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Investigation of p-type Silicon Heterojunction Radiation Hardness

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Abstract — The space sector is facing significant upheavals, in particular in terms of cost reduction challenges, driven by the emergence of Low Earth Orbit constellations. Concerning solar power generation, it opens up perspectives for alternative solar photovoltaics technologies, instead of the highly performant & expensive III-V multi-junction devices. Crystalline silicon solar cells, which have fueled initial space developments, spark a renewed interest, thanks to their industrial maturity, high efficiencies on p-type substrates & costs of two to three orders of magnitude lower than those of III-V. In this context, we present here the results of electrons radiation hardness studies on p-type (Ga-doped) silicon heterojunction solar cells. Devices with thicknesses down to 60 μm are manufactured and then characterized before and after 1MeV electrons irradiations. The best ultra-thin heterojunction cell shows an end-of-life ($1.5 \times 10^{14} \text{ e/cm}^2$) externally certified efficiency of 15.9% under AM1.5G at room temperature; this translates into $\sim 14.3\%$ with AM0 spectrum. The benefits of thickness reduction with respect to radiation hardness are presented, and the cells improvement pathways discussed.

I. INTRODUCTION

Currently, mainstream solar generators for satellites are made of several photovoltaics arrays based on Coverglass Interconnected Cells, with III-V triple-junctions, bonded to a honeycomb. This architecture benefits from a strong space heritage and excellent and long lasting performances in this harsh environment. However, the expensive III-V multi-junction cells still struggle to cut the cost down. In this context of increased space PV power needs and cost reduction pressure of the Low Earth Orbit (LEO) constellations, alternative/game changing solutions are needed, to switch from the standard “premium” approach to a “good enough” one. A promising way at short/midterm perspectives for offering significant cost reductions in this sector (and suppress the use of Ge critical materials at the same time), is to leverage the well-established and industrially-mature silicon-based terrestrial photovoltaic solutions, while taking into account the specificity of space constraints. Cells radiation hardness and their degradation behaviors 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[1]–[5]. It is however mandatory to investigate the radiation hardness of modern high efficiency silicon solar cells[6], 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[7]–[10].

In this study, we present the investigation of p-type silicon heterojunction solar cell electrons radiation hardness. While

LEO orbits are rather proton rich, we choose electrons beams as a first step here, for there high penetration depth creating uniform defects throughout the various Si thicknesses considered here. Amorphous/Crystalline Si heterojunction solar cells were manufactured on the industrial pilot line of CEA[11], 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. Irradiations were performed using SIRIUS facilities[12], on half M2 cells format. The effect of bulk thickness reduction on cells EOL performances are quantified and radiation hardness improvement paths are discussed.

II. DETAILED EXPERIMENTAL PLAN

The experimental approach used in this study is schematically represented in Figure 1 below. The first step consisted in the fabrication of p-type heterojunction silicon solar cells. To this end, we have chosen state-of-the-art Ga-doped wafers. Indeed, on the one hand Ga-doped BO-LID-free Cz silicon wafers have recently reached the terrestrial market at no extra-cost[13], with the outstanding efficiencies of 26.5% demonstrated[14], and on the other hand the switch from B to Ga seems to be beneficial for radiation hardness, thanks to mitigation of radiation-induced recombination centers[15], [16]. Prior standard heterojunction fabrication process steps, M2-wafers, with 30 Ohm.cm resistivity, were chemically thinned down to achieve three different thicknesses: 160 μm , 110 μm and 60 μm . Sets of front emitter bifacial cells were manufactured on the CEA INES pilot line and laser cut in half. One split of the 60 μm thick. cells (hereafter named second batch) has received double layers anti-reflection coating (TCO & dielectrics) to improve light coupling within the device. AM1.5G IV measurements and EQE were performed to quantify initial performances. Irradiations exposure consisted of 1MeV electrons, at room temperature, with fluences of 1.5×10^{14} , 7.5×10^{14} and $1.5 \times 10^{15} \text{ e/cm}^2$. Final performances were assessed with IV & EQE characterizations on the same set-up, as well as by an external calibration for the best performing cell.

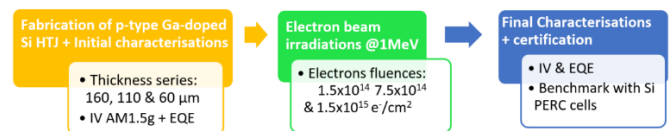


Figure 1 – Experimental plan for testing p-type Si Ga-doped heterojunction radiation hardness

III. RESULTS & DISCUSSIONS

Begin-of-life evaluation

With thickness down to around $60\mu\text{m}$, the flexibility of crystalline silicon wafers is greatly improved. Silicon heterojunction solar cells with $60\mu\text{m}$ thickness and M2 format can for instance be rolled like a sheet of paper, as shown in Figure 2; curvature radius in the few centimeters range are not harmful for the cells. Recent literature results also demonstrated that with specific edge treatments, curvature radius below 1 cm can be safely applied without performance loss on $60\mu\text{m}$ heterojunction cells[17].

