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DEVELOPMENT AND ESCC EVALUATION OF A MONOLITHIC SILICON PHOTOTRANSISTOR ARRAY FOR OPTICAL ENCODERS

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I. INTRODUCTION

Optoelettronica Italia Srl, better known as Optoi, is an Italian Company dealing with optoelectronics and microelectronics and focusing on back-end technologies. The growing volume of activities concerning the aerospace field has recently brought to the creation of a company unit, with collaborations with ESA, CNES and ASI [1]. In this context, Optoi's key partner for the microelectronic front-end is Fondazione Bruno Kessler (FBK) and specifically its Micro Nano Facility (MNF).

In 2006, a first development for CNES centred on an 8-channel monolithic silicon phototransistor array for aerospace optical encoders was initiated. In the two subsequent R&D projects in 2008 and 2009 [2, 3, 4], Optoi's activity has gradually covered not only the manufacturing of the silicon devices, but also their packaging, successfully assessing its technology with respect to space-related requirements. These achievements were considered encouraging, based on the fact that no European source was available, for a potential usage of that component typology by space European optical encoder manufacturers.

More recently, a new project for ESA started in early November 2011, following Optoi's proposal on an open invitation to tender published earlier in the same year. This activity was funded in the framework of the European Component Initiative (Phase 3), for the development and ESCC approval of an European source of a 8-channel monolithic silicon phototransistor array for optical encoders, targeting its inclusion into the European Preferred Part List (EPPL) based on a complete radiation campaign and subsequent ESCC evaluation.

This paper reports the main aspects on the manufacture of the component, together with the most representative electro-optical performances, mainly focusing on the results recently collected in a complete radiation campaign. Besides, the details of the upcoming Evaluation Test Plan and the activities of the parallel development of a hermetic device variant are presented.

II. DESIGN AND MANUFACTURE

The developed device is an 8-channel phototransistor array for last-generation optical encoders [5]. Each channel is a silicon-based *npn* vertical phototransistor with floating base and emitter termination, the collector on the back of the die being common to the whole device (8 channels). The transistor base corresponds to the photosensitive area.

The die dimensions are 2.25 x 1.70 x 0.30mm³ (L x W x T). The package is a ceramic LCC (Leadless Chip Carrier) with gold plated terminations measuring 4.57 x 4.57 x 1.14mm³. The microelectronic assembled package is finally closed with an optical borosilicate glass lid measuring 4.50 x 4.50 x 0.55mm³, by using an adhesive. The resulting assembled component is illustrated in Figure 1.

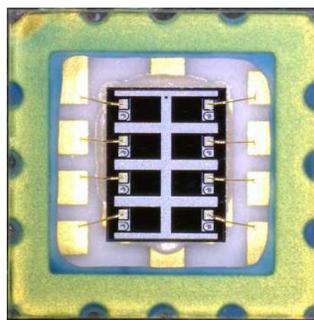


Figure 1: 8-channel phototransistor array

The manufacturing of the wafers has been successfully completed by FBK's MNF, in their class 100 front-end clean room, in close collaboration with Optoi and after technical discussions centred on the device simulation and design, upon ESA's supervision.

Optoi's back-end process makes use of a fully automatic microelectronic assembly line, internally available and upgraded in 2012, in order to become compliant with ISO-6 standard requirements (equivalent to class 1000).

Intermediate quality process checks are usually implemented, in order to reach the MIL and ESCC visual inspection specifications for the mounting procedures [6, 7, 8].

All the quality checks are performed during the process on each assembled device, except for the destructive quality tests that are performed on sample basis. The past R&D activities for CNES have progressively led Optoi to the achievement of the requested quality and repeatability standards, for the device manufacturing process.

Following an internal usual approach for similar developments, a few different technological options have been manufactured and experimentally compared in terms of functionality, radiation hardness and HTRB. In this context, one specific split, which showed very promising results, has been selected for the upcoming ESCC evaluation programme; the next sections focus on this specific device type.

II. DEVICE PERFORMANCE

Electrical and electro-optical tests on the devices were performed in close collaboration with Optoi's partner FBK, the main monitored parameters being represented by the device dark current, the phototransistor gain, the dynamics and the photocurrent. The application requirements imply to operate the phototransistor with low incoming light signals; the infrared LED should lead the phototransistor to generate as low values of current as 20-100 μ A, with a load resistor equal to 10kOhm.

