

# International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

*Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas*



## *Development and characterisation of MCT detectors for space astrophysics at CEA*

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## DEVELOPMENT AND CHARACTERISATION OF MCT DETECTORS FOR SPACE ASTROPHYSICS AT CEA

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### I. INTRODUCTION

The Laboratoire Electronique et Traitement de l'Information (LETI) of the Commissariat à l'Energie Atomique (CEA, Grenoble, France) has been involved in the development of infrared detectors based on HgCdTe (MCT) material for over 30 years, mainly for defence and security programs [1]. Once the building blocks are developed at LETI (MCT material process, diode technology, hybridization, ...), the industrialization is performed at SOFRADIR (also in Grenoble, France) which also has its own R&D program [2].

In past years, LETI also developed infrared detectors for space astrophysics in the mid infrared range – the long wave detector of the ISOCAM camera onboard ISO – as well as in the far infrared range – the bolometer arrays of the Herschel/PACS photometer unit –, both instruments which were under the responsibility of the Astrophysics department of CEA (IRFU/SaP, Saclay, France).

Nowadays, the infrared detectors used in space and ground based astronomical instruments all come from vendors in the US. For programmatic reasons – increase the number of available vendors, decrease the cost, mitigate possible export regulations, ... – as well as political ones – spend european money in Europe –, the European Space Agency (ESA) defined two roadmaps (one in the NIR-SWIR range, one in the MWIR-LWIR range) that will eventually allow for the procurement of infrared detectors for space astrophysics within Europe.

The French Space Agency (CNES) also started the same sort of roadmaps, as part of its contribution to the different space missions which involve delivery of instruments by French laboratories. It is important to note that some of the developments foreseen in these roadmaps also apply to Earth Observations.

One of the main goal of the ESA and CNES roadmaps is to reduce the level of dark current in MCT devices at all wavelengths. The objective is to use the detectors at the highest temperature where the noise induced by the dark current stays compatible with the photon noise, as the detector operating temperature has a very strong impact at system level. A consequence of reaching low levels of dark current is the need for very low noise readout circuits.

CEA and SOFRADIR are involved in a number of activities that have already started in this framework. CEA/LETI does the development of the photo-voltaic (PV) layers – MCT material growth, diode technologies –, as well as some electro-optical characterisation at wafer, diode and hybrid component levels, and CEA/IRFU/SaP does all the electro-optical characterisation involving very low flux measurements (mostly dark current measurements). Depending of the program, SOFRADIR can also participate in the development of the hybrid components, for instance the very low noise readout circuits (ROIC) can be developed either at SOFRADIR or at CEA/LETI.

Depending of the component specifications, the MCT epitaxy can be either liquid phase (LPE, which is the standard at SOFRADIR for production purposes) or molecular beam (MBE), the diode technology can be n/p (standard at LETI and SOFRADIR) or p/n (under development for several years now) [3], and the input stage of the ROIC can be Source Follower per Detector (SFD for very low flux low noise programs) or Capacitive Trans Impedance Amplifier (CTIA for intermediate flux programs) [4].

This paper will present the different developments and results obtained so far in the two NIR-SWIR and MWIR-LWIR spectral ranges, as well as the perspectives for the near future. CEA/LETI is also involved in the development of MCT Avalanche Photo Diodes (APD) that will be discussed in other papers [5,6].

## II. DEVELOPMENTS IN THE NIR-SWIR SPECTRAL RANGE

### A. Very low dark current, very low noise detectors for astrophysics: the NIR Large Format Array program

In the frame of its NIR-SWIR roadmap, ESA is funding the development of a 2Kx2K 15 $\mu$ m pitch array with the aim of reaching the level of electro-optical performances that are required for astrophysics missions such as EUCLID. The first phase of this activity was devoted to the demonstration of the performance of the MCT material (dark current and quantum efficiency), while the second phase was devoted to the manufacturing of a  $\geq 512 \times 512$  hybrid component. The main goal is to reach a very low dark current, operating the detectors in the 100K temperature range. CEA has been selected for the first two phases of this activity, and developed MCT components built from MBE epitaxy using p/n diode technology, with a target cutoff wavelength of 2.1 $\mu$ m. The dark current specification to achieve for these components was 0.1e-/s/pixel at 110K. In phase 1, the PV layers have been hybridized on a 384x288 SFD ROIC already existing at SOFRADIR from a previous CNES contract [7]. In phase 2, the larger (640x512 diodes) PV layers have been hybridized on a new ROIC developed at CEA/LETI and based on the SOFRADIR design. During phase 1, additional devices with longer (2.45 $\mu$ m) cutoff wavelength (MBE, p/n) or different technology (LPE, n/p) have also been characterised in order to compare the performances [8].

