THE BELT AND ROAD INNITIATIVE TOWARDS ALBEDO INSENSITIVE SUNSENSORS

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ABSTRACT

Practically all satellites use Sunsensors to ensure a high-quality attitude acquisition during launch and early orbit (LEOP) and safe mode operations. These sensors are in general based on analogue photodetectors which allow to provide a solution that is combining a very high reliability and radiation tolerance with a wide temperature range of operation when properly designed.

These solutions however have two major disadvantages:

1) Photodiodes generate currents that will require an analogue interface to the on-board computer
2) The measurements are hampered by albedo sensitivity (error signals generated by sunlight that is reflected on the Earth’s surface or satellite parts)

In order to mitigate the first issue, several suppliers have added electronics to the sensors that will convert the generated analogue signals into digital signals thus producing what is generally known as a digital Sunsensor.
These additions however will not reduce the albedo sensitivity and other mitigation measures are needed to reach a sensor whose accuracy is not significantly affected by albedo signals.
This paper describes two significantly different solutions that are expected to lead to albedo insensitivity of Sunsensors for space applications.

1 THE NEED FOR ALBEDO IN-SENSITIVITE SUNSENSORS

Earth albedo is known to have a significant influence on the measurement accuracy of analogue Sunsensors. Depending on the type of sensor used, coarse Sunsensors that use the cosine dependence of the generated current to the incidence angel can be in the order of 3° to 5° accurate and fine Sunsensors (that typically use a four-quadrant photodiode and membrane) can be less than 0.5° accurate. Albedo errors generated can be as high as 25° or 15° respectively depending on attitude and inclination.

These albedo errors are only temporarily present, but still cause a large disturbance in the attitude control loop of the satellite. In many cases a significant amount of software is used to mitigate these effects as in worst case the satellite can even go into what is called Earth lock and start tracking the Earth instead of the Sun.

As more satellites start using electric propulsion (especially for orbit raising) the availability of power during LEOP is becoming more important and there is an increased call for albedo insensitivity.

The simplest way to decrease albedo sensitivity is by adding a baffle as is done for the BiSon64-ET-B shown in Figure 1.

Figure 1 BiSon64-ET-B

When carefully placed such a baffle can guarantee albedo free Sun attitude measurements for an Earth pointing satellite, but it cannot prevent significant albedo errors during the early stages of LEOP when the satellites attitude still needs to be stabilized.

2 ALBEDO INSENSITIVITY OPTIONS

In order to be able to determine which options there are to reach albedo insensitivity, the subject albedo needs a bit more discussion.

For a space based Sunsensor, there are two types of albedo that are important as can be seen in Figure 2:

1) Earth Albedo
2) Reflections on satellite parts

Figure 2 Albedo sources (picture courtesy ESA)

Earth albedo signal is generated by reflections of Sunlight on the Earths surface. Although the intensity of the reflected light is much less than the intensity of the direct Sunlight, the extend of the input angles is much larger.

Although not clearly visible due to saturation effects in the imager, the angular extend of the sun is approximately 0.5° and depending on the orbit, the angular extend of Earth visibility is always much higher and quite often expands over the entire field of view of the Sunsensor (especially for satellites in low earth orbit (LEO)). As a result of the larger angular extend, Earth albedo signal can generate significant signals in analogue Sunsensors, thus ruining the accuracy or even leading to signal chain saturation if not properly accounted for.

Figure 2 also shows some sources of the albedo signal generated by spacecraft parts like antennae, isolation blankets and solar panels.

For all of these sources one has to consider that the albedo signal is typically build-up of two components:

1) Diffuse reflection
2) Specular reflection

The diffuse reflection produces a signal that is relatively constant and slowly fluctuating with time when the satellite rotates around the Earth.
Specular reflections however tend to contribute with a flash like signal that is generated when the optical path allows directly reflected light to reach the sensor. Due to the high velocity of a satellite this generally leads to short flashes causes by reflective surfaces on the satellite for instance.
For reflections on sea surfaces however this can also lead to high levels of signal for a longer period of time, because each wave will have part of its surface reflecting to the satellite and depending on sea state and wind direction waves can be aligned to the satellite movement.

