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Radiation effects model for Ultra-Thin Silicon Solar Cells

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Abstract. This work is focused on investigation of radiation effects in Ultra-Thin Silicon solar cells with a particular emphasis on electron irradiation. The study is motivated by the application of these solar cells, developed by Solestial, Inc., for powering space missions, including those led by NASA, the Department Of Defence (DOD), and commercial satellite missions. Our research encompasses both experimental and theoretical approaches, addressing unique challenges posed by ultra-thin solar cell technology that deviates from the traditional models. From the experimental point of view, the test structures were irradiated with 1 MeV electrons up to the fluence of 1E+15 e/cm^2. Radiation effects due to accumulated electron dose were noticed as a drop in open-circuit voltage (V_{oc}). An analytical expression for modeling the Voc characteristic of the UT-Si cell after exposure to electron irradiation was formulated and subsequently compared with experimental data. The theoretical foundation of the proposed approach builds upon the Non-Ionising Energy Loss (NIEL) concept, a fundamental parameter in addressing radiation damage modelling and survivability predictions.

1. Introduction

Degradation of solar cells in space environment mainly arises from their interaction with incident protons and electrons [1]. These charged particles can originate from two sources: either being trapped within the Earth's radiation belts, known as the Van Allen belts, or emitted during solar events. It becomes essential to devise a method to predict a degradation level cells undergo in such radiation harsh space environment. The degradation rate for a particular type of solar cell depends initially on the energies of the incident particles, but also on the shielding mechanisms. Typically a front side of the solar cell is shielded by a cover glass, and a rear side - by the substrate material and/or supporting array structure. These serve to attenuate the incident particles prior to they reach bare cell active region. Furthermore, the response to irradiation varies across different types of solar cell technologies [2]. This divergence arises from such factors as materials used, thickness of the active regions, the specific types and concentrations of dopants and impurities, solar cell architecture but also environmental factors. All these parameters should be taken into account to develop a comprehensive understanding of how different solar cell technologies will perform in such challenging radiation conditions.
Two main approaches are currently employed to model solar cells degradation in space - the first formulated at the US Jet Propulsion Laboratory (JPL) [3, 4], and the second one developed

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at the US Naval Research Laboratory (NRL) [5]. Although both methods are similar, the key difference is that the NRL approach is based on the classical Non-Ionizing Energy Loss (NIEL) hypothesis built-on the assumption that all damage scales with the displacement energy, so-called direct hardness factor scaling. Unfortunately it doesn't take into account the fact that same imparted displacement energy results in different distribution of damage on the microscopic level (point-like defects to the clusters) for different particles and particle energies. The issue of NIEL violation has arisen within both the High-Energy Physics (HEP) and Space communities [6–8], indicating that the conventional model occurs incomplete describing the radiation damage effects in the given circumstances. Radiation-induced damage effects associated with the creation of point defects do not comply with the conventional NIEL scaling concept, which typically relates damage susceptibility to particle type, e.g. proton versus neutron damage, despite having the same NIEL value. Furthermore, these damage effects are often influenced by the presence of impurities within the silicon material, which significantly impact the kinetics of point defect formation, thereby altering the damage effects observed. On the other hand, damage effects that do scale with the classical NIEL concept typically originate from the intrinsic defects. These defects consist solely of silicon vacancies (V) and interstitials (I), such as e.g. clusters V_2, V_3 or I_2. A prominent example of this phenomenon is observed in leakage current, where the defect generation rate is predominantly driven by the creation of cluster defects [9]. Typically, clusters are large agglomerations of vacancies or interstitials in a volume of $\sim$20 nm^3 with 1E+5-1E+6 atoms. Driven by the Shockley˘2013Read˘2013Hall (SRH) mechanism, the defects might act like trapping, generation or recombination centers, depending on the energy level of the defect within the bandgap. Additionally, recombination centers have the effect of diminishing the diffusion length, whereas trap centers reduce the overall quantity of carriers, resulting in so-called carrier removal effect. Consequently there is a crucial need to develop a more sophisticated model but also rely on experimental data to better understand and predict the radiation damage within particular scenarios.
The purpose of this paper is to make a direct comparison of the experimental and theoretical approaches using a particular case of electrons incident on Ultra-Thin Silicon (UT-Si) solar cells as radiation response of the specific solar cell technology.

