIR. Overall, the quality of the devices grown on alternative substrates is inferior to those grown on CdZnTe.[3] Major problems are the large lattice mismatch and thermal mismatch between the substrate and MCT material which produce dislocations and affect the quality of the devices.

4.2 Material Growth

For a MCT photodiode, the active and capping layers can be grown using either LPE, metalorganic chemical vapor deposition (MOCVD), or MBE. The unstable nature of Hg in the system makes the control of composition, doping, and interface profiles very difficult when the material is grown, especially for reproducible LWIR, VLWIR, and multicolor devices. LPE, the most mature technology for MCT growth, has been used routinely for large volume production in SWIR, MWIR and LWIR linear arrays. The 640x480 LWIR FPA reported also used LPE growth.[3] The major problem with LPE is the precise control of x across the $Hg_{1-x}Cd_xTe$ wafer, which causes spectral non-uniformity, especially at LWIR and VLWIR. Precise control of the layer thickness and interface is another problem that makes extending MCT to multilayered multicolor devices difficult. The advantages of the MBE are that it offers low temperature growth under an ultra high vacuum environment, in-situ n-type and p-type doping, and precise control of composition, doping, and interfacial profiles. However, because Hg has both a high vapor pressure and low sticking coefficient, the growth temperature must be very low (<200°C). Special Hg sources are required in the MBE system, which makes the system more complicated and costly than regular MBE for III-V material growth. So far, the device performance of MBE growth and LPE growth is comparable at present time[5] in the LWIR. In the VLWIR, MBE has demonstrated 128x128 arrays at 15 μm, which is one step ahead of LPE. MBE technology has the potential to improve the MCT material quality and device performance for VLWIR and multicolor devices.

The junctions of an epilayer MCT diode can be formed by ion implantation, or in situ doping during the active and cap layer growth. The ion implantation has the advantage that it is a planar process and requires only a simple surface passivation. Its disadvantages are that it is difficult to totally repair the damages created by the process, and it is nearly impossible to use the process to build multilayer structures for advanced detectors. The advantage of the in-situ doping approach is that it is a simple layer by layer growth process, so it is relatively easier to build a multilayer structure. The challenge of the in-situ doping approach is that it requires tight control of growth temperature and fluxes and has a rather narrow window for the optimal growth. In addition, it requires a very stringent passivation for mesa structures.[5]

For QWIPs of GaAs/AlGaAs, MBE is used to precisely lay the atomic layers down to form the quantum wells. The GaAs MBE growth technology is a very mature and proven technology in III-V electronic industry and MMIC applications. The MBE technology guarantees the success and repetition of the material growth and has precise control of layer thickness, chemical concentration and doping profile. In order to produce the detection wavelength to MWIR, InGaAs/AlGaAs is usually used to increase the well depth. Strain is introduced during growth due to the lattice mismatch between GaAs and InGaAs. There is a critical thickness that can be grown pseudomorphically depending on the indium concentration. Two-stack, two-color QWIPs with 35% of indium concentration have been grown with 3 quantum wells in each stack and 20 quantum wells in each stack. The devices demonstrated excellent performance, which proved very high quality material growth.[20,21]

4.3 Processing

Due to the unstable nature of the material and the mechanically soft yet brittle wafer and substrate, MCT is hard to handle and difficult to process in general. Because of the weak bond of Hg-Cd-Te, the chemical etching is very sensitive to the etching solution and the process, which affects the uniformity, yield, and reproducibility. Dry etching has proven to be more successful than wet etching. The band bending at the surface gives MCT a surface leakage problem; hence, the surface passivation is needed for MCT arrays. Passivation is a critical step in the MCT photodiode technology, which greatly affects surface leakage current and device thermal stability. Passivation of photodiodes is very difficult, since the same coating must simultaneously stabilize regions of n- and p-type materials. Some widely used passivation material for n-type MCT, such as anodic oxide, causes an inversion layer on a p-type material and cannot be used for junction devices.[23] Tremendous progress has been made in passivating MCT diodes using CdZnTe.

Device processing and array fabrication for QWIPs use standard III-V processing technology which is very mature and highly repeatable. Any laboratory with a decent clean room should be able to process QWIP devices. No surface passivation is needed. For n-type GaAs/AlGaAs and InGaAs/AlGaAs systems, normal incidence is forbidden due to the selection rules, and extra grating layers are needed to effectively couple IR light into the detectors. Grating layers introduce extra steps into the processing, but add no fundamental difficulties to the standard procedures.

5. Device Performance

5.1 Quantum Efficiency and Responsivity

MCT is an intrinsic detector using band to band transition. It has large optical absorption and wide absorption band. The quantum efficiency of MCT is very high around 70%. When operated in the PV mode, the optical gain is one. The responsivity is directly proportional to the quantum efficiency of the device. High quantum efficiency is always desirable for single devices and scanning arrays. However, the current staring array performance is mostly limited by the charge handling capacity on the readout circuit and the warm optics as the background. Adjustable quantum efficiency sometimes is desirable to suit the integration time, while maintaining certain signal to noise ratio.