Where reflections on satellite parts will be rather predictable and repeatable (and can be avoided in many cases by proper Sunsensor placement), Earth Albedo signal generated errors depend on multiple non deterministic and highly fluctuating parameters like Ice cover, sea state, wind direction cloud cover, cloud height (ice content) etc.

While evaluating the various options that are available to reach albedo sensitivity the main emphasis has been on balancing commercial perspective, technological developments and reliability.

As a result of this trade-off, it was concluded that we currently see only two viable options that would lead to a potential commercially attractive solution:

1) Single chip true digital Sunsensor in silicon CMOS technology using a 2D sensor array
2) Wide bandgap semiconductor albedo insensitive analogue sensor

2.1 Silicon CMOS technology.

Silicon CMOS technology has by now been widely demonstrated and can me made more radiation tolerant by using specific design against radiation effect (DARE) rules. The technology allows to produce imagers, signal and data processing in a single chip in a very cost-effective way and is therefore seen as the most likely way to get to albedo insensitivity and in the meantime provide a direct digital interface to the on-board computer.

By splitting up the wide field of view (typically 120°*120°) in multiple much smaller fields of view the solution becomes much less sensitive to albedo errors. As an algorithm can determine if the Sun is within a pixel or not by simply looking at the signal level, the area where the albedo still can play a role is limited to attitudes where the Sun is very close to eclipse. Even in this area’s the albedo influence is very limited as the angular extend is drastically reduced.
As a consequence, this type of solution is generally considered to be fully albedo insensitive if sufficient pixels are used (FOV in the order of 1°/pixel)

As the processes are well known, and experience is building, this technology seems very suited to build highly integrated sensors. Single chip solutions that only require a single silicon chip and some passive components are expected to be cost efficient, small and relatively easy to produce in higher volume. As a consequence, there have been several developments over the last decades aimed at developing exactly this type of device. (Reference [1],[2] are reporting on this for example) but these developments have shown that it is far from simple to develop a radiation hardened commercially attractive device.
Based on available knowledge it is expected that this type of device will not be able to reach the high radiation tolerance and high operating temperatures that have been demonstrated with silicon analogue Sunsensors

2.2 Wide bandgap materials

Wide bandgap materials like gallium nitride (GaN) and silicon carbide (SiC) are known to have properties that make them suited for use at high temperatures (Ref [4][5]) Apart from this they are know to have an extremely high radiation tolerance without any design alteration or optimisation as well as a photo-response that is limited to the UV wavelength range.
As there are currently a lot of developments ongoing that can potentially lead to mixed signal integrated single chip solutions, (especially SiC) is seen as a potential viable alternative to a single silicon chip solution. (Ref [6])

