Infrared Detection Workshop - 3 to 5 July 2018
Abstract list

Issue 1 – 16/05/18

Tutorials

2-6 or 3-5's for quantum IR imaging ? Is it a simple question of columns or figures ?

O. Gravrand
CEA-LETI, 17 rue des martyrs, 38054 Grenoble, France

Since more than 30 years, HgCdTe has been the 'king of the hill' in IR imaging. Due to it's versatility (ie the ability to address different spectral bands) as well as it's extremely high performances (in QE and dark current), this 2-6 semi-conductor material has shown a remarkable resilience against the incursions of alternative material systems in the domain of high performance IR imaging, especially for the space industry. However, the exotic nature of this semiconductor material imposes the maintenance of dedicated production lines. This is often seen as a factor limiting the cost and the development lifetime of such detector arrays, or even, sometimes limiting the production yield.

Apart from QWIPs, most of those alternative solutions are also based on photodiodes but processed in 3-5 materials, which olds the reputation of a more conventional material system, meaning easier to manufacture with high yields for lower costs. Among those alternative material systems are bulk narrow gap semiconductors (such as InGaAs, InSb and now InAsSb). In those materials, the trade-off between cutoff wavelength and operating temperature is fixed, therefore limiting the versatility of the material systems. However, the performance reached are sufficient for a strong commercial interest, and the resulting photodiodes may sometimes overcome the reference performances of HgCdTe in terms of dark current.

However, another 3-5 player is expected to offer a versatility similar to 2-6 HgCdTe. Indeed, in the type-2 superlattice material system, the choice of superlattice stack formula allows the full design of narrow gap minibands in the whole IR spectrum. Therefore this synthetic narrow gap material is nowadays the focus of a strong interest, especially in the US which dedicated a strong research effort in the last few years to setup this technology.

This tutorial intends to depict those different material systems for high performance IR imaging based on first order FOMs (such as QE, dark current or MTF) but also taking into consideration second order parameters (residual fixed pattern noise, stability and radiation hardness). Those second order FOMs being usually not perfectly known in the different material systems, this part of the tutorial will discuss those aspects based on literature data as well as considerations about the physics of the detection in each of those material systems.

Type II superlattice detectors – detector physics and current state-of-the-art

L.Höglund, S. Naureen, M. Pozzi, E. Costard
IRnova AB, Isafjordsgatan 22 C5, SE-16440 Kista, Sweden

In recent years antimony based Type-II superlattices (T2SL) have proven to be excellent material for high end infrared (IR) detectors and this technology is now competing with the traditional state-of-the-art technologies. The desirable properties needed for good detector performance such as low dark current, high quantum efficiency (QE) and good focal plane array (FPA) performance have improved significantly in the last decade. Initially, results on InAs/Ga(In)Sb superlattice (SL) detectors were mainly presented by research groups, but now both mid wave infrared (MWIR, 3-5 µm) and long wave infrared (LWIR, 8-10.5 µm) FPAs based on T2SLs are mature enough to be manufactured by several companies. The rapid improvement in detector performance is mainly due to novel barrier designs that utilize wide bandgap barriers to block the flow of majority carriers while allowing unimpeded transport of the minority carriers. As a result of these barrier designs, strong reduction of the generation-recombination (G-R) and tunneling dark currents has been demonstrated, which results in improved detector performance.

T2SL offer a great flexibility, as the bandgap (cut-off wavelength) of T2SL can be tailored to any desired detection wavelength in the IR wavelength region, from short wave infrared (SWIR, 0.9 -1.7µm) to very long wavelength infrared (VLWIR, 10.5-16 µm), by individually varying the thickness and composition of the alternating layers in the SL. Different advanced barrier detector designs, such as the complementary barrier infrared detector (CBIRD) design and the M-structure, W-structure, nBn, pBn designs are enabled by using combinations of superlattices and bulk layers from the 6.1 Å material system (InAs, GaSb, AlSb) as well as alloys of these materials with InSb, AlAs and GaAs.

The InAs/GaSb T2SL is the most commonly used T2SL for MWIR and LWIR applications and is currently commercially available for detector arrays up to 640 × 512 pixels, 15µm pitch (for instance by IRNOVA, AIM – Fraunhofer, IAF and SCD). Another novel T2SL that shows promising benefits in terms of even lower dark current, great uniformity and easier passivation is the InAs/InAsSb T2SL. The simplified passivation is a great advantage when increasing the array format and decreasing pixel sizes.

In this presentation, a tutorial of the T2SL detector physics will be given with a summary of the different designs available. Furthermore, the main benefits of this technology will be demonstrated, such as high uniformity, high operability, good manufacturability and great stability over time. Finally, a summary of the current state of the art in this technology will be presented, including 4K × 4K MWIR FPAs and 1K × 1K VLWIR FPAs with excellent performance.

Session 1 On-going and future mission technology review

Ref 1.1 : CNES IR detector developments for space missions: status and roadmap

H. Geoffray(a), L. Tauzière(a), A. Ledot(a), O. Gravrand(b), B. Fièque(c), A. Bardoux(a)
(a) CNES, (b) CEA-LETI, (c) Sofradir

CNES (French Space Agency) is involved in several science and remote sensing space missions. CNES also continuously drives the development of detectors for those space missions. Technological developments are of primary importance to reach the demanding performances of space applications. The main detector performance drivers are low noise, large format detector, low consumption, detectors free of any parasitic effects allowing excellent signal-to-noise ratio. Several promising infrared HgCdTe technologies are being developed at CEA and Sofradir. This paper gives a status on these developments as well as an overview of the associated roadmap.

Ref 1.2 : The status of European Space Agency supported infrared detector developments

Nick Nelms, Kyriaki Minoglou, Heidrun Weber, Alessandra Ciapponi and Sarah Wittig
ESA-ESTEC

The European Space Agency (ESA) has a very strong interest in the availability of high-performance, space-qualified infrared detectors for future Earth Observation and Astronomy missions. To this end, and in line with the Agency's remit to support European technology, ESA pursues an ongoing program of coordinated and targeted detector developments within the ESA member states. This presentation provides details of current and recent detector development activities in the NIR to VLWIR range.

Ref 1.3 : Development status of NIR to VLWIR IR detectors integrated within under development space optical payloads and recommendations for future space programs

Michel Bréart de Boisanger(a), Aurélien Albert-Aguilar(a), François Aumonier(a), Terry Bastirmaci(a), Amandine Buffaz(a), Christophe Delettrez(a), , Saï Guiry(a), Markus Haiml(b), Romain Jalabert (a), Denis Marchais(a), François Robert(a), Anne Rouvié(a), Olivier Saint-Pé(a), Michael Skegg(b), Cyril Vetel(a), Dirk Viehman(b)
(a) Airbus Defence and Space SAS, (b) Airbus Defence and Space GmbH

Airbus is a major European prime contractor for space optical payloads, with a track record of 37 optical instruments already in flight. 15 new instruments are currently in development in Toulouse, Ottobrunn and Friedrichshafen facilities, 7 being exploiting infrared detectors from 0.6 to 16 µm. Most of these devices are based on custom PV MCT technologies while custom or COTS PC MCT, InGaAs APD and microbolometers arrays technologies are filling some specific needs. After a technical review of the main characteristics of such custom and COTS detectors, the main lessons learnt during their developments will be discussed. Derived recommendations will finally be presented in order to brighten IR detectors developments for future space missions.

Ref 1.4 : Infra Red Detection at Thales Alenia Space : from past to on-going developments and interests

Geoffroy BORDOT, Thierry DARTOIS, Hubert GARDETTE, Adrien LEFEBURE, Frederic PISTONE, Nadège REMOUE.
THALES ALENIA SPACE

Thales Alenia Space is involved in the development of Infra Red Instrument since several decades starting from ISOCAM in the eighties using intrinsically doped silicon detectors (SiGa). This first generation of IR camera using small 2 D array and large pixel pitch (100 µm) has been followed rapidly by more ambitious IR Instruments for several different applications as for example : high resolution earth observation, early warning, Scientific (Exoplanet exploration), Environment (CO2 detection) and Meteorology. The presentation consists in an overview of the last on going IR detection subsystem which are generally based on HgCdTe detectors. The whole Infra Red detection chain of MTG Infrared Sounder (IRS) and Combined Imager (FCI) will be presented and will be supported by a review of the main performance based on EM model tests results. At the opposite of this cryo-cooled system, Thales Alenia Space has also studied since the first FUEGOSAT mission, different instruments using uncooled IR COTS detectors. This first generation used a 320 x 240 Siα microbolometer, replaced in a close past for the MISTIGRI instrument by the VGA format device, which was sensitive to Single Event Latch Up. Tests performed on the last generation of XGA format ULIS microbolometer under space environment are addressed. The last part of the presentation introduces a new HOT detector technology in SWIR region that Thales Alenia Space and its partners will develop in the coming years under EC fundings.

Ref 1.5 : Latest advances in cooled and un-cooled infrared detection technology at Leonardo MW

Keith Barnes
Leonardo MW

Leonardo MW will present its latest advances in cooled and un-cooled infra-red detector technology for space and astronomy applications. Recent developments have included enhancements in the performance of cooled Mercury Cadmium Telluride (MCT) detectors operating in both conventional and avalanche gain modes, along with validation of their performance for space environments, particularly under radiation. The presentation will also include details of uncooled DLATGS pyroelectric detectors for spectroscopy applications.
Recent developments of the SAPHIRA Avalanche PhotoDiode (APD) MCT focal plane array product have been targeted at single photon noise capability which exploits the inherent benefit of MCT material for near noiseless multiplication of signal levels to bring them above the noise floor of the host system. Further advances in the MCT technology have also extended the sensitivity in the short wave and near infrared wavelength regions for enhanced spectral response (0.8µm to 2.5µm). These short wave and near infrared MCT products can be used either in avalanche gain mode or in traditional unity gain mode depending upon the flux conditions and the sensitivity required.

In parallel to developing the MCT technology, the Leonardo silicon circuit technology is also being developed to give low noise, high speed read out integrated circuits on megapixel formats. Results of Proton and Gamma radiation test campaigns of focal plane arrays operated at cryogenic temperatures will be presented.

