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HOW LOW CAN YOU GO, SUNSENSORS FOR EXTREME SENSING APPLICATIONS

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I. INTRODUCTION

Lens R&D is currently working on an Artes 5-2 contract aimed at developing an ITAR free extended temperature sunsensor. This sensor should be able to survive the temperature excursions associated with mounting on an extendable solar panel of geostationary satellites. These solar panels go up in temperature to some +110°C at End of Life when illuminated by the sun more or less continuously, and down to some -110°C when the satellite goes into eclipse for several hours (a couple of days a year). Therefore, temperature excursions for the sunsensors will be in the order of 200°C throughout the lifetime of the mission. Including some margin, the survival temperature range has therefore been set from -125°C to +125°C. It should be obvious that this presents significant thermal cycle related stress to the sensors. When the before mentioned satellites come out of eclipse, the solar panels will heat to temperatures above -50°C within a couple of minutes as will the sunsensors. This means the sensors will need to survive the low temperatures, but need to function within specifications only in a temperature range of some -55%°C to +125°C (including margin). As this is the standard military temperature range, it is far easier to demonstrate correct performance within this range as more test equipment is available.

Next to the intended geostationary applications, the potential availability of a wide temperature sunsensor has opened up new possibilities for some other missions currently under consideration. Just to name a few:

- Exomars rover with a temperature requirement -120°C.
- Proba 3 in highly elliptical orbit with a temperature requirement of -140°C
- JUICE going to Jupiter with a temperature range requirement of -145°C till +120°C (due to the Venus flyby)

Looking at these missions it can be concluded that mission going to the moon or to be used for asteroid mining could also benefit from a sensor that can withstand a wide temperature range.

The difference between these missions and the original target missions is the fact that in all these cases the sensors will have to be able to operate reliably at these very low temperatures, which not only leads to very stringent requirements on the mechanical properties but could also start to affect the optical properties. Items to be considered when expanding the operating temperature range of a sunsensor are therefore:

1. Mechanical survivability
2. Retaining of the optical properties over the temperature range
3. Signal to noise considerations
4. Los of current generation capabilities due to freeze out of electrons at low temperatures

II. JUICE and Proba3 missions as an example.

As the JUICE mission has the most stringent temperature requirements (as stated in [1]) this mission is taken as an example of the extremes some sunsensors are supposed to work on. The JUICE mission uses some gravity assist maneuvers to reach Jupiter in a reasonable timeframe. One of the early gravity assists takes the mission to the vicinity of Venus which is considerable closer to the sun than earth (0.639AU), hence providing a serious increase in solar radiation and a high hot-case temperature. The main mission is around Jupiter though (5.8AU) leading to a much lower solar input and low operating temperatures. The Proba3 mission on the contrary doesn't need the extreme temperature range but is a mission with a highly elliptical orbit having an apogee of 60530km. This means the sunsensors do get very cold as well, but don't see the high temperatures like for the JUICE mission. As one of the concerns for very low temperature operation is freeze out of electrons (causing less current generation capacity for the photodiodes) and contrary to the JUICE mission the Proba3 mission is operating near earth, for the freeze out phenomenon the Proba3 mission is the most critical one. All known aspects to operating over an unprecedented large temperature range will be described in the following paragraphs.

III. Mechanical survivability

Without doubt, the mechanical survivability of the sensors is the prime parameter to consider. For each mission taken into consideration, the sensors must be able to not only to survive launch, but also the required thermal cycles (with sufficient margin). For the sunsensors under evaluation, trying to create a maximum chance of succeeding to complete the qualification successfully has been done by careful selection of the materials used.

The base material system consists of:

- TiAl4V6 for the housings
- Sapphire for the windows
- Zirconium oxide for the connector inserts
- Aluminum oxide for the diode carrier

The titanium and sapphire have been chosen for the close match in CTE, the Zirconium oxide for the good compression strength and available experience in injection molding of the material and the Aluminum oxide because it is also used for cryogenic detectors in terrestrial applications (Cooled detectors used in Astronomy). Each of these materials themselves are known to be capable of operating under cryogenic temperature conditions and therefore the base materials themselves are not to be considered critical. Therefore, the survivability is expected to be critically dependent on the selected glues used to connect the various parts rather than the parts themselves.

As thermal cycle verification testing can take more than half a year, some very crude tests have been performed to show that the selected and materials can withstand at least a limited number of thermal cycles.

