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INFRARED DETECTORS

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Abstract. Infrared detectors have wide application in a range of industry sectors, including defence, astronomy, medicine, environmental safety, and remote sensing. The applications requiring the highest sensitivity over a broad spectrum of wavelengths are usually based on the high performance mercury cadmium telluride (HgCdTe) ternary alloy, since HgCdTe-based detector performance dominates others in the mid-wave and long-wave infrared spectrum. HgCdTe is the dominant material currently in use for infrared (IR) focal-plane-array (FPA) technology. The subject is vast: IR systems combine a wide variety of disciplines, and image interpretation depends on the precise understanding of various phenomena. It has been predicted that, because of its excellent properties, HgCdTe technology will continue to expand the range of its applications well into the future.

Keywords: *Infrared detectors, HgCdT, infrared (IR), focal-plane-array (FPA) technology.*

Introduction

Radiation in the electromagnetic spectrum can be classified by wavelength into several bands, including γ-rays, X-rays, ultraviolet, visible light, infrared, microwave and radio waves. Infrared (IR) light is defined as electromagnetic radiation whose wavelength is greater than that of visible light and whose frequency is less than that of red light associated with heat. Therefore, an infrared detector is a tool that can detect thermal radiation emitted in a given environment.

Progress in IR detector technology is mainly connected to semiconductor IR detectors which are included in the class of photon detectors; they have very good signal-to-noise performance and very fast response, but require cryogenic cooling – the main obstacle to the use of IR systems based of these photo-detectors, making them heavy, expensive also inconvenient to use.

The last decades have seen considerable progresses, achievements, trends in detector concepts and performance, with quantum dot IR and type II super-lattice detectors – the so-called *third generation* detectors. With THz technologies the devices have found applications in imaging, biology and drugs, explosion detection, security, gases fingerprints, etc. with enhanced capabilities (larger number of pixels, better thermal resolution, higher frame rates, multicolour functionality). The applications domain was enlarged in aerospace sensors and systems, remote sensing, military and thermal imaging, light detection and ranging (LIDAR), IR spectroscopy or optical telecommunications.

Thermal imaging systems extend human perception beyond the visible spectrum. Since their principle is based on the natural emission of energy by physical bodies, they represent an interesting subject for many military and research fields; they are commonly used to observe night scenes vision or in order to increase the visibility range through haze and fogs. These applications exploit the properties of IR radiation; they link physical theory to each specific aspect of the elements involved in the detection process, filling the gap between theory and practical application. IR systems combine a wide variety of disciplines and image interpretation depends on the precise understanding of various phenomena.

Fueled by a broad range of government needs and funding, HgCdTe materials and device technology has matured significantly over the last decades. Also in this same time period, we have come to understand better the phenomenology which limits imager performance. As a result of these developments, HgCdTe arrays may be tailored in wavelength to outperform GaAs-based image intensifier devices in sensitivity and to compete with bolometric and pyroelectric imaging arrays in NEDT[1] [1] (noise equivalent differential temperature) at temperatures at or near room temperature (250 K-295 K). These benefits can be fully realized, however, only if HgCdTe can be brought to a level of maturity where the material and detectors made from it are limited by fundamental mechanisms.

Ir detectors

An IR detector is a photodetector (semiconductor with narrow band gaps) that reacts to IR radiation. The response time and sensitivity of photonic detectors can be much higher, but usually these have to be cooled to cut thermal noise (i.e., at 110 K to 150 K, the critical parameter is the dark current: it limits the exposure time, preventing a high signal-to-noise ratio). Photovoltaic detectors contain a *pn* junction on which photoelectric current appears upon illumination.

Due to re-absorption of photons generated by carrier recombination, also called the photon recycling (PR), the minority carrier lifetime is highly extended and depends on the semiconductor geometry and the strength of absorption coefficient. Thus, the radiative recombination is likely not to limit performance of properly designed HgCdTe photodetectors.

Although thermal imaging has been well established for military night vision, InGaAs-based shortwave infrared imaging (SWIR) is quietly earning a growing place. IR detectors have been called *the eyes of the digital battlefield*. Military applications in Western countries have spearheaded and dominated the requirements in this field akin to many other emerging fields. In addition to many military applications for IR systems such as target acquisition, search and track, missile seeker guidance, there is a great potential for IR systems in the commercial market. The staring array numbers of pixels are larger and larger and offer system solutions in the different IR wavebands. IR systems enhance automobile and aircraft safety, medical diagnosis, and manufacturing quality and control. Developed in response to lessons learned during Operation Desert Storm, the driver's vision enhancer provides the drivers both tracked combat systems and tactical wheeled vehicles with the ability to see and negotiate through conditions of dust, smoke, haze and darkness. With a 40-degrees horizontal by 30-degrees vertical field of view, the system allows drivers to

[1] NEDT refers to the minimum temperature difference that can be detected by a thermal sensor. The basic question comes down to this – how high must the signal–to–noise ratio be in order to detect a certain temperature change. NEDT is also frequently noted as NE⊠T, and also as NETD.

detect a standing human-sized target at 110 meters and a static vehicle at 1,200 meters. Another area of future thermal technology application involves the light thermal weapon sight (LTWS). With an eye towards reducing the weight burdens applied to the individual solder, LTWS design would complete and complement the thermal weapon sight family with a sight package weighting less than 3 pounds and powered by commercial AA-sized batteries and capable of detecting human-sized targets at 550 meters and vehicle targets at 1650 meters.