Leonardo MW also has a long heritage of supplying DLATGS detectors for spectroscopy instruments including those for space applications. Details of the detectors produced for the most recent space programme will be presented.

Ref 1.6 : Teledyne's High Performance Infrared Detectors for Space Missions

James Beletic(a), and Paul Jerram(b)
(a) Teledyne Imaging Sensors, (b) Teledyne e2v Space Imaging

Teledyne has developed a wide range of infrared detectors for Earth science, planetary science, and astronomy. These IR detectors are operating in low Earth orbit, geosynchronous orbit, around Mars, and for missions to the Moon, Pluto, and asteroids. Teledyne's IR detectors are key to several new missions being launched to Jupiter and neighboring bodies (Europa, Ganymede, Trojan asteroids). Teledyne's substrate-removed HgCdTe is a mature (TRL-9) technology that provides simultaneous visible and infrared detection for reflected sunlight imaging spectroscopy (hyperspectral imaging).

After a review of Teledyne's IR technologies for space applications, this talk will present Teledyne's latest readout integrated circuits (ROICs) and focal plane arrays (FPAs) optimized for space. We will discuss new initiatives to supply infrared detectors to the European space community. And we will present information on fully depleted HgCdTe, a technology that enables a new generation of high operating temperature detectors that will greatly ease thermal requirements for MWIR (5 µm) to VLWIR (14.5 µm) space missions.

Ref 1.7 : Ground based Infrared detector and camera system developments at ESO for the next generation of telescopes and instruments

Derek Ives
ESO Detectors Systems Group

The success of the next generation of instruments for both the ELT telescope and the VLTs depends on new developments in large format near Infrared detectors, sub-electron AO sensors, high frame rate mid-IR detectors, associated electronics and camera systems and in the continuous development of the ESO's NGC detector controller platform. It is also reliant on building even larger detector focal planes, operation of the detectors at much higher frame rates and in achieving the absolute best performance from the detector systems.

There are 3 first light instruments for the ELT, HARMONI, an IFU fed spectrograph, MICADO, a diffraction limited imager and METIS a long wavelength imager and spectrometer. Each instrument will be briefly presented with particular reference to their detector needs. Likewise, there is an ongoing VLT instrument program with many projects progressing. MOONS is a wide field fibre fed optical and IR spectrograph based on a novel Schmidt camera design. ERIS is an AO fed Infrared imager and spectrometer.

ESO also has an ongoing detector development program. In the past it funded the development of Infrared eAPDs for AO cameras, this development will continue with a new larger format device for similar applications. Finally, ESO has an ongoing detector controller development program. This includes two new AO camera systems and continued developments of NGC, the ESO generic detector control system. An ASIC development is also funded to produce a new multi-channel cryogenic preamplifier with gain and bandwidth switching.

Ref 1.8 : The Infra-Red Telescope on board the THESEUS mission

Diego Gotz
CEA-IRFU

The Transient High Energy and Early Universe Surveyor (THESEUS) is a candidate ESA M5 mission dedicated to time domain astronomy, and in particular to the cosmological use of Gamma-Ray Bursts. Its payload is composed by three telescopes: the Soft X-ray Imager (SXI), sensitive in the 0.5-2 keV energy range provided by a UK led consortium, the X- and Gamma-Ray Imaging Spectrometer (XGIS), sensitive in the 2 keV - 10 MeV energy range, provided by an Italian led consortium and the Infra-Red Telescope (IRT), sensitive in the 0.7-1.8 microns range, provided by a consortium led by France.
Here we present the scientific goals of the mission, and we focus specifications and the requirements of the IRT.
The IRT will have a 0.7 m primary mirror, and its camera will provide a wide FOV (10 x 10 arc min) in imaging mode, and low (~20) to moderate (~100-500) spectroscopic capabilities. THESEUS will be operated in a Low Earth Orbit implying a challenging thermal environment for a NIR telescope, a limited pointing accuracy and some jitter. This will require dedicated detector readout modes, especially for the spectroscopic mode.

Ref 1.9 : Constraints on the Infrared Technologies for Land and Airborne Defense applications.

Eric Belhaire, Véronique Besnard, Vincent Guériaux
THALES LAS

Thales, through its Optronics and Missile Electronics Business Line, is involved in the development of Infrared equipment for Land, Airborne and Naval Defense applications since several decades. Several technologies have been used for the different generations of equipment. The specific constraints on those technologies for this type of applications will be presented with a focus on the maturity and stability requirements on LWIR infrared technologies for land applications. The foreseen roadmap and evolutions on the cooled and uncooled infrared technologies will then be presented for SWIR, MWIR, LWIR and multiband applications.

Session 2 : ROIC and SFD detectors

Ref 2.1 : Detector chain calibration for the Euclid flight IR H2RGs

R. Barbier, C. Buton, S. Ferriol, B. Kubik, G. Smadja, IPNL-CNRS Lyon University A. Secroun, J-C. Clemens, A. Ealet, W. Gillard, B. Serra, J. Zoubian, CPPM-CNRS Aix-Marseille University C. Rosset, APC CNRS, Paris 7 Denis Diderot University
R. Kohley, L. Conversi, ESA/ESAC

Euclid is an ESA mission to map the geometry of the Dark Universe with a planned launch date in 2021. Two primary cosmological probes, weak gravitational lensing and baryonic acoustic oscillations, are implemented through a Visible imager (VIS) and a Near-Infrared Spectrometer and Photometer (NISP).The NISP instrument focal plane is composed of a 4x4 assembly of Sensor Chip Arrays (SCA).The SCAs are 16 Teledyne Imaging Sensors HgCdTe H2RG detectors with 2.3 um cut-off wavelength readout in parallel by the 16 Sensor Chip Electronics (SIDECAR). They are characterized and selected by NASA.On-ground tests are being performed by the Euclid Consortium (EC) detector teams for characterization and calibration of the detector response per pixel. Specific illumination sequence scenarios are executed and continuously monitored during 40 days per detector.This paper covers the characterization and analysis strategy to maintain the detector chain relative accuracy to within 1%. The EC Test Flow is presented and the main concerns of the detector chain calibration, such as persistence, charge trapping and their consequences on the non-linearity correction are discussed on the basis of the analyses of the first 8 flight detectors.

Ref 2.2 : Characterization of H2RG flight detectors in preparation of the Euclid mission: testflow and initial results

A. Secroun, J.-C. Clémens, A. Ealet, W. Gillard, J. Zoubian, CPPM
R. Barbier, S. Ferriol, B. Kubik, G. Smadja, IPNL
C. Rosset, APC
R. Kohley, L. Conversi, ESAC

Euclid is a major ESA mission due to launch in 2021 aimed at mapping the geometry of the dark Universe. Euclid is optimized for two probes, weak gravitational lensing and baryonic acoustic oscillations, which will be measured thanks to a visible imager (VIS) and an infrared spectrometer and photometer (NISP) both designed and built by the Euclid Consortium teams.
The NISP focal plane array is an assembly of 4 by 4 Teledyne H2RG detectors with 2.3 um cutoff, which are a key element to the performance of the NISP, and therefore to the science return of the mission.
Thorough on-ground testing of the detectors has started at CPPM since June 2017 for characterization and calibration purposes with a view to producing a reference database of pixel maps of detector performances in terms of dark current, noise and quantum efficiency, among others.
Dedicated test benches as well as the whole acquisition and L1 level (Data Quality Checking) analysis codes have been previously designed, built and validated thanks to several pilot runs. This work has led to an efficient and reliable fully integrated acquisition and validation system. Already 8 flight detectors have been tested and a straightforward analysis has been done, in order to derive models for science needs. This talk presents the testflow of characterization as well as some initial results from the first 8 flight detectors introducing matters of telemetry and showing some results on dark current, noise and conversion gain.

Ref 2.3 : Low temperature dark current sources in HgCdTe detector and implication in SFD ROIC architecture

C.Cervera1, O.Gravrand1, O. Boulade[2] and N.Baier1
1 CEA-LETI-Minatec Campus, 17 rue des martyrs, 38054 Grenoble France
2 CEA-IRFU-DAp, CEA Saclay, 91191 Gif sur Yvette France

Nowadays, MCT detectors hybridized on Source Follower per Detector (SFD) ROIC for low flux space application are very demanding and all wavelengths from SWIR (2-3µm) to LWIR (12.5µm) are interesting. One of the main goal of the ESA and CNES is to reduce the level of dark current at all wavelengths. An efficient way to do that, in a quantic detector, is to reduce the FPA temperature below 77K. In this range of temperature, different dark current sources are competing. The dark current limitations (Diffusion, Depletion and tunneling current) as function of the wavelength at low temperature (from 40K to 77K) based on ECHO, NIRLFSA and ARIEL programs results will be presented. Then, the implication of the diode current behavior in SFD will be discuss.

Ref 2.4 : Modelling of luminescence induced by proton irradiation in HgCdTe infrared detector array in space environment.

T. Pichon a, S. Mouzali a, O. Boulade a, G. Badano b, O.Gravrand b, O.Limousin a
aCommissariat à l'Energie Atomique, DAp, Gif-sur-Yvette, France
bCommissariat à l'Energie Atomique, LETI, Grenoble, France

The French Alternative Energies and Atomic Energy Commission (CEA) is deeply implied in the development of ALFA (Astronomical Large Format Arrays), a 2048x2048 short-wave infrared (SWIR) detector array with a 15µm pixel pitch and a cutoff wavelength of 2.1µm. [1] The development is mainly funded by the European Space Agency (ESA), for the future space missions, and by the French national research agency.

In the ALFA detector structure, the light sensitive layer is made of Hg1-xCdxTe (mercury cadmium telluride) grown on a Cd1-yZnyTe (cadmium zinc telluride) substrate. The HgCdTe layer is then hybridized on a silicon read-out circuit with the use of indium bumps (figure 1). Similar Infrared (IR) detectors have generally their substrate either partially removed or completely removed.