N-type QWIP uses intersubband transitions in the conduction band. IR photons in resonance with the energy spacing between the ground state and excited state can be absorbed. The absorption quantum efficiency is relatively small, about 25% using 2-D grating. Although the spectral band width is adjustable, overall is much narrower than that of MCT. The quantum mechanical rules forbid normal incidence absorption. Even through normal incidence absorption without grating has been observed,[20,24] the value is relatively small and the physics behind it is not yet understood. Different gratings have been used with 1-D, 2-D, ring, checkboard,[24-26] and random gratings.[27] New grating designs are under study to improve the quantum efficiency, such as EQWIP,[28] antenna grating,[29] and corrugated grating.[30] Since QWIP is a photoconductor, the responsivity is proportional to the conversion efficiency, which is the product of the absorption quantum efficiency times the optical gain. The optical gain is defined as the ratio of the photoelectron lifetime to the transit time. The optical gain in bound to miniband QWIP is around 0.2 with regular 30 to 50 wells. Other QWIP structures have demonstrated optical gain values from 0.2 to larger than 1.

It is well known that the typical conversion efficiency of a regular QWIP array is smaller than 6% at the present time. However, one fact that has been neglected is that, so far, most efforts on QWIP are for tactical applications. The structure designs and the doping are optimized to increase the operating temperature and suit the readout charge handling capacity. Using a smaller number of quantum wells and bound to continuum structures could increase the optical gain and improve the detector performance for low temperature applications. With slightly increased doping density, a three-well QWIP (S-QWIP) has been demonstrated with high performance and a 29% conversion efficiency.[22] By optimizing the device structure, the number of wells, and doping density, and the new grating schemes, improvement in QWIP's conversion efficiency is expected. The conversion efficiency, along with the dark current of QWIP, can be tailored to suit the desired integration time for specific applications. Due to the intersubband nature, however, it is very hard for QWIP to achieve a quantum efficiency at MCT's level.

5.2 Dark Current and R_0A

Dark current and R_oA products are important figures of merit in evaluating the device performance. They reflect the quality of the material and device design. R_oA is defined as the dynamic resistance at zero bias voltage for PV devices. QWIP is a photoconductor, the impedance $R_D=V/I_D$ is usually used to evaluate the device quality and ability of matching the readout. $R_DA=V/J_D$ could be used for comparison with MCT with specified bias V, and dark current density J_D. The major effects of the dark current are that, first, it causes noise and therefore reduces the signal to noise ratio, and second, it fills the charge well of the readout capacitor.

The dark current in a photodiode can consist of diffusion current, generation-recombination (g-r) current, tunneling current and surface leakage current. Diffusion current is the fundamental current mechanism in a p-n junction photodiode. It arises from the random thermal generation and recombination of electron-hole pairs within a minority-carrier diffusion length on either side of the deletion region. The g-r current appears at the depletion region in which the Auger process is the only fundamental limit to device performance. Other mechanisms of g-r current, such as Shockley-Reed-Hall (SRH), are not intrinsic and should be able to be reduced with progress toward purer and higher quality materials. The tunneling current is caused by electrons directly tunneling across the junction from the valence band to the conduction band (direct tunneling) or indirect tunneling through trap assisted tunneling. Actual p-n junctions often have additional dark current, particularly at low temperature, which is related to the surface. Surface phenomena play an important role in determining PV detector performance. The surface of actual 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. In MCT diodes, the dark current sources could come from diffusion, g-r, band to band tunneling, trap-assisted tunneling, and leakages due to dislocations, precipitates, and surface and interface instabilities. The dark current could come from the base and cap layers, depletion layers, surfaces and contact regions. From Fig. 11.44 and Table 11.4 in ref. 31, one could get an idea of the main sources of a photodiode dark current. In MCT, the Auger mechanism governs the high temperature lifetime and the SRH mechanism is mainly responsible for low temperature lifetimes. The g-r current varies with T as n_i, 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.[3] At low temperature, such as 40K, large spreads in R_oA distributions are typically observed due to the onset of tunneling currents associated with localized defects.[32] The tunneling mechanism is still not well understood, and it varies from diode to diode.

Single MCT devices are operated at near zero bias and R_oA is usually used as the figure of the merit for the device quality. Top quality MCT diodes have shown R_oA products close to theoretical limit. For example, a 10 μm cutoff MCT diode at 77K has shown $R_oA = 665\ \Omega cm^2$ at 0 bias,[33] which is within a factor of two of that predicted for the Auger 7 limit. In practice, the non-fundamental sources dominate the dark current of the present MCT photodiodes, with the exception of specific cases of near room temperature devices and highest quality 80K LWIR and 200K MWIR devices.[31] Typical values of R_oA at 77K as a function of cutoff can be found in Fig. 1 of ref. 5 including both LPE and MBE growth. From the figure one can see that the average R_oA at 10 μm is around 300 Ωcm^2 and drops to 30 Ωcm^2 at 12 μm. At 40K, the R_oA varies between 10^5 and 10^8 Ωcm^2 with 90% above the $10^5 \Omega cm^2$ at 11.3 μm.[32]