Important optical parameters

The most important optical parameter for IR detector materials is the absorption coefficient near the band edge, specifically in the region within 20 meV from the conduction band edge [2]. Direct bandgap semiconductors, such as HgCdTe, have a sharp onset of the optical absorption as the photon energy increases above *Eg*. In contrast, indirect semiconductors, such as silicon or germanium, have softer absorption curves [3]. The strong optical absorption allows HgCdTe detector structures to absorb a very high percentage of the incident signal while being relatively thin, on the order of 10−20 μm. Minimizing the detector thickness leads to minimization of the volume of material which might otherwise generate noise and excess thermal carriers.

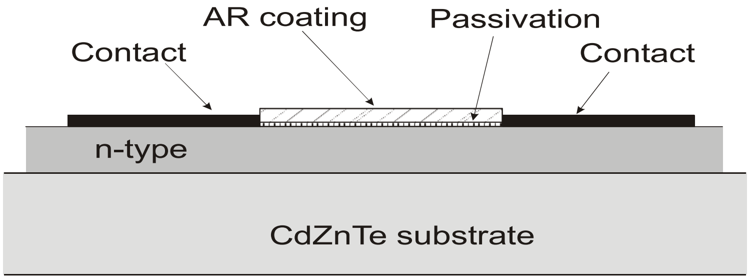

Figure 1. Cross section of a basic HgCdTe photoconductor (after [2]).

HgCdTe can be grown on natural infrared-transparent lattice-matched CdZnTe substrates (Figure 1), thus allowing growth of high-quality HgCdTe epitaxial layers with very low dislocation densities (10^4 cm^{-2}); metal electrodes are applied to pure *n*-type material thinned to approximately 10 μm. Typical photoconductors are passivated with anodic oxide and antireflection coated with zinc sulphide; it provides the possibility to grow complex multilayer heterojunctions that are needed for the *third generation* FPA [3].

The main motivations to replace HgCdTe are technological problems of this material. One of them is a weak Hg-Te bond, which results in bulk, surface and interface instabilities. Uniformity and yield are still issues especially in the long wavelength IR (LWIR) spectral range. Nevertheless, HgCdTe remains the leading semiconductor for IR detectors.

HgCdTe detectors

HgCdTe IR detectors have been intensively developed since the first synthesis of this ternary alloy in 1958. Recent advances of backside illuminated HgCdTe heterojunction photodiodes have enabled *third generation* of multispectral instruments for remote sensing applications and have led to the practicality of multiband IR focal plane array technology.

The specific advantages of HgCdTe are the direct energy gap, ability to obtain both low and high carrier concentrations, high mobility of electrons and low dielectric constant. The extremely small change of lattice constant with composition makes it possible to grow high quality layered and graded gap structures. HgCdTe can be used for detectors operated at various modes, and can be optimized for operation at the extremely wide range of the IR spectrum (1−30 μm) and at temperatures ranging from that of liquid helium to room temperature.

HgCdTe is a pseudo-binary semiconductor alloy that crystallizes in the zincblende structure. Several properties of HgCdTe qualify it as being highly useful for infrared (IR) detection. These include adjustable bandgap over the 1–30 μm range, direct bandgap with high absorption coefficient, and the availability of wide bandgap lattice-matched substrates for epitaxial growth.

One of the key factors which determine HgCdTe photodiode quality is acceptor doping efficiency. Figure 2 presents example of the structure of HgCdTe photodiode. Symbol “+“ denotes high level doping, capital letter – wider gap. High acceptor doping is required for P+-contact layers, whereas low doping is necessary for *p*-type absorbing base layers.

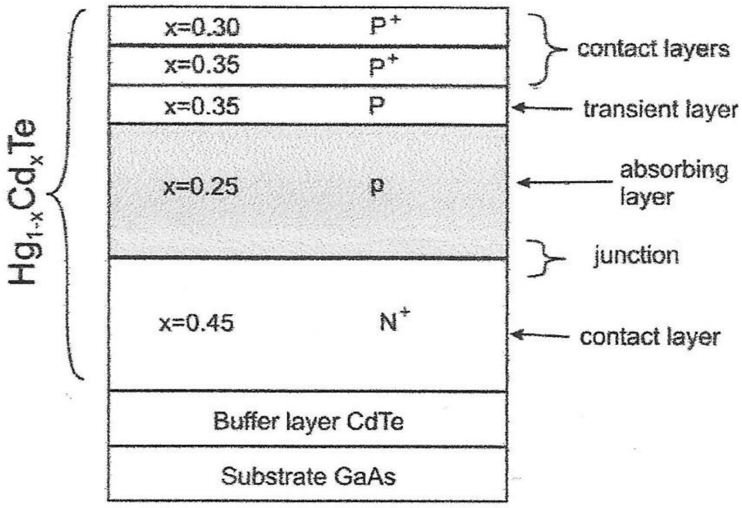

Figure 2. Example of the structure of HgCdTe photodiode (after [4]).