The quantum efficiency (QE) of the devices is very good (Fig. 1) and is above 65% from 0.8 to 1.85 $\mu$ m. Unfortunately, the cutoff wavelength happened to be shorter than expected, around 1.9 $\mu$ m.

All dark current measurements performed in the 2 phases of the NIRLFSA program are synthetised in Fig. 2. The NIRLFSA devices proper are shown in dark blue (phase 1) and pink (phase 2) data points. A technological accident happened in the process of the phase 2 devices which resulted in a very high surface leakage current. The net result is an overall dark current at 110K much higher (2e-/s/pixel) than the specification, where the dark current measured with the phase 1 devices was 0.7 e-/s/pixel.

The black data points correspond to the standard LPE n/p LETI technology at a cutoff wavelength of 1.96 $\mu$ m, showing that this technology also has the potential of reaching very low dark current, even though the dark current seems to reach a floor at around 1e-/s/pixel at low temperatures.

The plain lines at high temperatures are fits used to derive the band gap energy of the MCT material from the dark current measurements. These energies are in very good agreement with the band gap energies derived from the cutoff wavelengths measured from the spectral responses of the devices under photon flux.

Both SOFRADIR and LETI SFD ROIC show a very low readout noise of about 7e- rms (single readout) for a readout rate of typically 100kpixel/s. At the operating bias voltage choosen for the dark current measurements, the non linearity of the LETI SFD ROIC is typically 3% over a 60ke- dynamic range.

Some devices have also been characterised at 40K. At this very low temperature, the two ROICs used are fully functional with no significant degradation of performances.

ESA funded an additional batch that will be characterised in Fall 2014. The batch will comprise both MBE and LPE epitaxies in ordre to properly compare their performances.

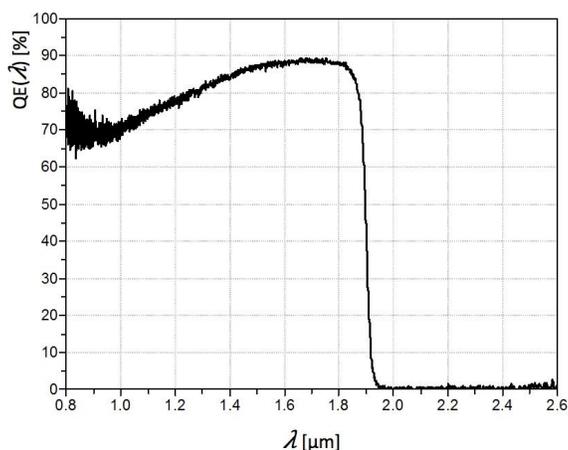


Fig. 1 Typical quantum efficiency of the NIRLFSA phase 2 devices, measured on individual diodes at 77K.

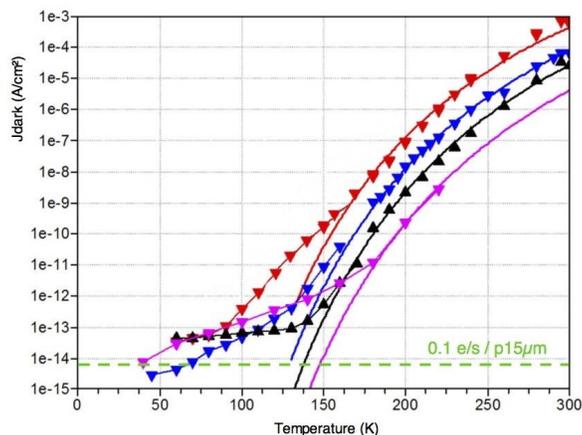


Fig. 2 Dark current vs temperature for the NIRLFSA devices. Red: 2.45µm cutoff p/n MBE, dark blue: 2.03µm cutoff p/n MBE phase 1, black: 1.96µm cutoff n/p LPE, pink: 1.90µm cutoff p/n MBE phase 2.

