STATUS OF SPACE ACTIVITY AND SCIENCE DETECTORS DEVELOPMENT AT SOFRADIR

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1. INTRODUCTION

SOFRADIR is one of the main companies involved in the development and manufacturing of infrared detectors for space applications leading to many space studies and programs from visible up to VLWIR spectral ranges. Numerous programs are currently running for different kinds of missions: meteorology (MTG), Copernicus with the Sentinel detectors series, Metop-SG system (3MI, Sentinel-5 and Metimage), Mars exploration (Exomars), moon exploration (Chandrayaan mission with Indian space agency)…

Apart from these programs, the development of scientific missions is increasing. In particular, for the last 5 years, Sofradir and CEA-LETI have worked on specific detectors in SWIR bands to address these needs. The ALFA detector development in progress is the result of these developments. It is expected to propose the first generation of this detector in 2019 for upcoming scientific mission and / or ground universe exploration.

In this paper, an overview of space activity at Sofradir with the main space programs and developments will be described, followed by a description of very large detector developments made for science.

2. SPACE ACTIVITY AT SOFRADIR

2.1 A General overview

The domains covered by space activity at Sofradir are Earth observation for military or commercial applications, and science, deep space and scientific applications. Thanks to close relation with agencies, Sofradir benefits for more than 25 years of experience in Space domain.

Flight models are manufactured on a state-of-the-art qualified process and quality level production line that is producingseveral thousands of military detectors per year meaning a high level of reproducibility and reliability.

From now, Sofradir has delivered more than 70 flight models over the past decade. Among these flight models, 36 second generation infrared detectors have already been operated or are currently operating in various spacecrafts. One of the last significant results could be illustrated by the successful Second Generation Global Imager (SGLI) instrument, which is the first operating Sofradir VLWIR detector, aboard the JAXA satellite Global Change Observation Mission-Climate (GCOM-C). The next figure illustrates an earth image taken from GCOM-C satellite in IR waveband and presents SGLI focal plane array and package at detector level (See Figure 2-1 for more details).

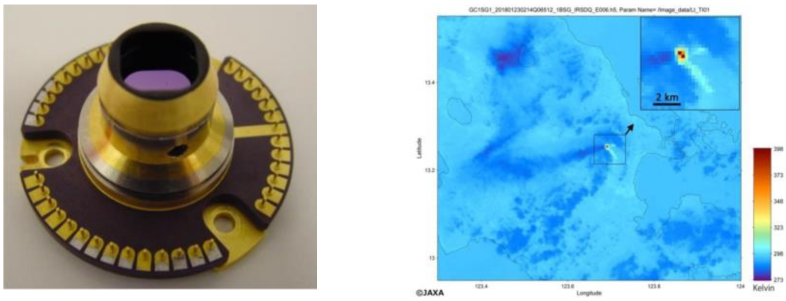


Figure 2-1: SGLI Focal Plane Array, Detector Package and cartography in temperature of Mayon volcano with GCOM-C satellite in IR waveband using SOFRADIR detectors (courtesy of JAXA)

2.2 Sofradir Infrared detector offer for Space Application

Thanks to more than 30 years of experience in manufacturing infrared detectors, Sofradir is able to propose HgCdTe detectors to cover a wide field of applications from visible to VLWIR.

Sofradir has a leading position in the world. Indeed, Sofradir is one of the only manufacturers that master the production of infrared detectors from raw material to fine testing. The picture below presents all the activities where Sofradir is involved in.

