High reliability IR detectors for space and military application

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Abstract

In this paper we present the results of reliability tests performed on infrared detectors produced by VIGO System S.A. An evaluation test program of the PVI-3 and PVI-5 photodiodes for the EXOMARS space mission is described and the results of environmental, electrical and mechanical tests are presented. The article features as well the testing procedures of the thermoelectric coolers against large accelerations as well as method for monitoring of stability.

Keywords: optoelectronic, space, IR detectors, MCT

I. INTRODUCTION

The detectors for space and military applications need to meet special rigorous requirements. Their working conditions are very specific and differ a lot from what is present on the surface of the Earth. Moreover, they can not fail in the field: their failure would mean the loss of data which could constitute an epoch-making discovery. To prove the reliability of the detectors, they are being subjected to the series of preliminary tests.

The application of infrared detectors in space is often related to laser spectrometry aimed at detecting specific substances. 3.27 µm is the absorbed wavelength characteristic for CH_4, absorption of wavelength 2.78 µm would indicate the presence of CO_2 and H_2O [1]. The detectors evaluated for such application (e. g. for the EXOMARS space mission) were heterostructural HgCdTe photodiodes [2][3]of the spectral characteristics typical for PVI-3 and PVI-5 operating in 300 K – Table 1.

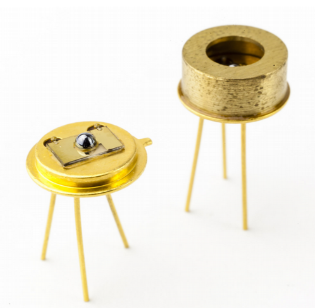

Fig. 1: PVI detector in TO39-based package.

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Table 1. Basic detector characteristics.

<table>
<tr><th>Series</th><th>Reference</th><th>Characteristics</th></tr>
<tr><td>PVI-3</td><td>PVI-3-0.5x0.5-TO39-NO WINDOW-35
50% $\lambda_{co\ (300\ K)} = 3$ µm
$\lambda_{peak} = 2.7$ µm</td><td rowspan="2">Package : TO-39
Optical area : 0.5x0.5 mm²
No window
Optically immersed
Lens : hyperhemispherical
Field of view : 35 deg</td></tr>
<tr><td>PVI-5</td><td>PVI-5-0.5x0.5-TO39-NO WINDOW-35
50% $\lambda_{co\ (300\ K)} = 5.4$ µm
$\lambda_{peak} = 4.5$ µm</td></tr>
</table>

The layers have been grown on the thick GaAs substrate during a metaloorganic vapour phase epitaxy process. The role of sidewalls mesa passivation has been fulfilled by the CdTe deposited during the magnetron sputtering process. Illuminated from the back, optically immersed detectors have been bonded to the sapphire submount and additionally attached with the underfiller. The contact between the chip carrier and the wire has been done with the silver polymer paste and reinforced with the glue.

A lot of tests have been performed according to the norm MIL-STD-883 [4]. The choice of testing methods and the evaluation program depends on the target application. Schematic evaluation test program which has been performed on a series of VIGO detectors is depicted in the Fig. 2.