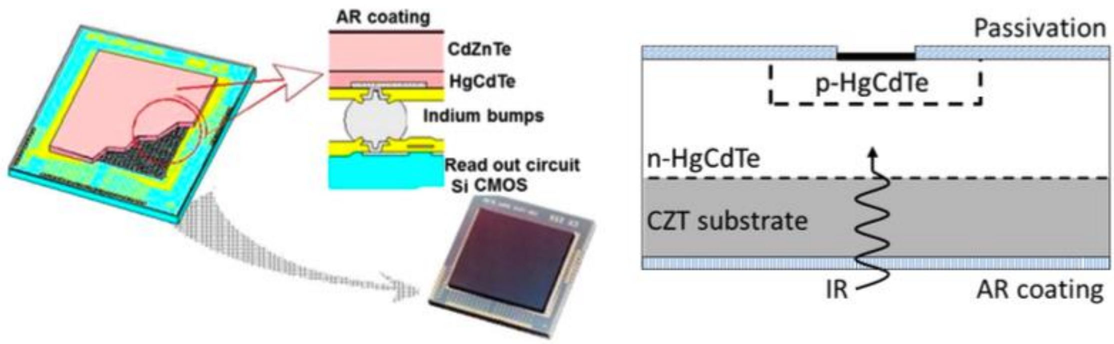

Figure 1 - Schematic Representation of the HgCdTe P on N photodiodes and arrays

Since ALFA is dedicated to space applications, it has to be hardened against radiation effects. It is therefore essential to understand the effects of space radiations on these IR detectors. In particular, in addition to the study of energy deposition directly into the HgCdTe sensitive layer, it is mandatory to address the effects of particles energy deposition in the CdZnTe substrate for detector structures where the substrate is not completely removed.

It has been shown in the past that the interaction of energetic protons with the substrate adds an undesired photonic signal which pollutes the acquired images [2] [3] [4] . In their article, R. Smith and coworkers [2] showed that a complete removal of the substrate reduces this pollution (figure 2). Waczynski et al. have investigated this elevation of the background in 1024x2014 HgCdTe arrays grown on a CdZnTe substrate with a cutoff wavelength of 1.7µm [3]. The detectors were irradiated with different proton energies (15,7MeV, 29.9MeV and 63.3MeV). Their conclusion showed that, apparently, the elevated background signal was linked to the energy deposited in the substrate which is converted into 800nm photons before being detected by the sensitive volume of HgCdTe.

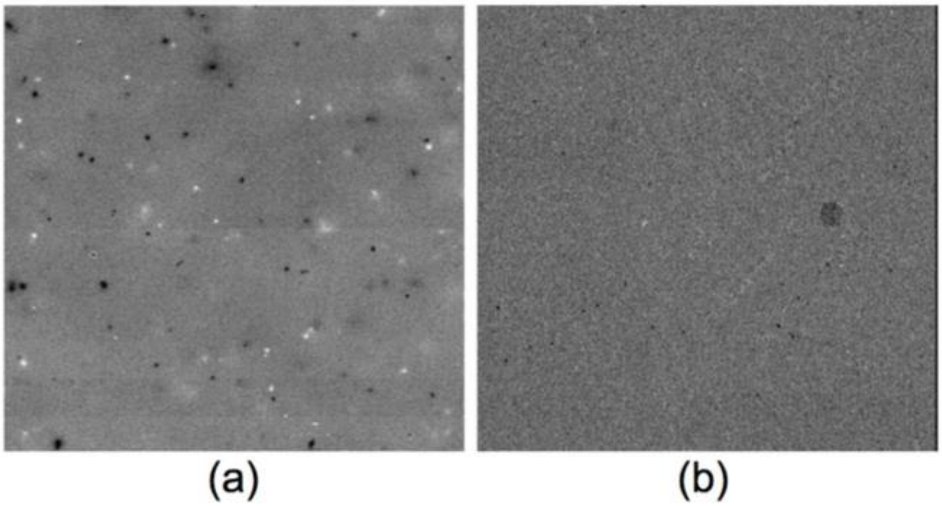

Figure 2 - Difference of two consecutive dark frames under proton irradiation of 1.7µm H2RG IR detectors. (a) with intact CdZnTe substrate, (b)without CdZnTe substrate.

We adopt a modelling approach in order to investigate the physical processes leading to the luminescence effect in the CdZnTe substrate. To achieve this, we use several simulation tools, such as SRIM (Stopping and Range of Ion in Matter) [5], GEANT4[6] and Silvaco [7] , in order to describe the different physical phenomena. The first results obtained using Monte Carlo simulation with GEANT4 are presented, where the spatial distribution of the deposited energy in the substrate is studied. The final goal of this study is to optimize the substrate thickness in order to have an acceptable image contamination for space application. The detector with this adapted substrate thickness will be subjected to further thermomechanical simulations in order to validate its behavior at the low operating temperatures (typically 100K). The next step will be to validate the simulation results experimentally by irradiating detectors with different substrate thicknesses in order to estimate the images pollution by luminescence.

Bibliographie

[1] O. Boulade, V. Moreau, P. Mulet, O. Gravrand, C. Cervera, J.-P. Zanatta, P. Castelein, F. Guellec, B. Fièque, P. Chorier et J. Roumegoux, «Development activities on NIR large format MCT detectors for astrophysics and space science at CEA and SOFRADIR,» Proceeding of SPIE, High Energy, Optical, and Infrared Detectors for Astronomy II, vol. 9915, n° 199150C, 2016.

[2] R. Smith, C. Bebek, M. Bonati, M. G. Brown, D. Cole, G. Rahmer, M. Schubnell, S. Seshadri et G. Tarle, «Noise and zero point drift in 1.7um cutoff detectors for SNAP,» Proceeding of SPIE, High Energy, Optical, and Infrared Detectors for Astronomy II, vol. 6276, n° 162760R, 2006.

[3] A. Waczynski, P. W. Marshall, C. J. Marshall et R. Foltz, «Radiation Induced luminescence of the CdZnte substrate in HgCdTe detectors for WFC3,» Proceedings SPIE, vol. 5902, n° 159020P, 2005.

[4] M. L. Dorn, L. Pipher Judith, C. McMurtry, S. Hartman, A. Mainzer, M. McKelvey, R. McMurray, D. Chevra et J. Rosser, «Proton Irradiation results ofr long wave HgCdTe infrared detector arrays for Near-Earth Object Camera,» Journal of Astronomical Telescopes, Instruments and Systems, vol. 2, n° 13, p. 36002, 2016.

[5] J. Ziegler, J. Biersack et M. Ziegler, SRIM The stopping and Range of ions in Matter, 2008.

[6] S. Agostinelli et e. al., «Geant4 - a simulation toolkit,» Nuclear instruments and methods in physics research section A: Accelerators, Spectrometers, Detectors and Associated Equipmen, vol. 506, n° 13, pp. 250-303, 2003.

[7] «Silvaco,» [Online]. Available: https://www.silvaco.com. [Access on 01 30 2018].

Ref 2.5 : Update of SEE Radiation Hardness Assurance of Readout Integrated Circuit of Infrared Image Sensors at Cryogenic temperatures

Laurent Artola1, A. Al Youssef1, Samuel Ducret2, Franck Perrier2, Raphael Buiron2, Olivier Gilard3, Julien Mekki3, Mathieu Boutillier3, Guillaume Hubert1, Christian Poivrey4
1 ONERA / 2 Sofradir / 3 CNES / 4 ESA

This work presents SEE irradiation tests under heavy ions in DFF testchips and complete ROIC devices as a function of temperature down to 57K. The results allow for proposing an update of the SEE qualification of the CMOS technology used in the ROICs developed by Sofradir for their infrared image sensors. This update of radiation hardness assurance is confirmed by the SEE prediction tool MUSCA SEP3

Ref 2.6 : Recent advances in compact ("SPICE") modeling of integrated semiconductor devices at cryogenic temperatures for defense and space applications: a review of requirements for accurately simulating and predicting electrical characteristics of ASICs in terms of noise, statistical variations and reliability

Bertrand ARDOUIN (a), Oskar Holstensson (a)
a XMOD Technologies, 74 rue G. Bonnac, 33000 Bordeaux, France

XMOD is an SME specialized in characterization and modeling of integrated semiconductor devices with 15 years of experience in improving circuit simulation accuracy for cryogenic temperatures. EDA and simulation tools play a major role in the development of integrated circuits and ASICs in the semiconductor industry, as a link between circuit designers and semiconductor foundries. The predictive capability of such tools ultimately rely on the accuracy of compact (electrical) device models (so called "SPICE" models), which are provided by semiconductor manufacturers for standard temperature ranges (typically -40°C to 125°C). Nevertheless, for cryogenic operation, which is of utmost importance for defense and space products, the accuracy of such standard models is strongly degraded. The specific requirements to adapt these models for cryogenic operation, and therefore to allow the development of circuits operated at cryogenic temperatures, are reviewed in this paper. Various aspects are covered, from basic electrical characteristics, electrical noise, statistical variations and device mismatch. Moreover, a recent concept consisting in the introduction of dynamic reliability simulation in compact models is also detailed (such as hot carrier degradation / life time prediction), and its fundamental advantages in terms risk mitigation and development time reduction are discussed.

Ref 2.7 : Real-time Ultra-High Dynamic Range InfraRed Imaging

David Darson1, Julien Dubois2
1 Laboratoire Pierre Aigrain, Département de physique de l’ENS, École normale supérieure, PSL Research University, Université Paris Diderot, Sorbonne Paris Cité, Sorbonne Universités, UPMC Univ. Paris 06, CNRS,2 Laboratoire Electronique, Informatique et Image (le2i), Université de Bourgogne Franche Comté (UBFC), 21000, Dijon

Nowadays, in visible domain, the High Dynamic Range imaging is available in most cameras and these methods can even be used for real-time video generation [1]. Nevertheless in Infrared domain, no implementation has been proposed to capture on a single image very low signals as well as the high signals.

The HDR Infrared imager can be based on the solutions available in visible domain. Two main strategies exist to generate the HDR images: using an intrinsic sensor [2] or multi-exposure images stack [3]. The first class of solutions can only propose limited dynamic (<140 dB) compared to the second class. Indeed, the number of images can be fixed (and increased) according to the scene's dynamic. However, these approaches request longer acquisition time. A recent research [4] proposes an expensive multi-sensor solution as an alternative. In this paper, we propose two main contributions: a novel approach based on Multiple Non Destructive ReadOut during a Single Exposure and a real-time implantation of this method for InfraRed imaging. The proposed method enables the acquisition time to be significantly reduced meanwhile still reaching Ultra-High Dynamic Range. A specific algorithm has been designed to generate the HDR image on the fly using the captured exposures. The image dynamic is then gradually improved and the acquisition trigged to stop at any time according the application's constraints. For this process, a single memory bank is then required contrary to any state-of-art. Based on this concept, an IR camera has been designed [5]. The electronic controls have been developed to minimize noise and the different cooling systems have been experimented. The resulting IR camera enables Ultra-High Dynamic be reached (>180 dB) during a signal exposure.