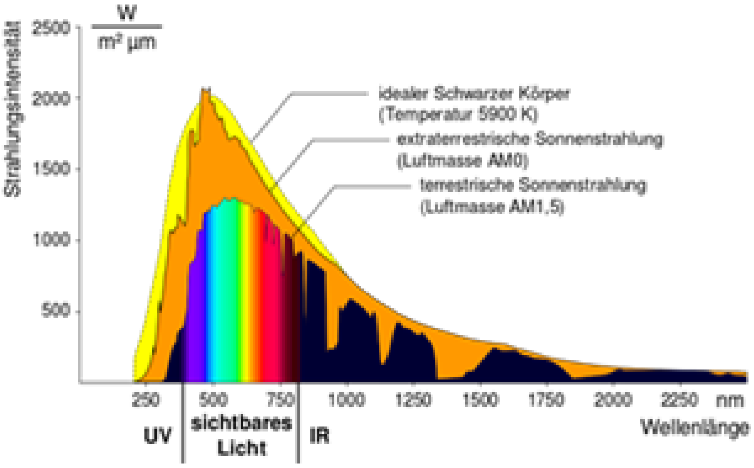

Figure 3 top of atmosphere versus ground level wavelength intensity profiles

Figure 3 shows intensity profiles for a theoretical black body radiation source, the spectral content of the Sunlight at the top of the atmosphere (TOA) and at ground level (AM(0)). From these graphs it can be seen that there is a distinct difference between the TOA and AM(0) levels especially in the UV and some infra-red wavelengths. TNO and the university of Delft have investigated albedo insensitive Sunsensors before (Ref[3]) but at that time all investigated solutions had to be multi-chip solutions as no integrated signal processing was available at that time.

For the last years SiC electronics integration has made major improvements and maturity of the technology is rapidly increasing. As a result, it seems necessary to consider a single chip SiC solution as an alternative to a single chip silicon solution.

3 STATE OF THE ART

Based on the above a discussion on the state of the art in silicon single chip and SiC single chip albedo insensitive Sunsensors will be provided.

3.1 SiC single chip digital Sunsensor developments

State of the art in SiC Sunsensors has been demonstrated by the Delft technical university in frame of a Dutch STW program. The four-year PhD research program investigated several aspects associated with the potential development of an albedo insensitive analogue Sunsensor for space applications and has reported some significant findings (Ref[6][7]).

The findings are based on measurements performed on and experiments performed with SiC multi project wafers (MPW) that have been produced in cooperation with the German Fraunhofer institute. These wafers (one of which is shown in Figure 4) were produced by means of a so called 4H-SiC CMOS process using poly silicon gates and double well technology.

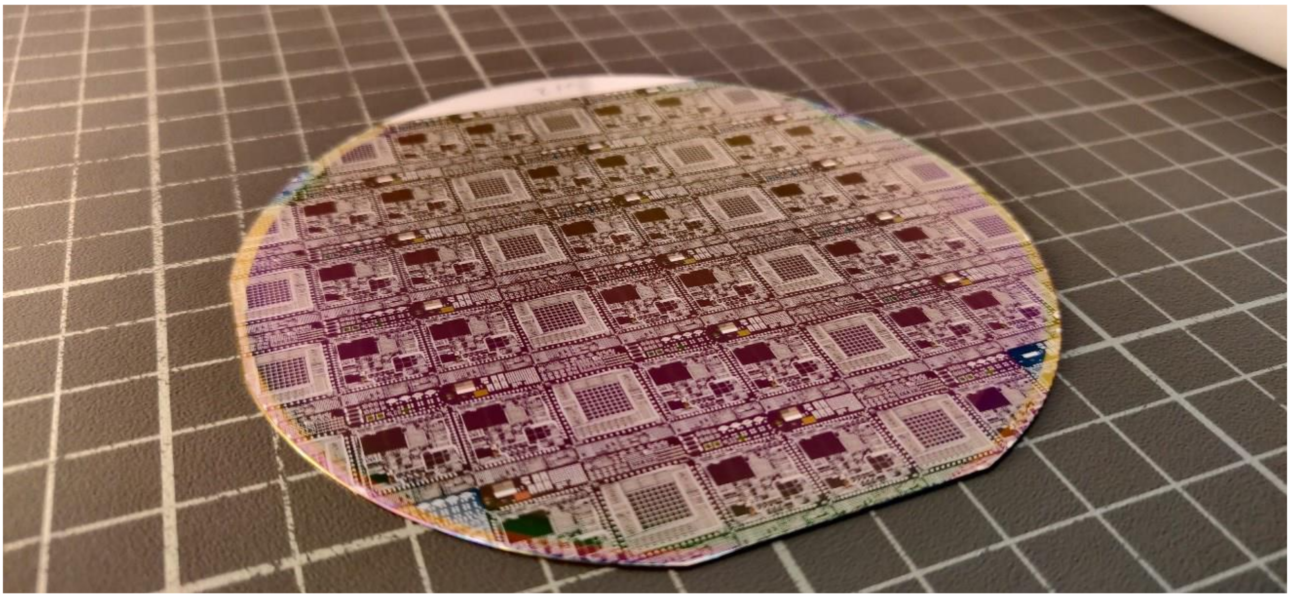

Figure 4 Fraunhofer SiC multi project wafer

As a Sunsensor is more than the detector and also needs a membrane, next to the wafer and chip measurements, also bonding experiments were performed to determine the optimum bonding parameters for the required membranes.