In the last decade of XX century, *third generation* of HgCdTe detectors emerged from tremendous impetus in the detector developments, and provides enhanced capabilities like larger number of pixels, higher frame rates, better thermal resolution as well as multicolour functionality and other on-chip functions.

The design and progress toward realization of a high sensitivity 1.06 micrometers field-assisted heterojunction photocathode are reported by Harris [5]. Major emphasis has been placed on developing a Cs activation process for heterojunction devices and on a device fabrication technology which is consistent with Cs activation requirements. The *first heterojunction devices* (cold cathodes) were successfully activated and emission into vacuum was observed. The progress of HgCdTe molecular beam epitaxy (MBE) technology has been very significant over the last years. There are two functional IR detectors: photon (quantum) and thermal detectors (Figure 3).

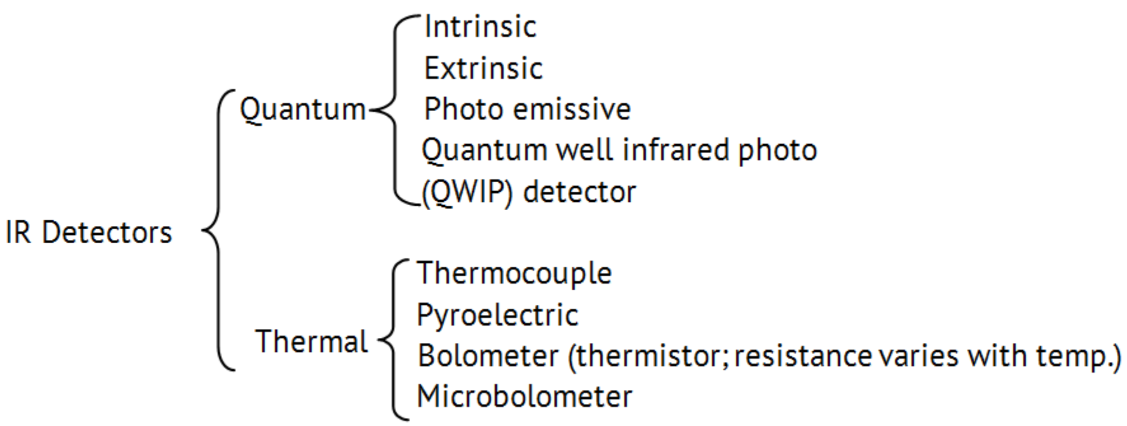

Figure 3. Classification of detectors.

MCT Mercury Cadmium Telluride $Hg_{1-x}Cd_xTe$ is the most important semiconductor for mid and long-wavelength (1-30 μm) IR photodetectors. Relative concentrations of two molecules i.e. x and 1-x are deliberately adjusted in growth process to obtain desired mixture. This help to adjust cut off wavelength; hence, MCT exhibits extreme flexibility. It can be tailored for optimized detection at any region of the IR spectrum.

NATO is funding development of components for passive IR detectors used for target surveillance, tracking, discrimination, and engagement during boost ascent, midcourse and terminal phases. In the future, the performances of detector formats with cooled and uncooled focal planar array (FPA) technologies will be further enhanced by development of new detection methodologies and signal processing techniques. Modern IR FPA systems are aimed to have the portability of video-camcorders and the imaging quality of black-and-white TV cameras. Moreover, the concept of military and commercial dual-use technology in IR detector formats will lead to lower cost, small size, reduced weight and increased user friendly application-oriented development.

Industry is looking to expand into the commercial market because the military market is decreasing and concurrently becoming more specialized [6]. The military in all countries is paying serious attention to developments in infrared and laser technology. Increasingly, optical and advanced infrared countermeasures systems and technologies play a significant and important role in modern military engagements.

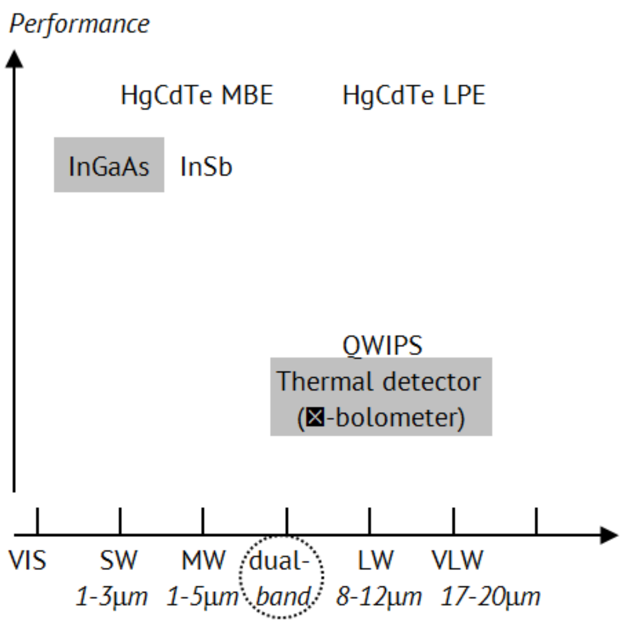

Figure 4. HgCdTe detectors grown by MBE and LPE deliver better object identification capability than the detectors, such as ⊠-bolometers and those based on InGaAs and InSb [grey box] = *uncooled*; all other: *cooled* (after [7]).