*B. Low dark current at high temperature detectors for small satellites: the SWIR\_HT program*

Reaching very low dark currents may become very difficult in small satellites where system constraints (low Earth orbit, low power and mass budgets) make it impossible to operate the detectors at low temperatures. In this case, it is important to know the highest operating temperature where the dark current stays compatible with the scientific requirements. CNES funded the manufacturing and characterisation of NIR devices to assess this, in the frame of the study of projects such as microCarb. The components were identical to the ESA phase 2 components, with the exception of the MCT epitaxy, which in this case was the standard LETI LPE grown material. p/n process was chosen to reach the highest level of performance at high temperatures. The dark current specification for this program was 0.03 nA/cm<sup>2</sup> at 200K, which translated into about 420 e-/s per 15µm pixel.

Two devices have been characterized at CEA/SAP. The dark current at 200K for these two devices are 34 and 41 pA/cm<sup>2</sup>, very close to the 30 pA/cm<sup>2</sup> specification (see Fig. 3). The dark current follows a diffusion trend line from 240 to 200K. Unfortunately, the SWIR\_HT devices were manufactured shortly after the ESA NIRLFSA devices. The technical problems encountered in the facility that plagued the NIRLFSA program, as well as several other programs, also affected the SWIR\_HT program. This resulted again in a very high surface leakage current, resulting in a very poor dark current performances at temperatures lower than 200K.

The typical quantum efficiency of the SWIR\_HT devices is shown in Fig. 4. The cutoff wavelength is 2.1µm as expected, and the QE is above 70% all the way from 0.8 to 2.05µm. As was the case for the NIRLFSA devices, the substrate was not removed for the SWIR\_HT devices.

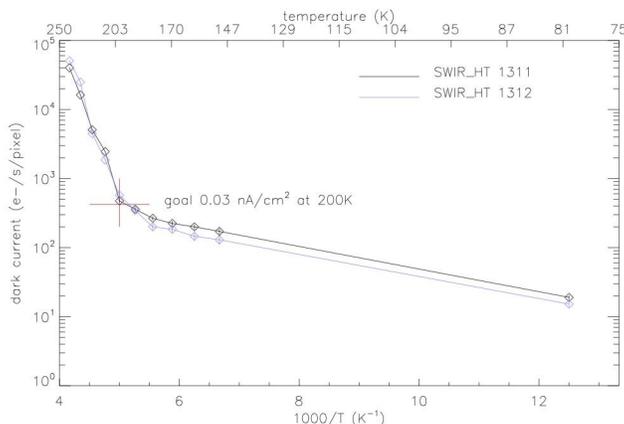


Fig. 3 Dark current vs temperature for the SWIR\_HT devices.

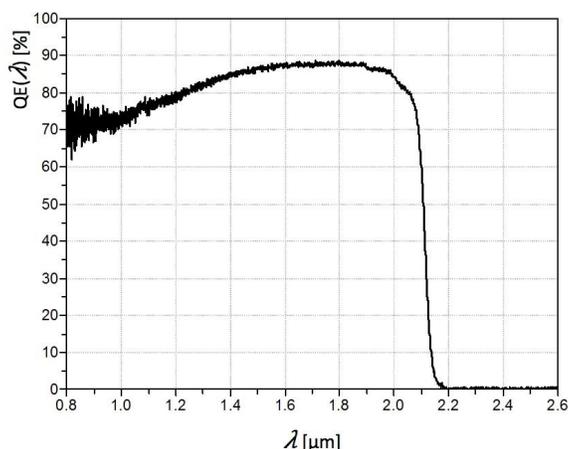


Fig. 4 Typical quantum efficiency of the SWIR\_HT devices at 180K.

### III. DEVELOPMENTS IN THE MWIR-LWIR SPECTRAL RANGE

In parallel to the NIR-SWIR activities, several programs have started in the frame of the assessment phase of the EChO mission proposed to ESA for the Cosmic Vision M3 slot.

#### A. Existing technology assessed at very low temperatures: the ESA EChO program

ESA funded a program to assess the performances of existing technologies but used at temperatures (30-40K) much lower than their nominal operating temperature. To address this issue, CEA built several detectors covering the EChO spectral channels 3 (2.8 – 5 μm), 4 (5 – 8.3 μm) and 5 (8.3 – 11 μm) with targeted cutoff wavelengths at 40K of 5.7, 10.1 and 12.5 μm. The PV layers used the standard LETI/SOFRADIR n/p (channels 3 and 4) and p/n (channel 5) diode technologies built on LPE epitaxy. The PV layers were hybridized onto an existing 320x240 30 μm pitch ROIC developed at CEA/LETI and using an CTIA input stage. In some devices, a number of variations of diodes were implemented (diode geometry, passivation type, ...).