To save the available SiC wafers most of these experiments were performed on processed silicon wafers

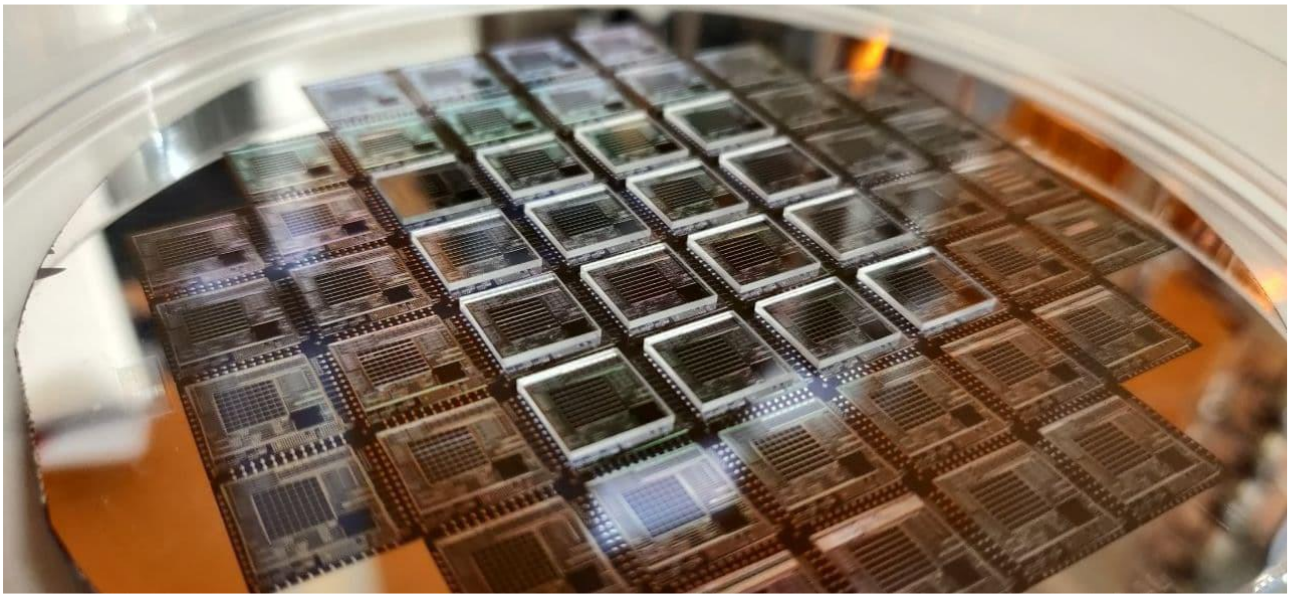

Figure 5 silicon wafer with bonded membranes

One of the issues associated with SiC sensors is that the SiC substrate is semi transparent for visible light and many UV absorbing layers are not visible to the naked eye. Where this does open up specific opportunities (being able to optically inspect through UV absorbing layers) it also presents risks (presence of UV absorbing contamination that cannot be detected without additional equipment for instance). As a result, UV sensitive detectors are more difficult to handle than visible light sensors like silicon sensors especially when radiometric accuracy or stability is required.

As SiC CMOS technology is far less mature than Si CMOS there were several issues taken into consideration while designing the MPW circuits.