This in turn is driving the need for more advanced, higher performance infrared countermeasure systems.

Several properties of HgCdTe qualify it as highly useful for infrared detection. These are [3]: *(a)* Adjustable bandgap from 0.7 to 25 μm; *(b)* Direct bandgap with high absorption coefficient; *(c)* Moderate dielectric constant / index of refraction; *(d)* Moderate thermal coefficient of expansion; *(e)* Availability of wide bandgap lattice-matched substrates for epitaxial growth; *(f)* Very high quantum efficiency; *(g)* Growth technology has matured.

Junction formation in HgCdTe by any known technique, such as diffusion, heterojunction or implantation, raised problems not encountered in any other semiconductors. The issue arose because the transport properties in either side of the junction are determined not only by the electrical activities of impurities, but also by the defects and deviation from stoichiometry.

Moreover, any kind of anneal process of HgCdTe involved in junction formation is associated with an impurity redistribution process and a change in Hg vacancy content [8].

The formation of photovoltaic junctions in $Hg_{1-x}Cd_xTe$ is still an open research task. Today, the best results for research and production, and the best products quality, are obtained with molecular beam epitaxy (MBE) – for the great majority – and less with liquid phase epitaxy (LPE) – Figures 4 and 5.

The best performances are obtained if the implantation is made planar, for both *p*-on-*n* and *n*-on-*p*. The same thing can be said about Mesa. High performances were obtained with *p*-on-*n* heterostructures and with implantation. Over years, the only one assessed model, basic for the whole technology *n*-on-*p,* is the Bubulac model, mentioned in paper [8]. This model considers ion implantation not as a direct source of either Hg or the implant species. Recent progress in the realization of high performance devices opens prospects of new planar structures in HgCdTe, thereby expanding the possibilities of new applications, including microelectronics.

The emergence of uncooled detectors has opened new opportunities for IR detection for both military and commercial applications. Development of such devices involves a lot of trade-offs between the different parameters that define the technological stack. These trade-offs explain the number of different architectures that are under worldwide development. The key factor is to find a high sensitivity and low noise thermometer material compatible with silicon technology in order to achieve high thermal isolation in the smallest area as possible.

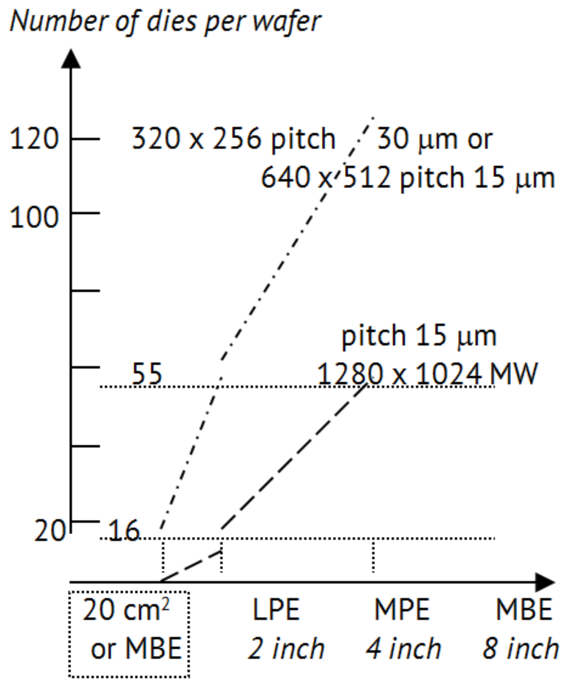

Figure 5. Switching from CdZnTe substrates to those made from Ge can substantially boots the number of dies per wafer (after [7]).

Ferroelectric thermometer based hybrid technology and electrical resistive thermometer based (micro-bolometer) technology are developed.

Thermographic application needs high stability infrared detector with a precise determination of the amount of absorbed infrared flux. Hence, infrared detector with internal temperature stabilized shield has been developed and characterized [9].

In paper [10], laser treatment of *n*-type $Hg_{1-x}Cd_xTe$ samples resulting in the formation of a photovoltaic junction is studied. The YAG:Nd^{3+} laser with pulse duration of 250 μs or 40 ns was used. The energy density of laser beam was below the threshold of sample surface melting. The idea of the presented method bases on Bubulac model of defect formation and interstitial mercury diffusion after implantation of HgCdTe single crystals [9].

