ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

CNES infrared detector development for space missions: status and roadmap

Hervé Geoffray

L. Tauziede

O. Gravrand

B. Fièque

et al.

icso proceedings

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 1056242 · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296234

CNES INFRARED DETECTOR DEVELOPMENT FOR SPACE MISSIONS: STATUS AND ROADMAP

H. Geoffray[1], L. Tauziède[1], O. Gravrand[2], B. Fièque[3], A. Bardoux[1]
[1] Centre National d'Etudes Spatiales. [2]Commissariat à l'Energie Atomique, [3]Sofradir

I. INTRODUCTION

Growing interest for space missions requiring IR detection is consistent with the constant improvement of IR detectors technologies. Earth observation missions requiring IR imaging capabilities have now reached an excellent level of maturity. IR detectors future developments are more driven by spectroscopic capabilities.

The main detector performance drivers for future Earth Observing missions are: linearity at low flux, low noise, medium to high frequency readout, moderate power consumption,…

CNES (Centre National d'Etudes Spatiales) is continuously pushing the developments to increase the maturity level of the technologies and enhance the key performances in the field of IR detections for space missions.

A. IR detectors main architecture

The **Fig.1** below displays a schematic of the main functions of infrared quantum detector. Classical architecture requires a detection circuit with a suitable semiconductor material for IR detection and a readout circuit, assembled together to form a hybrid detector. The detection circuit provides infrared radiation absorption, charge generation and collection. The most commonly used material to detect infrared wavelength is HgCdTe. The photodiode is the best detector architecture as it can be optimized to provide excellent performance. Typical pixel pitch is 15µm for short and medium IR wavelength (from 0.8 to 5µm) and 30µm for long IR wavelength (to 15µm).The resulting signal is processed by a silicon CMOS readout circuit (or ROIC, Readout Integrated Circuit), whose main function is to perform an integration of the charges, conversion to voltage per pixel and signal multiplexing. A CMOS read out circuit takes benefits from the large library of functions. It also offers a large panel of architectural solutions.

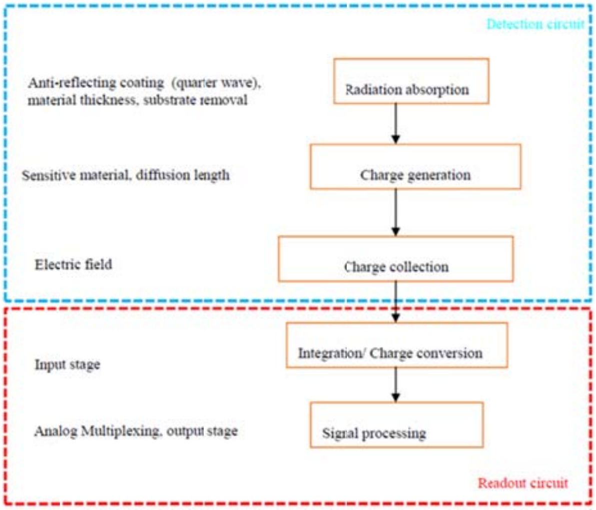

Fig. 1: Functional diagram of infrared quantum detectors.

B. Key technologies

The technologies associated to the detection circuit are of primary importance. The HgCdTe material requires complex but mature processes. This material is grown on a specific substrate (typically CdZnTe to reach the best performance). The tuning of its composition allows a sensitivity of the material from SWIR (Short wave Infrared, or NIR, near Infrared typically 2.5µm), to VLWIR (Very Long Wave infrared) wavelengths, ie 18+µm, by adjusting the cutoff wavelength (i.e. the gap energy, photons whose energy is higher than the gap is detected). Substrate removal allows sensitivity in visible domain also. An antireflective coating is added to enhance absorption efficiency.