For MCT FPA operation, certain bias is necessary to assure a uniform repsonsivity of each device in the FPA. The R_oA product is supposedly increased with a small negative bias, but the actually FPA has shown larger leakage current and smaller R_oA. A good quality 128x128 FPA grown by MBE from Hughes Research Center gives an R_oA of 220 Ωcm^2 at 80K with 9.92 μm cutoff.[34] Santa Barbara Research Center's LPE growth showed similar values.[3] The LWIR 128x128 FPA grown by MBE at Rockwell International has an R_oA of 83 Ωcm^2 at 80K with 10.1 μm cutoff.[4] The LWIR R_oA in a two-color MCT is usually lower than the single color LWIR R_oA, indicating a lower quality of two-color devices. For example, the R_oA product is 100 Ωcm^2 for the LWIR of a two-color device from Hughes Research Center grown by MBE. In an MOCVD grown two-color MCT structure from Lockheed Martin, the R_oA product of the LWIR is 16 Ωcm^2 at 80K with 10.5 μm cutoff.[35] The dark current of the LWIR of this two-color device at 77K is around 10 nA with 75×75 μm^2 pixel size which gives a dark current density of 2×10^{-4} Acm^{-2}. This value is similar to that of a QWIP at 77K.

The behavior of the dark current of a QWIP is better understood. It has three mechanisms as shown in Fig. 5. Usually one mechanism dominates at one temperature range even though all three mechanisms contribute at all temperatures. At low temperatures (T<40K 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. A typical LWIR QWIP at 40K has a tunneling current density of 10^{-7} Acm^{-2}, which is smaller than 1 pA for a 24×24 μm^2 pixel. In the medium operating temperature range (40-70K for 10μm cutoff), the thermally assisted tunneling (TAT) dominates. Electrons are thermally excited and tunnel through the barriers with assistance from the defects and the triangle part of the barrier at high bias. At high temperature (>70K for 10 μm cutoff), thermally excited electrons are thermionically emitted (TE) and transport above the barriers. The value of the dark current could be adjusted using different device structures, doping densities, and bias conditions. For TE current, the dark electrons have energy, and therefore transport mechanisms, similar to photoelectrons. It is very hard to block this dark current without sacrificing the photoelectrons. Typical LWIR QWIP dark current density at 77K is about 10^{-4} Acm^{-2}, which is in the nA range for a 24×24 μm^2 pixel. QWIP is a photoconductor which operates at a bias voltage from 1 V to 3 V depending on the structure and the periods of the devices. Using the voltage divided by the dark current density, the R_oA products are usually larger than 10 $M\Omega cm^2$ and 10 $K\Omega cm^2$ when operated at 40 K and 77 K, respectively, which reflect very high impedance.

Due to the nature of intersubband transitions, the lifetime of thermal electrons are very short (<100 ps) in QWIP, which gives a larger thermal generation current than MCT. In the past, an estimate by Kinch and Yariv in 1989[36] gave a dark current of QWIP five orders of magnitude higher than that of MCT at 77K. Improved material growth, device design and optimized doping made this value much smaller, only 10 times larger[37] at 77K. Therefore, a high quality MCT diode should have a dark current 10 times smaller than QWIP's at 77K. At a relatively high temperature (>80K), MCT's dark current is diffusion limited and fairly uniform. For extremely high quality MCT devices, this temperature could go down to 65K. The intrinsic long lifetime of hot electrons in MCT determines that this dark current is much smaller than QWIP's. The dark current of QWIP might be able to be further suppressed to meet the system requirement at T>80K, but it is very hard to compete with MCT in this temperature range. At low temperature operation, the thermally generated dark current in QWIPs is reduced exponentially and maintains very good uniformity down to 40K.

5.3 <u>Noise</u>

Detector noise can be distinguished in two types: radiation noise and intrinsic detector noise. Radiation noise includes signal fluctuation noise and background fluctuation noise. Intrinsic detector noise could have many sources, such as shot noise, Johnson noise, g-r noise, 1/f noise, and pattern noise. Johnson noise is the minimum intrinsic noise at zero bias. Usually shot noise is the major noise for photodiodes, and g-r noise and Johnson noise are the major noises for photoconductors. However, MCT also has large Johnson noise and g-r noise due to the low R_oA product and the material problems. At FPA level, the pattern noise is the major limitation to the array performance at low temperature. The fixed pattern noise results from local variation of the dark current, photoresponse, and cut off wavelengths.

In QWIPs, the dark current is the major source causing noise. Johnson noise is neglected in most cases, especially at high temperature operation due to the high dark current. But when the operation temperature goes down and the array pixel size gets smaller, Johnson noise becomes comparable to dark current noise and must be considered in noise calculations. Fixed pattern noise is also a limiting factor for QWIP array performance, but it is much smaller than that of MCT due to its material quality and better controlled cutoff wavelength. There is very little 1/f noise observed in QWIPs owing to its stable surface properties.