1) Large area SiC detectors are prone to a low yield
2) SiC CMOS integration complexity doesn't allow to produce medium or high-resolution ADC's yet
3) SiC CMOS on chip switching speed is much lower than for common silicon CMOS
4) An albedo insensitive chip in itself will not be a viable solution unless it has a digital interface

Advantageous for the wide bandgap solutions though is that reduced Earth Albedo sensitivity is provided by the spectral response of the photodiodes so in SiC or GaN, less diodes will be needed to obtain the same albedo insensitivity as for a more complex silicon 2D array

As a result of the above considerations, it has been decided to design an 8*8 array of sensors that can be read out by means of a 2-bit flash analogue to digital converter (ADC). A circuit block which has been reported on in Ref[4].

The spectral response is expected to lead to a significant albedo signal reduction and splitting up the field of view in a number of smaller sub-fields is expected to lead to a situation where the albedo signal is sufficiently reduced to be in the order of the sensor accuracy only (target 3° including albedo error)

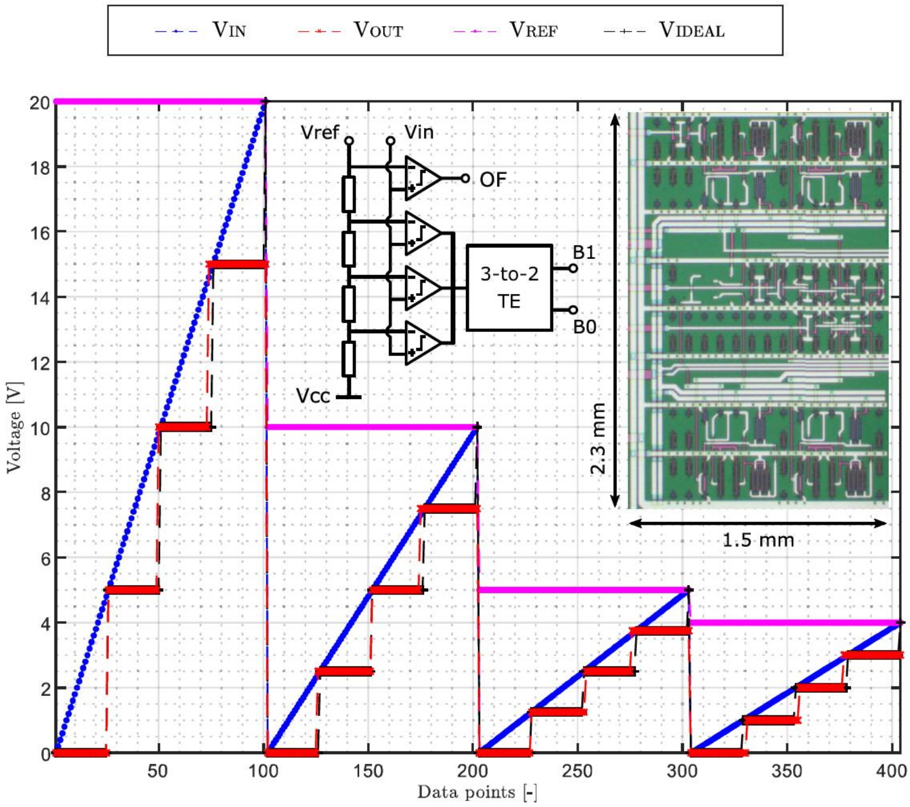

Figure 6 pixel 2bit flash ADC

During the evaluation of the SiC circuits a number of observations could be made that are important for future use in space applications.

- For the ADC to operate an external reference was still needed.
- A 20V supply is needed to operate the circuits
- The speed of operation is limited
- Basic performance of the circuits has drastically approved over previous performance but is still significantly behind common silicon implementations.

Next to the above it has to be realized that although the basic sensor core probably will be able to handle very high temperatures and radiation levels, the total solution is far from a final realisation.

Interconnect technologies that are capable of handling very high temperatures will probably need to be changed and are without doubt more expensive than regular technologies and/or likely to have worse properties and heritage.

Production infrastructure will probably need significant adjustment (like adding UV sources to a solar simulator assembly robot and calibration setup) and handling procedures will become more complicated. As non-visible contamination can potentially impair performance, the handling of the sensors will need to be carefully considered.