CMOS silicon used for the readout circuit must combine good performance and reliability. The important function of the CMOS readout circuit is the input stage, which, combined to the photovoltaic diode drive the input dynamic (and gain), noise, and linearity. Different readout modes are possible, such as integration while read (IWR) or rolling shutter mode. The output stage choice is a compromise between readout frequency, external load, readout noise and power dissipation.

Finally, the assembly of both detection circuit and readout circuit is performed with an indium bump hybridization process: this ensures the thermo-mechanical assembly and the electrical contact between detection circuit and readout circuit.

The main technologies of HgCdTe infrared detectors for demanding space applications are the followings:

- p/n technology: although n/p technology (Hg vacancy doping) offers excellent yield and production capability, p/n technology is necessary to achieve low dark current and thus, allows good signal to noise ratio performance. Compared to n/p technology, the focal plane temperature can be higher from 10 to 20K while keeping the same performance. In some cases, this makes possible the use of passive cooling. Photovoltaic diode performance and definition should also be optimized in order to reduce unexpected parasitic dark signal: heterojunction or graded junction structure are necessary to reach ultimate performance.
- APD (Avalanche Photo-Diode) technology: the HgCdTe n/p photodiode has the advantage to present a low excess noise factor when used in avalanche mode. The avalanche mode allows a signal gain at diode level, which could relax constraints on the readout circuit (the more gain at the entrance stage, the less the noise of the readout circuit in the noise budget). Coupled to more classical readout circuit, it is a potential way to improve performance for readout noise limited applications. This technology, well demonstrated for n/p diode, makes the developments by CEA-LETI and Sofradir in France directly applicable.
- Input stage of readout circuit and associated low flux linearity and noise: the readout circuit has to be optimized to limit readout noise and current leakage. To do so, the most commonly used is the SFD (Source Follower Detector) input stage which has the advantage of offering very low noise and low power consumption. This kind of circuit has intrinsic limitations such as small charge capacitance together with poor linearity, low frequency readout (to achieve low readout without degrading input stage noise) and poor capability to drive large impedance at output stage level. However, as mentioned above, much classical circuits may take advantage of APDs. Those circuits turn SFD drawbacks to advantage ie high frequency readout, large impedance driving capability for the output stage. Another key development for spatial mission is the hardening of the readout circuit in order to reach a level of reliability in accordance with mission needs.
- Large format: detector arrays have to reach at least 1k format. 2k detectors are preferable but need to overcome strong technological limitations such as compatible CMOS foundry, large substrate growth and adequate hybridization technology.

C. Content of the paper

This paper provides a synthesis of the main current developments conducted by CNES and partners in the field of cooled infrared detector for Earth Observation space missions, in order to provide adequate solutions for future space missions. A similar discussion, focused on scientific space missions can be found in [1]. Section II focuses on the driving requirements of future space missions. Section III provides a synthesis on the main issues raised by the requirements. As an example, Section IV gives an overview of current limitation of the existing ROIC based on SFD input stage. Section V and VI are an example of current development on critical technologies (p/n technology and large format arrays). Section VII ends the discussion a brief proposition for future developments.

II. Driving requirements

One of the main requirements driving detector choice is the flux range reaching the detector, which depends on the instrument concept, spectral band and resolution. Indeed, together with the integration time, this requirement gives the amount of charges at pixel level the detector needs to be able to integrate but also the part of dark signal acceptable in order not to be dominated by non-useful signal.

The amount of charges that can be integrated depends on the input capacitance of the detector. Beyond this, flux ranges impact the needs in terms of noises to meet the signal to noise ratio requirement. In particular, readout noise can be the main contributor to the signal to noise ratio when measuring low signal level.

To illustrate, this section focuses on an example: the Microcarb mission [2]. This mission aims at measure vertically integrated carbon dioxide (CO2) concentration from a space observatory in Low Earth Orbit. The CO2 concentration will be retrieved by measurements of the absorption of reflected sunlight by CO2. The payload consists in a passive spectrometer. The observation is in several narrow spectral windows in addition with dispersive optics providing high spectral resolution that results in low signal at pixel level. Mission’s measurement accuracy is driven by the tiny variability in the CO2 column, variations being around +/- 1ppm out of 380ppm. Beyond signal to noise ratio, one of the main issue for this type of instrument is linearity which is considered as a bias that cannot be corrected and impacts the measurement accuracy.