5.4 <u>BLIP Temperature</u>

Background limited photodetection (BLIP) temperature is defined that the device is operating at a temperature at which the dark current equals to the background photocurrent, given a field of view (FOV), and a background temperature. BLIP is usually desirable but becomes more difficult at low background radiation. For a high quality MCT diode, the dark current is 10 times smaller than

QWIP's at 77K, and its quantum efficiency is about 10 times larger. Even for a poor quality MCT with similar dark current as QWIP's at 77K, the BLIP temperature of MCT is usually still higher than that of a QWIP with a 300K background. When the background goes lower, the dark current has to be reduced in order to achieve BLIP conditions. From 77K to 40K, QWIP's dark current reduces 3 orders of magnitude uniformly, while MCT's dark current is SRH and tunneling limited which varies from diode to diode. Thus, QWIP has the potential to perform better than MCT at low background and low temperature operation.

5.5 D^*

The D^* is an important figure of merit in evaluating IR detectors at single device level. It reflects the signal to noise ratio at a certain temperature with unit noise bandwidth and detector area. Under BLIP condition, the D^*_{Blip} is determined by the quantum efficiency (or conversion efficiency for QWIP) and the background flux. With a 300K background under BLIP operations, the D^* of a single MCT device is usually higher than that of a QWIP due to its higher quantum efficiency. When the temperature goes down, the tunneling current in MCT dominates and the D^* of QWIP could be higher than MCT[38] and is definitely more uniform. At 77K, the D^* of a LWIR QWIP is about 10^{10} $cmHz^{1/2}W^{-1}$, which could lead to a very good thermal imaging with NEDT of 15mK[7] for thermal imaging. When D^* is beyond certain limit, increasing D^* will no longer increase array performance. In this situation, the array performance is uniformity limited[7].

6. Focal Plane Array

Besides the detector performance, major concerns in FPA applications are the array size, uniformity, operability, integration time, and matching to the readout circuit.

6.1 Uniformity

The uniformity among pixels within an array is important for accurate temperature measurements, background subtraction, and threshold testing. High uniformity and operability are extremely important for tracking and discriminating multiple unresolved targets. Dead pixels in an array could totally miss a target during the tracking, and the nonuniformity of an array increases the false alarm rate. FPA evaluations show that the fixed pattern noise is one of the main factors limiting the array performance.[39] The fixed pattern noise is a nonuniformity appearing across the array which does not vary with time. It reflects the intrinsic properties of a FPA. The nonuniformity value is usually calculated using the standard deviation over mean, counting the number of operable pixels in an array. For the same array, the nonuniformity can be different depending on the specification of operability. For example, a higher requirement on the operability usually leads to a lower uniformity and vice verse. Fig. 7 in ref. 40 shows the corrected response nonuniformity as a function of the number of bad pixels. In the figure, the corrected responsivity nonuniformity of the center 64x64 elements in a 256x256 QWIP array by Lockheed Martin is 0.04% with 10 pixels excluded, which means a 99.75% operability. If only 4 pixels are excluded which means a 99.90% operability, the nonuniformity is increased to 0.045%. The nonuniformity (and operability) directly affects the NEDT or NEI, therefor the array performance.

Owing to the mature GaAs growth and processing technology, large size LWIR QWIP FPAs have demonstrated with high uniformity and high operability as shown in the above example. The uncorrected response non-uniformity for that 256x256 array is 1-3% with an operability greater than 99.5%.[40] For the 128x128 15 μm array by JPL[10], the uncorrected standard deviation is 2.4 % and the corrected nonuniformity 0.05 %.

The nonuniformity and operability have been 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 in improving the uniformity in MCT array. For example, a 128x128 LWIR array by Rockwell[4] has achieved 97.7% operability and 0.017% corrected nonuniformity. At VLWIR, the uncorrected nonuniformity of the 128x128 array by Rockwell[6] is 10% at 98.85% operability. By looking at the material and device properties, one can see that it is very hard for MCT to compete with QWIP for high uniformity and operability with large array format, especially at low temperature and VLWIR.

6.2 NEDT and NEI

Noise equivalent temperature difference (NEDT) is the minimum temperature change of a scene required to produce a signal equal to the rms noise. The importance of the uniformity for thermal imaging can be reflected by NEDT, as described in ref. 7 by B. Levine. When the D^* is approaching certain limit, increasing D^* will no longer increase NEDT. The nonuniformity factor becomes the major parameter and an improvement of nonuniformity from 0.1% to 0.01% after correction could lower the NEDT from 63 to 6.3 mK.