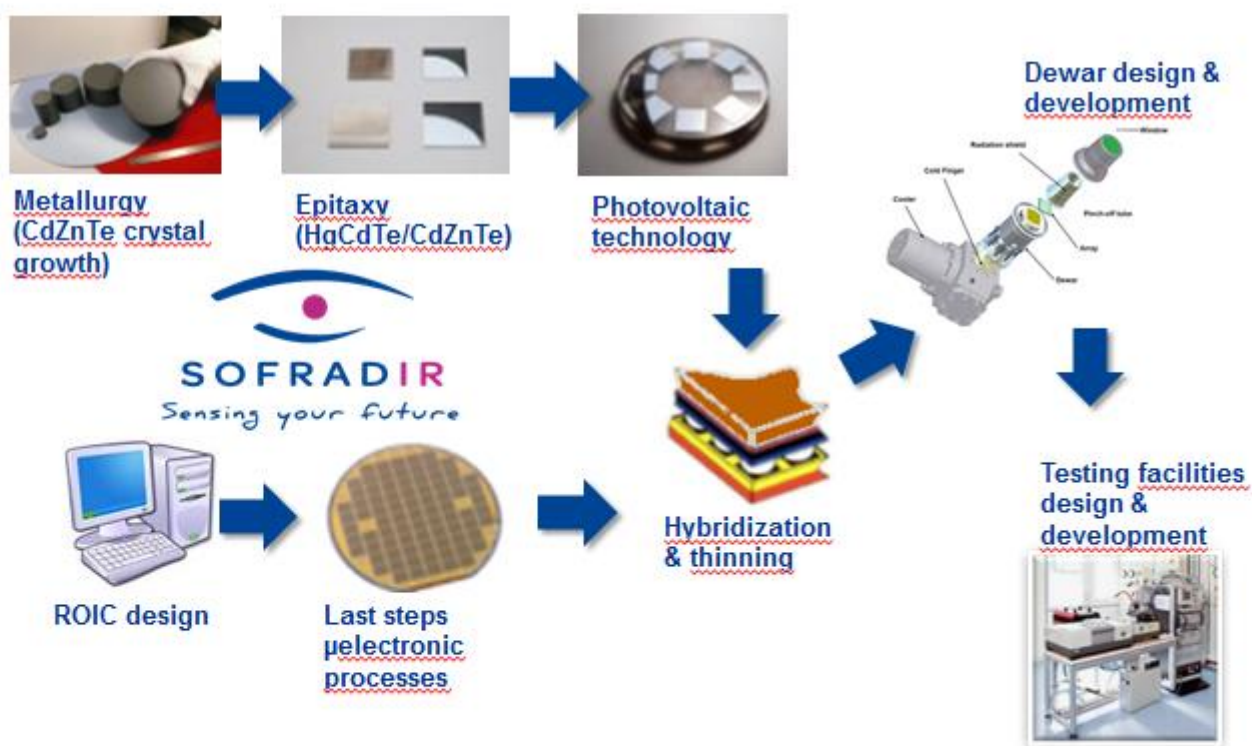


Figure 2-2: Sofradir skills areas

As the CdZnTe boules and substrates are fabricated in our facilities, it allows choosing the most appropriate ones according to the type of missions and detectors. Concerning the epilayer and diode process, the challenge in the coming years is to increase the size of the wafers in order to address both larger detector format size and higher number of chips for tactical production line. Hybridization of larger detector (up to 2048x2048) with relative low pixel pitch (down to 15µm for space) is the state of the art that can be found in Europe. The various types of packaging available (active or passive cooling, low conductivity interconnexion flex, filter integration, …) is an acquired advantage thanks to the different space programs conducted over the past 10 years . Finally, the set of test benches that have been developed for space missions is also a great asset for Sofradir (spectral benches from Visible to VLWIR, MTF bench, geometric bench, radiometric bench…). All those activities are located in the same place at Veurey-Voroize, at only 15km from our historical partner CEA-LETI. This situation highly facilitates the progress of the programs with high synergy between the people involved in those missions at Sofradir.

This paragraph describes the different types of detectors, derived from military production line or fully customized for a dedicated application. Each product will be presented with a status of the attached program, a description of its architecture and electro-optical performances. At the end of this section a table will summarize the IR detector portfolio.

2.2.1 Visible – SWIR - MWIR range

Detection in the extended SWIR wavelengths is one of the first wishes of Sofradir. Indeed, since early 2000, Sofradir developed various detectors in order to answer customers' needs for imagery or hyperspectral applications. The first applications were mainly addressed by matrix sensitive arrays: Neptune (500x256 30µm pitch), Saturn (1000x256 30µm pitch), Mars (320x256 30µm pitch) and Scorpio (640x512 15µm pitch).

As examples, a Neptune detector with an adapted cut-off wavelength was launched in December 2014 onboard HAYABUSA-2 probe of the Japanese Space Agency (JAXA) that aims to study an asteroid "1999 JU3" after a 3-years space journey.

More recently, three detectors have been launched in March 2016 in the scope of ESA EXOMARS TGO mission. Therefore, three new SOFRADIR detectors flew to Mars, bringing onboard two MARS SW-MW ([2.2;4.3µm]) detectors and one SCORPIO SW-MW ([2.6;4.2µm]) detector (see Figure 2-3). These detectors are respectively integrated in NOMAD (Nadir and Occultation for Mars Discovery) and ACS (Atmospheric Chemistry Suite) instruments.

Figure 2-3 : MARS MW IDDCA integrated in NOMAD instrument

Another Neptune SW-MW detector was implemented into the MicrOmega IR microscope developed by IAS (Institut d'Astrophysique Spatiale at Orsay, France) with the support of CNES (Centre National d'Etudes Spatiales, the French space agency). This detector is expected to be launched in the next ESA EXOMARS mission, aiming to analyze Mars ground surface composition.

For METOP-SG mission, another program named 3MI instrument integrates a NEPTUNE FPA. This program has been started at SOFRADIR mid-2015 and the selected detector design is derived from a NEPTUNE FPA with an adjusted cut-off wavelength (2.3µm at 185K) coupled with a SATURN package in its passive cooling version (see Figure 2-4).

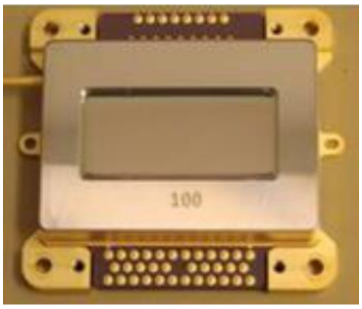


Figure 2-4 : SATURN SWIR – Passive cooling

Indian space agency (ISRO) has chosen Sofradir for the CHANDRAYAAN-2 mission. A derivative of NEPTUNE detector in its active cooling version (with a RICOR K508 cryocooler) will be delivered. This program started at the end of 2015 and consists in using a NEPTUNE detector ROIC coupled with a SWIR MWIR detection circuit. The packaging integrates a specific filter located between the FPA and the window in order to address the four requested bands. The first flight model delivery is expected beginning of 2019.