Mercury cadmium telluride ($Hg_{1-x}Cd_xTe$) (MCT) photoconductive long wavelength infrared (LWIR) linear arrays are still in demand due to several advantages. The linear array technology is well established, easier, economical, and is quite relevant to thermal imaging even today. The scan thermal imaging systems based on this technology offer wider field of view coverage and capacity for higher resolution in the scan direction relative to staring systems that use expensive and yet to mature focal plane array (FPA) detector technology. A critical review on photoconductive *n*-$Hg_{1-x}Cd_xTe$ linear array detector technology for LWIR range has been presented in [11]. The emphasis lies on detector design and processing technology. The critical issues of diffusion and drift effects, Hi-Lo and heterostructure blocking contacts, surface passivation, and other related aspects have been considered from the detector design angle. The device processing technology aspects are of vital importance. For high-performance applications such as thermal imaging and radiometry, photoconductive MCT provides better sensitivity, faster response, and lower bias voltage [6].

High performance *second generation* infrared imaging systems require high density FPAs which utilize intrinsic HgCdTe photodiodes for photon detection and Si CCD signal processors in a hybrid configuration. Limitations on system performance are established by both input circuit as well as detector requirements. In the paper [12] performance of LWIR photodiodes in the 8-12 μm spectral region are discussed.

LWIR HgCdTe photodiodes have been fabricated by two basic techniques: ion implantation and liquid phase epitaxial LPE heterojunctions. In the 8-12 μm region dark current components include diffusion, generation-recombination, tunneling, and surface leakage currents.

Each of these components may be minimized and therefore performance maximized by proper choice of material parameters and device design. In this paper a trade-off analysis including thin base lateral diffusion (TBLD) as well as heterojunction design concepts utilized to minimize dark current sources are presented. A review of recent and current work on HgCdTe ion implantation and heterojunction technology including material growth, surface passivation and device fabrication are presented and experimental results compared with predicted device performance.

HgCdTe staring arrays for infrared detection do show constant improvements regarding their compactness and performances. New detectors are now proposed offering system solutions in the different IR wavebands and taking advantage of the latest technology improvements as well as MCT performance advantages and cost reduction. Based on 20 years of experience in 50 μm to 15 μm pitch IR detector production, the challenge of mass production of low-cost small-pixel pitch detectors are reviewed in [13], from the IR chip manufacturing including detection material, hybridization, return on invested capital (ROIC), to the integration in final packing.

Taking advantage of its simple well known existing process, then the analyzes of all technological steps adapted to small pitch IR detector are presented, in terms of product performance, reliability, process statistics and capability in order to achieve high yield and low product cost. Answers given the low-cost small-pitch IR detector mass productions finally give benefits to application in terms of high performance, cost reduction, extended life time, and - on the field system - life cycle support (LCS).

At present, efforts in infrared detector research are directed towards improving the performance of single element devices, large electronically scanned arrays and higher operating temperature. Another important aim is to make IR detectors cheaper and more convenient to use. All these aspects are discussed in paper [14]. Investigations of the performance of infrared thermal detectors as compared to photon detectors are presented. Due to fundamental different types of noise, these two classes of detectors have different models of detectivity vs. wavelength and temperature.

Next, an overview of FPA architecture is given with emphasize on monolithic and hybrid structures. The objective of the next sections is to present the status of different types of detectors: HgCdTe photodiodes, Schottky-barrier photo emissive devices, silicon and germanium detectors, InSb photodiodes, alternative to HgCdTe III−V and II−VI ternary alloy detectors, monolithic lead chalcogenide photodiodes, quantum well and quantum dot infrared photodetectors. Final part of the paper is devoted to uncooled two-dimensional arrays of thermal detectors. Three most important detection mechanisms, namely, resistive bolometer, pyroelectric detectors and thermopile are considered. Sofradir[2] space technology is based on the use of a qualified MCT technology hybridized with silicon readout circuit covering a bandwidth from 0.8 to 14 μm. Consequently, Sofradir technology can answer to the most of current space needs in terms of infrared instrument. Future space applications require also an extension of the sensitivity range of infrared detectors to higher wavelength (typically higher than 15 μm) and to lower wavelength, in order to offer IR components able to operate both in the visible and short wave infrared range.

Physically, MCT material is able to operate in the visible range and has a potential to offer a high quantum efficiency and large field factor thanks to the hybrid structure. Another issue of future space applications concerns the size and power consumption of the detectors and the associated cryogenic systems. Very compact cryogenic systems were developed by Sofradir, which can be used advantageously for space applications with limited adaptations and qualifications. An overview of Sofradir technology has shown the capabilities for space applications with an emphasis on new potential applications of MCT technology in visible range and for very long wave infrared components [15].

Tactical applications are very sensitive to maintenance periodicity and in lot of cases maintenance position is critical regarding mission availability. Moreover, maintenance has a cost that becomes quickly prohibitive when the cooler or the vacuum has to be repaired too often. Sofradir has worked a lot during last years on reliability and life cycle cost optimization considering all the IR detectors subassemblies. This work has lead to an increased robustness of detectors and technologies even under severe environmental conditions, and to reduced variability in production.