For low background applications, noise equivalent irradiance (NEI) is usually 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: $NEDT=NEI x(dP_b/dT)^{-1}$, where P_b is the background photon flux. The argument about how the nonuniformity affecting NEDT in ref. 7 still stands for NEI. When the array is nonuniformity limited, NEI is proportional to the nonuniformity factor U. When U is reduced, a lower NEI is obtained. The BLIP operation is very difficult to achieve at very low background. In this situation, NEI is limited by the temporal noise in which the dark current nonuniformity plays an important role in device performance.[41]

6.3 <u>Bias Voltage and Impedance Match</u>

Another factor adds to MCT's non-uniformity is the small bias voltage. The direct injection (DI) input is one of the simplest and most popular readout circuit for IR FPAs[35], but the fluctuation on the threshold voltage is around 2%[42]. Since the dark current and responsivity of MCT diodes are very sensitive to the bias voltage at small bias, this bias fluctuation adds on extra nonuniformity to MCT array performance. A large bias is desirable in the MCT FPA operation, but it strongly depends on the material quality of the array. For a very high quality LWIR MCT array, -1 V bias is possible with MBE growth.

The material quality of MCT is mostly reflected by the R_oA product. A small R_oA not only allows a very small bias on the array, but also gives a very small detector impedance. In order to guarantee an efficient injection and sufficient signal-to-noise ratio, the input impedance of the detector must be much larger than that of the injection circuit. Low impedance of the detector gives a smaller injection efficiency, which causes extra noise called transfer inefficient noise.[39] MCT in MWIR has a R_oA product in the range of 100 $K\Omega cm^2$ to 10 $M\Omega cm^2$ which makes it easy to match the readout circuit and has a high injection efficiency. In the LWIR, MCT has a much smaller R_oA products compared with those of MWIR MCT and LWIR QWIP which makes matching the readout difficult and a relatively low injection efficiency. Buffered DI or capacitor feedback transimpedance amplifier (CTIA) can be used to increase the injection efficiency. But they also accentuate the 1/f noise and the operability,[6] besides occupying larger real estate and requiring higher power to operate.

The bias voltage on a QWIP array usually is around 2 to 3 V. A small bias fluctuation does not affect the array performance, which gives very good bias uniformity. Even though the bias on a QWIP array is much larger than that of a MCT array, the power consumption of the QWIP FPA is still negligible compared with the readout electronics. For example, a 640×480 QWIP array has a tested total power consumption of <150 mW.[43] The readout power consumption is similar for QWIP and MCT, while MCT's readout consumes more power if buffered injection or CTIA is used. The impedance of QWIP is very high, at the $G\Omega$ range at 77K for a pixel size of 24×24 μm^2. This high impedance makes the readout design very easy in achieving low noise and high efficiency. For example, the injection efficiency of a 640x480 LWIR QWIP array is 99.5%[9]. This high injection efficiency makes up for some of the low quantum efficiency of QWIPs, especially at low temperature operation where most injected electrons are photoelectrons.

6.4 <u>Charge Handling Capacity and Integration Time</u>

Comparing a 2-D staring array with a scanned single-element detector, the dwell time is increased by the large number of elements in the array. For example, a 256×256 array has more than 65,000 times more signal available to it than a single-element scanned one.[44] In most detector systems, signal strength is no longer the main concern for high background applications. The charge handling capacity of the readout and the integration time become the major issues. The well charge capacity is the maximum amount of charge that can be stored on the storage capacitor of each unit cell. The size of the unit cell is limited to the dimensions of the detector element in the array. For a 30×30 μm^2 pixel size, the storage capacities are limited to 1 to $5x10^7$ electrons. Assuming a $5x10^7$

electron storage capacity, for example, the total current density of a detector with a 30×30 μm^2 pixel size has to be smaller than 27 μAcm^{-2} with a 33 ms integration time. If the total current density is in 1 mAcm^{-2} range, the integration time has to be reduced to 1 ms. The integration times for the LWIR MCT are usually <100 μs. Since the noise power bandwidth $B=1/2\,\tau_{in}$, a small integration time causes extra noise in integration. Even though QWIP has a smaller quantum efficiency, filling the charge capacitor is usually not a problem at high background application. The optical gain could be adjusted to allow different integration times according to the requirement. For LWIR thermal imaging at T<77K, QWIP allows a longer integration time, which gives a relatively lower NEDT. At a temperature larger than 80K, the dark current of QWIPs is high and fills the charge capacitor very quickly. Pushing QWIP to T> 80K by only optimizing the device structure is quite difficult. Both QWIP and MCT used a number of schemes to increase the effective charge capacity of the readout. QWIP arrays with 80K operation have been demonstrated by Lockheed Martin[43] using dark current subtraction and a noise filter on the readout. However, the readout circuit is complicated and requires extra real estate space, which limits the size of array. Both MCT and QWIP need multiplexers for multicolor and low background readout.

6.5 Thermal Image

Achieving FPA images has been the major effort for tactical applications. Both MCT and QWIP demonstrated thermal images at LWIR, in which QWIP arrays have better performance at lower temperature and MCT arrays can operate at T>77K. JPL also demonstrated a camera at 15 μm. A thermal image sometimes is not necessary, such as in some strategic applications where the target is unresolved throughout most of the flight. However, an image can still be used in this situation at the developing stage to exam certain features of a FPA, such as the uniformity, number of dead pixels, operability, yield, integration time, 1/f noise, operating temperature, and cooling cycling. While a FPA after nonuniformity correction demonstrates the capability of thermal imaging, uncorrected FPA images sometimes give more information about the array quality and performance. Dead pixels on an array sometimes can be seen through human eyes with an image. In the developing stage, an image is a effective and convincing way to demonstrate a FPA's quality and performance.