Apart from these "standard" sensitive arrays, SOFRADIR has developed other specific detectors for space applications in order to fit with customer needs in SWIR range: a linear detector (Sentinel-2), and two large size detectors (NGP and ALFA). Sentinel-2 and NGP detectors have been selected for first missions, as briefly presented hereafter, while ALFA detector is currently under development, and aims to address in a first time astronomy and science applications. This detector as well as its design and definition is more detailed in chapter 3 of this paper.

SOFRADIR was selected in 2008 by AIRBUS Defense & Space and ESA for the development of infrared detectors for the Sentinel-2 mission (part of the Copernicus program). For this mission, linear arrays detectors have been designed and screened to operate for the in-orbit lifetime of Sentinel-2 satellites (over 7 years). They include three SWIR linear arrays of 1298 pixels at 15 micron pitch, incorporated in two different MCT detection circuits which are hybridized on the same readout circuit (see Figure 2-5 for retina and associated package). A significant flight models production phase have been performed for this program leading to the delivery of 27 flight models in total for the completion of the first phase (satellites A/B) in early 2014.

Then in 2015, the second phase (satellites C/D) has been started, with the objective to deliver 24 supplementary detectors. Delivery of these models is scheduled over 2017 and 2018.

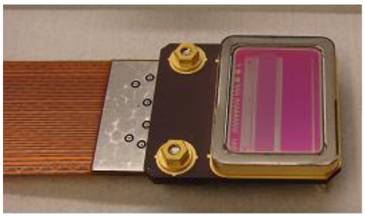


Figure 2-5 : Sentinel-2 Focal Plane Array, Detector Package and image of French Riviera with Sentinel-2A satellite in IR waveband using SOFRADIR detectors (courtesy of ESA)

Regarding NGP detector, it has been selected by Airbus DS and ESA for Sentinel-5 mission, also part of Copernicus program, which aims to do air-quality mapping. After a precursor phase (TROPOMI) launched in December 2017 with a Saturn SWIR detector onboard, the next phase will be done with NGP SWIR models (1024x1024 15µm pitch) proposed in a passive cooling version (see Figure 2-6). First flight models are aimed to be delivered end of 2018/beginning of 2019.

Figure 2-6 : NGP sensor in Sentinel-5 detector package

The same detector is also used for Microcarb mission, which aims to monitor Carbon quantity in the atmosphere. For this application, the NGP detector is currently being adapted to VISIR configuration in order to fit with the mission needs.

Table 1 gives an overview of the different SWIR detectors developed by SOFRADIR, from visible to MWIR wavelengths, and their status (some programs have been completed by Sofradir but have not been launched yet).

Product	Bandwidth	Mission/Instrument	Program status (at Sofradir)
SATURN SW - active cooling	0.9 – 2.5µm	APEX (airborne)	Completed
SATURN SW and VISIR - passive cooling	0.9 – 2.5µm and 0.4 – 2.5µm	PRISMA hyperspectral mission (space)	Completed
SATURN SW - passive cooling	0.9 – 2.5µm	Hyperspectral instrument HISUI (space)	Completed
SATURN SW - passive cooling	0.9 – 2.5µm	TROPOMI instrument - Sentinel-5 precursor satellite (space)	Completed
NEPTUNE SW-MW	Not given	SPIRALE mission – Early warning preparation (space)	Completed
NEPTUNE SW-MW	0.9 – 3.8µm	Russian PHOBOS GRUNT mission (space)	Completed
NEPTUNE SW-MW	0.9 – 3.8µm	Japanese HAYABUSA 2 mission (space)	Completed
MARS SW-MW - active cooling	2.2 – 4.3µm	EXOMARS 2016 – NOMAD instrument (space)	Completed
SCORPIO SW-MW- active cooling	2.3 – 4.6µm	EXOMARS 2016 – ACS instrument (space)	Completed
NEPTUNE SW/MW - active cooling	0.9 – 3.8µm	EXOMARS 2020 – Micromega instrument (space)	Completed
NEPTUNE SW - passive cooling	0.9 – 2.2µm	3-MI (space)	In progress
NEPTUNE SW/MW - active cooling	0.9 – 5µm	CHANDRAYAAN-2 (space)	In progress
SATURN SW - active cooling	0.9 – 2.5µm	GISAT Mission (space)	In progress
SENTINEL 2 SW	0.9 – 2.5µm	SENTINEL 2 A/B (space)	Completed
SENTINEL 2 SW	0.9 – 2.5µm	SENTINEL 2 C/D (space)	In progress
NGP	0.9 – 2.5µm	SENTINEL 5 (space)	In progress
NGP	0.4 – 2.5µm	MICROCARB (space)	In progress