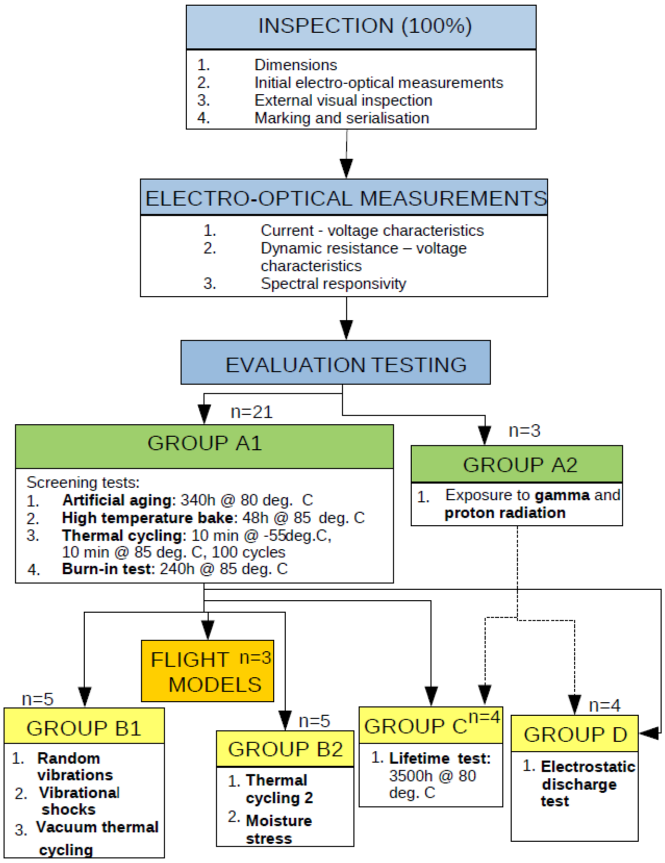

Fig. 2: Evaluation test program of the PVI-5 detectors dedicated for the EXOMARS space mission.

The EXOMARS testing program was aimed at selection of the so-called Flight Models (FM's) which were implemented in the final device. After standard measurements of I-V, Rd-V, $R_i(\lambda)$, $D^*(\lambda)$ characteristics the detectors have been divided into groups. The majority of them (group A1, Fig. 2) have been subjected to screening tests. At this stage, the statistical analysis has been performed in order to reject the devices that did not fulfill the 6σ condition. The resultant histograms are presented in Fig. 3 and Fig. 4. Among the group A1 three Flight Models have been selected. Tests performed on the detectors from the groups A2, B1, B2, C and D were aimed at simulation of demanding environmental, mechanical, electrical conditions and observation of the behaviour of the detectors. Some of these results are described in parts II, III and IV of the following article.

II. Environmental tests

The environment in space implies extreme temperatures – both hot and cold, abrupt and high temperature changes, elevated magnetic field, solar wind, sand storms and cosmic radiation. The detectors for the military applications often require to be able to operate at elevated humidity conditions. Environmental tests are aimed at demonstrating the reliability of the detectors in demanding circumstances.

All of the screening tests were environmental tests related to the operation of the detector at extreme temperatures. Elevating the ambient temperature is a method of artificial aging of the detector. Using the Arrhenius relation the activation energy of the material can be defined. A series of tests on MCT detectors have shown that its value is close to 0.5 eV. Therefore the artificial aging test (340h at 80ºC) corresponds to about 375 days at 20ºC. The temperature of 80ºC is considered as the maximum safe long-term operating temperature for VIGO detectors. The histograms presented in the Fig. 3 and Fig. 4 demonstrate the tendency of the slow degradation of the semiconductor material at higher temperatures, e.g after the burn-in test. The thermal cycling is aimed at introducing the stresses engendered by contracting and expanding of the semiconductor material, wires, glue etc.

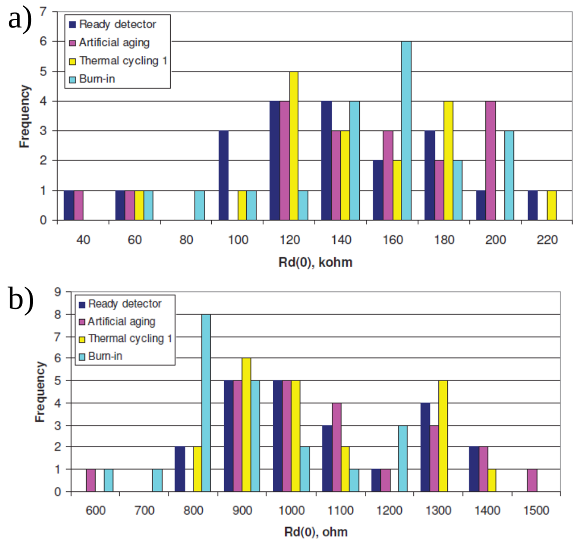

Fig. 3: Histogram of Rd(0) distribution after the screening tests for a) PVI-3 and b) PVI-5 photodiodes.