7. Low Background Applications

For low background applications, the major difficulty is achieving BLIP operation assuming cooled optics. Increasing quantum efficiency and reducing dark current are desired at the same time. MCT has a high quantum efficiency; reducing dark current is the major effort. 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. However, the amount of dark current reduced by removing certain active materials through the grating structures is too small for low background operation. The only way of reducing dark current on a large scale is to decrease the operating temperature. QWIP's dark current reduces three orders of magnitude uniformly from 77K to 40K. At low temperature in MCT, the SRH mechanism dominates the dark current through defect and impurity related tunneling, and dark current becomes very non-uniform.[3] Reducing the dark current in MCT for low background operation is not as simple as just reducing the operation temperature. The lateral collection scheme used by Rockwell improves the R_oA at 40K to some extent,[32] but the distribution of the R_oA is still spreading out to three order of magnitude. Purifying the substrate, source material, growth, and processing conditions are methods in improving the MCT device quality at low temperature, but is very costly and hard to achieve. Compared with MCT, QWIP has the potential to perform better at low temperature (40K) for low background operation.

8. VLWIR

VLWIR sensors are very important in strategic missile defenses and space applications. 12-18 μm FPAs are very useful in detecting cold objects such as ballistic missiles in midcourse[45]. When it comes to VLWIR, the band gap of the detector is even narrower, and the operating temperature has to be lower to suppress the thermally excited dark current. Both of these requirements aggravate the problems associated with the MCT material. The narrower band gap makes the MCT material system even more unstable and harder to control. Direct and defect assisted tunneling current will be increased with decreasing band gap and operating temperature. The variation of x across the MCT wafer can be a severer problem and causes a much larger spectral nonuniformity. For example, at 77K, a variation of $\Delta x = 0.2\%$ 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 $\Delta\lambda_c = 0.5$ μm for VLWIR (14 μm). Therefore, the required composition control is much more stringent for LWIR and VLWIR than for MWIR. This spectral response nonuniformity due to the compositional inhomogeneity cannot be fully corrected by the two or three point corrections.

Extending QWIP to VLWIR is relatively easier since there is very little change in material properties, growth, and processing. The only requirement for maintaining the device performance is to lower the operating temperature. 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 77K, the temperature needs to be cooled down to 55K for a 15 μm cutoff[10] and 40K for a 18 μm cutoff.[46] An unoptimized 128×128 QWIP FPA at a 15 μm cutoff wavelength has been demonstrated by JPL[10] with a NEDT 30 mK at 45K and 300K background. This initial array gives excellent images with 99.9% operability, and corrected nonuniformity 0.05%. The high quality of the array demonstrated the maturity of the GaAs technology and its potential for VLWIR applications. A 128x128 MCT array[6] also demonstrated operability of 98.85% at 8.1×10^{15} cm^{-2}-s background flux, but the uncorrected responsivity nonuniformity is 9.8%. Lower background will bring more nonuniformity out due to the dark current nonuniformity which has been covered to certain extent with a relatively higher background.

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 is to improve the nonuniformity of both dark current and responsivity. From the performance of the two arrays demonstrated, QWIP has more potential to be realized at VLWIR and low background operation.

9. Multicolor

As the IR technology continues to advance, there is a growing demand for multicolor IR detectors for advanced IR systems. For military applications, multi-color detectors are needed for better target temperature estimation, and target discrimination and identification. So far, the multiple waveband measurements have been achieved using separate FPAs with 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. It also has the advantages of simpler optical design, and reduced size, weight, and power consumption.

Both QWIP and MCT detectors offer the multicolor capability in the MWIR and LWIR atmospheric window bands, while QWIP can also easily go into the VLWIR region. For MCT, a two-color, dual-band (MWIR/LWIR) detector has been demonstrated by using an n-p-p-n four layer back-to-back diode structure grown by the MBE at Hughes Research Laboratory.[47] Similar efforts are also being pursued at Lockheed Martin, Texas Instrument and Rockwell International. But, in general, the device performance of the LWIR in a two-color MCT is not quite as good as in a single-color LWIR MCT device (see data in section 5.2). This is due to the more complicated device structures, much thicker material growth, precise layer thickness control requirement and bias in both directions, besides the aggravated problems related to the nature of the LWIR MCT materials. Combining VLWIR into multicolor MCT is very difficult. The 128x128 MCT array at 15 μm[6] uses a planar structure which is very difficult to be incorporated in multicolor structures.