The state of the art in the reliability of integrated detector dewar cooler assembly (IDDCA) shows the production means and the methods that allow Sofradir to propose detectors with very high reliability, virtually without maintenance [15]. These detectors are a breakthrough for life cycle cost for tactical applications as portable cameras, airborne systems, and missiles.

The IR detectors produced in France are using up to date and well mastered technologies based on HgCdTe-MCT material. Based on the maturity of these IR detectors and technologies, IR systems have been produced and are more and more used in different

[2] Sofradir's hybridization MCT technology is a silicon-like implantation process that it is high yield and has well established simplified steps. MCT technology is able to cover all the useful waveband of the infrared spectrum, from the visible (0.4 mm) to non-visible (15 mm). Sofradir is one of the few manufacturers to produce very large focal plan arrays integrated in tactical dewars, which is a result its skill and experience in components technology, and also mechanical and cryogenic technologies. Sofradir's manufacturing facilities are located near Grenoble, France. In June 2018 Sofradir and its subsidiary Ulis announced a structural reorganization to improve overall efficiency of service and time-to-market of its IR technologies for commercial, aerospace, and defence markets, as well as emerging automotive and smart building sectors. This will bring more added value to customers, create operational synergies and streamline IR developments in all these domains.

applications including military, security, process control, environment monitoring, science and space.

The produced IR cameras are the so-called second and second and half generations which are very performing but still have some limitation regarding identification, their ability to operate in all weather conditions, and in terms of compactness and reliability. Therefore researches for moving to the next generation (the *third* one) of cooled detectors have started to overcome these limitations with the use of bi-colour or dual-band as well as to offer more performances.

To conduct these researches Sofradir and CEA-LETI have set up a specific organization, called DEFIR (design of excellence for the future of IR), necessary to increase the efficiency and to reduce the time to production of this new generation. In France, the approach about key technologies for the *third generation* takes into account different parameters, from performance to system cost criteria. [The definition of *third-generation* devices is not particularly well established.

The technical developments which are key ones to *third-generation* devices include dry etching, vapour-phase epitaxy (VPE), optical coatings, and advanced readout concepts. There are four technologies that may meet specifications of *third-generation*: multispectral detectors, dualband monopixel, quantum-well (QWIP), uncooled microbolometer, and antimonide based materials. Uncooled detectors will probably be used for most low and mid-level applications in the near future. Among all the technologies candidates, a new HgCdTe technologies based on molecular beam epitaxy (MBE) growth have been chosen. Then prototype demonstrations are in progress and confirm the validity of the chosen key technologies [16].

Novel tactics employed in carrying out military and antiterrorist operations call for the development of a new generation of warfare, among which sophisticated portable infrared (IR) imagers for surveillance, reconnaissance, targeting and navigation play an important role. The superior performance of such imagers relies on novel optronic technologies and maintaining the infrared FPAs at cryogenic temperatures using closed cycle refrigerators.

Traditionally, rotary driven Stirling cryogenic engines are used for this purpose. As compared to their military off-the-shelf linear rivals, they are lighter, more compact and normally consume less electrical power. Latest technological advances in industrial development of high-temperature (100 K) infrared detectors initialized R&D activity towards developing micro-miniature cryogenic coolers, both of rotary and linear types. On this occasion, split linearly driven cryogenic coolers appear to be more suitable for the above applications.

Their known advantages include flexibility in the system design, inherently longer life time, low vibration export and superior aural stealth. Moreover, recent progress in designing highly efficient "moving magnet" resonant linear drives and driving electronics enable further essential reduction of the cooler size, weight and power consumption. The paper [17] reports on the development and project status of a novel Ricor model K527 micro-miniature split Stirling linear cryogenic cooler designed especially for the portable infrared imagers.

The emergence of uncooled infrared detectors has opened new opportunities for IR imaging both for military and civil applications.

Infrared imaging sensors that operate without cryogenic cooling have the potential to provide the military or civilian users with infrared vision capabilities packaged in a camera of extremely small size, weight and power. Uncooled infrared sensor technology has advanced rapidly in the past few years. Higher performance sensors, electronics integration at the sensor, and new concepts for signal processing are generating advanced infrared focal plane arrays (IRFPA).

This would significantly reduce the cost and accelerate the implementation of sensors for applications such as surveillance or predictive maintenance.

The uncooled IR detector operation principle and the development at CEA/LETI from the 256 x 64 with a pitch of 50 µm to the 320 x 240 with a pitch of 35 µm is presented in paper [18].

This silicon IR detection is now well mastered and matured. Industrial production of 320 x 240 micro-bolometer array with 45 µm pitch is started. After a description of the technology and the methodology for reliability enhancement, paper [18] presents the readout circuit architectures designs and its evolution from the 256 x 64 array to the different version of 320 x 240 arrays. Electro-optical results obtained from these infrared CMOS (IRCMOS) are presented. Noise equivalent delta temperature (NEDT) close to 30 mK is now obtained with standard micro-bolometer amorphous silicon technology.