At the end of the wafer manufacturing process in FBK, various automated tests were carried out at wafer level, based on automated testing routines. On the assembled components, the phototransistor gain was measured on devices with a pinout variant, where only 4 channels are connected. This allows the bonding of the bases, necessary to perform the electrical gain measurement, but is not actually representative of the application where all the 8 phototransistor emitters are connected.

The photocurrent was evaluated with a calibrated light source in two ways:

- power response: the photocurrent is measured for different values of incident optical power at fixed wavelength (865nm), the optical power being measured with a calibrated reference detector;
- spectral response: the photocurrent is measured at different wavelengths; since the optical irradiance of the source is wavelength-dependent, the photocurrent has been divided by the measured value of the optical irradiance acquired using a calibrated detector, in order to obtain the SR parameter [A/W]. Such parameter corresponds to the base-collector junction's responsivity multiplied by the transistor gain, so it takes into account both optical and electrical properties of the phototransistor (transmittance of the anti-reflective coating, quantum efficiency and electrical gain)

All measured parameters resulted compliant with the application performance requirements:

- dark current below $2.45 \cdot 10^{-10}$ A;
- electrical gain ranging between 830 and 920;
- rise time and full time below 300 μ s, half-rise time and half-fall time below 150 μ s;
- power response being linear in the optical range between 10pW and 0.1 μ w (Figure 2(a));
- spectral response peaking at around 400A/W in the wavelength range from 600nm and 900nm (Figure 2(b))

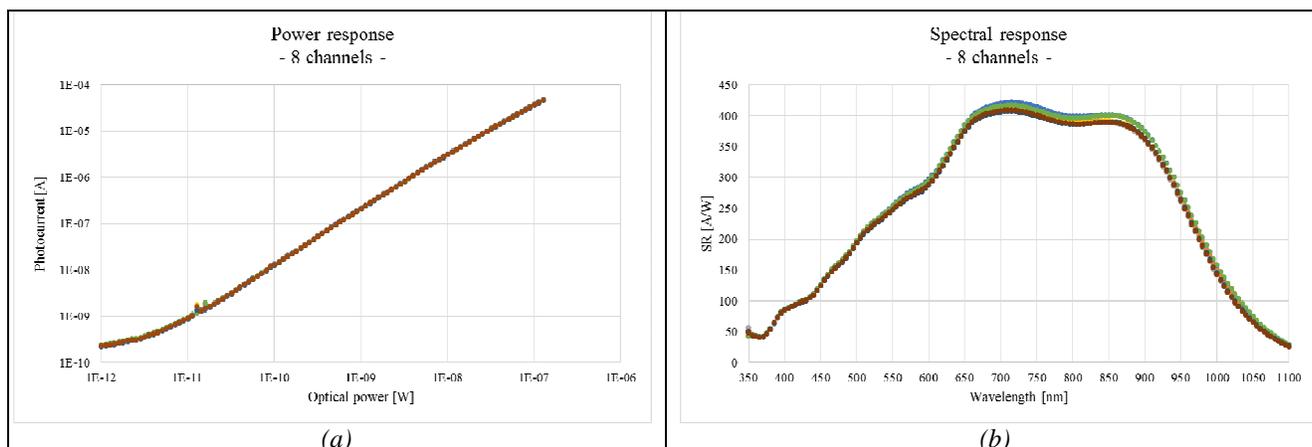


Figure 2: power response (a) and spectral response (b) of a representative device
(all the 8 channels are plotted)

III. RADIATION CAMPAIGN

A. Description of tested devices

In the radiation campaign, around 130 devices were submitted to irradiation and underwent comparative analyses before and after being irradiated.

Both biased and unbiased devices were included in the campaign, the former simulating the phototransistor in the condition of its reference application. The unbiased devices were partially with nominal pinout and partially base-bonded (BB), so that extrapolations respectively of dark current and gain degradation after radiation were possible through quick automated measurements.

B. Irradiation

Tests under gamma rays have been conducted on 56 devices in ESTEC (The Netherlands), with a Co-60 source [9]. Irradiations were conducted at two comparative dose rates, i.e. 400 and 40rad(Si)/h, in order to reach 102.0 and 36.6krad(Si) respectively.