By employing different designs, multicolor can be achieved in QWIP without extra difficulty. Two-stack, two-color QWIPs of MWIR/LWIR have been demonstrated at the single device level with either three terminal simultaneous registration,[20] or voltage tunable between the MWIR and LWIR.[24] Devices with two colors show the same high performance as single-color ones. Using the same principle, multi-stacked QWIP structures for any combinations of the MWIR, LWIR, and VLWIR can be achieved with a much thinner detector structure than MCT's. The restriction is that the operating temperature has to be at that of the longer wavelength. A two-color (MW/LW) 256x256 QWIP array with a sequential readout has been demonstrated by Lockheed Martin. Within one atmospheric window, asymmetrically coupled quantum well structures are used to achieve voltage tunable three-color detection, and Stark shift has been used for fine peak wavelength tuning.[48,49] Owing to the high quality material and mature GaAs technology, the material growth and FPA processing do not change when the multicolor is added. The narrow spectra of QWIPs eliminate more cross talk between colors. Compared with MCT, QWIP is much more feasible to achieve for multicolor detection than MCT and maybe the only way to incorporate the VLWIR into multicolor FPAs.

10. Cost

So far, all large size LWIR and VLWIR FPAs are developed in R&D laboratories without mass production experience. The cost of a FPA depends strongly on the maturity of the technology and is reflected by the yield. The production cost varies with production quantity and the learning curve varies with different companies. The substrate, manufacturing equipment, and the number of potential vendors available also affect the price. Another major cost is in the process of developing IR detector arrays that have high performance, fast cycle time, prompt delivery, reliable, low maintenance, and at an affordable manufacturing cost.

MCT detectors have been the center of a major industry with a worldwide turnover of billions of dollars.[50] 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. The technology is relatively mature at MWIR, but it does not fold over to LWIR or VLWIR. Development of LWIR, VLWIR and multicolor MCT for low background, low temperature performance requires the development of ultra-high purity material growth, device processing and the extreme minimization of crystalline defects. All of these requirement involves a large amount of investment. Development of VLWIR and more than two colors in MCT are extremely difficult, especially for low background applications. The ultimate challenge in producing large MCT array at LWIR, VLWIR, and multicolor is the reproducibility and yield. MBE growth of MCT might be able to meet the challenge, but the resulted products will have very limited vendors for production, and the manufacturing cost will be higher than for QWIP.

QWIP is based on a thriving, commercial III-V material technology which comprises the basis of a multibillion dollar electronics industry. Because of the maturity of the GaAs growth technology and stability of the material system, no investment is needed for developing QWIP substrates, MBE growth, and processing technology. The major challenge is at the device and grating designs to improve the device performance and meet specific applications. Since there is little material problem involved, the investment needed is relatively small and the cycling time is fast. The fast development of QWIP in the past ten years has proved that QWIP has a lower cost in developing the technology and will have a lower cost in production compared with MCT.

11. Summary

A discussion of MCT and QWIP has been given, with emphasis on the material properties, device structures, and their impact on FPA performance and applications. From the discussion, one can see that even though QWIP is a photoconductor, it has some good properties of a photodiode, such as high impedance, fast response time, long integration time, and low power consumption. It is also easy to match with the readout circuit. Since it is a photoconductor, it avoids the major problems involved in a photodiode, such as p-type doping, SRH related g-r tunneling, and surface and interface instabilities. The major problems in QWIP are its relatively low conversion efficiency and a relatively high thermal generation rate at T>77K. Improved device structures and readout circuits could push QWIP to T>80K operation, but it is hard to compete with MCT in this temperature range. Due to the high material quality at low temperature and VLWIR region, QWIP has the potential to fulfill the system requirement for low background, low temperature applications. Further study is needed to optimize the device design, improve the device performance, and extend it to VLWIR and multicolor FPAs.

MCT has a very high quantum efficiency and wide spectral bandwidth. Its thermally generated dark current is relatively low at T>77K compared with QWIP's. However, MCT has its material related problems which could make it sensitive to the bias, have a low operability, large nonuniformity and low yield. MCT has the potential to be improved at LWIR for large size FPAs at high temperature operation. However, development of MCT into large size arrays at VLWIR and multicolor is very difficult and costly, especially for low temperature and low background applications.

12. Conclusion

The conclusion drawn here is that even though QWIP cannot compete with MCT at the single device level and at high temperature operation due to the fundamental limit associated with intersubband transition, QWIP has potential advantages over MCT for LWIR and VLWIR FPA applications in terms of the array size, uniformity, yield, cost, and reliability of the systems. QWIPs are especially promising for VLWIR at low temperature operation and when multicolor detection using a single FPA is desired. Achieving VLWIR detection at low background is very challenging to both QWIP and MCT, while QWIP has more potential to be realized.

13. Suggestion

In October 1992, a consortium was assembled and supported by DARPA to develop MCT with the technical approach focused on optimizing flexible MBE manufacturing, refining the procedures and processes necessary to fabricate p-on-n HgCdTe double layer heterostructures IRFPAs.[51] Significant progress has been achieved in MBE growth of MCT during the past five years. Even though QWIP has been developed very quickly and have the potential to be used in LWIR, VLWIR, and multicolor both for tactical and strategic applications, the resources and efforts have mostly been limited to increasing operation temperature for tactical applications. In order to fully develop QWIP toward strategic applications, a consortium is presently needed, with a collaborative effort involving DoD research labs, defense industries, and universities. The emphasis should be on a systematic development of QWIP FPAs by refining the design and manufacturing process, carrying on a research and development effort from device design, array fabrication, and readout integration, all the way to field testing, toward a solid goal of meeting specific system applications.

