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Silicon photovoltaics, a low cost technology for lunar power installations

*Romain Feilleux, Romain Cariou, Philippe Voarino, Timoté Lombard, Jean-Baptiste Charpentier, Clément Jamin, Adrien Danel, Nicolas Enjalbert, Frédéric Jay, Sébastien Dubois**

** Univ. Grenoble Alpes, CEA, Liten, Campus INES, 73375 Le Bourget du Lac, France*

romain.cariou@cea.fr– romain.feilleux-anginieur@cea.fr

Abstract

Space PV power needs, driven by LEO constellations and HAPS (High-Altitude Platform Station) are significantly increasing, deeply changing the game in terms of volume and cost requirements. Adaptation of terrestrial PV technology for space application appears then as a potential solution for these industrial and economical challenges. In terms of architecture, the terrestrial PVA uses a single frontsheet covering several strings of cells embedded in adhesive films and assembled in one single step using lamination. This approach is industrially mature, suppresses the risk of electrostatic discharges (triple points) and offers compatibility with several type of materials and solar cells technologies: qualified III-V [2], Commercial-Off-The-Shelf (COTS) Silicon, and emerging Perovskites. In addition, this approach offers room for increased specific power (W/m^2), as illustrated in terrestrial PV where efficiency cells to module ratio beyond 90 % are reported. In terms of materials, the introduction of COTS components is highly expected provided that performance compromises can be found. In that sense, radiation and thermal cycling are key ageing tests in the selection process. Experimental results of electrons COTS Si cells irradiations (1MeV) and thermal cycles on laminated Si PVA coupons (-140/+140 °C) are presented. The experimental results of Si PVA thermal cycling will be analyzed with insights from thermo-mechanical simulations of the cells interconnects behavior. Careful design and selection of COTS Si PVA components allows to reach EOL AM0 efficiencies for LEO in the 10-14% range, with a stable performance demonstrated over ~ 2000 cycles so far; improvement paths will be discussed.

Introduction

Currently, solar generators are made of several photovoltaics arrays (PVA) based on III-V triple-junction cells bonded to a very lightweight honeycomb stuctuture. This architecture benefits from a strong space heritage and excellent and long lasting performances in space environment. However, this technology is relatively expensive because built on ~ 100 €/W cells, which represents ~30-40 % of the solar generators cost. In the context of increased space PV power needs and HAPS (High-Altitude Platform Station) market and cost reduction pressure of the Low Earth Orbit (LEO) constellations and lunar applications, game changing solutions are needed. A promising way, at short/midterm perspectives, for offering cost reduction and suppression of critical raw materials such as Ge, is to leverage the well established and industrial mature silicon terrestrial photovoltaic solutions, while taking into account the specificity of space constraints. The work presented here will focus on the PVA more specifically.

1. From terrestrial PV to Space PV: success conditions

Terrestrial PV is usually designed to offer a controlled level of performance over a 25 years lifetime. Obviously, environmental constraints to be considered are significantly different when it comes to space environment. Typical temperature range considered for terrestrial PV is, for example, limited to -40/+85°C, while LEO solar array experience -120°C/+120°C. In terrestrial PV, reliability tests should comply with high humidity and but only reasonable UV exposure for instance.

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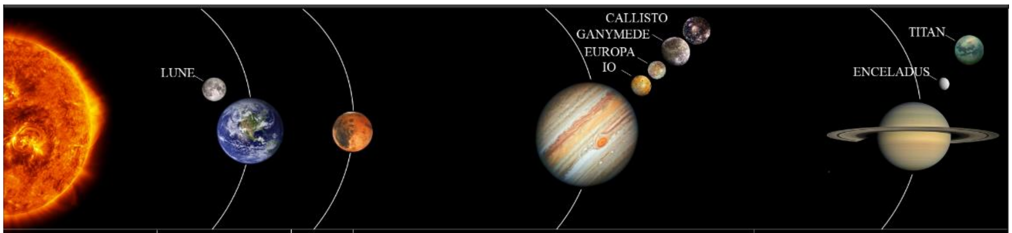
Considering carrying over terrestrial PV developments for space application starts with in depth gap analysis between terrestrial validation specifications and spatial ones for the suitable application. An example of screening CPV potential with the various constraints of space environment [1] is presented in Figure 1.