To quantify, the low signal levels of Microcarb mission are in between 1500 and 50 000 electrons/pixel for around 1s integration time. Taking into account a typical flux range of 10 000é/s and an integration time of 1s, to be photon limited, the total noise should be around 100 electrons. Considering a total noise of 120 electrons and allowing equal budget for dark signal noise and readout noise implies 50 electrons per contributor, that is to say, an allocation of 50 electrons for readout noise and 2500 electrons/s for dark signal.

III. Main issues

A. CMOS Readout Circuit

Two types of input stage are mainly used for low flux applications: the SFD and the CTIA (Capacitive Trans Impedance Amplifier), see **Fig. 2**.

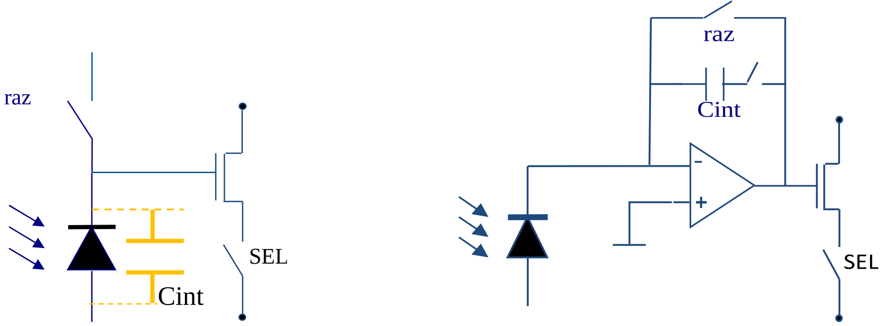

Fig. 2 SFD input circuit: the signal is integrated in the photodiode capacitance. After reset, and during integration, the detection node is isolated (left) and CTIA input circuit: the signal (input current) is integrated on a capacitance adjusted by design (right)

As a first approach, the consequence of the two input stages on the ROIC performance is given in **Table 1**. One can stress the fact that each one of the solution consistently result in a coherent set of performance.

Performance	SFD	CTIA	comments
Noise without CDS(*)	15-20e- rms typ.	30-100 é rms	The noise figure can be lowered with CDS(*) or multiple (and non-destructive) readout. Few e- rms noise can be reached with SFD
Flux range	0.01 e-/s/pixel to $<10^4$ e-/s/pixel	few 10^4e-/s/pixel to few 10^8 e-/s/pixel typ.	See discussion below for CTIA
Charge capacity	$< 10^5$ e- typ.	10^5 e- to 10^6e- typ.	Charge capacity depends on the photodiode wavelength detection range for SFD
Readout frequency	up to 500 kHz	up to 20 MHz	SFD ROIC drive an output capacitance of ~2pF, whereas CTIA ROIC can drive ~100 pF capacitance.
Power dissipation	1 mW typ.	50-150mW	

(*) CDS: correlated double sampling

Table 1

The main intrinsic limitation of the SFD input circuit is the relatively small integration capacity (associated with a large potential offset dispersion). This limits its use for medium input fluxes. The architecture is compatible with the implementation of an output amplifier with a cost on the power dissipation. Some specific study have been performed to assess the limitations of SFD ROIC: a discussion is presented section IV.

The **main limitation of the CTIA** based ROIC is it compatibility with input fluxes in the range few 10^2 to 10^3 e-/s/pixel. It is still an open issue whether a glow (self-parasitic light) from the ROIC itself and/or current leakage effects can affect the performance, either by degrading the noise budget (parasitic flux), or the linearity at very low level (floor/threshold effect,…).