Bibliography:

[1] Mustapha Bouderbane, Dominique Ginhac, Julien Dubois, Barthélémy Heyrman, Pierre-Jean Lapray, "Real-time ghost free HDR video stream generation using weight adaptation based method", ACM 10th International Conference on Distributed Smart Cameras (ICDSC), Paris (France), Sept. 2016

[2] Shunichi Sukegawa, Taku Umebayashi, Tsutomu Nakajima, Hiroshi Kawanobe, Ken Koseki, Isao Hirota, Tsutomu Haruta, Masanori Kasai, Koji Fukumoto, Toshifumi Wakano, et al. "A 1/4-inch 8mpixel back-illuminated stacked cmos image sensor". In 2013 IEEE International Solid-State Circuits Conference Digest of Technical Papers, pages 484–485. IEEE, 2013.

[3] Paul E Debevec and Jitendra Malik. "Recovering high dynamic range radiance maps from photographs. In ACM SIGGRAPH 2008 classes, page 31. ACM, 2008.

[4] D.J. Griffiths and A. Wicks, "High Speed Dynamic Range Video", IEEE Sensors Journal, Vol.17, Issue 8, pages 2472-2480, April 2017.

[5] David Darson, Julien Dubois, Mustapha Boudernane, Barthelemy Heyrman, Pascal Morfin, Abdelali Douiyek, Dominique Ginhac, "Real-time High Dynamic Range based on Multiple ReadOut during a single exposure: application to IR imaging", ACM 11th International Conference on Distributed Smart Cameras (ICDSC), Stanford (USA), September 2017.

Ref 2.8 : A VGA 18 bit digital output CMOS ROIC for shutterless uncooled LWIR 17µm VOx microbolometer FPAs

M. Ruiter, S. Gierkink, A. Smeenge, M. de Ruiter
Teledyne Dalsa, Enschede, The Netherlands

A VGA resolution CMOS Read Out IC (ROIC) with wide dynamic range 18 bit digital output is presented for uncooled LWIR imaging using 17µm VOx microbolometer pixels, enabling shutterless operation across -40°C to 85°C die temperature range without using any ROIC calibration. Power consumption is 220 mW in high-sensitivity mode and 90 mW in low power mode. Maximum frame rate is 120 fps. Die size is 212mm².

Session 3 : MWIR-LWIR detectors

Ref 3.1 : Improved Low Dark Current MWIR/LWIR MCT Detectors: first results of ROIC and MCT tests

Holger Höhnemann1), Stefan Hanna1), Ajit Kumar Kalgi2), Dirk van Aken2), Rashme Sudiwala3), Peter Hargrave3)
1)AIM Infrarot-Module GmbH, Theresienstraße 2, 74072 Heilbronn, Germany
2)Caeleste CVBA, Hendrick Consciencestraat 1b, B2800 Mechelen
3)Cardiff University, School of Physics & Astronomy, 5 The Parade, Cardiff CF24 3AA

Within the ESA TRP program „Development of Low Dark Current MWIR/LWIR Detectors" new MCT material was tested with reduced dark current for low photon flux applications. A specific ROIC design was set up within this program to allow a proper characterisation of the material and act as a demonstrator for further ROIC derivates. Demonstrator assemblies were prepared and tested.
Within this presentation the design of the ROIC and the MCT will be presented. The test setup will be highlighted.
The detector assemblies and the test site have been ramped up successfully. The available test results and characterisations of the ROIC and the MCT will be presented within this talk.

Ref 3.2 : HgCdTe p-on-n technology for space applications

N. Péré-Laperne*,1, N. Baier2, C. Cervera2, J.L. Santailler2, C. Lobre2, C. Cassillo1, E. Carrère1, J. Berthoz1, R. Taalat1, V. Destefanis, D. Sam Giao1, S. Rigal1, A. Lamoure1
1SOFRADIR, avenue de Vauve - CS20018, 91127 Palaiseau, France
2 Univ. Grenoble Alpes, CEA-LETI, MINATEC Campus, 38054 Grenoble, France

Space applications are requiring low dark current in the long wave infrared for low flux missions. The applications envisioned with this type of specification are namely scientific and planetary missions. Within the framework of the joint laboratory between Sofradir and the CEA-LETI, i.e. DEFIR, specific developments of a TV format focal plane array with both a cut-off wavelength of 9.4µm at 80K and 12.5µm at 40K have been carried out.

For these applications, the p on n technology has been used. It is based on an In doped HgCdTe absorbing material grown by Liquid Phase Epitaxy (LPE) and an As implanted junction area. This architecture allows decreasing both dark current and series resistance compared to the legacy n on p technology based on Hg vacancies.

In this paper, the technological improvements are briefly described. These technological tunings led to a 40% decrease of dark current in the diffusion regime. CEA-LETI and Sofradir demonstrated the ability to use the p on n technology with a long cutoff wavelength in the infrared range.

Ref 3.3 : MW and LW infrared detectors based on III-V semiconductors for space applications

L. Langof, O. Cohen, P. Klipstein, and I. Shtrichman
SemiConductor Devices (SCD), P.O. Box 2250, Haifa 31021, Israel

SCD has been developing and manufacturing infrared detectors of various technologies for over 40 years. For many years, the leading sensing technology for 2D mid-wave infrared (MWIR) array detectors has been InSb p/n photo-diodes. This technology has a 5.4 µm cut-off wavelength, 80% quantum efficiency, and is

operated at 77 K to reduce the generation-recombination limited dark current to a level well below the photo-current.

Barrier photo-detector, based on III-V semiconductor materials, is a relatively new type of detector device, which exhibits diffusion limited dark current and high quantum efficiency. SCD first developed, and then for several years has been manufacturing, InAsSb/AlAsSb XBn MWIR focal plane array (FPA) barrier detectors with a 640×512 (VGA) format and a 15 μm pitch. These detectors have a 4.2 μm cut-off wavelength and an operating temperature of 150 K. The detector material is grown by molecular beam epitaxy (MBE) on GaSb substrates. The digital readout integrated circuit (ROIC) is fabricated with a low noise 0.18 μm CMOS process. The integrated Dewar-cooler assembly (IDCA) has small size and weight, low power consumption, and long mean time to failure (MTTF). An additional product based on the same technology has the same pitch and a 1280×1024 (SXGA) format. A series of lab experiments performed on the SXGA ROIC and FPA proved that this detector can withstand a space radiation environment of up to 30 kRad and is latch-up free. New generation XBn FPAs with a 10 μm pitch have also been developed and introduced recently.

For long-wave infrared (LWIR) applications, SCD introduced the XBp type-II superlattice (T2SL) barrier detector with a 640×512 format and a 15 μm pitch. The detector is based on MBE grown InAs/GaSb and InAs/AlSb T2SL layers, which are from the same 6.1 Å lattice-constant material family as used in the MWIR detectors. The cut-off wavelength is designed to be 9.5 μm, the quantum efficiency is 50%, and the pixel operability is 99.5%. This detector is operated at 77 K. The ROIC and IDCA are similar in design and process to those for the MWIR detectors.

Ref 3.4 : METimage infrared detectors development and first results

Sofradir : Laurent VIAL, Jean-Noël MOURNET, Philippe CHORIER, Lilian MARTINEAU, Sauveur TIRANO, Véronique BOURILLON
ADS : Michael SKEGG, Michel BREART de BOISANGER, Anne ROUVIE
DLR : Victor BENITEZ-COSMA

For more than 20 years, SOFRADIR has been involved in many space programs from visible to VLWIR spectral ranges. In the frame of these activities, some of the latest developments of detectors are conducted in the frame of future meteorological applications. As a matter of fact, in the frame of the METimage instrument development conducted by AIRBUS, SOFRADIR has developed two new MCT infrared detectors, one in the SWIR-MWIR domain and the other in the LWIR-VLWIR domain. Many challenges had to be overcome in this program. In particular, a specific pixel architecture had to be implemented in order to fit with the optical design of the instrument, the ROIC as well as the MCT designs had to be optimized with respect to the required electro-optical performances and the aimed operating temperature. Package and electrical interfaces were developed in order to comply to the specified mechanical, thermal and electrical constraints, and reliability has to be compatible with the storage duration and mission profile. In this presentation we show in a first part a summary of the MCT retina and detector package designs of both detectors and then we present the first electro-optical results obtained at IRFPA level.

Ref 3.5 : Issues with Aquarius detector for METIS, the mid-infrared instrument of ELT

S. Mouzali 1, O. Boulade 1, D. Ives 2
1 Commissariat à l'Energie Atomique, Institut de Recherche sur les Lois Fondamentales de l'Univers, Service d'Astrophysique, Orme des Merisiers, 91191 Gif sur Yvette, France ;
2 European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany

METIS is the Mid-infrared ELT Imager and Spectrograph, the third instrument on the Extremely Large Telescope (ELT), and the only one to cover the mid-infrared wavelength range from 3 to 14 µm (goal : 19 µm). The instrument includes two subsystems: an imager (in both the LM band and the N band) and a spectrograph (in the LM band).
The baseline detector for the N band imager is Aquarius, a Si:As Impurity Band Conduction array manufactured by Raytheon Vision Systems and funded by ESO (European Southern Observatory) several years ago.
As previously published, Aquarius detector suffers from an important excess low frequency noise (ELFN) [1,2]. A test campaign led by the METIS team has shown that this excess noise increases with the flux, which is a real issue as very high fluxes are expected in METIS. This campaign has shown that increasing the chopping frequency to decorrelate the noise can be a solution to reduce the noise, but is not sufficient to be photon noise limited. The results will be presented.
Several alternatives are being investigated, including MCT (Mercury Cadmium Telluride) detectors [3]. The latter may be suitable provided that the combination of the detector full well and readout speed can handle the very high fluxes expected in the imaging mode. The most challenging issue is to achieve the very low dark current required in the longslit spectroscopic mode foreseen in METIS. The different alternatives and the choice of the readout circuit will be discussed with the community in order to fulfill the needs of METIS in the N band and more broadly those of the mid-infrared ground based astronomy.