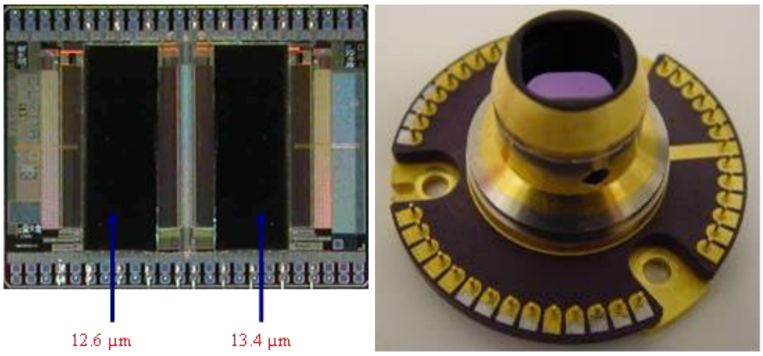
Table 1 : Main programs using SWIR detectors

2.2.2 VLWIR range

VLWIR MARS detector (see Figure 2-7) development for space has been started in 2014 with SAC ISRO in the frame of GISAT program. This detector is composed of a FPA of 320x256 with a 30µm pitch sensitive in the VLWIR band, with a cut-off wavelength of 14.9µm and an operating temperature at 50K. The spectral range is defined by a six bands strip filter from 7.1µm to 13.5µm. The retina and the filter are mounted in a sealed package closed by a germanium window, which is optimized for transmission in the waveband from 7µm to 13.5µm. For this program, six flights models are expected to be delivered in 2020.

Figure 2-7 : MARS detector

For the SGLI instrument (on board GCOM-C), SOFRADIR has been selected by NEC TOSHIBA Corporation and the Japanese space agency (JAXA) for the development and production of the long wave infrared detector sensitive up to 13 µm at an operating temperature of 55 K. This detector is sensitive in two definite wavebands, with a central wavelength of 10.8µm for the first one and 12µm for the other. The package and the retina are presented in Figure 2-8. The program has been completed successfully in 2013 with the delivery of all flight models, meeting both customer requirements and the schedule of the program. This detector is now successfully used in space on board the GCOM-C satellite since end of 2017.



SGLI VLWIR retina **SGLI package**

Figure 2-8 : SGLI detector

Product	Bandwidth	Mission/Instrument	Program status (at Sofradir stage)
MARS	7.1 – 13.5µm	GISAT (space)	In progress
SGLI	10.8 – 12µm	GCOM-C (space)	Completed

Table 2 : Main programs using VLWIR detectors

2.2.3 Custom products

Sofradir was selected in 2011 by Thales Alenia Space and ESA (European Space Agency) to develop and produce the infrared detectors for the European future meteorological program **MTG** (Meteosat Third Generation). For this program, Sofradir is developing the detectors for two different systems:

- the infrared detectors for the Flexible Combined Imager (**FCI**),
- the infrared detectors for the InfraRed Sounder (**IRS**).

For the FCI satellite, four types of detectors (see Figure 2-9), covering wavebands from 1.3 µm up to 14 µm shared in 11 spectral channels, are developed for use around 60K.

	NIR			IR1			IR2		IR3		
Center of Spectral bandwidth in µm	**1.3**	**1.6**	**2.2**	**3.8**	**6.3**	**7.3**	**9.7**	**8.7**	**10.5**	**12.3**	**13.3**
Bandwidth in µm	**0.03**	**0.05**	**0.05**	**0.4**	**1**	**0.5**	**0.4**	**0.3**	**0.7**	**0.5**	**0.6**

Each detector has the same overall definition. It is comprised of a retina (one ROIC on which one or two MCT arrays are hybridized), a sealed package with spectral filters and an entrance window associated to a space cryogenic flex cable with a space connector. The retinas of the different FCI detectors are linear arrays of pixels with pitches varying between 15 and 25 µm.

Figure 2-9 FCI NIR/IR detection assemblies

Five flight models of each type of detectors (meaning 20 flight models in total) have to be manufactured and delivered in the frame of this program between mid-2018 and end of 2019.

Regarding the IRS satellite, two types of detectors (see Figure 2-10) covering infrared waveband from 3.3 µm up to 14.7 µm are developed for use around 55K.

Figure 2-10 : IRS detection assembly

Each detector has the same overall definition. It is comprised of a large size retina with a format 160x160 and 90 µm pitch, a non-sealed package and a space cryogenic flex cable with a space connector. Three flight models of each type of detectors (meaning 6 flight models in total) have to be manufactured and delivered in the frame of this program between mid-2018 and end of 2019.

More recently, in 2015, Sofradir has been selected by the German Space Agency to develop and to manufacture the **METimage** infrared detector ot be integrated in the instrument by Airbus Defense and Space Germany in the frame of METOP-SG mission.

For this development, several detectors are expected; all with the same packaging design (see Figure 2-11): one covering both SWIR and MWIR wavebands, with cut-off wavelength is around 5.5µm, one covering LWIR waveband, with cut-off wavelength is around 12.5µm, and one covering VLWIR waveband, with cut-off wavelength is around 14µm. All these detectors have to operate with a FPA temperature of 60K. SMWIR FPA will be composed by an equivalent of 180x153 sub-pixels array with 30µm pitch, whereas LVWIR FPA will be composed by two detection circuits “LWIR” and “VLWIR” respectively equivalent to 108x153 sub-pixels array and 36x153 sub-pixels array with 30µm pitch.