Proton irradiations have been conducted on 73 devices in UCL (Belgium) [10] at two beam energies, i.e. 60 and 20MeV, with five fluences per energy. Details are shown in Table 1.

Facility	Radiation	Details
ESTEC	Co-60 γ -ray	Overall ionizing dose = 102krad(Si) Dose Rate = 400 rad(Si)/h Four intermediate steps
		Overall ionizing dose = 36.6krad(Si) Dose rate = 40 rad(Si)/h Three intermediate steps
UCL	Proton	Energy = 60 MeV Five fluences
		Energy = 20 MeV Five fluences

Table 1: test facilities and irradiation summary

C. Gamma results

The robustness against gamma radiation proved in line with expectations, based on previous analyses on manufacturing runs for CNES, and equivalent to non European parts currently used for the same reference applications.

The dark current increases with the total ionizing dose, with a relative increase up to $\approx 600\%$ at 102krad(Si) - 400rad(Si)/h and up to up to $\approx 300\%$ at 36.6krad(Si) - 40rad(Si)/h, the maximum values always remaining below 1.2nA after radiation. The electrical gain decreases to ≈ 600 at 102krad(Si) - 400rad(Si)/h and to ≈ 730 at 36.6krad(Si) - 40rad(Si)/h, with relative decreases of 30% and 20% respectively.

All dynamic parameters show a decrease of value (quicker dynamics of response after irradiation) with increasing gamma dose, leading to an improved performance of the devices.

Both power response and spectral response show a relative decrease in photocurrent: $\approx 30\%$ at 102krad(Si) - 400rad(Si)/h and $\approx 20\%$ at 36.6krad(Si) - 40rad(Si)/h. These values correspond to the degradation found on the electrical gain, and since the photocurrent takes account of both electrical and optical properties of the phototransistor, this result suggests that the effects of gamma rays act mostly on the electrical gain, and less (or not at all) on the transmittance of the anti-reflective coating or on the quantum efficiency of the device.

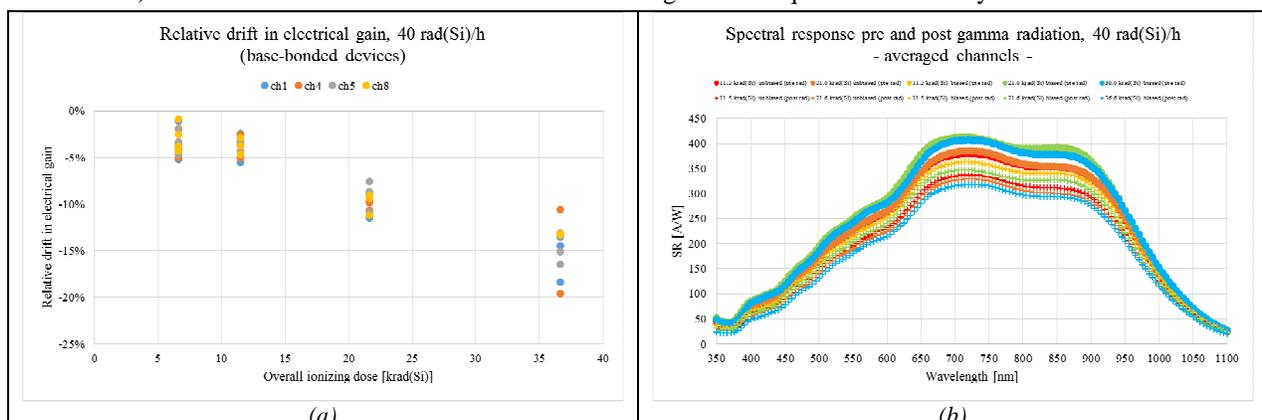


Figure 3: device degradation of gain (a) and spectral response (b) after exposure to gamma irradiation

D. Proton results

Proton radiation hardness is the most critical aspect within the radiation study, although improvements have been attested with respect to the past.

The dark current increases with the proton fluence, with a relative increase of $\approx 200\%$ at $60\text{MeV} - 2 \cdot 10^{11} \text{ p/cm}^2$, and to $\approx 100\%$ at $20\text{MeV} - 1 \cdot 10^{11} \text{ p/cm}^2$, the maximum values always remaining below 1nA after irradiation.

The electrical gain decreases to ≈ 600 , with a relative diminution of $\approx 30\%$, in both mentioned conditions.