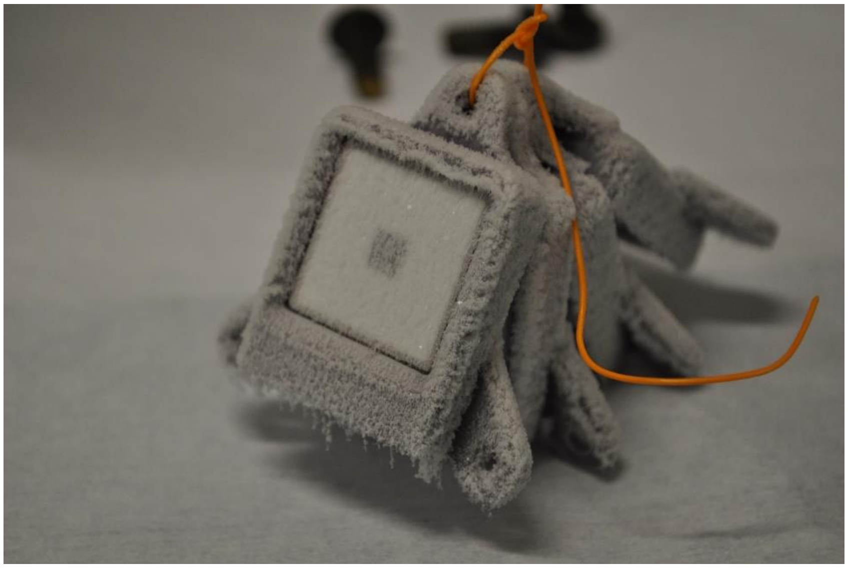

Photo 1. BiSon64-ET sunsensor housings heating up after liquid nitrogen dipping.

These tests consisted of dipping in liquid nitrogen (as shown in Photo 1) followed by some thermal shock testing (-55°C to +125°C).

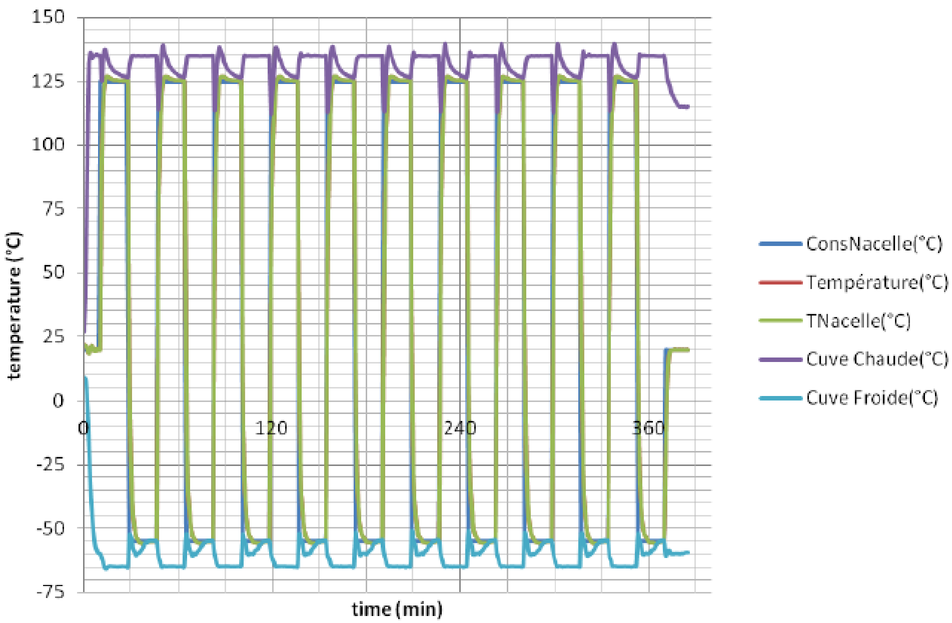

Figure 1. Thermal shock testing profile

Although these tests were performed before the ceramic and diodes were mounted they at least give some confidence in the fact that the units will be able to survive the qualification testing currently ongoing. In any event it is sure that the membranes themselves will be able to survive the given temperature range as the coating used is cured at 240°C and the wafers are dipped in liquid nitrogen as part of the regular quality control inspections (see Photo 2).