A considerable progress in IR detectors was demonstrated by the research group at Rockwell Science Center and Sofradir.

While ion implantation requires activation of the implanted atoms at relatively high temperatures, an alternative technology (ion milling or plasma induced type conversion) has received considerable attention during the past few years. LWIR devices with performances close to the theoretical limit have been demonstrated for cut-off wavelengths from 9 to 12 µm. In future, it is envisaged that HgCdTe planar photodiodes will be grown directly on silicon or even silicon multiplexers for the very low cost detectors [19].

A large 1000 x 256 IRFPA detector with a pitch of 30 µm, dedicated for SWIR hyper spectral imagers, will be implemented on earth observation satellites. It operates in the 1 to 2.5 µm waveband at an operating temperature compatible with passive cooling, largely used in satellites.

The retina of the detector is based on a photovoltaic HgCdTe array hybridized to a full custom silicon CMOS readout circuit. In paper [20], major trade-offs regarding detector design and performances are presented with a particular emphasis on the capability of the retina in terms of noise and dynamic range. The FPA structure demonstrated more than 1000 thermal cycles without degradation of the indium bumps reliability and electro-optical performance.

The technology of very high performance cooled infrared detectors made with HgCdTe has progressed continuously for the last ten years and reached today an industrial maturity that allows the production of large size arrays at a more and more reasonable cost. At the same time, new prototypes of more complex sensors have appeared (megapixel arrays, multicolour arrays, high definition long linear arrays, etc.) that show the strong potentialities of this very high performance technology [5].

The origin of 'hot spot' defects is unresolved – however, the analysis of [21] has shown 'hot spots' can arise due to molecular beam epitaxy spit defects and CdZnTe substrate defects. The estimated 'hot spot' density is 30 cm^2.

Control of impurities is another challenge and an important requirement, if CdZnTe is to be used as a substrate material for the growth and fabrication of HgCdTe IR detectors. Especially the control of copper and iron impurities is of prime importance as they lead to the loss of useful signal in the mid-IR region and also their propagation into the HgCdTe epilayer affects the subsequent device performance.

Impurity ‘hot spot’ macro-defects—high impurity level macro-defect contaminates were examined. ‘Hot spots’ have very high localized concentrations of: K, Mg, Ni, Cr, Mn, Ca, Al, Na, Fe, and Cu. For example, these ‘hot spot’ macro-defects can have Cu concentrations $>1\times10^{18}$ cm^{-3}. Focused ion beam scanning transmission electron microscopy analysis of four ‘hot spots’ was performed [25].

Because of their high impurity contamination levels, it is believed that ‘hot spot’ macro-defects can be a significant yield limiter for HgCdTe/CdZnTe IRFPAs. The presence of impurity ‘hot spot’ macro-defects in HgCdTe/CdZnTe is confirming evidence for the occurrence of L. Bubulac’s impurity ‘pipe’ mechanism[3].

Instead of conclusion

Much of the effort to develop MBE growth of HgCdTe layers on lattice-mismatched alternative substrates has been focused on meeting the demands of novel *3rd generation* device structures, which require lower production cost, larger wafer size, lower defect density, and higher yield, etc. However, several issues continue to restrict the fabrication of HgCdTe devices on alternative substrates, such as high misfit dislocation density (10^6~10^7 cm^{-2}), rough surface, and especially the need to grow thick buffer layers (7~20 μm) to achieve a high degree of relaxation for subsequent growth of a strain free HgCdTe absorber layer.

References

1. Norton, P., “Understanding the ☒☒☒☒ of tactical infrared focal plane arrays,”Opto-Electronics Review, September 2012, Volume 20, Issue 3, pp. 275–278.
2. Rogalski, A., Rep. Prog. Phys. 68, 2267 (2005).
3. Norton, P., “HgCdTe infrared detectors,” Opto-Electron. Rev. 10, 159–174 (2002).
4. Madejczyk P., Gawron W., Piotrowski A., Kłos K., Rutkowski J., and Rogalski A., “Influence of TDMAAs Acceptor Precursor on Performance Improvement of HgCdTe Photodiodes,” Acta Physica Polonica A, Vol. 118 (2010) No. 6.
5. Harris J. S. Jr., Sahai R., Waldrop J. R., and Bubulac L. O., “1.06 Micron High Sensitivity IR Photocathode,” Rockwell International, Thousand Oaks, California Science Center, Final report, 6 January–30 June 1975.
6. Dombrowski M., and Wilson P., SPIE Proc. 3753, 100 (January 2000).
7. Tribolet, Ph., “Sofradir Builds a New Factory to Ramp HgCdTe Chip Production,” compoundsemiconductor.net, May 2007, p. 22; Tribolet, Ph.,“HgCdTe Technology in France,” Comptes Rendus Physique Vol. 4, Issue 10, December 2003, Pages 1121–1131.
8. Bubulac L. O., "Defects, Diffusion and Activation in Ion Implanted HgCdTe," Journal of Crystal Growth 86, 1988, pp. 723–734.
9. Destafanis G., “New Generations of Infrared Detectors Based on HgCdTe,” Comptes Rendus Physique, Vol. 4, Issue 10, December 2003, pp. 1109–1120; Tissot, J.-L., “La détection infrarouge avec les plans focaux non refroidis: état de l'art, “ Comptes Rendus Physique, Vol. 4, Issue 10, December 2003, pp. 1083–1088.
10. Dumanski L., Virt I., and Kuzma M., “P-N Junction Formation in HgCdTe by Laser Annealing Method,” Conf. European Material Research Society E-MRS 2005 Spring Meeting, Strasbourg, May 31–June 3, 2005.

