

Low dark current P-on-N technology for space applications



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Low dark current *p*-on-*n* technology for space applications

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ABSTRACT

Space applications are requiring low dark current in the long wave infrared at low operating temperature for low flux observation. 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, a specific development of a TV format focal plane array with a cut-off wavelength of 12µm at 40K has been carried out.

For this application, 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 35% 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.

Keywords: Space, infrared detector, HgCdTe, long wave infrared, p-on-n photodiodes, dark current

1. INTRODUCTION

SOFRADIR is the European leader in high performance imaging related to Defense, Space and Civil systems. As a worldwide company, Sofradir brings to its customers its experience and expertise in the development of leading-edge technologies. Our company masters and proposes a wide range of technologies: Indium Gallium Arsenide (InGaAs), Indium Antimonide (InSb), Mercury Cadmium Telluride (HgCdTe) and Quantum Well-Infrared Photodetector (QWIP) technologies.

With the access to and control of these complementary infrared (IR) technologies under one roof, Sofradir joins a very small circle of IR detector manufacturers with expertise in all the cooled and uncooled IR technologies. Sofradir is able to provide the best-suited technology with respect to its customers' applications. These different technologies are used depending on applications requirements mainly concerning the detection range as well as detection performance in various weather conditions. Figure 1 presents the atmospheric transmission spectrum defining the different IR bands, like the Mid-Wave infrared range (MWIR) or the Long-Wave infrared range (LWIR) in regards with the Sofradir's technologies.



Figure 1. SOFRADIR's Technologies cover the entire infrared spectrum.

SOFRADIR started development of infrared detectors for space applications beginning of the nineties. As a matter of fact, SOFRADIR has now a heritage of more than 25 years in space activity by working in close cooperation with national space agencies and companies worldwide. It concerns the following fields:

- Earth observation for military applications;
- Earth observation for commercial applications (agriculture, atmosphere chemistry, meteorology, environment and disaster monitoring);
- Science, deep space and scientific applications (astronomy).

Thanks to the flexibility of the MCT technology and the high reliability of the hybridization process, SOFRADIR is able to offer space qualified detectors that cover a wide spectral range from the visible spectrum up to very long wavelength ($\geq 15 \mu$ m), with linear or array formats, with long-life coolers or without coolers for passive cooling. Screening and qualification flow charts were established in cooperation with the French, European or other national space agencies and are based on the most relevant testing methods for space environment. All these contributors have enabled SOFRADIR to deliver more than 70 flight models over the past decade and more than 20 second generation infrared detectors among delivered flight models have been or are currently operating in various spacecraft.[1]

In this paper, a prototype addressing science and deep space applications is presented. It has been developed in order to reach a low dark current with a cut-off wavelength of $12\mu m$ at 40K. This prototype is a TV format, 640x512 with a 15 μm pitch. First, this paper is describing the focal plane array technology used for this prototype. Then, in a second part, the electrical and electro-optical characterizations are presented.

2. FOCAL PLANE ARRAY TECHNOLOGY

For 30 years, Sofradir developed and industrialized the legacy technology based on a *n*-on-*p* planar homojunction structure. [2] The HgCdTe photodiode is built thanks to a *p*-doped absorbing material by Hg vacancies and *n*-type regions made by ion implantation creating the array. Mercury vacancies are leading to a short minority carrier lifetime due to Shockley-Read-Hall recombination. Electron lifetime in V_{Hg} doped HgCdTe is in the range of nanoseconds at the operating temperature. This range of lifetime induces a large dark current.

Moreover, in the legacy planar structure, due to a large resistivity of the p type HgCdTe material compared with the *n*-type one, a large series resistance is induced in the absorbing layer. Under a high flux, as in LWIR, a large current is going through the photodiode leading to a lower bias applied by the ROIC.

For both reasons, in the framework of DEFIR, the joint laboratory between Sofradir and the CEA-LETI, the *p*-on-*n* technology has been developed for the last ten years. This new technology allows to increase minority carrier lifetime as well as to decrease series resistance. [3]

2.1 P on N technology

The first key aspect in development of high performances FPA IR detector is the ability to grow high quality HgCdTe material on a perfectly lattice matched and high quality substrate CdZnTe.