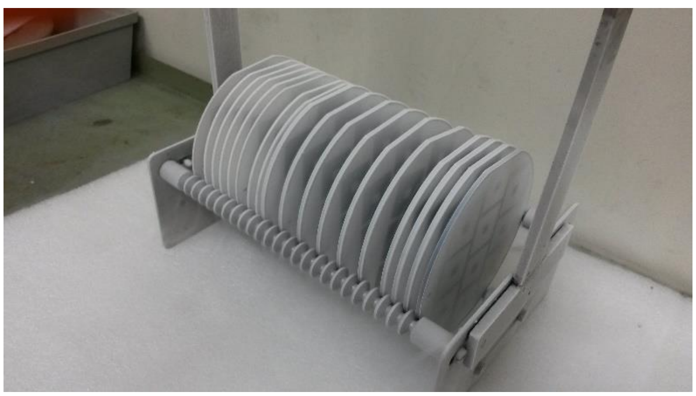

Photo 2. Wafers after liquid nitrogen dipping

As silicon detectors on alumina substrates are used for cryogenically cooled astronomical applications, it is certain that this material combination can be qualified when the right glues are used. This means that suitability of all basic materials has been verified and mechanical survivability seems to be possible.

IV. Retaining the optical properties.

Retaining the optical properties for an analog sunsensor is generally not a real challenge. As the diodes are used in zero bias, the only parameter to be considered is normally the change in collimator length caused by the different materials used while building the sensors. This change in collimator length will lead to a change in field of view which must be compensated for when high accuracies are sought for. For very low temperature operations though it seems that small levels of contamination can still lead to considerable differences according to some very elaborate research reported on sapphire properties [2]. All of these differences identified however lead to a negligible effect on the sunsensor performance.

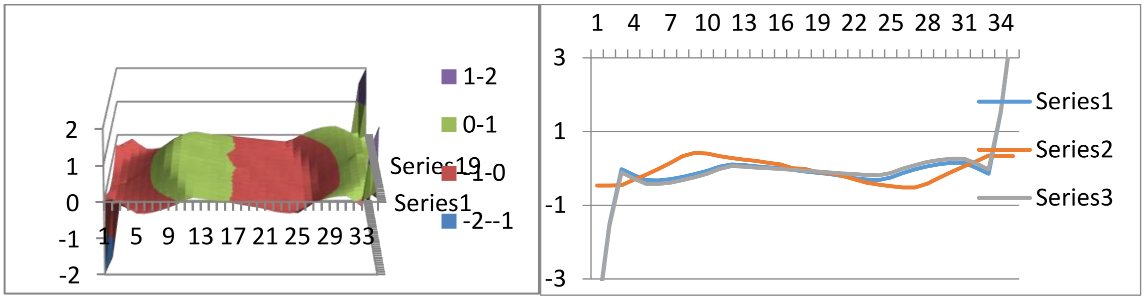

Figure 2. Generic error profile, caused by backside reflection of the sapphire window

Sapphire itself seems to be the ideal material for the window due to the high level of radiation shielding and good coating adhesion properties. The high thermal conductance and affordability. As not all potential effects can be theoretically determined, it has been decided to just test the sensors at low temperatures and see what happens. The known birefringence of sapphire is compensated for during the calibration of the sunsensors as is the deviation from nominal value (as shown in Figure 2) caused by a combination of the reflection on the diodes and a reflection on the sapphire surface. Changes in the refractive index of the sapphire or the anti-reflex properties of the diodes as a function of temperature will lead to changes in the given profile. As this reflection is known to lead to deviations from the actual sun aspect angle of some 0.5 degree (for a BiSon64) refractive index changes are expected to be limited to less than 0.1 degree. Nevertheless, this should be born in mind if high accuracy application of an analog sunsensor is sought for at low temperatures as it might lead to the need to perform a dedicated calibration at low temperatures (which is expected to be very expensive). As the membrane that defines the sunspot is actually behind the sapphire, it is not to be expected that the sun spot will be affected by any temperature induced changes in the sapphire.

V. Signal to noise ratio

Especially for a mission like JUICE where the spacecraft travels between Venus and Jupiter, the signal to noise calculations require some attention.

In order to exploit the full potential of the BiSon sunsensors, a 12-bit signal acquisition is needed (To ensure the resolution of the data acquisition doesn't add an appreciable error to the calculated angle). Although the effect of ADC resolution depends on the maximum field of view of the sensor, as an order of magnitude it can be considered that a 10-bit resolution adds an error of approximately 0.12 degrees for a sensor with a field of view of 64 degrees in diagonal. This means that at Jupiter the signal to noise should be equivalent to at least a 10-bit resolution or about 1:1000. Around the earth the solar power density is 1360W/m^2 which is leading to a generated current of approximately 1,6 mA. At 1.6.10^{-19} C/e this means in the order of 10^{16} electrons/s. As the shotnoise limit is related to the square root of the number of electrons the signal to noise is in the order of 1/10^8 and sufficiently large to state that the signal shotnoise is not important as long as the sensors are operated in a near Earth orbit. Next to this the diode dark current noise is negligible if the readout circuit is properly bandwidth limited.