Mean Distance (AU)	~1					1.67	5.5								10			
Solar Flux (W/m²)	1,366					589	51								15			
WORLD	EARTH			LUNE		MARS	JUPITER	IO	EUROPA		GANYMEDE		CALLISTO		SATURN	ENCELADUS		TITAN
MISSION / CONDITION	LEO	MEO	GEO	O/F	L/R	O/F	O/F	O/F	O/F	L/R	O/F	L/R	O/F	L/R	O/F	O/F	L/R	O/F
Atomic Oxygen	●	○				○			○		○		○			○	○	
Dust					○													
Extreme Temperatures	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●
Harsh Radiation e- p+	○	●	●				●	●	●	●	●	●	●	●	○	○	○	○
Micrometeoroid	●	○	○	○	○		○								○			
Plasma	○	○	●				●	●							○	○		
Thermal Cycling	●	●	●	●	●	○	○	●	○	○	○	○	○	○	○	○	○	○
UV Radiation	●	●	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	○

Convention: ● High impact ○ Moderate impact on Concentrator PhotoVoltaics (CPV)
AU : Astronomical Unit (~150 $x10^9$m). Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and GEosynchronous Orbit (GEO). O: Orbiter, F: Flyby, L: Lander, R: Rover. e-: electrons, p+: protons.

Figure 1 – Impact on CPV production potential of various space constraints across the solar system [1].

While thermal cycling, dust and UV radiations are already taken in account in terrestrial solutions development (with usually less stringent requirements), specific conditions like atomic oxygen, extreme temperature, harsh charged particles irradiations or high velocity micrometeorite impacts need to be added to assess accurately potential of terrestrial-inspired PV for space application and adapt PVA design in a reasonable way to withstand life in space.

Adaptation of terrestrial PV to space application is currently mainly driven by LEO constellations demand. According to Figure 1, Low Earth Orbit is at least as stringent in terms of harsh condition as Lunar soil except, obviously, for dust impact which is a specific point to be analysed for lunar missions.
Therefore, it is reasonable to suggest that studies carried out to adapt terrestrial PV for LEO application will be widely reused for lunar applications.

2. Impact of radiation environment

Electron and proton irradiations are reported to have a huge impact on Si-based PVA performance over time.

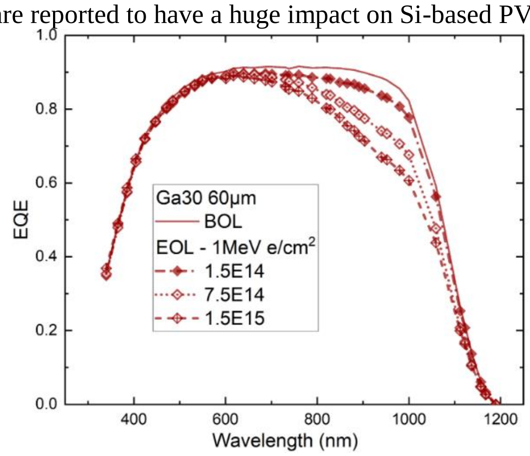


Figure 2 - EQE measurement on 60µm Si heterojunction cell before and after irradiation with increasing 1MeV electron fluencies [2].

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Cells radiation hardness and their degradation behaviours are of particular importance in this context. Since crystalline silicon has powered the space developments from its beginning, there are lots of papers and knowledge already available on this topic[3]-[7]. It is however mandatory to investigate the radiation hardness of modern high efficiency silicon solar cells[8], since both materials composition (doping, impurities) and solar cells architectures have evolved significantly since the last century. This topic is attracting a growing numbers of R&D initiatives, from both academics and industrial players[9]–[12]

We present the investigation of p-type silicon heterojunction solar cell electrons radiation hardness. Amorphous/Crystalline Si heterojunction solar cells were manufactured on the industrial pilot line of CEA[13], with state-of-the-art gallium-doped Si wafers. *Ex-situ* Begin-Of-Life (BOL) and End-Of-Life (EOL) current voltage and external quantum efficiency characterizations were used to quantify the degradation linked to electrons irradiation.

Overall the ultra-thin Si heterojunction shows a promising radiation hardness, with better performances than PERC at every fluence tested here, for a mass ×3 smaller (see Figure 3). The best ultra-thin 60µm DARC Si cell has been certified externally and reaches 15.9% AM1.5G at 1.5x10^{14} e/cm^2 [2].