Large mono-crystalline CdZnTe substrates ($\Phi = 90$ mm) are routinely grown in Sofradir. These substrates are (111) oriented to allow HgCdTe growth. Zn ratio is precisely mastered in the range 1% to 5% to ensure a lattice match with the HgCdTe layer. Temperatures profiles and Cd pressure control lead to high quality material with a typical dislocations density in the range 1.10⁴ cm⁻². No micro-defects larger than 1µm, such as precipitates, are observed. [4]

The absorbing material, HgCdTe, is grown by liquid phase epitaxy with a (111) orientation. HgCdTe crystalline quality is as high as or better than that of the substrate. The X_{Cd} content is tuned to address LWIR or MWIR spectral range at the operating temperature. Doping level of the absorbing material is in the 10^{15} cm⁻³ range. Compared to the legacy technology, the doping level has been decreased by one order of magnitude in order to decrease the diffusion dark current. The homogeneity of the doping level and its reproducibility has been tracked to ensure a high technology yield. Flatness of the epitaxial layer has been optimized to ensure a high flip-chip hybridization yield.

10 wafers were processed and characterized in terms of cutoff wavelength, thicknesses of the epilayers and doping level as a function of temperature from 80K up to 300K.

Then, a dedicated planar process is realized on the epi-layer. A sketch of the planar *p*-on-n technology is represented in Figure 2.



Figure 2. Sketch of the planar p-on-n technology.

The main steps of the planar *p*-on-*n* process are passivation of the top surface of HgCdTe, arsenic implantation and metallization. Arsenic implantation is defining the junction area. The shape and the depth of the arsenic area have been optimized to limit the generation-recombination current contribution in the space charge region. Annealing is required to activate the arsenic atoms as *p*-type dopants. The process flow of this prototype is similar as the one used to process Sofradir's product Scorpio LW with a 9.5µm cutoff wavelength at 80K. [5], [6]

Thanks to the *p*-on-*n* technology and a lower doping level, a significant decrease in dark current is expected compared with the legacy one. Figure 3 represents dark current density as a function of 1000/T for both Sofradir's *p*-on-*n* and *n*-on-*p* technologies in a diffusion regime with $X_{Cd} = 0.22$ ($\lambda_c = 12\mu$ m at 40K). Energy gap as a function of temperature is described by Hansen. [7] In the range from 40K up to 100K, *p*-on-*n* technology exhibits a two decades lower dark current than the legacy technology. This improvement thanks to the *p*-on-*n* technology can be used to increase the signal to noise ratio or to increase the temperature with a constant dark current.



Figure 3. Simulated dark current density as a function of 1000/T for both p-on-n and n-on-p technologies in a diffusion regime for $X_{Cd} = 0.22$

Furthermore, for this prototype different process flows were used in order to decrease dark current and to enlarge bias plateau. To do so, we focused the development on the passivation of the absorbing layer. These variants are based on the previous studies dedicated to space and science imaging applications. [8], [9]

2.2 ReadOut Integrated Circuit

ROIC used for the prototype has been designed to integrate low currents, and thus use CTIA architecture input stage. The photodiode current is integrated in the CTIA capacitance. In this case, the photocurrent is directly integrated in the feedback capacitor of a transimpedance amplifier. This structure has the advantages to provide a very good linearity of the input stage because of the wide input electrical bandwidth. Therefore, whatever will be the input flux (especially for low flux ranges), this type of structure is perfectly compatible with the requirements. In addition, this architecture is flexible and can answer different application needs.

The specifications of the ROIC are described in Table 1. This ROIC presents two charge handling capacity, the first one is 98 000 electrons to work in a high gain mode whereas the second one is 776 000 electrons to work in a low gain mode. The read out noise are 20 electrons and 176, respectively. The power consumption of the ROIC is 150mW.

Table 1. ROIC specifications.

Parameters	Specifications	
Format	640*512	
Pitch	15 μm	
Input stage	CTIA	
Operating temperature range	40K - 300K	
Correlated Double Sampling	External Function	
Power	150 mW	
Frama fraguancy	60 Hz (maxi. with CDS)	
Traine frequency	120Hz without CDS	
Video Output :		
• Type	Analogic	
Pixel Frequency	• 10 MHz	
• Number of output	• 2 or 4	
Integration Mode	Rolling Shutter IWR	
Integration Time	User defined	
High Gain		
• Charge handling capa.	• 98 000 e-	
Read out noise	• 20e- @ 80K	
Low Gain		
• Charge handling capa.	• 776 000 e-	
Read out noise	• 170e-	
Non linearity	<±1% @ 300K	

2.3 Flip-chip hybridization

An important work has been done to optimize the CMOS ROIC preparation and hybridization. Hybridization is performed by Indium bumps with a flip-chip equipment. This hybridization allows maintaining excellent process yield and reliability at cryogenic operating temperature.