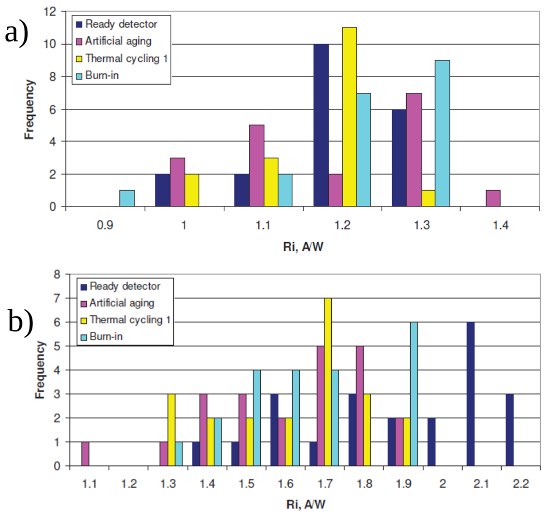

Fig. 4: Histogram of Ri(0) distribution after the screening tests for a) PVI-3 and b) PVI-5 photodiodes.

In general, the artificial aging and thermal cycling do not contribute to changes in the distribution of Rd(0) and $R_i(\lambda)$ both for the group of PVI-5 and PVI-3. It means that one year of operation would not degrade the semiconductor in any aspect. The major changes are caused by the burn-in test. It can be noticed that detectors with larger energy gap, like PVI-3, are less vulnerable to thermal tests. From the group of 21 PVI-3 detectors only one has been rejected after the burn-in test, from the group of PVI-5, 5 out of 22 detectors have not been qualified after the burn-in test.

The environmental tests performed on groups A2 and C have been conducted in the Centre National d'Études Spatiales (CNES) and they involved the exposure of the photodiodes to the gamma and proton radiation, as well as lifetime tests during which the detectors have been held for 3500 hours (145.8 days) at 80ºC. This time would correspond to around 10 years at ambient temperature of 20ºC. The parameters of the detectors have been measured before the test, after 1000 hours and 3500 hours.

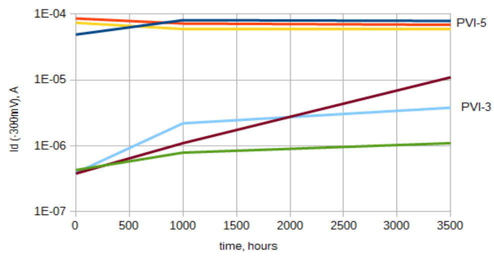

Fig. 5: The drift of the dark current of the PVI-3 and PVI-5 detectors during lifetime test.

The PVI-5 devices do not show any significant drift, whereas for the PVI-3 devices an increase in dark current is noticed. The possible explanation of this phenomenon is the fact, that long-term heating increases the surface leakage current but does not influence significantly the volume dark current. As the volume dark current is much bigger for longer-wavelength devices, the drift due to the augmentation of the surface leakage current is less visible in PVI-5 detectors.

III. Electrical test

Centre National d'Études Spatiales (CNES) has examined the susceptibility of VIGO detectors to damage from electrostatic discharges according to the norm MIL-STD-883J, Method 3015.8. This method applies to the human-body model (HBM) as it simulates a person which is discharging from a bare finger to the ground through the tested circuit. In the course of the experiment 3 positive and 3 negative electrostatic discharges have been applied on the detector. The ESD voltage varied from 0.5 kV to 12 kV. Fig. 6 and Fig. 7 show the behaviour of the dark current and photocurrent for both series of photodiodes.

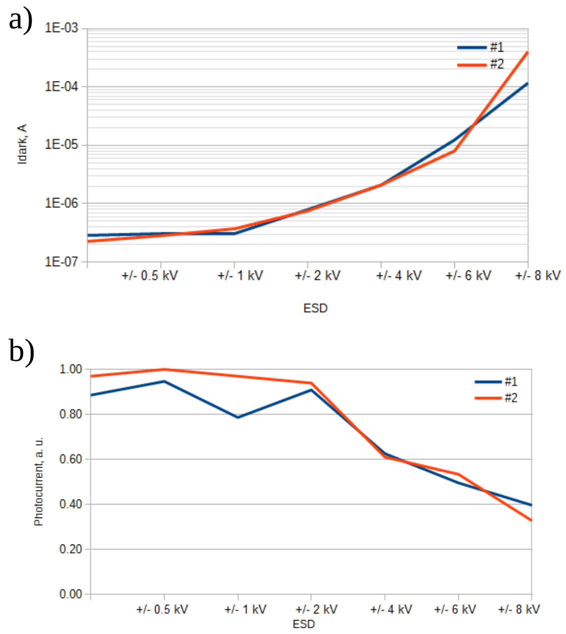

Fig. 6: The dark current and photocurrent at 3 µm of 2 PVI-3 as a function of the ESD value.