[1] : Ives, D., Finger, G., Jakob, G., Eschbaumer, S., Mehrgan, L., Meyer, M., & Steigmeier, J. (2012, September). AQUARIUS, the next generation mid-IR detector for ground-based astronomy. In High Energy, Optical, and Infrared Detectors for Astronomy V (Vol. 8453, p. 845312). International Society for Optics and Photonics.
[2] : Ives, D., Finger, G., Jakob, G., & Beckmann, U. (2014, July). AQUARIUS: the next generation mid-IR detector for ground-based astronomy, an update. In High Energy, Optical, and Infrared Detectors for Astronomy VI (Vol. 9154, p. 91541J). International Society for Optics and Photonics.
[3] : Baier, N., Cervera, C., Gravrand, O., Mollard, L., Lobre, C., Destefanis, G., Bourgeois, G., Zanatta, J.P., Boulade, O. & Moreau, V. (2015). Latest developments in long-wavelength and very-longwavelength infrared detection with p-on-n HgCdTe. *Journal of Electronic Materials*, *44*(9), 3144-3150

Ref 3.6 : Si:As detector characterisation for JWST MIRI

Dan Dicken
CEA-Saclay

Telescope promises breakthrough science for a vast range of astronomical topics. This capability comes from the giant 6.5m mirror but also relies on the performance of the detector technology at the back end of the instruments. Therefore, over the last 6 years, we have been involved in an extensive test and characterisation campaign for the MIRI instruments Si:As hybrid arrays. The MIRI instrument is the only instrument onboard JWST sampling the wavelength range 5-28 microns, where the other 3 instruments sample the near-infrared range below 5 microns. Therefore, the detector and cooler technology is unique to MIRI and presents a number of challenges above that of the other instruments. I will present the highlights of our detector test campaigns focusing on the characteristics, performance and challenges facing us for the upcoming mission in 2020.

Ref 3.7 : Sun Exposure Damage to a Microbolometer in Low Earth Orbit

Ross M. Henry and Kevin H. Miller
NASA Goddard Space Flight Center, 8800 Greenbelt Road
Greenbelt, MD 20771, USA

In February 2017, the Satellite Servicing Projects Division (SSPD) at NASA's Goddard Space Flight Center (GSFC) began on-orbit operations of their newest technology demonstration experiment on the International Space Station (ISS). Launched on the SpaceX Commercial Resupply Services 10 (CRS-10) mission, the Raven experiment flew as a hosted payload on the Space Test Program's STP-H5 mission. Raven is a real-time autonomous relative navigation system that images visiting vehicles arriving to the ISS. Using multi-wavelength sensors and advanced on-board avionics, Raven measures range, bearing, and six-degree of freedom pose in order to produce an optimal relative state estimate of the observed vehicle. One of Raven's on-board sensors is a long-wave infrared camera which utilizes a Commercial Off-The-Shelf (COTS) Vanadium Oxide (VOx) based uncooled microbolometer. While performing on-orbit operations in July of 2017, Raven's infrared camera directly imaged the full disc of the Sun. In this paper, we will explore the damaging results of that solar exposure on the sensor, efforts to remedy the damage over time, and our root-cause theory on the mechanism of the microbolometer damage. Additionally, we will share our efforts towards mitigation techniques to prevent future solar damage to SSPD's next microbolometer based infrared camera, set to fly to Low Earth Orbit (LEO) in 2021.

Ref 3.8 : Electrical and electro-optical characterizations of LWIR/VLWIR T2SL barrier photon-detector

R. Alchaar1*, J.B. Rodriguez1, R. Rossignol1, L. Höglund2, P. Christol1
1IES, Univ. Montpellier, CNRS, Montpellier, France
2IRnova AB, Electrum 236 - C5, SE-164 40 Kista, Sweden

Infrared (IR) detectors with cutoff wavelength beyond 11µm are useful for space applications. Among the well established IR technologies, InAs/GaSb Type II Superlattice (T2SL) is an alternative and attractive photodetector material for infrared sensor because of the maturity of III-V semiconductor technology associated with large format (up to 5") highly uniform defect free GaSb substrates which are now available [1].

In this communication, we report on electrical and electro-optical characterizations of InAs/GaSb T2SL infrared barrier photodetector in XBp configuration [2], grown by molecular beam epitaxy (MBE) on GaSb substrate, showing cut-off wavelengths at 11.5µm, 14.5µm and 16.5µm at 77K. Experimental measurements on samples were made by photoresponse, by capacitance-voltage (C-V) and dark current-voltage (I-V) characteristics performed on several diode sizes and as a function of temperature. The resulting dark current values are compared to the HgCdTe benchmark, known as rule 07 and are analyzed in term of residual carrier doping of absorbing and barrier layers by performing current simulations.

References :

[1] D. Lubyshev, J. M. Fastenau, M. Kattner, P. Frey, A. W. K. Liu, M. J. Furlong "Large-format Multi-wafer Production of 5" GaSb-based Photodetectors by Molecular Beam Epitaxy", SPIE 10177, 1017718 (2017)

[2] M. Delmas, R. Rossignol, J.B. Rodriguez, P. Christol "Design of InAs/GaSb superlattice infrared barrier detectors", Superlattices and microstructures 104, 402-414 (2017).

This work was partially funded by the French "Investment for the Future" program (EquipEx EXTRA, ANR 11-EQPX-0016) and ESA contract n° 4000116260/16/NL/BJ.

Ref 3.9 : Characteristics of type-II superlattices – a promising material for space applications

V. Daumer, F. Rutz, A. Wörl, J. Niemasz, R. Müller, T. Stadelmann, and R. Rehm
Fraunhofer Institute for Applied Solid State Physics IAF, Tullastr. 72, D-79108 Freiburg, Germany

Similar to HgCdTe, type-II superlattice (T2SL) infrared detectors offer a broad flexibility to tailor the bandgap from mid wavelength infrared (MWIR, 3-5 µm) up to the long (LWIR, 8-12 µm) or even very-long wavelength infrared regime (VLWIR, >12µm) when grown lattice-matched on GaSb substrates. The effective bandgap can be engineered by selecting the appropriate thick-ness for the alternating InAs and GaSb layers during the molecular epitaxial growth process with excellent homogeneity over the whole GaSb substrate, which is already available up to 6 inch in diameter. While T2SL provide quantum efficiency and responsivity comparable to HgCdTe, they excel in operability, stability over time, spatial uniformity, scalability to larger formats, produci-bility and affordability. For example in the frame of the 90M USD funding program VISTA (Vital Infrared Sensor Technology Acceleration) T2SL megapixel arrays for (V)LWIR have been demon-strated with dark currents below the heuristic trend line »Rule ‘07« for HgCdTe detectors, re-cently. At low operating temperatures modern InAs/GaSb T2SL devices exhibit reduced tunnel-ing current contributions to the dark current compared to HgCdTe due to a much larger effec-tive electron mass and the use of heterojunction concepts. In summary, this emerging material system offers comparable performance and benefits from mature III/V process technology. Hence, T2SL technology is a promising candidate for future space applications.

Fraunhofer IAF played a vital role in the development of III-As/Sb T2SLs right from the start. We have demonstrated mono- and bi-spectral focal plane arrays up to 640×512 pixels for the MWIR and LWIR, respectively. We have characterized our T2SL detectors down to low temperatures (below 40K) with promising trends regarding the dark current. For MWIR and LWIR detectors the resolution limit of the measurement setup with a dark current density of 2×10-10A/cm² has been reached at 77 K and 36 K, respectively. This paper will report on these measurements, compare them with published HgCdTe data and discuss possibilities for future improvements.

To make the T2SL technology available for European space applications, Fraunhofer IAF offers a broad spectrum of expertise. We have established validated band structure modelling for the design of high-performance heterojunction devices. With our MBE growth facilities and pro-cessing technology we have set up a pilot production line, which amongst other projects pro-vides TRL8 T2SL-FPAs to a commercial missile warner program for an airborne military platform. A wide range of characterization techniques allows for deeper understanding of material prop-erties and the discrimination of failure modes due to material or processing issues. In short, Fraunhofer IAF is the leading institution for T2SL research and development in Europe.

Ref 3.10 : High Reliability Packages for Thermal Imaging in Space

G.Chrétien, F.Dispérati, P.Maeder, M.Will,
EGIDE SA.

EGIDE is a group specialized in the manufacture of hermetic packages for sensitive electronic components, high demanding applications and harsh environments.
Our technical solutions perfectly meet the requirements of our customers in the Military, Space, Telecommunication and industrial uses.
They also bring and answer to the needs of many applications such as Thermal Imaging, Optoelectronic, Power Packages, Microwave/RF.
In this presentation we will focus on the technical solutions implemented for Thermal Imaging applications in space use.
We will be presenting our Ceramic-To-Metal-Seal (CTMS) solutions, our Glass-To-Metal-Seal (GTMS)

solutions to meet the needs of cryogenically cooled detectors or sophisticated "uncooled" detectors.
Our packages are tested for hermeticity up to 10-10 cm3/s atm and the high temperature processes reduce critical pumping time.
EGIDE can offer more than just the basic package by adding Connectors, Thermoelectric Coolers, Getters as required, allowing for the final customer to focus on its core business.
EGIDE is a European leader which manufactures its own ceramics and conductor inks and has the capability to manufacture its own glass beads/preforms.

Session 4 : Detector Characterization

Ref 4.1 : Operating Life Tests at cryogenic temperature: Tools, Methodology and Results

Franck Perrier ; Raphael Buiron
SOFRADIR, France

Infrared detectors are operating between 50K and 250K. Read Out Integrated Circuit for IR applications are designed in CMOS technology. CMOS circuits are sensitive to Hot Carrier Injection (HCI) and HCI is one of the major reliability concerns when CMOS devices are operating at low temperature. In order to address ROIC reliability in representative conditions specific test tools were developed (dewar, electronic and test bench). It was then possible to perform Life test at cryogenic temperature in dynamic mode (biased and clocked). The paper will present Tools, Life Test method and results obtained on Sofradir ROIC.