As a first order conclusion (based on the above) it can be stated that the performance has significantly improved over the last couple of years and a lot of research is going into approving it further, but at this moment in time the technology is not mature enough to be used for actual Sun sensing.

3.2 Silicon Single chip digital Sunsensor developments

In frame of an ESA ARTES 5.1 contract, Lens R&D is investigating the feasibility of implementing a Sunsensor on chip in 0.18µm CMOS technology.

Based on many lessons learned from developments performed at TNO and within the Leonardo digital Sunsensor-on-a-chip projects (reported on in Ref [1][2][3]) a novel design is currently being produced. The focus of the design is on a number of core properties which are deemed necessary for the project to become a commercial success. As such the property that is deemed most important is that in the end the outcome has to be a commercially attractive solution.

Based on that prime criterium, a number of core properties have been defined.
The final sensors will have to be:

- Reliable
- Albedo insensitive
- Equipped with a digital output
- Radiation tolerant
- Wide temperature operating range
- Single chip with passive support components only
- Low power
- Manufactured using automated assembly to the largest extend possible
- Performing with a guaranteed non-calibrated accuracy

As the ARTES project focusses on geostationary missions that use electric orbit raising as the target missions, radiation requirements are very high, and additional radiation shielding might be required. Commercially seen, LEO missions might be much more interesting though given the high number of satellites projected and increasing reliability requirements for the LEO market. Therefore, it cannot be excluded that there will be two versions in the end one optimised for each application. All of this however will depend on the radiation tolerance of the chip developed.

Because the current design is an upgrade of the previous version and the final sensor is dubbed IBIS the name of the current chip under development is IPS+ (for IBIS Photonic Sensor with increased radiation tolerance)

In order to test the chip in a real-life situation, a design has been produced that will be used to evaluate the functionality of the chip.

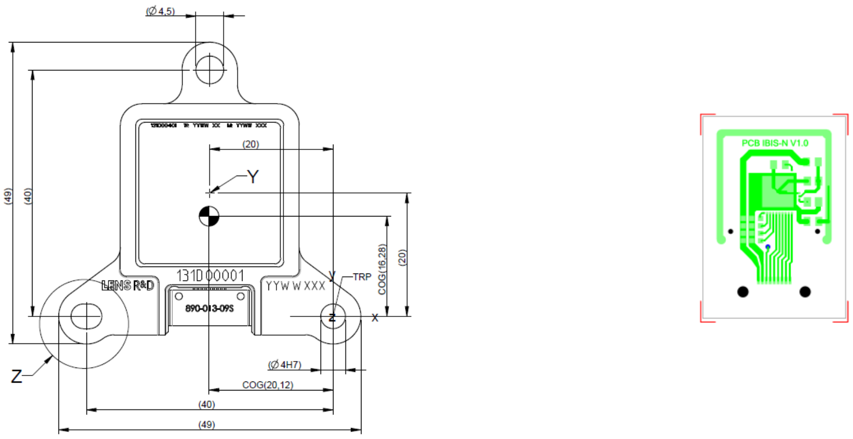

Figure 7 IPS+ testbed c.q nano-DSS

The design of this test bed led to the existence of the MAUS cubesat Sunsensor, which is currently flying on a number of satellites already and was recently qualified to such levels that it is without doubt the best qualified Cubesat ready Sunsensor in the world.

- Radiation up to 8E14 1MeV electrons on the bare diodes (19.2MRad TID, 25E9 MeV/g TNID)
- 40g sine
- 34.26g random @ $2g^2$/Hz
- 2000 cycles -45°C..+105°C

Figure 8 MAUS analogue Sunsensor for Cubesat applications

Based on the same assembly principle the testbed is expected to be able to sustain the same level environmental loading and therefore it is anticipated that the unit can be launched for a real in orbit verification if proper material selection ensures a low outgassing for all other components used.
Given the advantages associated with a true radiation hardened digital Sunsensor a number of companies have already expressed interest in flying the first prototype.