B. APD

In APD (Avalanche Photo-Diode) mode, the photodiode is biased in avalanche mode. In this case, the photo-generated charge, and the thermally generated (the dark signal) charge in the absorbing region of the photodiode are amplified, by the electric filed in the depleted region of the photodiode (note that those charge reach the depleted region by diffusion). The G-R component of the dark signal is partially amplified in the depleted region. The amplification factor is classically noted M. As shown in **Fig.3**, the higher the cutoff wavelength of the HgCdTe material, the higher the gain. A recent solution implemented by Leonardo (UK) is, for a given gap (and hence a given cutoff wavelength) in the absorbing layer, to increase the gap in the amplification region (the depleted region), in order to increase the gain [3].

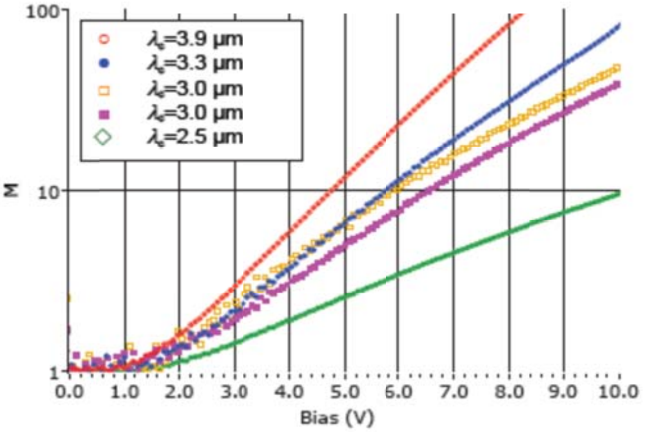

Fig. 3: APD gain (M) as a function of reverse bias of the photodiode, and material cutoff wavelength

The main advantage of the technic is to provide a gain at the first stage of the detection, namely at photodiode level, which has the effects to lower the other noise contributors of the different stages (ROIC noise, electronics noise, etc…), as expressed in electrons.

The main issues are the following:

- Reliability issue: the reliability of the APD needs to be assessed before it can be used for a space application. This includes: APD photodiode stability performance during lifetime (mainly ageing), sensitivity to radiation environment, etc…
- Performance: recent demonstrations of the use of APD and SFD input stage have evidenced performances well adapted to photon counting at high frame (in this case a buffered output is implemented on the ROIC, and a cryogenic amplifier is coupled to the detector). The application for which this solution has been developed is ground based adaptive optics [4]. APD dark signal is a limitation for long integration time for demanding scientific application, as the n/p technology has a lower performance compared to the p/n technology (see *section E* below). The performance of APD and CTIA input is potentially subject to CTIA limitations [4], as identified in *section A.*

C. Detector cosmetics and defects

Cosmetics and defects are mainly due to the detection circuit, and are related to material defects. Other kind of defective pixel is “hard” defects, mainly due to hybridization process. Finally, the ROIC can also contribute to defect budget.

Criteria have to be finely tuned in order to classify the defects:

- For hard defect, the criteria are relatively straightforward. Pixels outside the 10%-90% responsivity range represent generally a small fraction of defective pixels (ie less than 0.1%).
- The most common population of defective pixels can be classified as low frequency noise pixels, or potential RTS noise pixels. This population usually represents few percents of the total number of pixels. Although low frequency noise pixels affect the signal to noise performance, RTS noise is much more difficult to assess, as it can result in spatial noise features.
- Another source of defect is related to spatial noise, i.e. pixels which present some residual after calibration. The fraction of such pixel is usually quite small, and less than 0.1%.

There are continuous improvements on detector material in order to minimize the material defects and cosmetics. However, the best mitigation technics to fulfill the stringent requirements of space missions, together with the radiation environment impact, is currently to implement pixel deselection at ROIC level whenever it is possible.