Ref 4.2 :Comparison between Dark Current Random Telegraph Signal Characteristics in Several Technologies of Solid State Image Sensors

Clémentine Durnez [1], Vincent Goiffon[1], Pierre Magnan[1], Cédric Virmontois[2], Laurent Rubaldo[3], Alexandre Brunner[3], Pierre Guinedor[3]
[1]ISAE-SUPAERO, [2]CNES, [3]SOFRADIR

Imagers based on semiconductors are able to detect photons. However, the semiconductor chosen for a given application can only detect photons which are within a given range of energy. For example, Silicon is used to absorb photon in the visible range. In order to detect photon within the infrared range other materials are used, such as HgCdTe (also called MCT), InGaAs, or InSb [1]. Even if the functioning and measurement conditions are different for each material, they can all exhibit a same parasitic called Dark Current Random Telegraph Signal (DC-RTS). It corresponds to a signal that temporally switches randomly between discrete levels as shown in Fig.1. In the literature, it has been widely studied in silicon |2][3], but far less explored in HgCdTe [4], and sparsely explored in InGaAs or InSb [5].

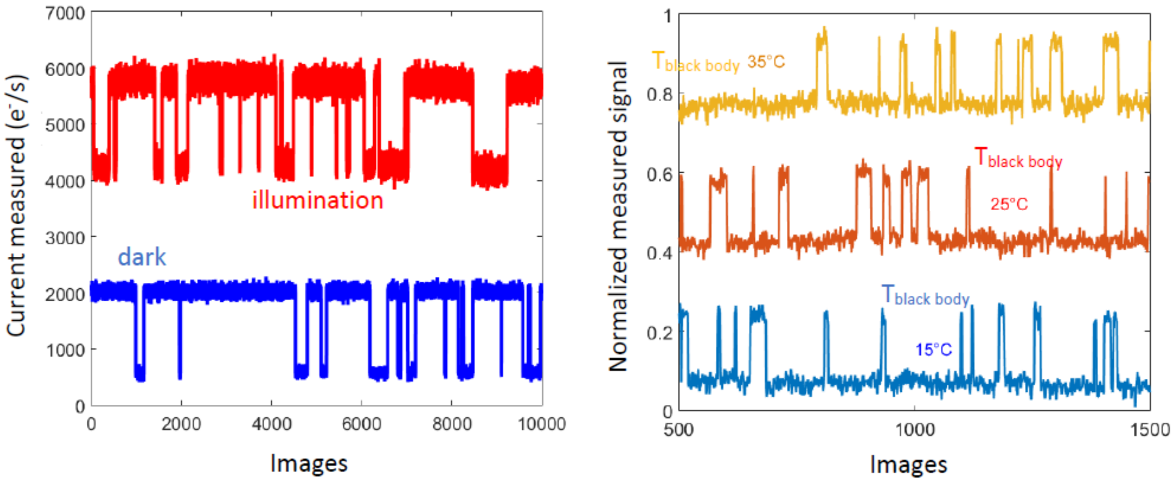

Figure 1 : Example of DC-RTS signals in Silicon (left) and InSb (right)

The aim of this work is to compare the signals observed in several imagers based of these materials: Silicon, InSb, InGaAs or MCT. First of all, it will be shown that DC-RTS signals come from the same origin. hen, a further analysis will show that their main characteristics (number of levels, amplitudes, time constants) are qualitatively similar and DC-RTS statistically exhibit the same trends. Finally, a temperature measurement will permit to extract a key parameter for each material and reinforce the hypothesis of a phenomenon which is intrinsic to semiconductors.

To begin with, in Fig.1, several signals are shown. On the left, the signal of a same pixel from a Silicon based image sensor is given in dark condition and under illumination. On the right, the signal of single pixel from an InSb imager is shown under three different black body temperatures. It is observed that the main characteristics (number of levels, amplitudes, time constants) seem to be similar. Consequently, incident photons have no influence on DC-RTS, this comes from inside the imager. In the final presentation, an analysis on exposure time will be shown.

Moreover, a statistical analysis of the main characteristics is conducted. As imagers contain thousands of pixels, RTS ones are detected automatically by a software developed at ISAE-SUPAERO. The number of pixels, amplitudes and time constants are then extracted. For example, the Fig.2 shows the number of RTS pixels which have a given amplitude for a Silicon imager on the left and an InSb based imager on the right. The trends are similar for both detectors. Some results on other parameters as well as on InGaAs detector will be presented in the final presentation.

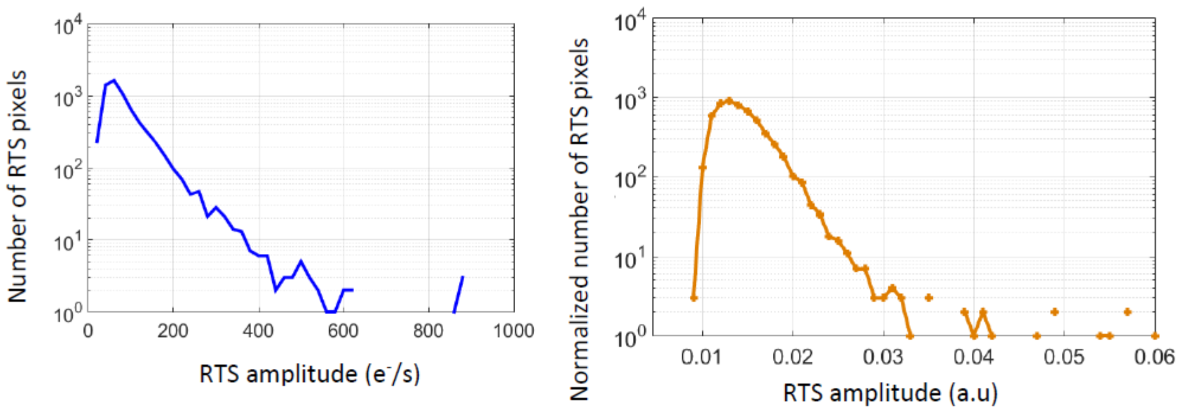

Figure 2 : Distribution of amplitudes for a silicon based imager (left) and an InSb imager(right)

Finally, it has been shown in the literature [1] that amplitudes and time constants depend on temperature. Amplitudes decrease and time constants increase when the temperature decreases. This influence permits to obtain the activation energy of these main parameters. It is observed that the mean values obtained for amplitude activation energies are generally around 0.6 eV for Silicon based image sensors. In HgCdTe, this value is about 0.1 eV for red MWIR technology, and 0.11eV for InSb. The absolute value is different for each material, but if they are compared to the band gap (1.12 for Silicon, 0.2 for HgCdTe red MWIR, 0.23

eV for InSb) the ratio is about 0.5. This shows that the activation energy seems to be half bandgap whatever the semiconductor used.

In conclusion, this work draws the comparison of DC-RTS observed in several technologies of imagers. It demonstrates that DC-RTS characteristics are similar whatever the semiconductor used: they come from a dark current phenomenon, they have the same statistical trends, and their behavior with temperature seems to be common with a half bandgap signature for amplitude activation energy. These results will permit to better understand the phenomenon and thus improve the performances of detectors based on semiconductors.

[1] Rogalski, Antoni. "Infrared detectors: an overview." Infrared Physics & Technology 43.3-5 (2002): 187-210.
[2] Hopkins, I. H., and G. R. Hopkinson. "Random telegraph signals from proton-irradiated CCDs." IEEE transactions on nuclear science 40.6 (1993): 1567-1574.
[3] Goiffon, Vincent, et al. "Multi level RTS in proton irradiated CMOS image sensors manufactured in deep submicron technology." Radiation and Its Effects on Components and Systems (RADECS), 2008 European Conference on. IEEE, 2008.
[4] Brunner, Alexandre, et al. "Improvement of RTS noise in HgCdTe MWIR detectors." Journal of electronic materials 43.8 (2014): 3060-3064.
[5] Pogany, D., et al. "Study of RTS noise and excess currents in lattice-mismatched InP/InGaAs/InP photodetector arrays." Solid-state electronics 38.1 (1995): 37-49.

Ref 4.3 : A linear treatment for 2D MTF and pixel spatial response recovery from sparse measurement

Edouard Huard, Julien Jaeck, Sophie Derelle and Jérôme Primot
ONERA, Palaiseau, France

A challenging point in the prediction of the image quality of infrared imaging systems is the evaluation of the detector modulation transfer function (MTF). In this talk, we present a linear method to get a 2D continuous MTF from sparse spectral data. The sparse data comes from the projection on the Focal Plane Array of a high resolved periodic image with predictable spectral content produced by a Continuously Self-Imaging grating (CSIG). The data is then treated to return the 2D continuous MTF with the hypothesis that all the pixels have an identical spatial response. Concerning metrological aspects, the linearity of the treatment is a key point to estimate directly the error bars of the resulting detector MTF (cf. Figure 1 (a)). The test bench will be presented along with measurement tests on a 25 µm pitch InGaAs detector. The treatment relies on the hypothesis that cross-talk effects are limited to the first neighbors of the pixel, but no strong a priori is needed on the pixel response shape. Therefore the method enables a 2D restitution of a complex pixel shape, such as it is the case for the InGaAs pixel presented in Figure 1 (b), which has a specific “shamrock” shape.