After flip-chip bonding, the initial CZT substrate is thinned down to the MCT absorbing layer. An antireflective coating is deposited on the incoming light surface.

3. ELECTRICAL AND ELECTRO-OPTICAL PERFORMANCES

In this section all the characterizations performed on test chip and FPA are presented. Up to now, the low temperature characterizations down to 40K are still running.

3.1 Test chip characterizations

After the detection circuit process, a first evaluation of the performances is done based on current measurements as a function of voltage and as a function of temperature. These characterizations are performed on test chips. Two diodes per variants and per wafer are characterized. The test chip is presented in Figure 4.



Figure 4. (a) Test chip characterized after the technological process at a 15µm pitch, (b) SEM image of a single test chip.

The test chip presented in Figure 4 allows characterizing single diodes in a 15μ m neighborhood. On Figure 4 (a), different geometries/processes are included. Both neighboring diodes and the studied diode can be separately biased. For all the characterizations presented in this section, both studied diode and neighboring ones are presenting the same bias.

Our set-up is presenting a significant photonic current for this cut-off wavelength. At 80K, the parasitic photonic current density is in the range of 1 to 2.10^{-3} A/cm⁻².

Two designs of passivation have been studied for the development of this prototype. These designs are labeled A, B in this paper. Design A corresponds to the standard design, the same as our product Scorpio LW. Design B is an improved one.

First, the aim of design B is to enlarge the bias plateau in order to lower the contribution of band to band tunnel current. In order to characterize it, i(V) characteristics are performed at 100K for the two designs and are presented in Figure 5, squares and triangles are the experimental data.



Figure 5. Current as a function of reverse bias at 100K for the two designs A and B. Dots are experimental data, lines are the simulated BTB current contributions at 100K and dotted lines are the extrapolated contribution of BTB current at 40K

As described in Figure 5, band to band tunnel (BTB) current is the limiting factor for large reverse bias; it has been simulated using the geometrical parameters of the p on n junction at 100K for both designs. Thanks to design B, dominant BTB tunnel current is minimized allowing the enlargement of the bias plateau by 0.5V compared to design A.

This modification in the process is successful. At 100K, focal plane arrays are not working at high reverse bias. Nevertheless, as the operating temperature decreases, the HgCdTe energy band gap is decreasing too. As a consequence, the BTB current becomes dominant at lower reverse bias. It is described by dotted lines in Figure 5 at 40K. The simulations at 40K are extrapolated to the ones at 100K. Design B can be useful for low temperature and low flux applications.

Second, design B is supposed to decrease dark current mean value by 30%. Thanks to i(V) characteristics, the mean value of current is extracted at a reverse bias of -0.3V from 80K up to 140K. Then, a comparison between designs A and B is operated leading to Table 2.

T(K)	1000/T (K ⁻¹)	Decrease of current	Comments
80	12.5	-1%	Photonic current
100	10	-23%	
120	8.3	-37%	Diffusion current
140	7.1	-22%	

Table 2. Decrease of current mean value thanks to design B compa	ared to design A.
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According to the results presented in Table 2, photonic current is comparable for the two designs. On the other hand, dark current, in the diffusion regime is decreased between 20 and 37% thanks to design B compared to design A.

3.2 FPA characterization at 80K

In this section, all the characterizations are performed at 80K. A 3.1° field of view was used under illumination. This aperture was chosen to lower the photonic current allowing a proper measurement with low integration time. The integration time was set to 324μ s for half well fill. At this temperature for such long wavelength infrared detectors, a significant contribution of the collected current corresponds to dark current. In front of a 25°C black body, about 20% of the DC level collected by the ROIC corresponds to dark current.

Responsivity measurements have been performed using two blackbody temperatures, 20-30°C. Figure 6 represents the responsivity histogram at 79K under illumination.



Figure 6. Responsivity histogram under illumination, 79K and 20-30°C BB.

This first prototype presents a homogeneous responsivity with a Gaussian distribution of the pixels. Mean value of the responsivity 3.07pA/K. Such homogeneity in response illustrates the high level of quality of the epilayer in terms of crystallinity, control of its thickness and Cadmium content. Some white pixels are appearing on the mapping. These pixels are corresponding to defective ones. These isolated pixels are attributed to saturated pixel or pixels mainly

dominated by dark current. The defective pixels are attributed to the technological process. These defects should be significantly decreased thanks to an increase in the maturity of the technology.