D. A/R coating vs spectral coverage

To improve detection efficiency, Anti Reflective Coating (ARC) is deposited at the backside of the detector. ARC is also a way to reduce reflectivity on the detector surface. Indeed, parasitic light is tracked on every optic part of the instrument in the objective to lower it to avoid parasitic signal. Monolayer quaterwave ARC is mainly used and is part of the standard process of detector manufacture. This type of ARC allows detection efficiency increase of 30% and below 5% reflectivity but in narrow spectral band, below 500nm width. For application like Microcarb described in *section II*, instrument concept used only one detector for the different spectral bands of interest, which means that the same detector has to be performant in detection efficiency and reflectivity from 0.7µm to 2.5µm. To achieve this goal, multilayer ARC coating is foreseen (see **Fig.4** extracted from [6], ESA development). The issue is that multilayer ARC deposition shall not impact detector performances so processes (temperature in particular) and handling are very critical.

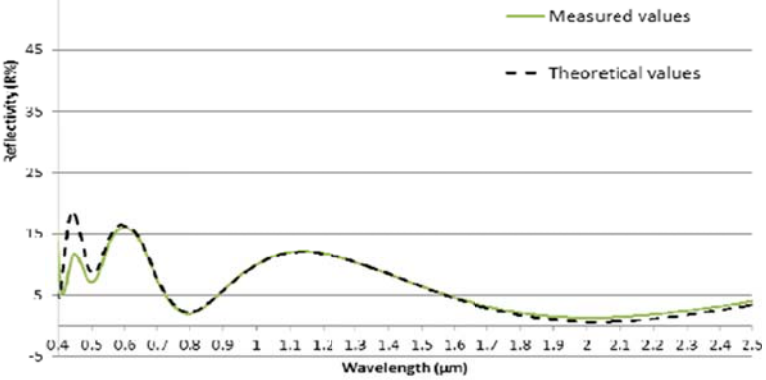

Fig. 4. Multilayer Anti Reflective Coatingreflectivity performance

E. p/n photodiode

The schematic for a p/n photodiodes is given **Fig. 5**. The main challenge is to decouple the absorbing region from the depleted region. The performance driver is a low dark current (diffusion limited) together with a high sensitivity and a low number of defective pixels. The definition of the photodiode has to cancel or minimize contributors which degrade the performances i.e.depleted region defect (G-R current contribution) and surface defects from interfaces. Good performance requires finely adjusted processes to get the best definition of the photodiode.

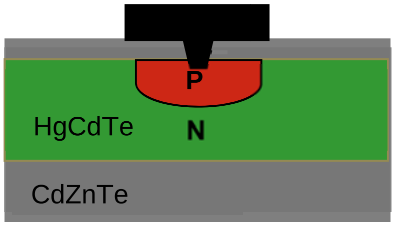

Fig. 5 p/n photodiode schematic.

IV. SFD limitations for Earth observation

SFD seems to be a great solution for low signal levels. As an example, the Microcarb mission is targeted to be compatible with microsatellite platform. In this objective, the instrument is not actively cooled and operates at 150K. SFD detectors are mainly used for astronomical applications that operate below 80K. That is why, CNES decided to conduct a study on SFD detector performances at high temperature at IPNL. The main performance that was expected to be degraded with the temperature increase was the operability with the apparition of hot pixels and even clusters of hot pixels. The study was realized in the range of 100K – 180K. In order to guarantee linear behaviour in the upper dynamic, photodiode bias designed as Vsub-Vreset on was increased. Despite the confirmation that offset dispersion increases with temperature and lower the total dynamic, this study showed that dark current at 150K does not generates big clusters as expected (see **Fig.6**).