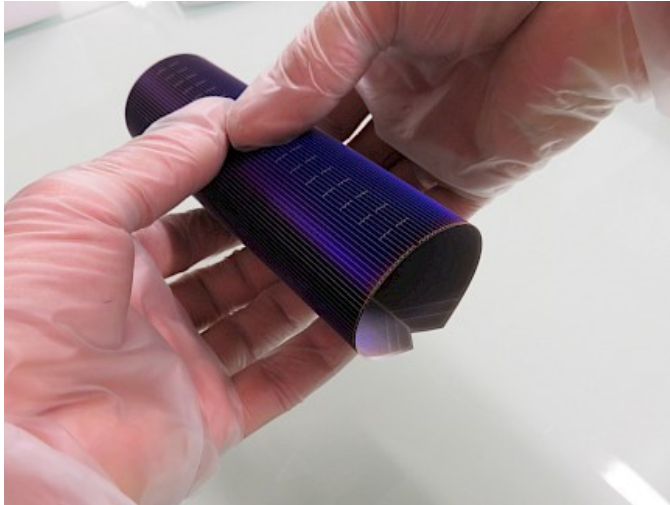


Figure 2 – Pictures of $60\mu\text{m}$ Si p-type heterojunction solar cells rolled like a paper sheet.

The IV AM1.5G parameters measured on full cell M2 format for the cells with single layer (TCO) and double layer (TCO + dielectric layer) anti-reflection coatings (DARC) $60\mu\text{m}$ Si heterojunction batches are presented in Figure 3. Overall, one can see that the spreading of the population in the second batch with DARC is less pronounced than for the first batch with only TCO layer. This is not related to this front side optical variations, but rather the results of the learning curve

concerning processing and handling such ultra-thin silicon wafer and cells. V_{oc} & FF median values are sensibly the same for the two batches, but I_{sc} is significantly boosted (~ 200 mA) thanks to the improved optical coupling achieved with DARC. This translates into an efficiency boost for the median of the DARC population of +0.6% abs (from 21.2 to 21.8%). The best performing cell from this DARC batch reaches 22% AM1.5G efficiency, before irradiation.

End-of life evaluation

Before irradiation exposure, all Si cells were laser cut in half to increase the number of irradiated cell samples for a fixed total beam time and surface. The performance of half cells were measured before and after electrons irradiations, and the results are plotted as function of 1MeV electrons in Figure 4. The variations of the open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}) and efficiency (from left to right) are color coded as follow: green for $60\mu\text{m}$ related data, light green for $60\mu\text{m}$ with DARC, pink for $110\mu\text{m}$ and purple for $160\mu\text{m}$. The black data points correspond to commercial $180\mu\text{m}$ thick PERC Si cells (boron-doped, 1.0 Ohm.cm). Dots are for experimental points and curves are semi-empirical functions fitted to data, used here as a guide for the eyes[18]. As one can see, the PERC solar cell happen to be more radiation hard in terms of open-circuit voltage, with $\sim 125\text{mV}$ loss at $1.5 \times 10^{15} \text{ e/cm}^2$ compared to $\sim 275 \text{ mV}$ degradation for those heterojunction cells. However, this trend is opposite for the short-circuit current: PERC losses are in the 13mA/cm^2 range while the best heterojunction loses only 3mA/cm^2 . In terms of EOL power conversion efficiency, $60\mu\text{m}$ p-type HJT without DARC matches the $180\mu\text{m}$ PERC performance at $7.5 \times 10^{14} \text{ e/cm}^2$, and outperform the PERC at $1.5 \times 10^{15} \text{ e/cm}^2$, with a cell mass reduced by $\times 3$. With the DARC, the $60\mu\text{m}$ heterojunction cell outperform the $180\mu\text{m}$ PERC cell for every fluence tested here; the thickness reduction is strong contributor of this result.