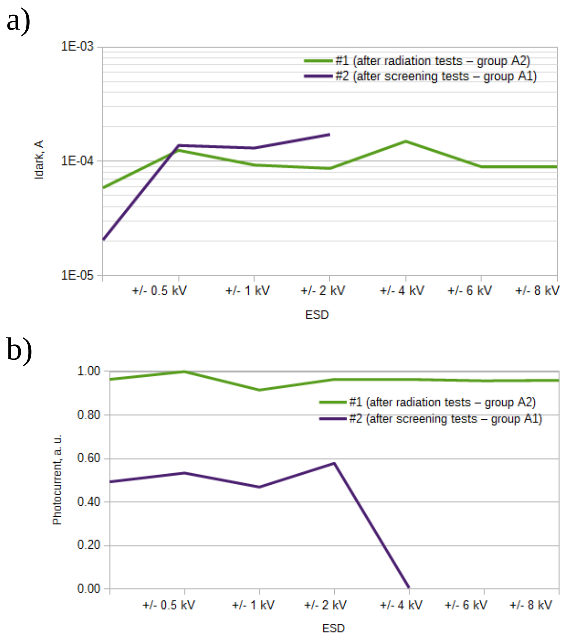

Fig. 7: The dark current and photocurrent at 5 µm of 2 PVI-5 as a function of the ESD value. Prior to the ESD test, detector #1 had been subjected to the radiation tests, detector #2 to the screening tests.

For PVI-3, a progressive degradation of the responsivity has been remarked after the discharge of 4 kV, but the detectors have stayed operational up to 8 kV. 12 kV destroyed the device. The photodiodes PVI-5 from the group A1 were more susceptible for degradation in this electrical test. They were destroyed by 4 kV discharge. A PVI-5 diode which hadn't been previously subjected to the screening tests could withstand the electrical shock of even 12 kV.

The detectors which have been subjected to ESD should be carefully examined under the microscope. From such observations the weak point of the detector construction can be discovered. To confirm the assumption that the increase of dark current and the reduction of the photoresponse is due to the deteriorated sidewalls, a surface etching followed by another measurement can be performed.

IV. Mechanical tests

In the space and military applications, the detector is often subjected to accelerations. As the majority of the environmental tests are meant to test the semiconductor material itself, the mechanical tests are destined to reveal the weak points of the detector like the wiring connection, the thermoelectric cooler etc.

There are two types of mechanical tests commonly performed on VIGO detectors, which were performed as well on the group B1 from the EXOMARS evaluation program One of them are sinusoidal random vibrations applied in 3 axes on the detector attached to a shaker. During one cycle the frequency of the vibrations raises from e.g 20 Hz up to 2 kHz and than decreases back to 20 Hz. The amplitude of the acceleration may be constant or may change with the frequency. Typically the root mean square value of the acceleration is of the order of several tens of g (where g is the gravitational acceleration). The other type of test is related to the application of the mechanical shocks. Such test may constitute for example of 5 shocks of 300 g with the duration of the pulse of 1 ms.

The opto-electrical measurements performed after mechanical tests usually do not reveal an increase of the dark current or the decrease in the responsivity. However, they can help to detect a weak ball- or wedge bonding connection, poor glue quality, microcracks in the wire etc.

VIGO System has developed and tested a thermoelectrically cooled model of the detector, that can withstand accelerations up to 30 000 g. The major change were thinner pellets, their thickness has been reduced form 5 mm to 3 mm. Transversal force acting on the cooler induces high torque which used to break the thicker pellets. As a transversal force is understood a force acting in the direction perpendicular to the cooler axis of symmetry, whereas the longitudinal force is acting parallel to it. The reduction of the pellets width results in the smaller torque acting on the cooler, which can therefore withstand larger transversal forces.

The simulations of different types and values of the acceleration are done by the application of the static forces in the given direction (Fig.8). The applied weight has to be equal to the product of mass of the top stage of the thermoelectric cooler with the detector and the desired acceleration.

The standard test procedure involves:

A) application of the transversal force on the top stage of the TE cooler (acceleration of 20 000 g),

B) application of the transversal force on the top stage of the TE cooler (20 000 g) and longitudinal pulling (6000 g),

C) application of the transversal force on the top stage of the TE cooler (20 000 g) and longitudinal pushing (20 000 g),

D) application of centrifugal acceleration of 20 000 g.