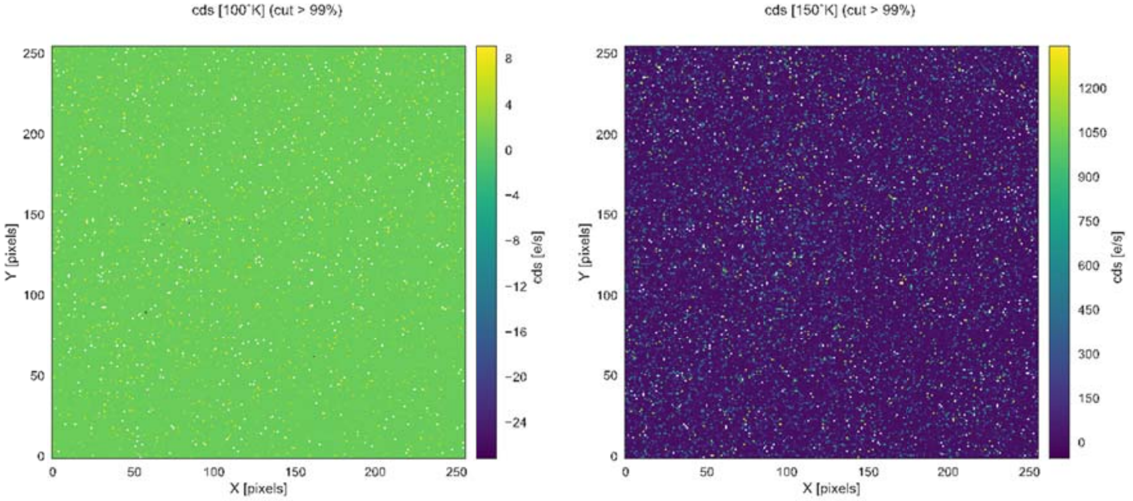

Fig. 6: Dark current on SFD detector at 100K (left) and at 150K (right)

To conclude on SFD limitations, it seems that dark current at high temperature can be acceptable but signal dynamic range is limited. Along with low frequency readout, SFD is not naturally adapted for medium range fluxes and high readout frame. Another issue to keep in mind is the persistence phenomenon that is observed for very low signal astronomical applications. The impact of this persistance should be analyzed for higher fluxes range like in Earth observation and planetary applications. In the 10^3 to 10^4 e-/s/pixel, CTIA input circuit would be a preferred solution, but we still need to address the limitations pointed in *section III.A*: floor or threshold effects, ROIC glow,…

V. p/n photodiode technology from SWIR to VLWIR

Some results have been presented in previous paper. The purpose of this section is to provide a synthesis of the past developments. As criteria of performance evaluation, the rule07 and the diffusion current limit are used. The rule07 has been set as a reference by Teledyne (US): although the rule is an empirical law based on measurements on detectors fabricated by Teledyne, it provides the state-of-the art performance for dark signal with p/n photodiode technology. The diffusion current limit demonstrates that the diode is limited by intrinsic physical phenomenon rather than material and diode imperfections.

For earth observation, developments of SWIR technology for high focal plane temperature have been done. The goal is to develop detectors that can be operated at high temperatures in spacecrafts where the system constraints (orbit, mass, electrical power, volume, weight,…) prevent cooling the detectors down to low temperatures. The performance drivers are to lower the dark current and the amount of defective pixel at temperatures above 150K. G-R contribution to the dark signal has to be minimized so that the diode dark current is diffusion current limited. Results are given **Fig. 7**, from [5].

In the frame of CNES R&T activities, VLWIR was developed first based on p-on-n technology (2005) and then p-on-n technology was introduced at CEA-LETI since 2011 for VLWIR. These activities showed that VLWIR is very sensitive to any default in the process due to the small gap of HgCdTe material. This implies, every issue encountered at lower wavelength has to be mastered before trying to adapt the technology to VLWIR. State of the art dark current has been achieved during the latest development (see **Fig.8**) but operability and yield are still to be improved [8].