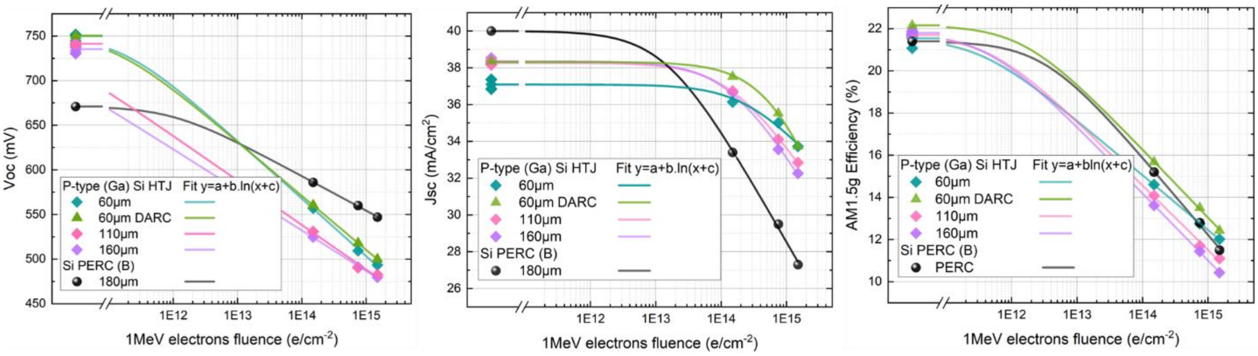
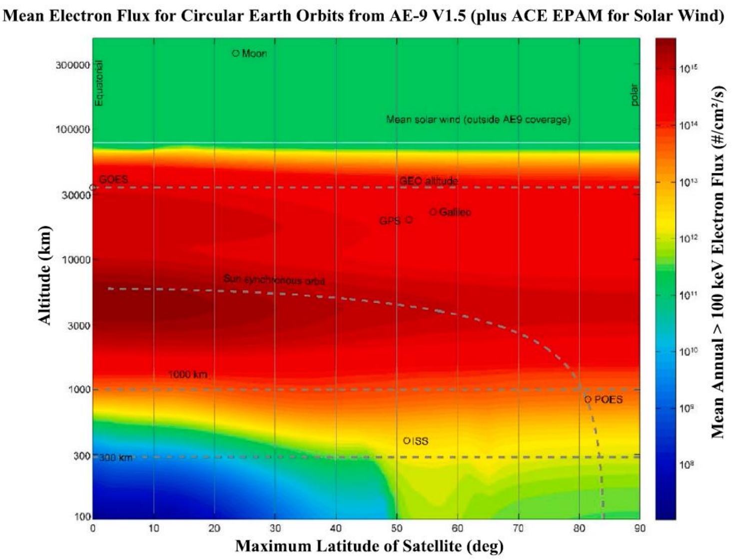


Figure 3 - Variations of Voc, Jsc & Efficiency as measured in-house under AM1.5G spectrum at room temperature for p-type Ga-doped Si heterojunction solar cells with various thicknesses. Comparison with commercial PERC cell.

Further development of defect annealing would enable to further improve end of life performance of ultra-thin Si heterojunction reaching an aggressive €/W target making it a clear candidate for LEO constellations applications requiring large cells quantities.



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These results can reasonably be carried over for lunar application. While LEO constellation typical mission life is around 5 years, we anticipate that lunar mission life will be more that 10 years and likely targeting 15 years of operation. Electron and proton radiation flux in the case of lunar surface activities will we below LEO one making us confident that, even on a longer mission time, hardened solution developed here will be perfectly suitable.

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While this section focuses on electron and proton radiation impact on cells, radiation impact, including UV, on other PVA elements should not be forgotten. An illustration of optical losses with irradiation on low cost coverglass is presented in Figure 4.