For all channels, the dark current specification was 100e-/s for a 18 μm pixel, which translated into 278 e-/s for a 30 μm pixel.

#### Channel 3 results

The measured cutoff wavelength of the channel 3 devices was 6.1 μm at 40K. The dark current specification was met at 70K for the small diode variation.

The quantum efficiency of these devices is strongly coupled to the level of dark current: the diffusion length in p type material is quite small, and the fill factor depends on the size of the diode. Large diodes have higher quantum efficiency, but in a generation-recombination regime, they also have higher dark currents.

#### Channel 4 results

The measured cutoff wavelength of the channel 4 devices was 10.1 μm at 40K. The dark current specification is not met even at 30K. The PV layers have been built from an existing alloy ingot which chemical composition gave a cutoff wavelength much longer than the scientific needs of the EChO channel 4. Extrapolating the results to the proper cutoff wavelength (9 μm), the dark current specification could be met in the 30-40K range with n/p technology, but the intrinsic reduction of dark current going from n/p to p/n technology would definitely add more margin.

As for channel 3 devices, the quantum efficiency of channel 4 devices strongly depends on the diode size.

#### Channel 5 results

The measured cutoff wavelengths of the channel 5 devices were 11.9 μm and 12.3 μm at 40K. The 11.9 μm device meets the dark current specification but only at a very low temperature of 19K (Fig. 5).

The diffusion length in n type material is much longer than in p type material, resulting in fill factors closer to unity and less dependency of the quantum efficiency with the size of the diode. The QE is very good, around 70% in the 60 to 80K range (Fig. 6). Still, the diffusion length starts to decrease around 40-50K and the quantum efficiency starts to decrease with decreasing temperature, first for small diodes, then for larger diodes at lower temperatures.

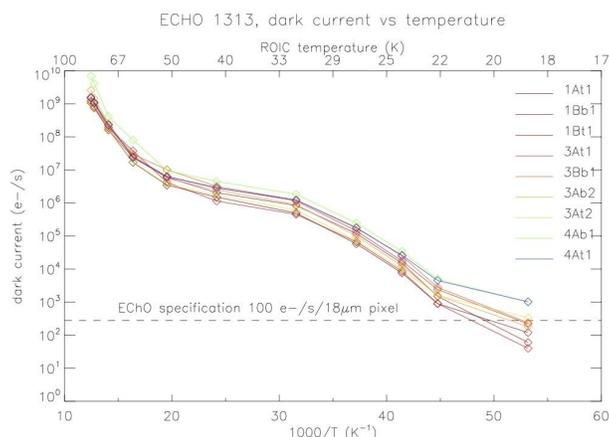


Fig. 5 Dark current vs temperature for different diode variations of one channel 5 device.

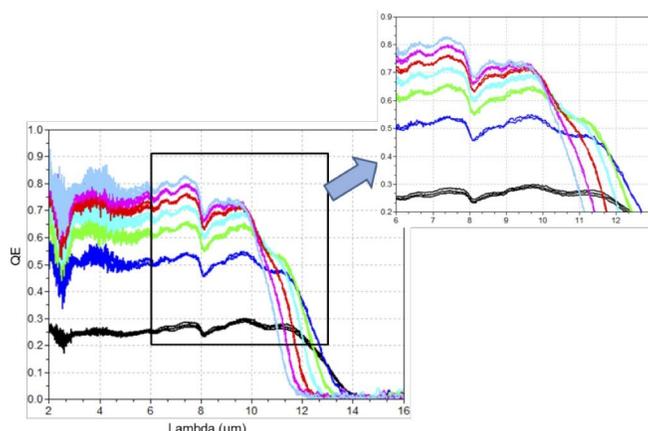


Fig. 6 Quantum efficiency for one channel 5 device, showing the increase of cutoff wavelength and decrease of QE with decreasing temperature (from top to bottom: 78, 70, 60, 50, 40, 30 and 20K).

It is worth noting that the ROIC was fully functional down to 20K, even though it was not designed to work at such low temperatures. The only noticeable degradation of performance was on the readout noise, which increased by about 30% at the lowest temperature.