As for gamma radiation, all dynamic parameters show a decrease of value (quicker response dynamics) with increasing gamma dose, leading to an improved performance of the devices after radiation.

Both power response and spectral response show a relative decrease in photocurrent of $\approx 70\%$ at $60\text{MeV} - 2 \cdot 10^{11} \text{ p/cm}^2$, (see Figure 5). This value is higher than the degradation found on the electrical gain, indicating that the effect of protons acts mostly on the transmittance of the anti-reflective coating or on the quantum efficiency of the device, and less on the electrical gain.

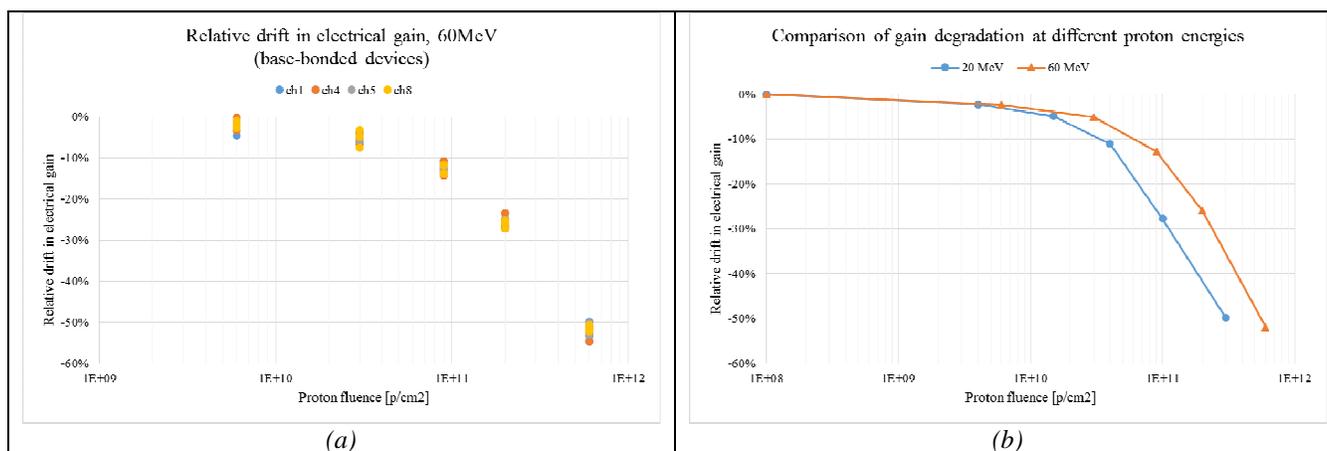


Figure 4: effects of proton energy irradiation on the device gain: 60MeV (a) and comparison between 20 and 60MeV (b)