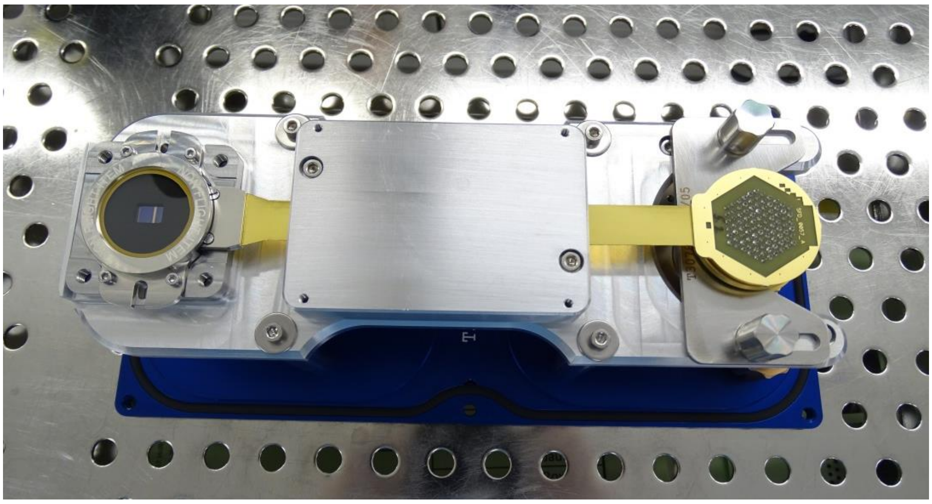


Figure 2-11 : METimage detector

Four flight models of each type of detectors (meaning 8 flight models in total) have to be manufactured and delivered in the frame of this program between mid-2019 and mid-2020.

Product	Bandwidth	Mission/Instrument	Program status (at Sofradir stage)
MTG - NIR	1.3 – 2.2µm	Meteosat Third Generation (space)	In progress
MTG – IR1	3.8 – 7.3µm	Meteosat Third Generation (space)	In progress
MTG – IR2	8.7 – 9.7µm	Meteosat Third Generation (space)	In progress
MTG – IR3	10.5 – 13.3µm	Meteosat Third Generation (space)	In progress
MTG – IRS 1	4.4 – 6.2 µm	Meteosat Third Generation (space)	In progress
MTG – IRS 2	8.3 – 14.7µm	Meteosat Third Generation (space)	In progress
METIMAGE – SMWIR	1.23 – 4.07µm	METOP-SG (space)	In progress
METIMAGE – LVWIR	6.54 – 13.3µm	METOP-SG (space)	In progress

Table 3 : Main programs with custom detectors

3. TOWARDS A 2Kx2K LOW FLUX LOW NOISE NIR DETECTOR

3.1 ALFA Detector specifications

Since years, ESA wishes to have a European large size detector available for scientific missions. Indeed, ESA started several studies in order to develop a technology answering this need. The last study which has been started aims to scale-up this technology to a large-sized prototype detector. This detector, named as per its funding activity Astronomy Large Format Array (ALFA), shall have the same performances as the detectors tested in the frame of NIRLFSA phase 2, which was ESA previous study, based on a 640x512 15µm-pitch detector. The main parameters expected are synthetized in Table 4.

Parameter	Value
Array size - pitch	2048x2048 – 15µm
Spectral range	Cut-on ≤ 0.8µm, cut-off 2.1µm / 2.5µm
Operating temperature	100 ± 1 K
Quantum efficiency	≥ 70%
Dark current (at 100K)	≤ 0.1 e-/pix/s
Linear well capacity	≥ 60ke-
Non linearity	≤ 3%
Cross talk : inter pixel capacitance / other contributions	≤ 2% / ≤ 3%
Readout noise (single CDS)	≤ 18e- rms
Readout speed	≥ 100kHz

Table 4 : Main specifications of the ALFA detector

3.2 ALFA ROIC

3.2.1 ROIC architecture

The ALFA ROIC is composed by a matrix of 2048 by 2048 pixels with 15µm pitch. Therefore its overall size is close to 30x30 mm². In order to achieve such dimension, the stitching technique has been implemented in foundry. The validation of this technique is very important for future ROIC developments, as from now there is no more limitation on ROIC size.

ALFA ROIC architecture is given in Figure 3-1. In green these are the analog parts, while in blue these are the digital ones. The data are provided through 32 outputs, with an additional reference output which is linked to a pixel not connected to photodiode: this pixel is maintained under the reference bias level.