*B. Improved p/n technology for the LWIR range: the CNES EChO program*

CEA/LETI started to improve its p/n diode technology in order to adapt it to the astrophysics needs. A first try at this improved technology was funded by CNES in the frame of the study of the MWIR-LWIR channel of the EChO payload. The CNES study only addressed the LWIR spectral range of EChO, with the same target cutoff wavelength of 12.5µm at 40K than the channel 5 ESA devices. LPE PV layers built from both standard and improved diode technologies were hybridized on the same 320x240 CTIA ROIC that was used for the ESA devices.

Fig. 7 compares the dark current level (normalised to the diffusion dark current) for both diode technologies. The standard technology leaves the diffusion regime at about 60K where the improved technology stays diffusion limited down to about 49K [9].

Unfortunately, the measurement of the spectral responses showed that the cutoff wavelength decreased very steeply below 50K, resulting in a very low quantum efficiency at 40 and 30K. The only way to recover the proper spectral responses at low temperatures was to drive the diodes at a much higher bias voltage (typically 1V instead of the standard 50 to 100mV). The most probable explanation is that this first try at the improved technology went too far and created a potential barrier prohibiting the photogeneration of the charge carriers.

Following this study, CNES funded a second batch of devices to allow for a finer tuning of the improved p/n technology. This second batch of devices will be characterized in Fall 2014.

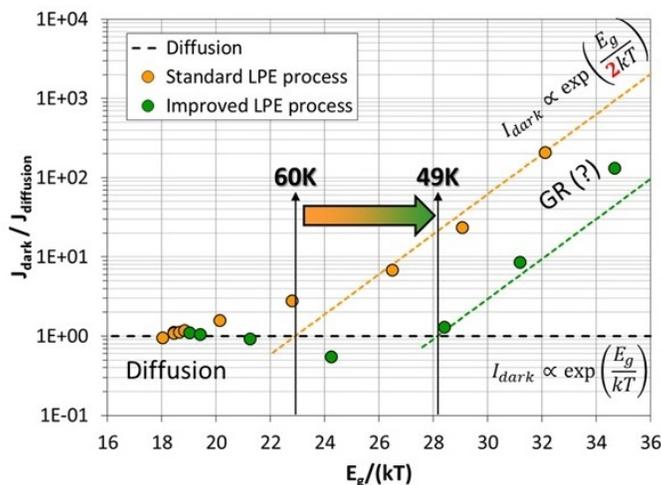


Fig. 7 Comparison between standard and improved p/n technology, showing a 10K gain in the transition between diffusion and generation-recombination regimes.

#### IV. DISCUSSION AND PERSPECTIVES

The different programs presented in the previous sections were the first tries to improve the low dark current performances of infrared detectors developed at CEA. Both MBE and LPE epitaxies, and both n/p and p/n diode technologies have been used. Fig. 8 compares the performances achieved so far at CEA with the published data of Teledyne and Raytheon diodes in the NIR-SWIR spectral range.

The standard LPE n/p technology in production at SOFRADIR delivers more or less the same performance as the less mature LETI MBE p/n technology. A more detailed comparison of the two epitaxies will be given at the end of 2014 once the last batch of devices built in the frame of the NIRLFSa phase 2 program is characterised.

Nevertheless, there is much more room for improvement in the p/n technology, an improvement that is definitely required as the dark current level achieved so far is still about one order of magnitude too high compared to what is needed for the very low flux space astrophysics.

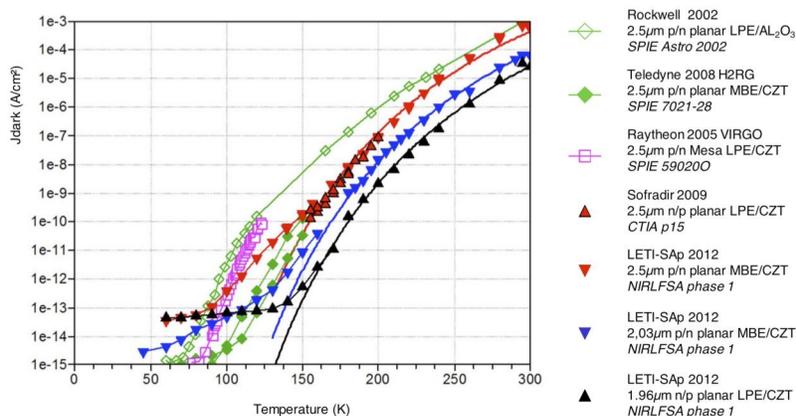


Fig. 8 Comparison of dark current performances for LETI, Teledyne and Raytheon diodes.