As the selected CMOS process allows to implement some extra functionality it has been decided to implement a means of excluding parts of the field of view for evaluation. This means that reflections coming from certain directions can be discarded without implementing straylight baffles or other light shields.

This exclusion can be simply done by programming a start and stop coordinate for the evaluated field of view. As can be seen in Figure 9 this defines a square area within which the Sun will be detected, thus allowing to mount a sensor even at the vantage point of Figure 2 without being bothered by reflections on spacecraft parts

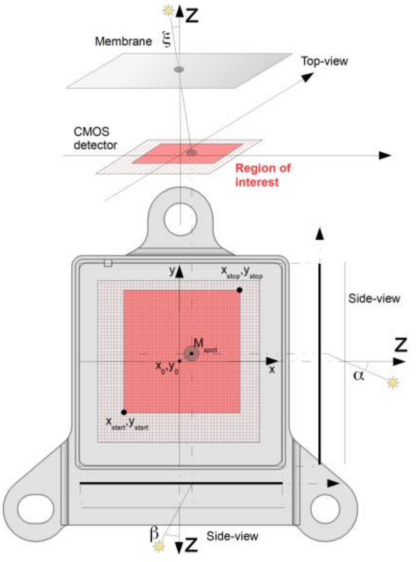

Figure 9 Evaluation field of view programming

4 CONCEPT EVALUATION

Looking at both discussed concepts, there is a trade that can be made weighting the pros and cons of both concepts. This trade has led to the below table

property	SiC CMOS	Si CMOS	Remarks
Reliability	+	++	Proven for Si but SiC can stand higher temperatures and radiation, total solution for SiC still to be designed
Albedo insensitivity	+	+++	
Digital output	+	+++	SiC output is slow and high impedance
Radiation tolerant	+++	+	
Wide operating temperature range	+++	+	
Single chip + passives	?	++	t.b.d. for SiC as there are no references yet for instance
Low power	?	+	SiC is low current but high voltage and low speed. Core power properties for CMOS still TBD
Automated manufacturing ready	+	+	
Guaranteed performance	-	+	Not demonstrated and contamination is considered a risk for SiC
Total concept	-	+	

Table 1 concept evaluation

As can be seen in the above table, there are still a number of uncertainties that make it difficult to perform a complete trade as not all relevant data is available yet.

It is however obvious that for the SiC approach a number of issues would still need further evaluation before a final conclusion can be reached.

Major advantages for standard silicon solutions are the relative low cost of production (once the design is validated and masks are available) and high level of process maturity.
This leads to a significant risk reduction even though it is known that radiation tolerance might potentially not be as high as required for the targeted geostationary missions without adding additional shielding. The use of DARE libraries mitigates these risks for the digital part of the design, but the analogue part may still be prone to single event upsets or even latch-ups as there are no standard rules for analogue designs to implement.

SiC technologies on the other is known to have an extreme radiation tolerance and very wide operating temperature range (leading to a very high robustness). That being said the technology itself is far less mature and only getting traction the last couple of years.

Depending on market demand (for high power electronics and lighting applications mainly), the developments can go very fast and it is not unconceivable that in the medium term (5 to 10 years) the design of a single chip albedo insensitive Sunsensor for space applications with a digital output can be made and the sensors produced in a cost-effective way. At this moment in time, it is however not seen as a sensible path for further investments without an increased processing maturity.

5 CONCLUSIONS

Given the technical maturity of the processes involved and issues associated with the high operating voltages required to operate the chips, monolithic SiC albedo insensitive Sunsensors are not expected to be a viable alternative to a single chip digital solution for the short term.

Rapid advances in SiC micro electronics integration technology however could change this situation in the future. As SiC chips would allow a much wider operating temperature range and would provide a radiation tolerance that can probably never be achieved with silicon chips, it is still advised (for any company that wants to stay abreast with the latest developments in the field of high reliability Sunsensors for space applications) to follow the development of high bandgap materials and processes.

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