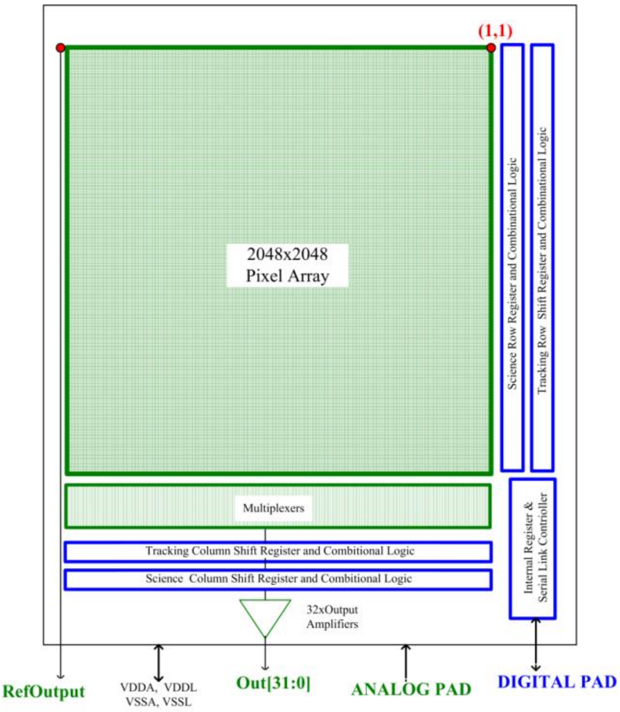


Figure 3-1 : ALFA ROIC architecture

3.2.2 ROIC operating modes

ALFA ROIC has four operating modes. The default one, called Science mode, allows the user to get images of the full matrix with its best performances (low noise, low power consumption, weak glow generation) with a readout frequency up to 100kHz. The data are available with 1, or 4 or 32 outputs. In order to operate the detector faster, a Fast mode is available, with a readout frequency up to 6MHz, giving a full frame reading time of 24ms with 32 outputs. The Window mode allows defining and reading up to 3 windows with adjustable sizes, as well as the Tracking mode which is an interlaced readout of the full field and the windows. Main characteristics of each mode are given in Table 5.

	Science	Fast	Windows	Tracking
Number of pixels read	2048x2048	2048x2048	Up to 3 Windows defined by SERDAT	Up to 3 Windows defined by SERDAT
Readout	Rolling shutter, non-destructive readout			
Reset mode	Line by line, pixel by pixel, global reset, single pixel reset			
Pixel readout frequency	Up to 100KHz	**Up to 6MHz**	100KHz	100KHz
Number of outputs	**1, 4, 32**	32	1, 4, 32	1, 4, 32
Full frame time with 32 outputs	1.43s	**0.024s**	Depends on window(s) size	Depends on window(s) size
Analog chain	Slow	Fast	Slow	Slow
Specificity	- Mode with low read noise and weak power consumption - The analog chain is Source Follower pixel and output Source Follower	- Sample and hold in the column and output amplifier	- 1, 2 and 3 windows per output ; the defined windows are the same for each channel - Unused outputs are not read - Global reset separated for each window	- The science and windows data are interlaced

Table 5 : Operating modes main characteristics

Thanks to SFD input stage, the ROIC readout mode is a non-destructive readout, and there are several types of reset, all available in both full frame modes and windowing modes. Indeed, the reset can be done on each pixel individually, or line by line, or also on the full frame/window.

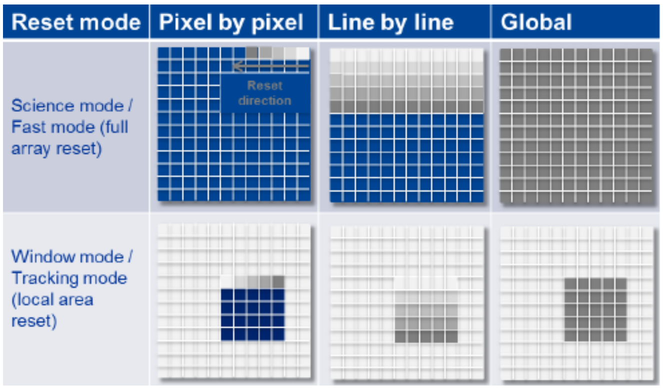


Figure 3-2 : ROIC reset types

3.2.3 ROIC expected performances

The table below summarizes the performances expected for ALFA ROIC:

Parameter	**Goal value**	**Evaluated value**
Size	2048 x 2048	2048 x 2048
Pitch	15 x 15 µm²	15 x 15 µm²
Output number	32	1, 4, 32
Linear well charge handling capacity (CHC)	≥ 60 ke-	135 ke-
Non-Linearity	≤ 3%	< 3%
Readout noise (single CDS)	≤ 18e- rms	~ 11e-
Cross-talk	≤ 3%	< 3%
Power consumption Science mode (32 output)	< 50 mW @ 70K	3 mW

Fast mode	NS	100 mW
Readout speed	≥ 100 kHz	100 kHz

Table 6 : ALFA ROIC performances

As one can see, the simulation results show that ALFA ROIC fits with ESA requirements, hence it is well adapted to science applications.

3.3 Program status

Regarding the program status, ROIC wafers have been manufactured and are currently under test at Sofradir. First results are expected before the end of 2018, and electro-optical characterization on first ALFA hybridized retinas is expected beginning of 2019.