[3] The numerous small line features running ~parallel to the growth direction are believed to be impurity "pipes" as have been confirmed by IR microscopy. One key advantage to this technique is that is able to provide a quantitative assessment of the probed region.

11. Risal Singh, and Vandna Mittal, "Mercury Cadmium Telluride Photoconductive Long Wave Infrared Linear Array Detectors," Defence Science Journal, Vol. 53. No. 3, July 2003, pp. 281–324.
12. Riley K. J., "LWIR HgCdTe Photovoltaic Detectors for Hybrid Focal Plane Arrays," International Electron Devices Meeting, Vol. 26, pp. 490, 2005–08–09.
13. Bercier E. J., Dessus L., Manissadjian A., and Tribolet Ph., "State-of-the-Art of Mass Production: Challenges for Low-Cost and Application Benefits of High-Performances Small-Pitch IR Detectors," Proc. of the Infrared Technology and Applications XXXIV SPIE Conf., Orlando, FL, 17 March 2008, Vol. 6940, 69400I (2008).
14. Rogalski A., "Infrared Detectors: Status and Trends," Progress in Quantum Electronics, Vol. 27, Issues 2–3, 2003, pp. 59–210.
15. Chorier Ph., and Vuillermet M., "Sofradir Infrared Detectors for Space Applications," Proc. SPIE, Vol. 5978, 597817 (2005). DOI:10.1117/12.627498.
16. Tribolet Ph., and Vuillermet M., "IR Detectors Design and Approach for Tactical Applications with High Reliability without Maintenance," Proc. of the Infrared Technology and Applications XXXIV SPIE, Orlando, FL, USA, 17 March 2008, Vol. 6940, 69400H (2008); DOI:10.1117/12.780048.
17. Veprik A., Vilenchik H., Riabzev S., and Pundak N., "Microminiature Linear Split Stirling Cryogenic Cooler for Portable Infrared Imagers," Proc. of the Infrared Technology and Applications XXXIII SPIE, Orlando, FL, 15 April 2007, Vol. 6542, 65422F (2007); DOI:10.1117/12.715622.
18. Mottin E., et al. "Amorphous Silicon Technology Improvement at CEA-LETI (Proceedings Paper)," In Brown G. J., and M. Razeghi (eds.) SPIE Proceedings Photodetector Materials and Devices, 21 May 2002, VII, Vol. 4650, pp. 138–149.
19. Rutkowski J., "Planar Junction Formation in HgCdTe Infrared Detectors," Opto-Electronics Review Vol. 12, Issue 1, 2004, pp. 123–128.
20. Chorier Ph. and Tribolet Ph., "High Performance HgCdTe SWIR Detectors for Hyperspectral Instruments," http://www.sofradir.com/_pdf/high_performance%20_hgcdte_swir_detectors_for_hyperspectral_instruments.pdf
21. Benson J. D., Bubulac L. O., Wang A., Jacobs R. N., Arias J. M., Jaime-Vasquez M., Smith P. J., Almeida L. A., Stoltz A., Wijewarnasuriya P. S., Yulius A., Carmody M., Reddy M., Peterson J., Johnson S. M., Bangs, J., Lofgreen D. D., "Impact of CdZnTe Substrates on MBE HgCdTe Deposition," Journal of electronic materials, Vol. 46(2017), No. 9.
22. Băjenescu T. I., and Bâzu M., Reliability of Electronic Components. A Practical Guide to Electronic Systems Manufacturing, Berlin and New York, Springer, 1999.
23. Băjenescu T. I., and Bâzu M., Component Reliability for Electronic Systems, Boston and London, Artech House, 2010.
24. Madni I., Characterization of MBE-grown HgCdTe and related II-VI materials for next generation infrared detectors, Ph. D. Thesis, 2017, The University of Western Australia
25. Benson J. D., Bubulac L. O., Wang A., Jacobs R. N., Arias J. M., Jaime-Vasquez M., Smith P. J., Almeida L. A., Stoltz A., Wijewarnasuriya P. S., Yulius A., Carmody M., Reddy M., Peterson J., Johnson S. M., Bangs J., Lofgreen D. D., "Impurity 'Hot Spots' in MBE HgCdTe/CdZnTe," Journal of Electronic Materials, (July 2018), https://doi.org/10. 1007/s11664-018-6523-z, pp. 1-9,