The RMS noise has been characterized. It can be compared to the current shot noise (theoretical ideal noise). The ratio between the two is around 1. This value indicates that the photodiodes do not present any excess noise and thus are limited by current shot noise.

Then, NETD (Noise Equivalent Temperature Difference) has been characterized with a 25°C BB. NETD histogram is presented in Figure 7.



Figure 7. NETD histogram under illumination, 79K and 25°C BB.

The mean value of NETD is 110mK. This value is in agreement with the measurement conditions (high F number, dark current noise contribution, and operating temperature 79K). Despite the dots with higher NETD, corresponding to a small tail on the histogram (Figure 7), the performances of this first prototype are promising.

Table 3 is summarizing the performances of this first prototype using design A. Cutoff wavelength has been evaluated for this FPA to $11.12\mu m$ at 78K which corresponds to $12.4\mu m$ at 40K.

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	Mean value
IR flux current (pA)	212.10
Dark current (pA)	39.59
Photonic current (pA)	172.40
Responsivity (pA/K)	3.07
IR flux RMS noise (mV)	1.40
IR flux excess noise	0.99
NEDT (mK)	109.50
Dark RMS noise (mV)	1.40
Dark excess noise	1.01

Table 3. Main performances of the first prototype, at 79K

In order to compare the two designs, the performances of two FPAs are compared, one with the improved design and the one presented above. It is summarized in Table 4.

First, the responsivity is nearly the same between the two FPA. It is 4% lower for the design B FPA. This value is interpreted by a shorter cutoff wavelength of design B FPA equal to 11.06µm at 78K. Dark current is significantly reduced for design B FPA compared with design A one. It is divided by a factor of 2.2 from variant A to variant B. Dark current reduction is not fully attributed to the improvement of the technology. Part of the reduction of dark current is attributed with design B FPA. Nevertheless, 35% of the reduction of dark current is attributed with design B is attributed to the improvement of the technology.

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	Variant	Design A	Design B		
Under	Current (pA)	212.1	184.6		
flux	Resp. (pA/K)	3.07	2.96		
conditions	NETD (mK)	109.5	104.1		
Under dark	Current (pA)	39.6	17.4		
conditions	Excess noise	1.01	1.00		

Table 4. Comparison of the performances for the two designs A and B at 79K

Despite the difference of cutoff wavelength, NETD of design B FPA remains lower than design A FPA. A complete characterization of these two FPAs has to be performed at lower temperature soon.

3.3 First evaluation at low temperature

An improved FPA has been characterized at low temperature down to 60K with a helium gas cryostat. Current-voltage measurements have been done (Figure 8): under dark conditions, the bias plateau is over 550mV at 80K and is more than 250mV at 60K. This last value is a mean one with a filter to exclude high defective pixels. At higher bias, leakage current attributed to BTB tunneling current becomes dominant.



Figure 8. Current-voltage characteristics for an improved FPA for different operating temperatures.

Figure 9 presents the evolution of dark current density with operating temperature down to 60K. The dark current density is below the Rule07 from 80K down to 60K. But it decreases with a pure diffusion-type law $(\exp(-\frac{E_g}{kT}))$ from 80K down to 60K and so, slower than the one of Rule07. [10] This result is very promising but has yet to be confirmed at lower temperature in order to determine at which temperature the transition to another limiting regime occurs and if it would be enough to meet the requirements of this study.



Figure 9. Arrhenius plot of dark current density, dots are data, dashed line is simulation of the diffusion dark current and dotted in the Rule 07.

4. CONCLUSION

Sofradir and the CEA-LETI have realized a prototype based on the HgCdTe p-on-n technology with a 12µm cutoff wavelength at 40K. ROIC used for this prototype is based on a CTIA input stage with two different gains. Characterizations have been performed and presented in this paper down to 60K. Two designs of detection circuit have been studied; the first one is close to Scorpio LW product whereas the second one is improved for low flux and low temperature applications. Thanks to the second design, on one hand a decrease in dark current has been demonstrated and evaluated to -35%, and on the other hand an increase in the bias plateau is achieved thanks to lowering the tunnel current contribution.

5. ACKNOWLEDGMENT

The authors would like to thank all the SOFRADIR and CEA-Leti (LIR) teams, dedicated to quality work. The authors would like to thank the European Space Agency (ESA) for funding this study through ESA Contract 4000113066/15/NL/RA.

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