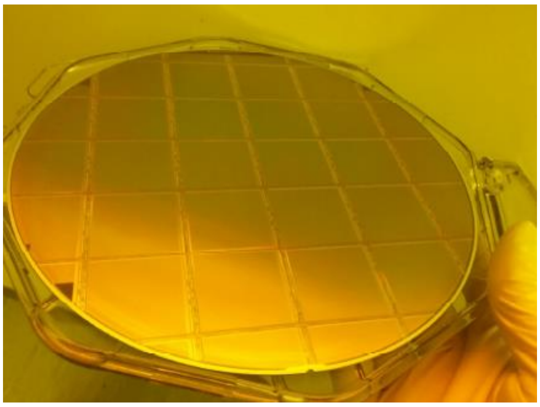


Figure 3-3 : 8 inches ALFA ROIC Silicon wafers

3.4 ASTEROID program: technology challenges and manufacturing of very large detectors

In May 2017, ASTEROID (AStronomical TEchnology EuROpean Infrared detector Development) program started at Sofradir. This program is founded by the EU (European Union) in the frame of H2020 development program strategy (contract 730161). REA (Research Executive Agency) follows the program at the EU, Sofradir is leading the program and the management of the consortium. The European consortium is composed of 4 other partners in Europe. The main objective of the ASTEROID project is to extend the dimension of high performance infrared FPA that can be manufactured in Europe to dimensions equivalent to that of the US competitors**.**

To be able to manufacture very large FPA, four key constraints exist. Indeed large FPAs require:

- Very large dimension Read Out Integrated Circuits (ROIC)
- Very large substrates (mono-crystalline CdZnTe alloy);
- The capacity to epitaxy high quality HgCdTe material on these substrates;
- A manufacturing line fully compatible with large substrate dimensions.

The axes of development are summarized in the next schema.

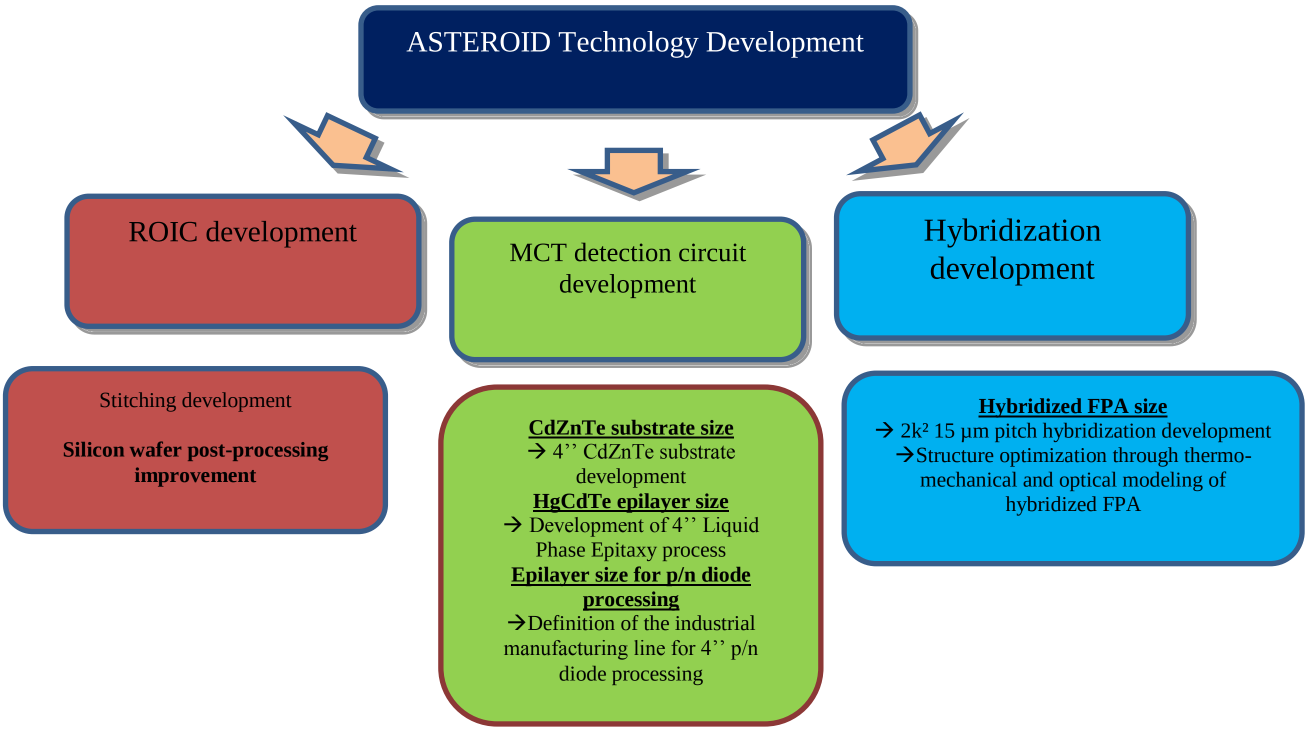


Figure 3-4 : Development axes in ASTEROID program

The ASTEROID consortium is composed of 5 complementary partners coming from three European countries. The following table gives an overview of the different partners' expertise and complementarity and demonstrate that the consortium is well prepared and committed to fulfil the project objectives and achieve its challenges. The ASTEROID consortium consists of an interdisciplinary team from:

- 3 European industrials (SOFRADIR, EVG and SME ADDL)
- 2 research organisations (CEA and IFAE)

Each partner of the project is leaders in their field of application. SOFRADIR is an international leader specialized in IR detectors manufacturing. Research partner CEA will focus on MCT wafer technology and SWIR p/n technology.