In the 5 to 12.5µm range, the n/p flavour is not an option, even in the blue part of the range as there is not enough margin in the dark current performance. The gain expected by the standard p/n technology is such that this option could fulfill the needs in the 5 to 8µm range. In the 8 to 12.5µm range, improvements over the standard p/n technology are needed for two reasons: first to actually meet the requirements in dark current, but also to allow for diodes large enough to mitigate the decrease of the diffusion length at very low temperatures and therefore still deliver a high quantum efficiency at these temperatures. The second batch of devices built in the frame of the CNES EChO program will help assess the progress made in this improved technology.

The detectors developed in all these programs use ROICs with either an SFD or an CTIA input stage. It is clear that the SFD architecture will always give a lower readout noise, but there is a price to pay.

First the SFD architecture is intrinsically non linear. The charges are integrated in the diode, which changes the capacitance of the diode during the integration and therefore the conversion gain of the system. The net result is a limited dynamic range with a very low (a few %) non linearity. The only way to make the system more linear is to have a MOS capacitance significantly larger than the diode capacitance, in which case the readout noise (expressed in e-) will also significantly increase. It would then be very interesting to investigate the feasibility of a very low noise CTIA architecture, where the charges are integrated in a fixed capacitance, making the system extremely linear. The second advantage of such a very low noise CTIA is that the biasing of the diodes would be very well controlled, all diodes being operated exactly at the same bias voltage. This would basically remove all capacitive coupling between diodes and therefore would improve the image quality of the detector.

The second disadvantage of the SFD with respect to the CTIA is that the operating point of the diodes keeps changing during the integration. In the NIR-SWIR range, the diodes have a fairly wide plateau of bias voltages within which the dark current performances do not vary much. This is no longer valid in the MWIR-LWIR range and, depending on the full well requirement, it may well be very difficult to use an SFD ROIC in this spectral range as the diodes may end up outside their operating range. One way of doing this would be to increase the MOS capacitance, provided the noise requirement is still met. The overall performances of such an SFD ROIC would not be very different from those of a very low noise CTIA architecture, provided the fairly high power dissipation of the CTIA ROIC meets the system thermal requirements.

Following this path, it would be very interesting to study the feasibility of a very low noise (about 15 e- rms single readout) low power dissipation CTIA architecture, or even assess the overall performances of a device made of a PV layer hybridized onto an SFD architecture having a standard level of readout noise, and a device made of the same PV layer hybridized onto an CTIA architecture having typically 50% more noise.

## V. CONCLUSION

Since 2010, CEA has been developing MCT detectors to address the needs of space astrophysics both in the NIR-SWIR and MWIR-LWIR spectral ranges in the frame of the roadmaps defined by ESA and CNES in this domain. The main goal of the activity is to reduce the level of dark current, while keeping a high quantum efficiency. These low levels of currents also require the development of very low noise readout circuits.

A number of devices have been manufactured, from LPE and MBE epitaxies, and using n/p and p/n diode technologies. The ROIC have either an SFD or an CTIA architecture, and have been developed at CEA as well as at SOFRADIR.

For the very low flux NIR-SWIR applications, the standard MBE p/n technology already gives good dark current results (0.7 e-/s at 110K for a 2 $\mu$ m cutoff wavelength) but this performance is still about one order of magnitude below what is required. The quantum efficiency of the devices is very good, around 70%.

The same technology applied at high temperatures already meets the dark current requirements.

In the MWIR-LWIR range, the LETI standard LPE p/n technology does not meet the requirement at the longer wavelengths. A first try at an improved p/n technology gave very encouraging results, as the dark current stayed in a diffusion limited regime down to 50K, compared to 60K for the standard p/n technology.

In parallel with the work on the PV layers, CEA and SOFRADIR also developed very low noise ROICs based on an SFD architecture, with typical single readout noise of 7e- rms.

Dark current measurements of additional devices will take place at CEA/Sap in Fall 2014, both in the NIR-SWIR range on MBE and LPE p/n devices, and in the LWIR range with a second try at the improved LPE p/n technology.

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#### ACKNOWLEDGEMENTS

The developments presented in this paper have been funded by ESA contracts 4200022949/10/NL/CP and 4000106410/12/NL/HB, CNES contracts 127094, 128100 and 130731 and additional CEA funding. This work has also been partially supported by the LabEx FOCUS ANR-11-LABX-0013.