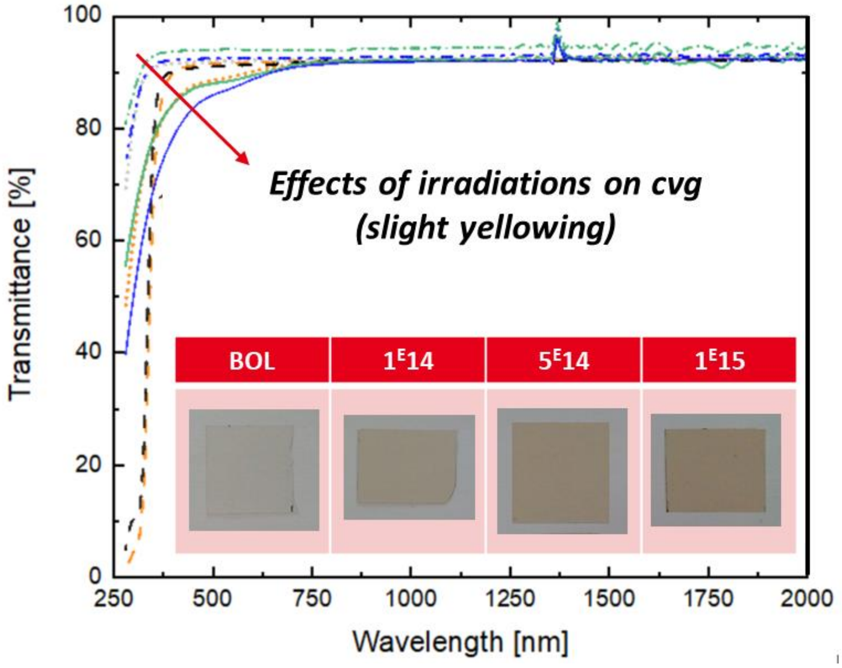

Figure 4 – Example of low cost coverglass optical degration with increasing 1MeV electrons fluence, and comparison with qualified coverglass.

Irradiation on COTS glass might lead to transmission losses overtime while polymer materials widely used on terrestrial PV might show some optical or mechanical losses over time. However, these mechanisms are now well documented and predictive numerical models are under development, putting this risk under a reasonable level of control.

3. Impact of thermal environment

Table 1 - Missions constraints on moon [1]

Mission type	Solar irradiance (W/m²)	Mission life (years)	Temperature range (K)	Environment
Orbiters (50 km)	1323 to 1414	> 10	74 to 340	● Negligible magnetic field and atmosphere ● Micrometeoroid (10 nm to 1 mm diameter; and speed of 10–72 km/s) ● Solar wind and flares ● Galactic cosmic rays
Human and Robotic lunar surface activities	1323 to 1414	> 10	98 to 348	● Dust adhesion and transport ● Solar spectrum scattering induced by “dust fountains”

Lunar thermal environment (see Table 1) will obviously strongly differ from what is considered from terrestrial PVA development and validation. This extended range of temperature is likely to have huge consequences on thermo-elastic stress cycles (e.g., cracks in solder joints of the interconnects).

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Therefore, materials behaviors and thermomecanic characteristics such as linear expansion coefficient, glass transition temperature, and tensile lap shear resistance need to be deeply looked with regards often on microstructural composition of it to withstand environment constraints.
Thermal analysis using differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA) will be key characterizations to validate candidate materials for such applications, especially for polymer layers usually part of terrestrial PVA bill of materials.

From interconnexion standpoint, we already evaluated that standard terrestrial interconnector ribbons (see Figure 5) is not robust on standard Si cells due to thermal linear expansion coefficient mismatch resulting in stress-induced breakage and shunts [14].

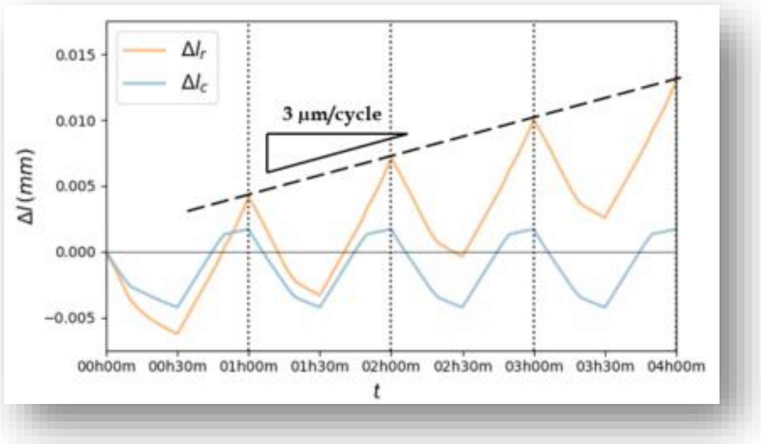

Figure 5 – Elongation of terrestrial standard interconnector ribbons with +/-140°C thermal cycles [14].

Mitigation of this issue will require work around interconnector material selection and Si cells metal grid adaptation to increase adhesion strenght and CLTE mismatches leading to stress-induced breakage. Interconnector shape optimization might also help providing dilatation capabilities by pure mechanical design.

4. Impact of Dust contamination

Dust contamination of PVA surface is probably one of the most specific challenge to raise for lunar application. Although this phenomena might look trivial, its impact on PVA performance might be tremendous and mitigation techniques are everything but obvious (see Table below and Figure 6).