Thickness variations among the tested heterojunctions provide also interesting insights. Thickness reduction allows V_{oc} boost in BOL conditions: this is reported in literature[19] and observed here as well, with 750mV reached for $60\mu\text{m}$ thick

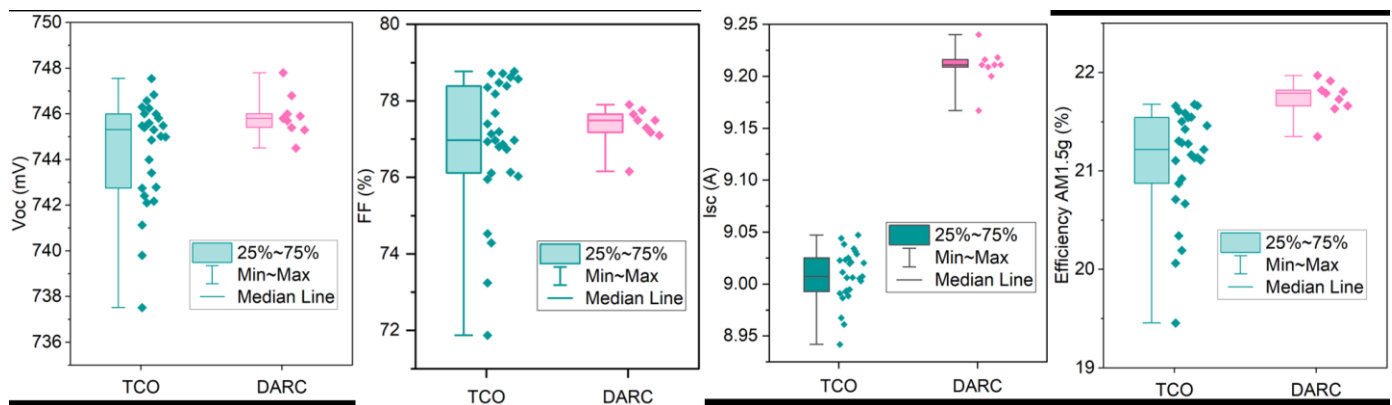


Figure 3 – V_{oc} , FF, I_{sc} & Efficiency under AM1.5g spectrum at room temperature for $60\mu\text{m}$ p-type Ga-doped Si heterojunction solar cells, with single layer (TCO) and double layer (TCO + dielectrics) antireflection coatings.

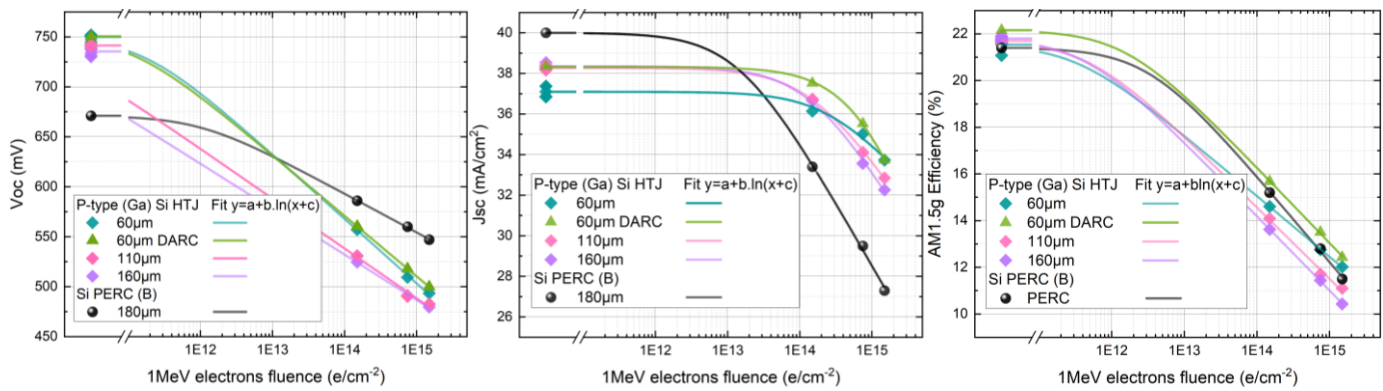


Figure 4 – Variations of V_{oc} , J_{sc} & Efficiency as measured in-house under AM1.5G spectrum at room temperature for p-type Ga-doped Si heterojunction solar cells with 160, 110 & 60µm thicknesses, without and with DARC. Comparison with commercial 180µm Si (B) PERC cell.