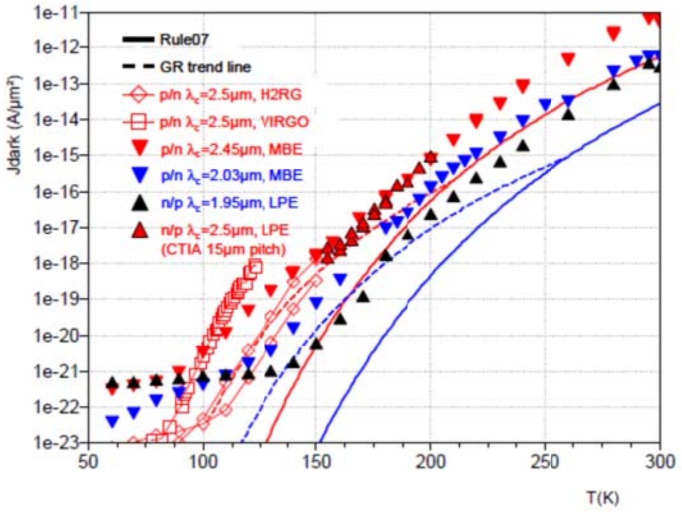

Fig. 7. SWIR band p/n technology: Dark current measurement at CEA/LETI and comparison to the state-of-the-art and previous works. See [5].

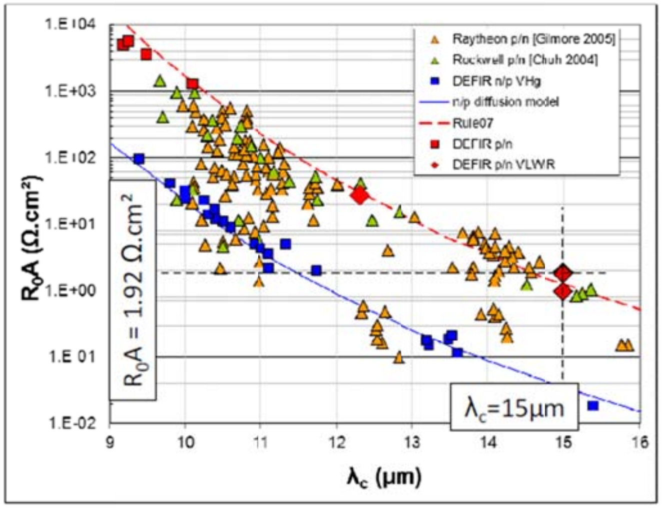

Fig. 8: R0A product vs. cutoff wavelength for various architectures: n-on-p doped by Hg vacancies or extrinsic species and p-on-n architectures found in literature. Plain line corresponds to n-on-p diffusion model while dashed line indicates Rule07 law. See [8].

VI. Large Format Arrays developments

The developments are focused on two major activities. The first activity is to enhance the production capabilities for 1k² detector format or more (under CNES contract). The second activity aims to demonstrate the capabilities to fabricate 2k detectors. Major achievements have been demonstrated as described extensively in [8]:

- Hybridization: in the frame of ESA study, Sofradir has demonstrated (on internal fundings)hybridization capabilities up to 2428x2428 format, with a 15µm pixel pitch. Mechanical test vehicles have been fabricated, with a number of defects compliant to the fabrication standards. One should also note that Sofradir is also developing hybridization technology for small pixel pitch, down to 10µm
- Large detection circuits (under CNES contract): a large number of processes are needed to obtain large detection circuits, from CZT ingot fabrication to photodiode process on large CZT substrates. Sofradir and CEA-LETI have shown excellent control of CZT ingots fabrication. 3.5’’ CZT substrate size is now under production at Sofradir. HgCdTe epilayer deposition (**Fig.9**) is well-controlled and within the production standard (uniformity of thickness, crystallographic quality and uniformity, expected lambda cut-off and its dispersion over the wafer). Photodiode processes on large substrates have also been demonstrated.