Dust	• Obscuration of solar panels leading to power loss • Surface contamination • Surface abrasion • Material degradation (e.g. cover glass) • Electrical discharge (electrostatically charged dust) • Altered thermal properties

Table 1.4: Synthesis of the effects of lunar environment on the conversion efficiency and durability of PVAs. Table adapted from *Bermudez-Garcia et al., 2021* [4]

Solution to this challenge require a strong knowledge about dust generation, transport and adhesion mechanisms.

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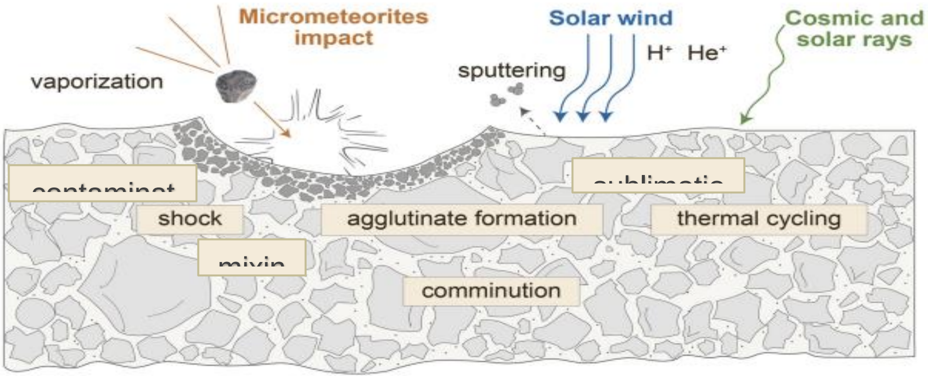

Figure 6 - The constituent processes involved in space weathering (SW) of airless bodies. Figure modified from Gu et al., 2022 [15] and Szalay et al., 2018 [16].

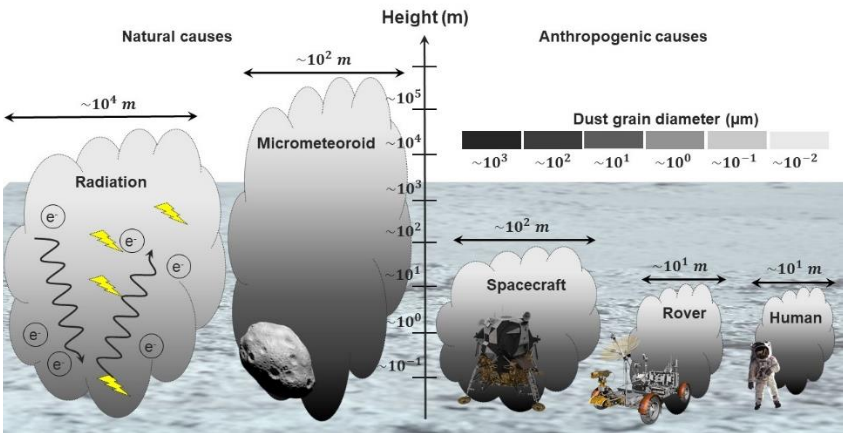

Figure 7 - Order of magnitude of height, range and size of lunar dust grains transported on the lunar surface

According to PVA location site, dust deposition can have various severity (see Figure 7). As particles next to lunar surface can be charged, electrostatic environment can play a huge role in surface contamination, considering that radiative transport is likely to occur on very large distance and is not linked to human activity.
Particle size distribution from previous lunar mission provides key insights about contamination source while countermeasure to either avoid contamination of PVA surface or remove contamination will be depending both on dust charge and particle size.

Although this challenge is not intrinsically linked to Si-based PVA, large developed surface of PVA to be implemented on lunar surface need to anticipate this condition. As Si-based PVA has less efficiency than III-V based one, surfaced to be set will be large making this point even more critical.

5. Conclusions

Carrying over terrestrial PV solutions for lunar power application is certainly not a straightforward question. However, recent development carried out around LEO constellations application and analysis of environmental lunar specific-constraints really place Si-based PVA as a good candidate.
PV cells optimization currently ongoing for harsh radiation environment will ensure reliability for lunar environment. Symmetrically, current interconnection hardening for LEO mission will be largely beneficial for lunar mission with very close temperature ranges.
Finally, the most specific challenge to be tackled for lunar environment seems not to be linked to Si-PV itself: dust management has to be carefully looked at.

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