cell. This initial voltage advantage with reduced thickness is also present in EOL conditions: the reduction from 160µm to 60µm brings 20mV boost in BOL and 10mV boost in EOL. Concerning the J_{sc} , the thicker cells have a high current until 2×10^{14} e/cm², and then the 60µm version (w/o DARC) outperform with only 3mA/cm² loss post-irradiation (instead of 6 mA/cm² for 160µm cell). For the 60µm with DARC, current density is better for all fluences, but the benefit tends to shrink at high fluences; further studies on DARC would be required to track the origin of this phenomena. Overall, these ultra-thin HJT are particularly radiation hard in terms of current generation. Finally, for the efficiency, the trend is clear: the 60µm version outperform the thicker HJT variations for all fluences above $\sim 5 \times 10^{12}$ e/cm². 14.6% efficiency under AM1.5G are measured in house on the 60µm ½ M2 cell at 1.5×10^{14} e/cm², and 12% after 1.5×10^{15} e/cm². The best cell with DARC shows 15.7% AM1.5G efficiency at 1.5×10^{14} e/cm² and 12.4% efficiency at 1.5×10^{15} e/cm². The efficiency gain at high fluence with respect to PERC is significant (+0.9% abs.), and as mentioned, the ultra-thin heterojunction offers in addition a factor of three in cell mass reduction.

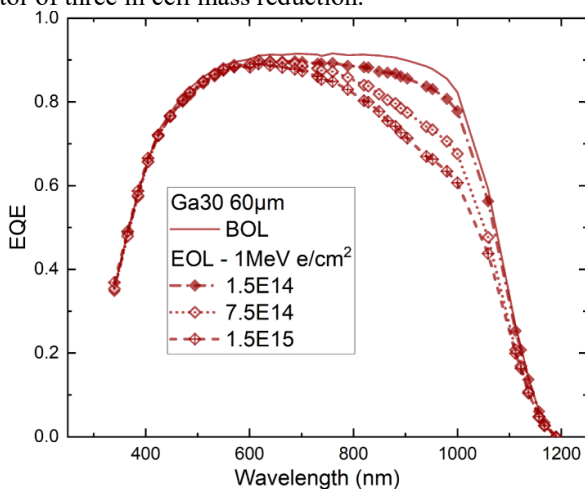


Figure 5 – EQE measurement on 60µm Si heterojunction cell (w/o DARC) before & after irradiation with 1MeV electron fluences

EQE analyses on thin 60µm Si heterojunction solar cells are presented in Figure 5. As expected the losses are pronounced in the long wavelength region, carriers are far away from the front side emitter and thus have less chance to reach the junction before crossing a recombination center. It is interesting to note that in the short wavelength region, no change is observed, suggested that damages in surface regions are less harmful.

Certification and AM0 performances

The accurate measurement of large and ultra-thin silicon cells can be tricky, especially with respect to handling/contacting and associated breakage risks.

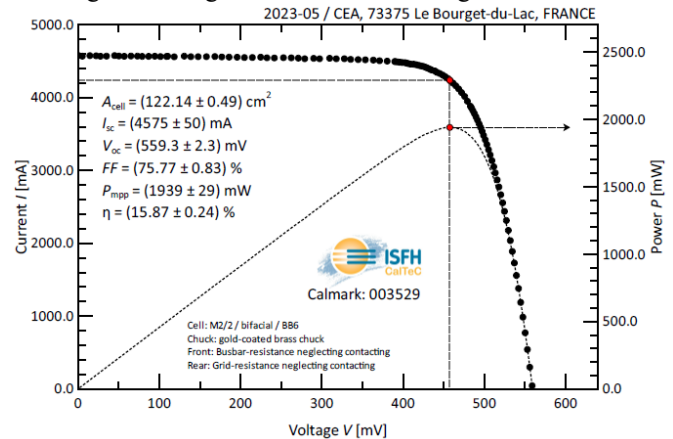


Figure 6 – Certified current voltage characteristics under AM1.5G for EOL (1.5×10^{14} e/cm² 1MeV) 60µm DARC Si heterojunction solar cells.

Thus, we decided to send the best 60µm DARC p-type silicon heterojunction irradiated at 1.5×10^{14} e/cm² for a certification externally (ISFH); the corresponding IV curve, and cells parameters are displayed in Figure 6. The certified AM1.5G EOL efficiency is 15.9%, 0.2% abs. higher than our in-house measurement (shown in Figure 4). This difference comes mainly from a higher FF (optimized contacting scheme). Overall, with this calibration results, the 60µm DARC silicon

Table 1 - Calculation procedure for AM0 IV parameters extrapolation from measured AM1.5G measured parameters