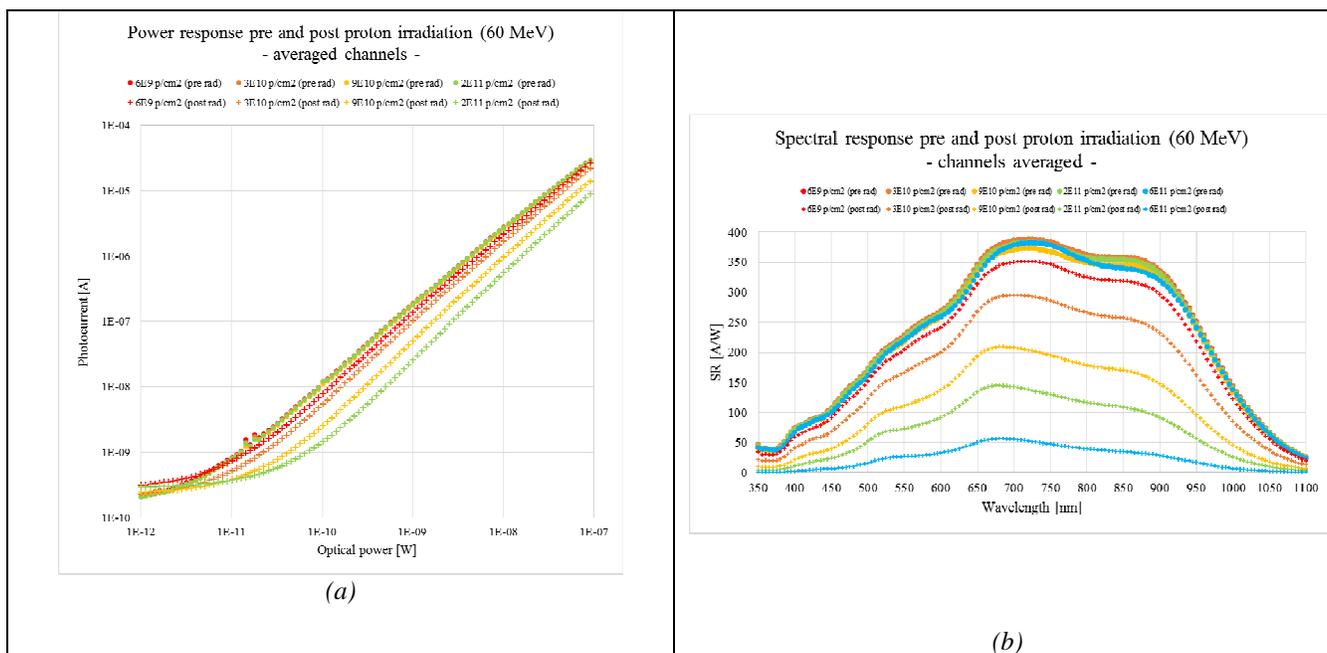


Figure 5: effects of 60MeV proton energy irradiation on the device, with different fluences: degradation in the photoresponse (a) and spectral responsivity (b)

A comparison of the electrical gain degradation on all base-bonded devices irradiated with the two different proton energies, 20 and 60 MeV, is shown in Figure 6.

The NIEL values correspond to Silicon material (0.00536 for 20 MeV and 0.0035 for 60 MeV [11]) and the Displacement Damage Dose (DDD) is calculated for all conditions (varying energies and fluences) with respect to the gain drifts.

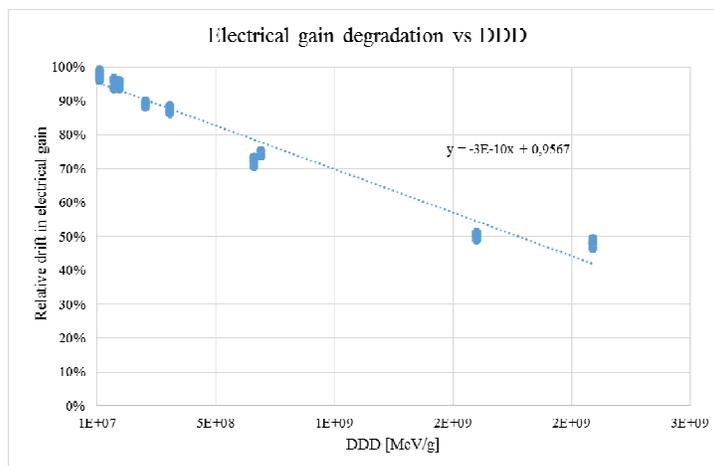


Figure 6: electrical gain degradation as a function of the DDD (each point represents an unbiased BB device)

E. Comparison with past results

The results obtained in the present radiation campaign have been compared to those obtained in past collaborations between Optoi and CNES and to a more recent preliminary study on the current lot. The results have been as well compared to the equivalent non European parts.

As far as gamma irradiation is concerned, the recent results confirm the robustness of Optoi devices already obtained in two past collaborations with CNES in 2010 and in 2012. The photocurrent degradation at dose rate ≈ 40 rad(Si)/h is shown in Figure 7(a): even though fewer dose steps have been tested in 2014, the mean relative drift is confirmed to be in the same range measured during the past for different manufacturing runs, attesting the reliability of FBK's and Optoi's developed technology.

Concerning proton irradiation, a more complete study has been performed in the present campaign in order to extrapolate a complete degradation figure of the current technology. Comparing the recent results to the past activities for CNES and to preliminary radiation tests on the current project (April 2013, same manufacturing run but different wafers with lower phototransistor gain), an improvement in the robustness against protons is visible (Figure 7(b)).

In conclusion, the developed technology is considered compatible with the requirements related to the reference application, i.e. optical encoders for space, and its radiation hardness is comparable with the non European counterparts currently used within the same context.