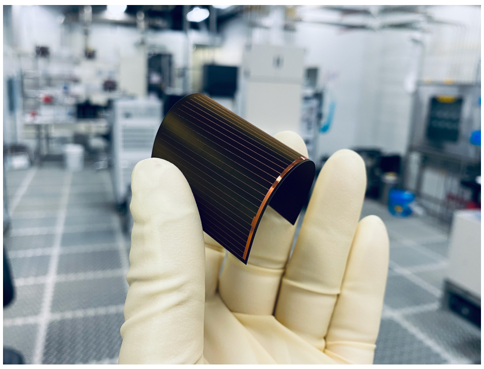

Figure 1. *Solestial* 20 μm thick Silicon Heterojunction solar cell.

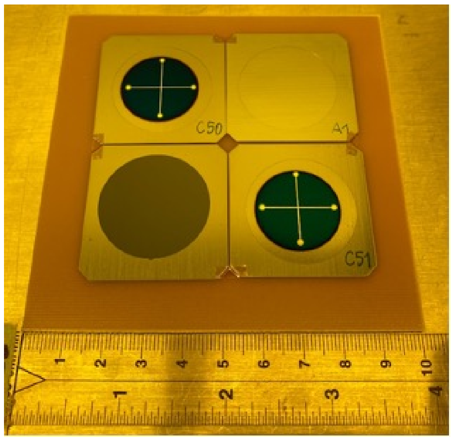

Figure 2. Packaging of the *Solestial* prototypes of selected dimensions assigned for 1 MeV electron irradiation at FNAL.

2. Experimental Approach

2.1. Test structures

Several Ultra-Thin (UT) silicon (Si) prototypes with an area of 3 cm^2, suitable for irradiation purposes, were manufactured by *Solestial, Inc.* The samples used in the described below irradiation experiment were Silicon Heterojunction (HJT) solar cells with thicknesses ranging from 20 to 80 μm, example of the thinnest cell is shown in Fig. 1. It is worth to mention that besides being radiation hard, the *Solestial* core technology - Ultra-Thin Silicon HTJ solar cell - has unique radiation damage self-curing capabilities [10], confirmed by a third-party verification as reported elsewhere [11].

2.2. Test facilities

The electron irradiation experiments were conducted at the Fermi National Accelerator Laboratory (FNAL), the Accelerator Applications Development and Demonstration (A2D2) research platform, led by Principal Investigator Charles A. Cooper. FNAL is equipped with a state-of-the-art linear accelerator, operated by a team with world-known expertise. The original electron beam parameters were as follows: a kinetic energy of 9 MeV, beam intensity of 8.33E+14 e/s and a Gaussian beam shape with a sigma value of 8.8 cm. To reduce the electron energy to the required 1 MeV, an aluminum plate, namely "Aluminum-6061", with dimensions of 20 by 20 cm^2 and thickness of 1.725 cm was designed and used as a beam degrader. Such aluminium block size was carefully selected in order to avoid undesired beam heating effects. The test prototypes were irradiated at nominal room temperature to fluences of 1E+12, 5E+12, 1E+13, 5E+13, 1E+14, 5E+14 and 1E+15 e/cm^2, two or more samples at each dose. The duration of the exposure required to achieve the highest fluence was approximately 82 s. In order to accommodate the 9 cm diameter of the electron beam and to ensure the safety of to the solar cells during irradiation, test structures were mounted by four onto a 1.5 mm thick fiberglass plate, as illustrated in Fig. 2.

3. Experimental results and discussion

In this paper we present the latest results on the electrical characterization of *Solestial* UT-Si solar cells. The gradual degradation of open-circuit voltage V_{oc} after electron irradiation is observed with a received fluence for all cell thicknesses. For the thinnest cell of 20 μm the results are shown in Fig. 3. On this plot blue empty symbols correspond to the experimental values whereas red curve represents the parametrization results. Values presented are normalized to those corresponding to non-irradiated devices.

We assessed the accuracy of the irradiation data by comparing obtained values for V_{oc} for a 20 μm thick solar cell irradiated at FNAL and previously at NIST. Notably, the first three digits of Voc measurements were identical, demonstrating an accuracy level of 0.2%.