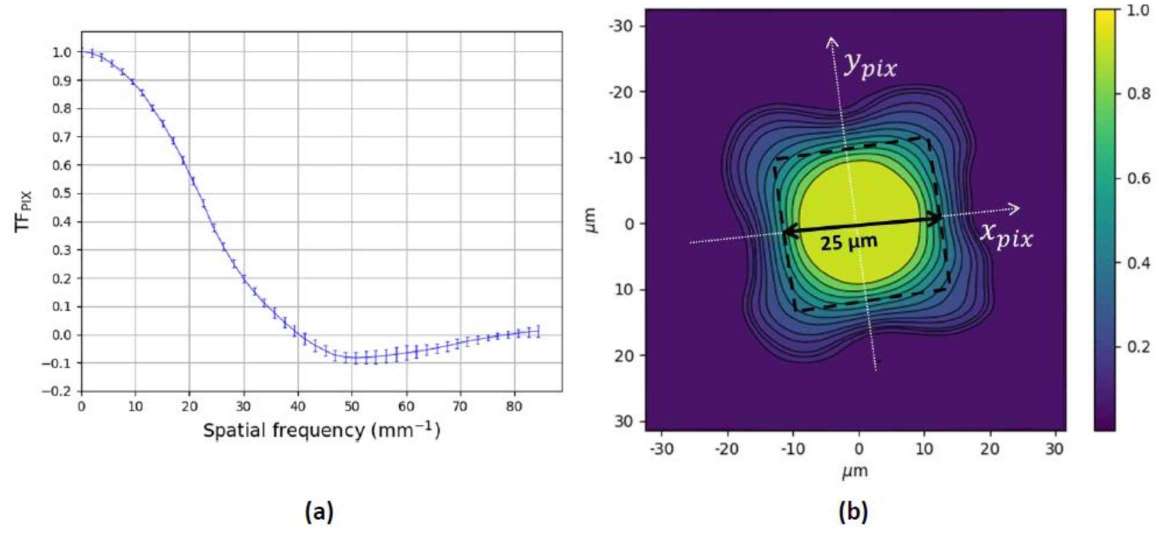

Figure 1. Transfer Function (a) and pixel shape (b) restitution of a 25 µm InGaAs pixel

[1] E. Huard, S. Derelle, J. Jaeck, J. Nghiem, R. Haïdar, and J. Primot, "Multi-frame linear regressive filter for the measurement of infrared pixel spatial response and MTF from sparse data," Opt. Express 26, 5200-5211 (2018)

[2] F. de la Barrière, G. Druart, N. Guérineau, S. Rommeluière, L. Mugnier, O. Gravand, N. Baier, N. Lhermet, G. Destefanis and S. Derelle,"Modulation Transfer Function Measurement of Infrared Focal-Plane Arrays with Small Fill Factors", Journal of Electronic Material, 41(10), 2730-2737 (2012).

Ref 4.4 : Crosscorrelating effects in the Sofradir Neptune and AIM EnMAP ROICs

A. Neuzner, S. Baur, H. Ceeh, M. Hering, C. Neumann, B. Sang
OHB System AG, Wessling, Germany

In the context of the German hyperspectral earth-observation mission EnMAP and a dedicated ESA contract, we tested the AIM EnMAP and the Sofradir Neptune ROICs for spatial crosscorrelating effects. In both cases we observed effects that result in shifts of non-illuminated regions caused by illumination in spatially disjoint regions. Depending on the particular application scenario and corresponding performance requirements, these effects can have significant impacts onto radiometric accuracy budgets. During flat-field and temporally constant illumination, the majority of these effects are easily overseen. During mission operation, constant flat-field illumination is an exception – spatially and temporally structured illumination is the typical illumination scenario under which radiometric accuracy requirements have to be met.
Effects of this type have a high relevance for current and upcoming earth observation missions like the ESA Copernicus Expansion Elements.

Ref 4.5 : Low flux NGP characterisation for MICROCARB application

A. Ledot1, G. Chevallier2, L. Tauziède1, H. Geoffray1, A. Bardoux1
1CNES, 2Intitek for Industry,

For the purpose of CO_2 sounding application Microcarb, CNES conducted performance characterization of infrared HgCdTe detector NGP from SOFRADIR in low flux conditions. Indeed, Microcarb instrument concept is based on echelle grating (dispersive element) which spreads light according to wavelength. This means that few photons come to the detector. NGP input stage uses Capacitive Trans Impedance Amplifier (CTIA) which linearity at low level is not known. The campaign focused on linearity level, shape and repeatability. CNES low flux facility was used.

Session 5 : SWIR detection

Ref 5.1 : e-APD and InGaAs fast low noise infrared camera systems at First Light Imaging

Philippe Feautrier a,b , Jean-Luc Gach a,c
a First Light Imaging, b Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France ;
c Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille

We will present First Light Imaging's CRED-ONE 320x256 e-APD SWIR camera capable of capturing up to 3500 full frames per second with a subelectron (routinely <0.4 e-) total noise. This breakthrough has been made possible thanks to the use of an electron initiated avalanche photodiode HgCdTe infrared focal plane array fabricated by Leonardo and named Saphira which is a real disruptive technology in imagery. In the visible spectrum, electron-multiplying charge-coupled devices (EMCCDs) improved imaging technique (especially in the life sciences). And yet, no significant breakthroughs have been made in infrared imagery since the hybridization of III-V or II-VI semiconductors with low bandgap on complementary metal-oxide semiconductor (CMOS) read-out integrated circuits (ROICs). CRED-ONE is the first e-APD camera, bringing a similar advance in the infrared spectrum as EMCCDs did in the visible. We will show the performances of this camera, its main features and compare them to other high performance cameras like EMCCDs in the visible and more classical cameras in the infrared. We will also present C-RED2 640x512 InGaAs camera inherited from C-RED ONE with 400 FPS at 22 electron readout noise and even the unprecedented <10 electron RON at 25 FPS. C-RED2 is based on the Snake InGaAs IR detector from Sofradir. The upgrade of this camera to 600 FPS frame rate will be also shown.

Ref 5.2 : A 400 KHz line rate 2048-pixel Stitched SWIR linear array

Patrick Merkena,b, Rosa Maria Vinellaa, Kristof Woutersa, Vincent Vervennea, Danny De Gasparia
aXenics nv, Ambachtenlaan 44, 3001, Leuven, Belgium;
bRoyal Military Academy, Avenue de la Renaissancelaan, 30, 1000, Brussels, Belgium

Xenics developed a family of stitched 12.5 µm pitch SWIR line-arrays achieving line rates up to 400 KHz, based on a modular ROIC design with modules of 512 pixels, stitched during fabrication into 512, 1024 and 2048 pixel arrays, enabling longer arrays to run at a high line rate irrespective of the array length. The front-end circuit is based on a CTIA ensuring stable detector bias, good linearity and signal integrity, input auto-zero allowing low detector bias, and CDS reducing noise and offsets. Five gain modes have been implemented with input referred noise of 35erms in the highest gain mode.

Ref 5.3 : Radiation Damage Factor of InGaAs photodiodes

C. Inguimbert1, T. Nuns1, K. Lemiere1, J.Barbero2, J. Moreno2, S. Ducret3, A. Nedelcu31ONERA-DESP, 2 avenue E. Belin, 31055 Toulouse, France2ATN : ALTER technology, T. Edison, 4, Cartuja, 41092 Seville, Spain

The work presented here has been performed under EDA (European Defense Agency) funding (ROVER project). This study addresses the radiation induced degradation of photodiodes operating in the infrared domain. The correlation with Non Ionizing Energy loss (NIEL) is shown. A set of different In GaAs photodiodes coming from different manufacturers has been irradiated with electrons from 0.5 MeV up to 20 MeV, with protons of 60 MeV, 100 MeV and 170 MeV and with an atmospheric-like neutrons spectrum. Depending on the type of incident particles and energy, the deposited damage dose goes from ~5 10+06 MeV/g up to 5 10+09 MeV/g. The dark current damage factor has been extracted from measurements made at different fluence levels. The dark current has been measured a short time after irradiation and several weeks later to analyse the annealing processes. The damage factor measured after ~one month has been scaled according to the Non Ionizing Energy Loss (NIEL). The reliability of the NIEL scaling law is discussed for InGaAs material.

Ref 5.4 : HgCdTe APDs for time resolved space applications

Johan Rothman, Gilles Lasfargues, Lydie Mathieu, Jean-Alain Nicolas, Jerôme le Perchec, Julie Abergel, Sylvain Gout, Leo Bonnefond, Philippe Ballet, Jean-Louis Santailler
CEA/LETI Minatec Campus

HgCdTe APDs have opened a new horizon in photon starved applications due to their exceptional performance in terms of high linear gain, low excess noise and high quantum efficiency. Both focal plane arrays (FPAs) and large array single element using HgCdTe APDs have been developed at CEA/Leti and Sofradir and high performance devices are at present available to detect without deterioration the spatial and/or temporal information in photon fluxes with a low number of photon in each spatio-temporal bin. The enhancement in performance that can be achieved with HgCdTe has subsequently been demonstrated in a wide scope of applications such as astronomical observations, active imaging, deep space telecommunications, atmospheric LIDAR and mid-IR (MIR) time resolved photoluminescence measurements. Most of these applications can be used in space borne platforms.
In the present communication we will focus on our ongoing development and tests of detectors for applications that only require the temporal information and can be addressed with only a few APDs, such as LIDAR and free-space optical. Lidar detectors are currently developed for atmospheric LIDAR measurements within the scope of R&T CNES projects and a H2020 project termed HOLDON. The aim of these projects is to optimize the HgCdTe APD detector characteristics to responds to the specific challenges imposed by atmospheric lidar measurements in terms of dynamic range, response time, temporal lag and background noise. Free space optical communication for deep space missions is addressed within a development funded by ESA. The objective of this development is to dispose of a 4 quadrant detector with single photon sensitivity and a bandwidth of 300 MHz on each detector. In parallel, we are working on the optimization of the response time of the APDs in order to reach bandwidth in excess of 10 GHz and to be able to address high data rate applications in space closer to earth.

Ref 5.5 : Time-of-flight Calibration of an MCT-APD sensor for a Flash imaging LiDAR system

Authors: Victor Emanuel Saraiva Parahyba, Eric de Borniol, Regis Perrier, Yoanna-Reine Nowicki-Bringuier, CEA LETI

Jocelyn Chanussot, Gipsa-Lab / Universite Grenoble Alpes

A 3D camera is a device that enables the perception of depth in images. It has been described as a key component for future space missions involving automatic Guidance, Navigation and Control (GNC) of spacecraft. However, up to now, systems possibilities were limited, because of the non-availability of adequate detectors: due to the low number of available pixels, most existing cameras are based on scanning mechanisms, which introduces reliability issues and limits the frame rate and in consequence the operability in fest motions conditions.
Flash Imaging LiDARs (Light Detection and Ranging) are active systems that resolves depth in a scene by time-of-flight measurements and are being seen as a competitive technological alternative that presents great advantages in the space scenario. This project is a partnership between ESA and CEA-LETI aiming the design of a LiDAR system based on a custom MCT-APD FPA detector developed by CEA-LETI and the formulation of a set of imaging processing algorithms. The target is to demonstrate the potential of such detector technology and to evaluate the performances of the full system chain in the frame of the targeted application.
A first step to improve the overall quality of the measurements is the calibration of the camera. There is a vast literature and well-stablished techniques concerning intensity calibration (2D information). However, for time-of-flight (3D information) the subject remains open to improvement and dependent upon the specific characteristics of the detector. This presentation demonstrates a proposed calibration scheme for CEA-LETI's LiDAR and presents the first enhanced results. In the future, a validation campaign on a real terrain, at ESA's campsite, will be performed to demonstrate the system in a close-to-real configuration.