From the JUICE SAS specification [1] we know that the direct solar radiation at Aphelion is 46 W/m^2 which is about thirty times lower and leads to a generated current of some 55 µA. Although this seems a small current, it should be realized that it still represents in the order of 3.3 10^{14} electrons/s and the shotnoise limited signal to noise is > 1/10^7 and well below the resolution of the analog to digital converter. In this situation it is advantageous that the sensors are cold, as the dark current resistance (responsible for some additional noise generation) increases approximately by a factor of 2 for every 7 degrees of temperature increase. For operation at -120°C this leads to a more than 10.000 fold decrease in dark current resistance. On the other hand, the dark current resistance will also increase by a factor of 2 every 7 degrees when going up in temperature. This means that for operation at 120 degrees the dark current resistance is about 2^{14} or 16384 times lower than at room temperature. As the dark current resistance is specified to be >10MΩ @20°C this leads to some 600Ω @125°C. It is generally known that the noise generated by a resistor can be calculated by means of below formula:

$$Vno = (\sqrt{4kTBR/Rd})*\mathrm{Rt}$$

Vno = output noise voltage
k = Boltzmann's constant
T = temperature (373K)
B= Bandwidth of the readout circuit
Rd= diode resistance
Rt= transimpedance of the readout circuit.

Around Earth the sun input is 1360W/m^2 which leads to a generated maximum current of some 2.5mA. This means that with a transimpedance of 400 Ω the output voltage of the photocurrent amplifier (or transimpedance amplifier) the maximum output voltage will be 1V. Using a 12 bit analogue to digital converter in for this full range will lead to a bit size of 1/4096= 244µV. Calculating the output noise voltage caused by the dark current resistance of the photodiode using the same 400Ω transimpedance and a bandwidth of 10 kHz we can calculate a noise voltage of 0.24µV. Statistically adding the noise generated by the previously calculated 600 Ω dark current resistance, the expected output noise voltage would be in the order of 0.3µV. This is why it can be safely concluded that high temperature operation around earth is not an issue. Operating around Venus (which is the actual hot case for JUICE) would lead to a significantly higher current generation, thus improving on the situation.

VI. Freeze out of electrons

This phenomenon is one of the largest unknowns with respect to using sunsensors at very low temperatures. For low temperature operation it is known that depending on the type of doping used, electron mobility will change as will the number of free carriers. This is called electron freeze out and has been investigated in relation to astronomical detectors.

As indicated before, the lower dark current generates less noise and will allow to detect lower quantities of radiation in astronomical applications (where people are looking for week stars). In our case though the worst case situation would be low temperature and full sun illumination. If the number of free carriers has been reduced to such an extent that the expected photocurrent can no longer be generated, this would lead to a serious non-linearity and fail readings for the sensors. Although this is not expected to be an issue if the sensors are used as a fine sunsensor due to the normalization performed during calculations it can be an issue if people decide to use the sensors as a coarse sunsensor. Therefore, it is deemed advisable to investigate this phenomena in a representative environment.

VII. Intended verification method

In order to investigate the freeze-out effect it is needed to use a special setup that will enable to cool the sensors sufficiently to reach the intended -125°C and illuminate the sensors with a 1AM(0) solar intensity source. As both requirements are a bit non-compatible (because the solar radiation will cause rapid heating of the sensors) the intended verification method is a dynamic test.

At ESTEC there is a dedicated test setup (called VIRAC) which consists of two thermally controlled chambers and is used to simulate eclipse transition.