EV Group (EVG) is a leading supplier of equipment and process solutions for the manufacture of semiconductors, microelectromechanical systems (MEMS), compound semiconductors, power devices, and nanotechnology devices. Key products include wafer bonding, thin-wafer processing, lithography/nanoimprint lithography (NIL) and metrology equipment, as well as photoresist coaters, cleaners and inspection systems.

Spanish research institute IFAE is specialized in testing with experience, the institute works at the cutting edge of detector technology and has made major contributions at experiments at CERN (ATLAS, ALEPH and several R&D projects), Neutrino physics (T2K), in Gamma-Ray astrophysics (MAGIC, CTA) and Cosmology (DES, DESI, PAU, Euclid).

Finally, the consortium will benefit from French SME ADDL which has expertise in finite element modelling. ADDL has developed a high level of expertise in simulation of multiphysics and multiscale systems (solid mechanics, CFD and electromagnetics) using advanced methods such as finite elements, finite volumes and boundary elements.

After one year of progress, Asteroid program has already demonstrated results at CdZnTe ingot growth and post processing. The first ingots with very large size has been done and characterized. With the substrates extracted from these ingots, epitaxy wafer with 4'' size have also been manufactured at CEA LETI as it can be seen in the next figure.

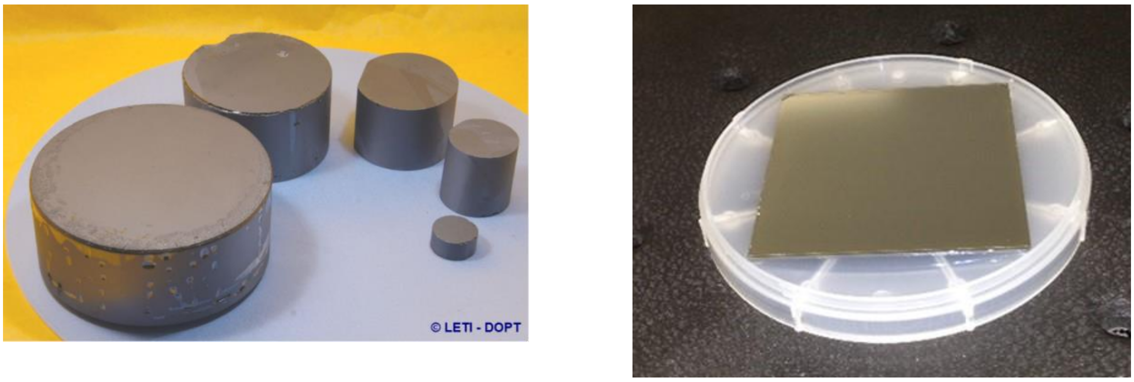


Figure 3-5 : First epilayer of $Cd_{1-y}Zn_yTe$ with a 4'' format @CEA LETI (Right) in ASTEROID program / Examples of different CdZnTe ingots at CEA-LETI (Left)

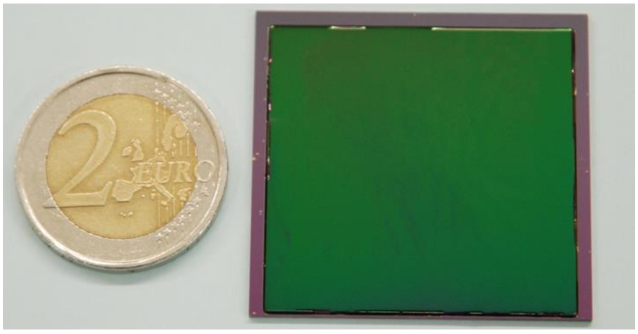


Figure 3-6 : First hybridized mock-up 2048x2048 manufactured at Sofradir

4. CONCLUSION

SOFRADIR confirms its position as a worldwide reference supplier for space IR detectors thanks to all current programs and successful pre-developments. The IR detector portfolio is available for space applications from visible to VLWIR up to 16µm cut-off wavelength.

For science and astronomy topic, the first 2048x2048 15µm pitch, ALFA prototype is up to come by end of this year 2018. In parallel of the product development, Sofradir prepares the future industrialization of the production of this detector at major scale.

ACKNOWLEDGMENTS

The authors thank all the SOFRADIR and CEA teams, dedicated to quality work and won challenges, which made SOFRADIR become a top-ranked key player in the infrared field for space applications. The authors would like to thank also the European Space Agency (ESA), the French space agency (CNES), the REA and European Union and the French MoD for their support through the different programs where SOFRADIR is involved.

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