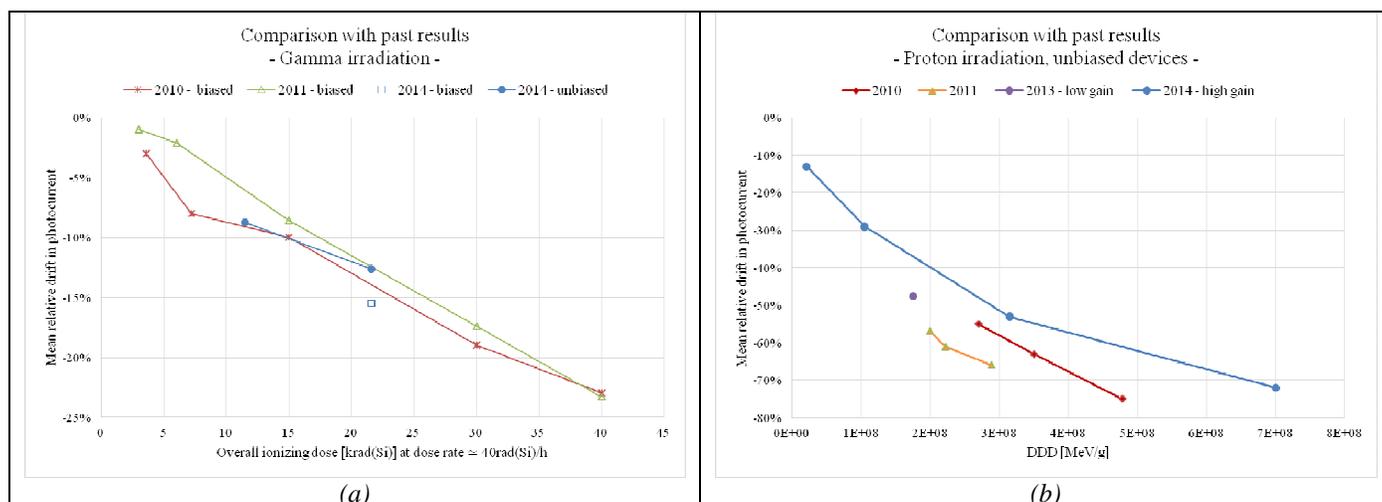


Figure 7: comparison with past results: gamma (a) and proton irradiation (b)

IV. CURRENT DEVELOPMENT STATUS

Optoi is currently collaborating with its French partner AdvEOTec in order to define an ESCC Evaluation Test Plan, in accordance with ESCC 2265000 and tailored to this specific device type, under the supervision of ESA. The start of this activity is scheduled in the second half of 2014 and its estimated duration is 5 months. The ETP plan currently considered is shown in Figure 8 and it is expected to involve around one hundred identical parts.