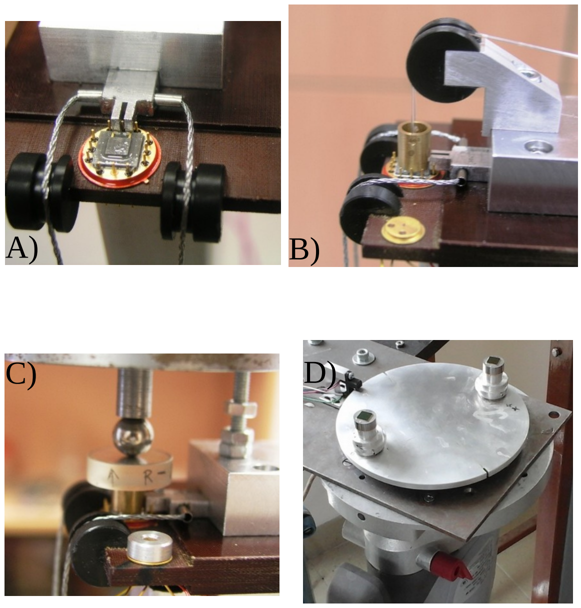

Fig. 8: The photograph of the experimental stands for application of A) transversal force, B) transversal force and longitudinal pulling, C) transversal force and longitudinal pushing, D) application of centrifugal acceleration.

The indicator of the thermoelectric cooler deterioration before it breaks, is the increase of resistance which is related to the formation of microcracks in the semiconductor pellets.

V. Stability testing

The detectors should not deteriorate, but as well the amelioration of their parameters after some tests would be an alarming sign. To test the stability, the photoresponse generated by the blackbody is registered over a long period of time, e. g. few days. For the detector to be qualified, the fluctuations of the signal should not exceed 3% during two-days measurement. As the changes in the ambient temperature influence the result of the test, the monitoring should be done in the room with controlled temperature, or a cooled diaphragm of the blackbody should be applied to eliminate the signal from the background.

Fig. 9: The measurement set-up for acquiring the signal from 11 4-element PV-3TE-5 detectors.

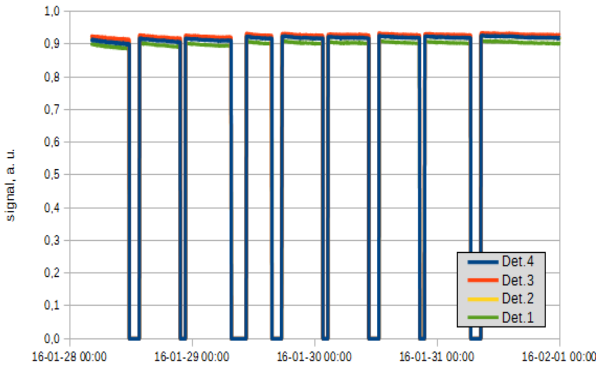

Fig. 10: The signal from the blackbody in time for a 4-element detector.

It can be noticed that the signal decreases slightly during the first 24 hours and then stays at a constant level for all detctors from the 4-element array. The lack of stabilization of the signal would indicate a technological irregularity.

VI. Conclusions

The reliability tests give information about the deterioration processes supervening in the device. For the regular detector, the change of the parameters such as dark current, dynamic resistance, series resistance is usually significant in the very beginning of testing and stabilizes in time, following the logarithmic relation. After possibly long period of time the detector deteriorates, and the dependance of its parameters on time follows the exponential curve. In the defective detector this process happens very rapidly or does not follow the model.

The test results show that the most vulnerable for damage of the detector are the side walls of the mesa structure. During heating, cycling, application of large voltages etc., the number of defects and free-electron states increases. As a consequence, the generation-recombination rate is elevated. Higher generation on the sidewalls induces an increase in the surface dark current, whereas augmented recombination reduces the photoresponse. Therefore the proper passivation is of great importance. Another consequence of the reliability tests may be the increase of series resistance, which would also reduce the photoresponse. The series resistance can become more significant as a result of an aggravated contact i.e. the microcracks in the wire, lack of adhesion of the metallization, oxides or contamination between the semiconductor and the metal. All of those can be revealed by the reliability tests.

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