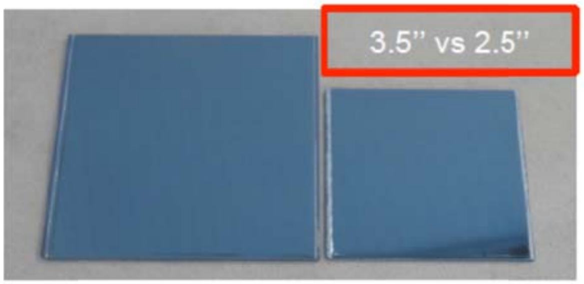

Fig. 9: Sofradir HgCdTe epilayer deposited by LPE on Sofradir susbtrates

VII. Roadmap schematic

Future trends for forthcoming developments are the following, see **Fig. 10.**

- Enhance optimized p/n technology: results given in this paper show that the improvements of performance can be achieved with CEA-LETI technology. Further developments still necessary to improve the performance.
- Evaluate the APD solution for scientific applications requiring low noise in the medium flux range: This requires to better understand the limitations of the APD technology and the limitations of CTIA imput stage at ROIC level.
- Availability of large format at CEA/LETI and Sofradir: with the objectives to follow up the technology developments in order to increase infrared focal plane arrays to a large format of class 2 k or more).

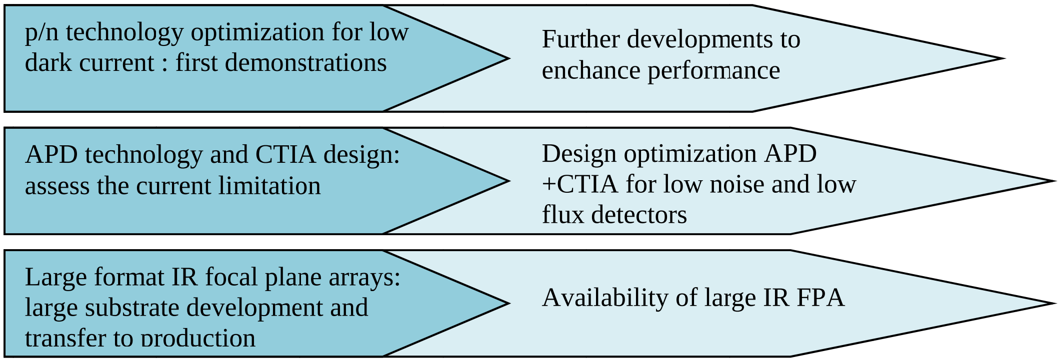

Fig. 10: future development trends in infrared technologies to fit the requirements of future Earth Observation space missions

REFERENCES

[1] H. Geoffray et al. “CNES detector development for scientific space missions: status and roadmap for infrared detectors” Proc. SPIE 9154, (2014).

[2] Pascal V. et al “An improved MicroCarb dispersive instrumental concept for the measurement of greenhouse gases concentration in the atmosphere”, ICSO, (2014)

[3] Baker I. et al “Leonardo (formerly Selex ES) infrared sensors for astronomy –present and future”, Proc. SPIE 9915, (2016).

[4] Hall D.N.B. et al, “Towards the next generation of L-APD MOVPE HgCdTe arrays: beyond the SAPHIRA 320 X 256”, Proc. SPIE 9915, (2016).

[5] Rothman, J. et al. “MCT APD Focal Plane Arrays for Astronomy at CEA-LETI”,Proc. SPIE 9915, (2016).

[6] Leroy C. et al, “SWIR space detectors and future developments at SOFRADIR”, Proc. of SPIE Vol. 8889, (2013)

[7] Gravrand O. et al. “Ultralow-Dark-Current CdHgTe FPAs in the SWIR Range at CEA and Sofradir”, Journal of Electronic Materials, Volume 41, 2686-2693 (2012)

[8] Castelein, P. et al., “Latest developments in the p-on-n HgCdTe architecture at DEFIR”, Proc. of SPIE Vol. 9070, (2014)

[9] Boulade O. et al, “Development activities on NIR large format MCT detectors for astrophysics and space science at CEA/SOFRADIR”, Proc. SPIE 9915, (2016).