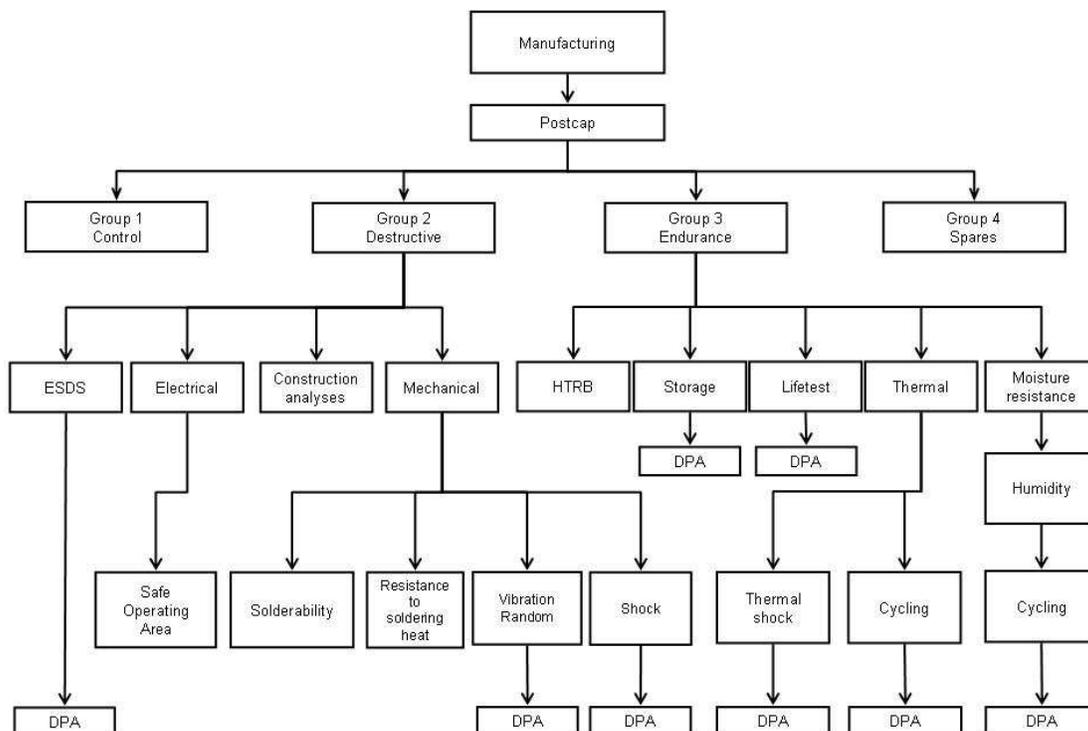


Figure 8: ESCC ETP

V. PARALLEL DEVELOPMENT OF A HERMETIC DEVICE VARIANT

Optoelectronic devices used in space projects are mainly available in packages closed with glass lids by means of glues or adhesives. This packaging solution could be the origin of problems due to loss of hermeticity or high moisture content encountered in some opto-parts, during on-ground testing within ESA projects.

Therefore, in the framework of a funded integration to the original activity for ESA, Optoi and FBK are in parallel investigating the possibility to replace the attachment of the protective glass lid currently implemented by means of epoxy gluing, through the eutectic process which is meant to achieve a higher degree of hermeticity and thus introduce a very relevant improvement in terms of robustness and reliability.

Specifically, Optoi is considering the AuSn process implementation, for reaching the best quality within the eutectic process. Internal experiments are currently in progress, in close collaboration with FBK's MNF where newly acquired equipment has become available for this activity. An example of the resulting device variant is shown in Figure 9.

First results have proven the actual achievement of the device hermeticity in accordance with MIL-STD-883 Test Method 1014.13, as well as the preservation of the device functionality after the eutectic process, although more work is required in order to reach a higher production yield and process repeatability. In this context, the main problematic aspect is represented by the presence of two different materials, i.e. ceramic and glass, to be soldered together despite having different thermal expansion coefficients. Besides, the eutectic process implementing AuSn solder alloys requires as high temperatures as 320-340degC, which influence the choice of materials used for example for the die attachment, and might impact on the device functionality if not properly mastered.

Optoi and FBK are now carrying out this activity as a parallel development, currently aimed at the improvement of the process; a successful control of the eutectic assembly technique would lead to a potential ESCC evaluation of this new hermetic part, based on the unquestionable improvement the device would benefit from.

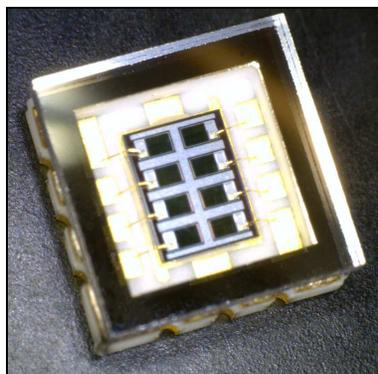


Figure 9: *hermetic device variant*

CONCLUSION

The present paper reports the status of the development and ESCC evaluation activities carried out on Optoi's phototransistor array developed in the framework of an ESA activity funded by the ECI-3 program, including the assessment of the technology radiation hardness.

The good results obtained together with the visible improvement of the developed component with respect to the past manufacturing runs, currently enable the initiation of the next project phase, i.e. the ESCC Evaluation campaign to start in the second half of 2014.

In parallel, the current involvement on the development of a hermetic device variant, where the glass lid is soldered by means of a eutectic process under optimization, is aimed at reaching a further improvement in the component robustness and reliability.

A successful ESCC evaluation and the potential inclusion of this part into EPPL would give the necessary confidence to the space European optical encoder manufacturers and users to procure this newly developed European source of phototransistor.

If the development of the hermetically sealed variant by eutectic way is successful, an ESCC evaluation of this specific product is foreseen due to the strong interest by the Photonics space community.

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