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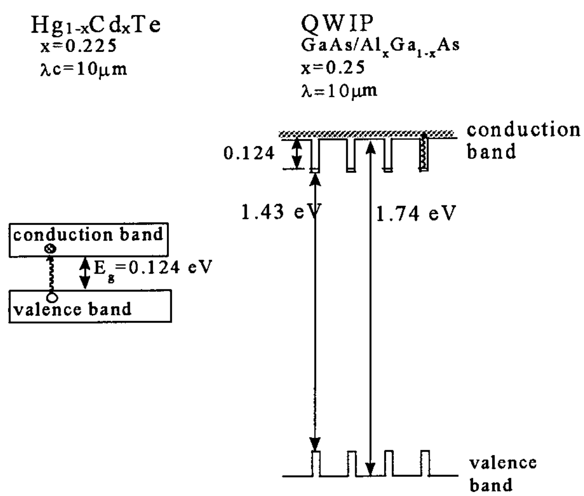

Fig. 1. The band gaps of MCT and QWIP materials.

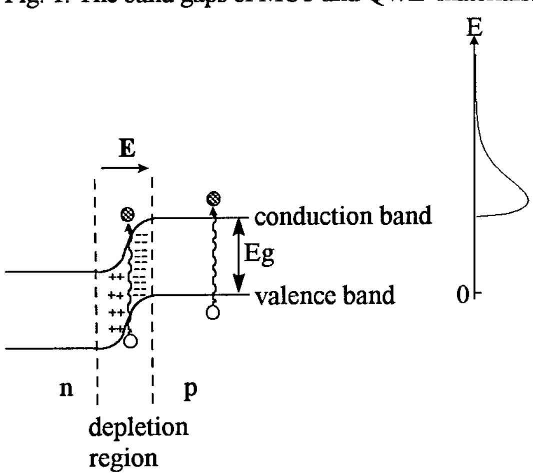

Fig. 2. The band gap diagram of a basic p-n junction photodiode.

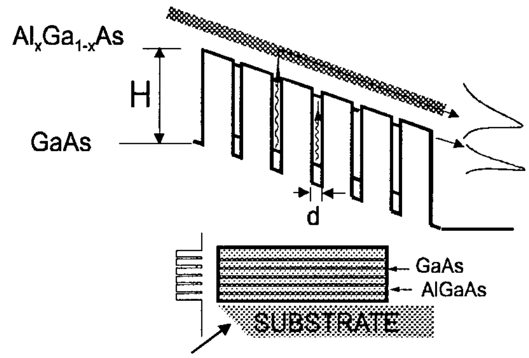

Fig. 3. The device structure and band gap diagram of a n-type GaAs/AlGaAs QWIP under bias condition.

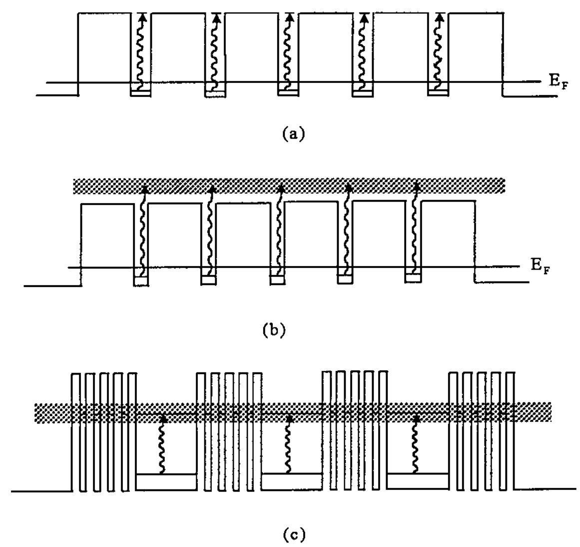

Fig. 4. Three most commonly used QWIP structures: (a) bound to quasi-bound, (b) bound to continuum, and (c) bound to mini-band transitions.

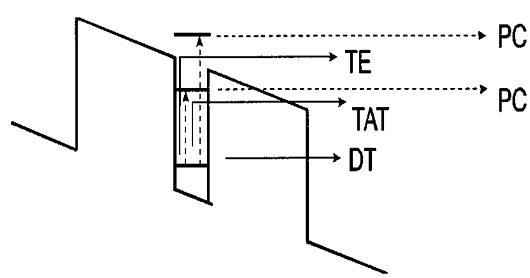

Fig. 5. Three dark current mechanisms of QWIP, where DT is direct tunneling, TAT is thermally assisted tunneling, TE is thermionic emission, and PC is photocurrent.