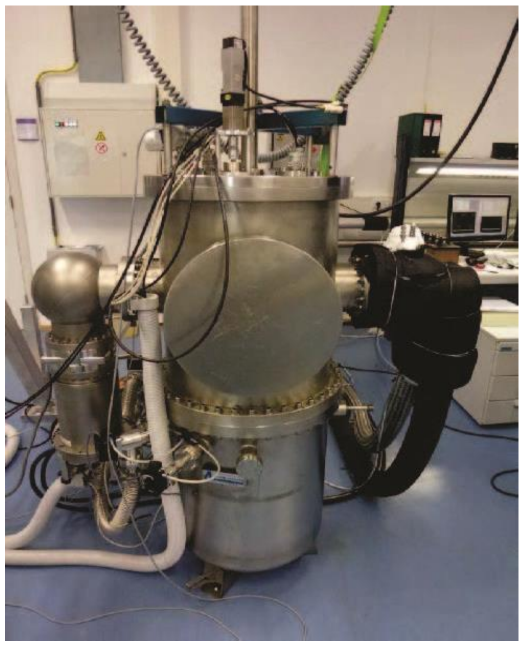

Photo 3. ESTEC VIRAC facility

The facility basically consists of two compartments of which the hot compartment is illuminated by a solar simulator (providing the requested 1 AM(0) intensity radiation input) and a second cooled compartment, cryogenically cooled with liquid nitrogen. The entire setup is evacuated and an internal elevator will allow to cycle the test specimen between the hot upper and cold lower compartment. This will lead to a fast thermal cycling test in vacuum.

This installation was used on the Lens R&D standard BiSon64 sunsensors to show their endurance to rapid thermal cycling in vacuum and typically doesn’t allow for a dwell time at either the low of high temperature limit because a significant temperature difference between the test specimen and the walls of the chamber is needed to allow reaching the desired temperature within an acceptable timeframe.

For the BiSon64 tests shown below, the upper chamber was at +120°C and the lower at -189°C and each cycle already took slightly over 3 hours.

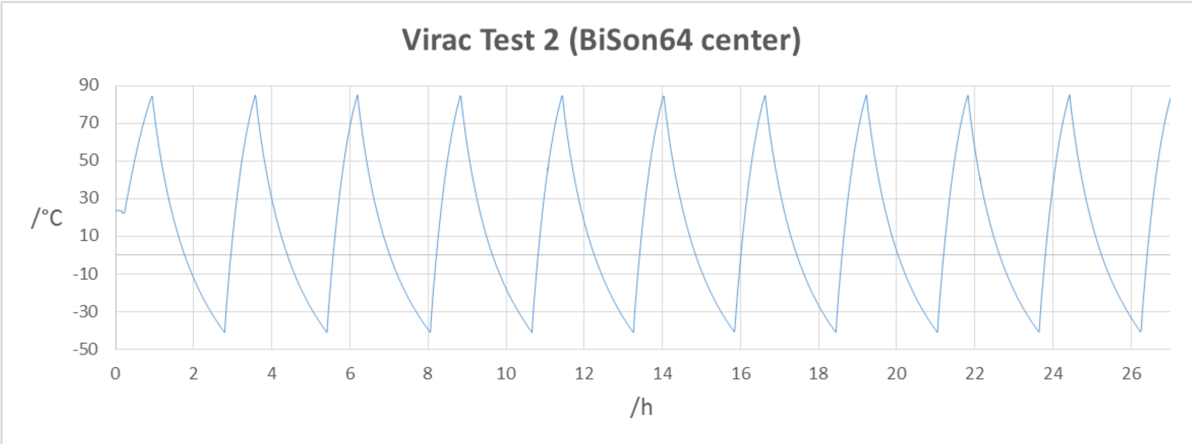

Figure 3. Typical thermal cycling profile used for BiSon64 sunsensors.

As the lower temperature is fixed by the boiling temperature of liquid nitrogen, the only gain that can be obtained is by putting the hot compartment at a higher temperature and reducing the thermal mass of the test specimen.

By cooling the sensor(s) to the desired temperature and monitoring the current generated when the sensor(s) are taken from the cold compartment into the hot compartment and in front of the solarsimulator, it is expected that by monitoring the current and correlating this generated current with the temperature, any non-linearities caused by freeze-out phenomena can be found and the relevant temperatures determined.

VIII. Conclusion

Current temperature extremes under discussion for sunsensors range from -145°C to +125°C. Based on current insights we are quite confident that the high temperature operation will not present any issues. Operating at very low temperatures due to the use of highly ecliptic orbits around earth as for the Proba3 mission in combination with 1 solar constant sun illumination could lead to some issues which will need to be investigated further. This will need some very specialized test setup and dedicated tests. The ESA VIRAC facility seems very well suited to execute exactly the type of test needed to demonstrate the ability to operate at the very low temperatures currently specified.

References

[1] JUI-SYS-ADST-RS-000168 JUICE SAS specification.
[2] properties of sapphire, Springer *9780387856940-c1.pdf*

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