AM1.5G IV measurements	$J_{sc-AM1.5}$ [$\frac{mA}{cm^2}$]	$V_{oc-AM1.5}$ [V]	$FF_{AM1.5}$ [%]	$Eff_{AM1.5}$ [%]
AM0 analytical calculation	J_{sc-AM0} $= J_{sc-AM1.5}$ $\times \alpha$	$V_{oc-AM0} = V_{oc-AM1.5} + \frac{kT}{q}$ $\times \ln(\alpha)$	FF_{AM0} $= \beta$ $\times FF_{AM1.5}$	$Eff_{AM0} = \frac{J_{sc-AM0} \times V_{oc-AM0} \times FF_{AM0}}{P_{in-AM0} (\frac{mW}{cm^2})}$
Parameters	$\alpha = 1.221$	$k = 1,38065E^{-23} [\frac{J}{K}]$ $q = 1,6021766208E^{-19} [A.s]$ $T \sim 298 [K]$ $\rightarrow \frac{kT}{q} = 0.0257 [V]$	$\beta = 1$	$P_{in-AM0} = 136.6 (\frac{mW}{cm^2})$
AM0 numerical expressions @298K	J_{sc-AM0} $= J_{sc-AM1.5}$ $\times 1.221$	$V_{oc-AM0} = V_{oc-AM1.5}$ $+ 0.0051$	FF_{AM0} $= FF_{AM1.5}$	$Eff_{AM0} = \frac{J_{sc-AM1.5} \times 1.225 \times FF_{AM1.5} \times (V_{oc-AM1.5} + 0.0052)}{136.6}$

heterojunction cell reaches higher efficiency values than PERC (+0.7% abs.) for every fluences and with only one third of its mass.

It is interesting to extrapolate this certified AM1.5G IV parameters to the values expected under AM0 spectrum. Starting from an AM1.5G measurement, we are thus applying the following methodology (see formula in Table 1) :

- Jsc: a scaling factor, here equal to 1.221, is applied for taking into account the additional AM0 current; this value is deducted from the ratio of the Jsc calculated from calibrated EQE curve & integration with both AM1.5G and AM0 spectrums
- Voc: the higher power density contained in AM0 results in a small Voc increase. This is quantified using the logarithmic formula. At 298K, it results here by ~ 5.1 mV increase.
- FF: the change of fill factor with spectrum is minimal (usually below 1%) and is linked to the cell metallization. In our case we keep the same value ($\beta=1$) of FF for both AM1.5G and AM0 spectrum.
- Efficiency: it is defined by the usually formula with the above mentioned cells calculation processes. The incident power, as defined in reference AM0 spectrum ASTM E-490, is thus taken equal to 1366.6 W/m².

Using this methodology, we can calculate the AM0 performance of the 60 μ m DARC Si heterojunction solar cell, using certified AM1.5G measurements (IV and spectral response) as inputs. The results are displayed for the initial measurements and calculated AM0 in Table 2. As one can see, the 15.9% AM1.5G certified results corresponds to 14.3% under AM0 space solar spectrum, at room temperature. This EOL performance results is a proof of superior radiation hardness of ultra-thin Si heterojunction solar cells compared to standard Si terrestrial solar cells.

Table 2 - JV parameters for EOL (1.5×10^{14} e/cm² 1MeV) 60 μ m DARC Si heterojunction solar cells: certified AM1.5G measurements & corresponding AM0 data (calculations).

Spectrum	Cells	Jsc [mA/cm ²]	Voc [mV]	FF [%]	Efficiency [%]
1MeV 1.5 ^E 14 e/cm ²	AM1.5G (Calibrated)	37.5	559	75.8	15.9
	60 μ m AM0 (Calc. from calibrated meas.)	45.8	564	75.8	14.3

IV. CONCLUSION

High quality Ga-doped Cz wafers are becoming terrestrial PV industry standard and this switch from boron to gallium is also reported as beneficial for silicon radiation hardness in space PV literature. Within this study, we have manufactured and explored the radiation hardness under 1MeV electrons of

p-type Ga-doped silicon heterojunction with 160, 110 and 60 μm thicknesses. Due to the irradiation, a significant voltage degradation was observed, but the current decrease was more limited; for this reason, we have shown that DARC significantly helps to improve EOL performances. EQE has confirmed that the long wavelength region, with photons absorbed away from the front junction, is the most affected by the radiation induced diffusion length reduction. Overall the ultra-thin Si heterojunction shows the promising radiation hardness, with better performances than PERC at every fluence tested here, for a mass $\times 3$ smaller. The best ultra-thin 60 μm DARC Si cell has been certified externally and reaches 15.9% AM1.5G at 1.5×10^{14} e/cm². A methodology is presented to calculate the corresponding AM0 performance using IV and EQE inputs; by doing so we obtain 14.3% AM0 at room temperature. Further improvement in EOL performances seems possible by tuning wafer's compositional properties, and device architecture.

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