Ref 5.6 : VIS/SWIR IR detectors for space applications at AIM: models and qualification status.

H. Höhnemann , S. Hanna, Alexander Sieck, M. Benecke, J. Wendler, A. Weber, D. Hübner, H. Figgemeier, R. Breiter, W. Gross
AIM Infrarot-Module GmbH, Theresienstraße 2, 74072 Heilbronn, Germany

AIM has developed SWIR modules including FPAs based on liquid phase epitaxy (LPE) grown MCT usable in a wide range of hyperspectral imaging applications. Silicon read-out integrated circuits (ROIC) provide various integration and readout modes including specific functions for spectral imaging applications.
An important advantage of MCT based detectors is the tunable band gap. The spectral sensitivity of MCT detectors can be engineered to cover the extended SWIR spectral region up to 2.5µm without compromising in performance.
AIM developed the technology to extend the spectral sensitivity of its SWIR modules also into the visible range (VIS). This has been successfully demonstrated for 384x288 and 1024x256 FPAs with 24µm pitch, having a spectral sensitivity from 0.4µm to 2.5µm. Several modules have been assembled and tested up to now.
The performance characteristics and latest qualification results for long time stability on 1024x256 FPAs will be presented within this talk.

Ref 5.7 : New IR-detector for anthropogenic gas detection and hyperspectral applications

J. Kamann, D. Eich, S. Hanna, K. Hofmann, H. Figgemeier, W. Gross
AIM Infrarot-Module GmbH, Theresienstraße 2, 74072 Heilbronn, Germany

Monitoring of anthropogenic gases from space requires radiometrically stable, large detector arrays in order to ensure the reliable detection of small atmospheric gas concentration differences with superior spatial and spectral resolution. The anthropogenic gas detector (AGD) is AIM's latest state-of-the art development dedicated to climate gas monitoring. It is designed for an excellent spectrometric stability by implementing a Capacitive Transimpedance Amplifier (CTIA) and Correlated Double Sampling (CDS) for each of the 1024x1280 pixels. In order to accommodate a 20 µm pixel pitch for an outstanding radiometric performance in this array format, the stitching of the read-out circuit (ROIC) die was necessary.

The photoactive Mercury Cadmium Telluride (MCT) layer is grown by liquid phase epitaxy (LPE) on Cadmium Telluride substrates and is designed and processed for a minimized thermal dark current. AIM's mid- and long wavelength infrared higher operating temperature technology (HOT) for low dark currents was transferred to the short wavelength infrared (SWIR) spectral region and applied for the AGD. Further reduction in dark current will be achieved by reducing the cut-off wavelengths from typically 2.5 µm to 2.25 µm at detector operating temperature. Numerical estimates predict dark currents less than 30 pA/cm2.

Another benefit is the intrinsic stability of the cut-off wavelength, as the composition of MCT results in hardly any variation of cut-off with detector temperature. The ROIC can be operated in Integrate While Read (IWR) and Integrate Then Read (ITR) mode, non-destructive read-out is possible. Numerical simulations predict linearity errors of less than 0.5% over a signal range of 5%-95% charge handling capacity. The integration capacitance offers two gain stages of 4 ke- and 1.2 Me-. Read-out Noise will benefit from analog or digital CDS and is expected to be below 100 e- in high gain mode.

The ROIC is designed radiation tolerant by implementation of a triple modular redundancy for the gain memory cells. A self-scrubbing circuitry detects single bit flips and refreshes the gain memory cell with the correct value. Further, reliable communication between ROIC and video electronics via serial peripheral interface (SPI) is secured by cyclic redundancy checks. Radiation testing in full operation is planned and will be conducted (p+, total ionizing dose) in the second half of 2018.

The AIM AGD sensor represents the next generation state-of-the-art hyperspectral SWIR imaging detector, and an extension to the VIS-SWIR spectral range is possible.

Ref 5.8 : Monolithic Infrared Image Sensors based on Thin-Film Quantum Dot Photodiodes

E. Georgitzikis1,2, P.E. Malinowski*,1, J. Maes3, Z. Hens3, Paul Heremans 1,2, D. Cheyns1
1imec, Kapeldreef 75, 3001 Leuven, Belgium
2KU Leuven, 3001 Leuven, Belgium
3Universiteit Gent, Gent, Belgium

Current image sensors operating in the short-wavelength infrared (SWIR) range typically use epitaxially grown III-V semiconductors as the photoactive material. To realize a two-dimensional focal plane array, the active layer chip is connected with a CMOS readout chip using solder bump hybridization, imposing a limit on the pixel pitch. One way to realize higher resolution and finer pixel scaling is to use a monolithic approach with the photoactive layer deposited directly on top of the readout chip. This work describes a CMOS-compatible pixel stack based on lead sulfide (PbS) quantum dots with tunable absorption peak and provides a roadmap for the integration of thin-film semiconductors on a CMOS based read-out circuit (ROIC).

Colloidal quantum dots (QDs) are a very interesting material group for the fabrication of infrared imagers due to their unique opto-electronic properties. Quantum confinement allows the tuning of the nanocrystal bandgap according to their size, enabling detection at different wavelengths of the infrared spectrum, while their electrical properties depend on the proper selection of ligands. Additionally, the fact that they can be dispersed in solution and deposited over a large area makes them great candidates for low cost sensors, since they can be facilely integrated on top of the readout circuit enabling monolithic infrared imagers.

As QD active layers for infrared detection are not widely explored, we select and optimize photodiodes using PbS QDs with diameter size of 3.3 nm and 5.4 nm for IR detection at 940 nm and 1450 nm respectively. We start by optimizing the QD film and developing the multilayer pixel stack. Electron and hole transport layers are selected to improve the photodiode performance while top and bottom contacts are optimized to allow top illumination. Optical interference simulations are used for calculating the optimal thicknesses of all layers (to enhance the cavity effect) and for improving the light in-coupling through a semi-transparent top contact supporting top illumination. Devices are realized on Si substrate using passive pixels of different sizes, down to 40x40 µm2, demonstrating dark current density of 10-3 mA/cm2 for the smaller bandgap QDs (peak at 1450 nm) and 10-5 mA/cm2 for the larger bandgap ones (peak at 940 nm) at -1V reverse bias corresponding to quantum efficiencies above 10% and 20% respectively, even though the active layer thickness is only 100 nm. Furthermore, the transient analysis of the fabricated devices show rise time of 13 µs and fall time of 41 µs, performance which is sufficient for imaging. Finally, cooling of the detector can further improve the current ratio to over 60 dB from 30 dB at room temperature.

Colloidal quantum dots provide a way to realize monolithic infrared imagers in a cost-effective way. Thin-film active layer enables scaling down pixel pitch beyond the limitations of flip-chip hybridization

Ref 5.9 : Safran Reosc coatings on Infrared detectors

E.H. Oubensaid*, B. Portier, M. Oussalah, L. Macé, F. Pradal, H. Leplan
Safran REOSC, avenue de la tour Maury, 91280 Saint-Pierre du Perray, FRANCE

Safran REOSC has acquired a great expertise in the elaboration of thin films for infrared applications. The deposition of complex antireflective coatings directly on the infrared sensors is already mastered. We can quote two spatial projects with Sentinel 5 and Microcarb, on which REOSC realize the AR coating on the IR detectors used in these two programs dedicated to the earth observation.

In addition, Safran REOSC has also launched a new way to realize a bi-spectral mode on IR detectors with a compact design. This can be achieved by structuring the AR coating directly on the detector after deposition at the size of the pixel (cf. fig. 1).

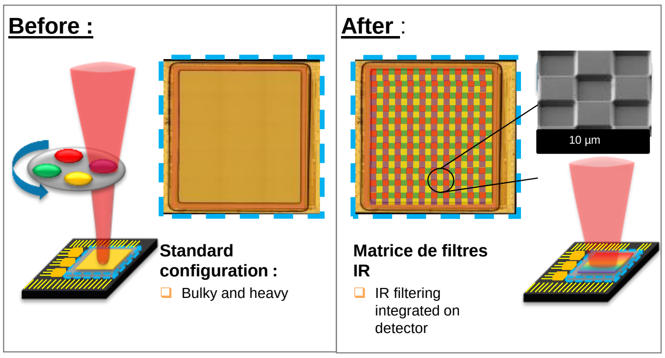

Fig 1: Principle of the structuration of the AR coating

Always to stay on the pixelated filtering, Safran REOSC is also working on the Zero Contrast Gratings (ZCG) in order to realize narrow band filters in the mid-IR range (cf. fig. 2a) [1]. By adjusting the periodicity of the gratings, it is possible to adjust the transmission of the narrow pass filter the mid-IR.

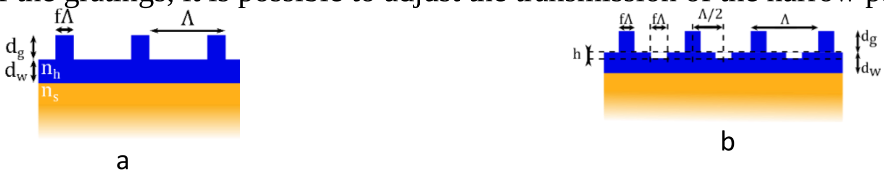

Fig 2: Principle of the Zero Contrast Gratings; a°) 1D structure; b) 1D “bi-atomic” structure

From this base structure, it is possible to enhance the angular tolerance of the filter by adding a corrugation to the main gratings (cf. fig. 2b). By improving the resonance and the angular tolerance, this technology is potentially compatible with a matrix technology with a size of 140 µm by pixel for now.

[1] L. Macé & al, Journal of the Optical Society of America A, Vol. 34 (4), 657, 2017