It is worth to mention that *Solestial* UT-Si solar cells undergo significant annealing of radiation damage at temperatures below 80 °C [12]. To demonstrate this, three sets of the cells of different thicknesses were subjected to a 36-hours or less isothermal annealing after electron irradiation at the highest available - 1E+15 e/cm^2 - fluence under the light exposure. The data do not follow the trends predicted by any methodology described in the literature [[13–15]]. This is primarily due to the fact that neither GEANT4 [16] nor TRIM simulations [17], which are commonly used in HEP and Space communities, can individually resolve the NIEL violation puzzle. Instead, a combined approach is necessary to address this complex issue. The results of such annealing studies performed at 100 °C are shown in Fig. 4 showing major radiation resistance.

The degradation of device parameters, as estimated through a semi-empirical equation derived from the NRL model, can be expressed using the following formula:

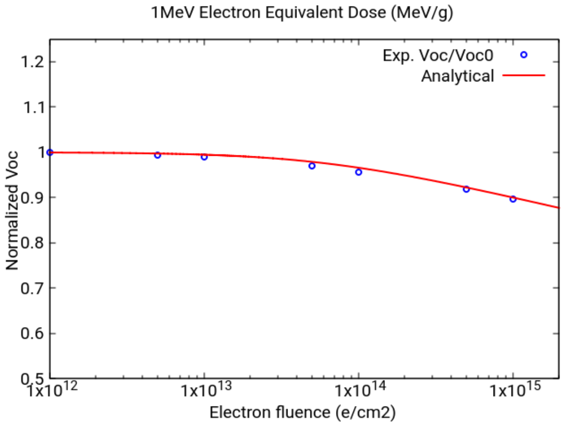

Figure 3. The comparison of V_{oc} from the analytical model to the experimental results for 20 μm thick *Solestial* solar cell.

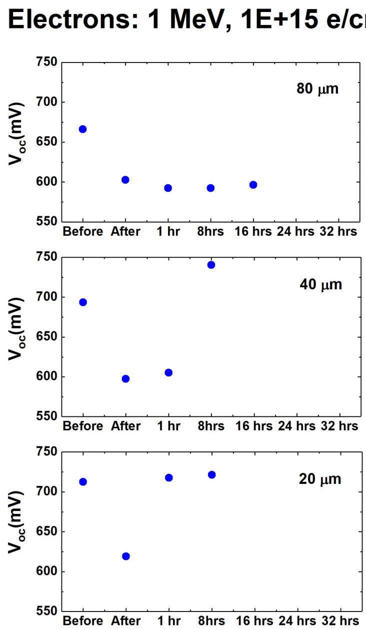

Figure 4. Curing of *Solestial* UT-Si solar cells of selected thicknesses at °C.

$$\frac{V_{oc}}{V_{oc0}} = 1 - C_x \log_{10}(1 + \frac{D_d}{D_x}). \quad (1)$$

Here, C_x and D_x represent the fitting parameters, D_d stands for the Displacement Damage Dose (DDD) in [MeV/g], V_{oc} corresponds to the measured parameter value after irradiation, and V_{oc0} is the value before irradiation. The interpolation parameters have been derived from the measured data to describe this relationship accurately. The DDD can be calculated by considering the flux of particles, their energy distribution, and the material's response to them:

$$DDD = \int \frac{\delta\phi(E)}{\delta E} S(E) dE, \quad (2)$$

where $\phi(E)$ is the irradiation fluence, $\delta\phi(E)$ stands for the differential fluence and $S(E)$ corresponds to the NIEL value for a given particle and energy. By analyzing the data in terms of DDD, data from a variety of different radiations can be easily extrapolated to a common curve.

The performance of UT-Si solar cells in the challenging space environment is a critical consideration for space missions. As mentioned above, these solar cells are exposed to a variety of radiation sources, including high-energy (1-10 MeV) electrons and protons. Understanding how these particles impact on the cells performance, particularly in terms of the production of Primary Knock-On Atoms (PKAs), is essential for designing reliable space-based power systems. When it comes to PKAs generation, the mechanisms differ significantly between electrons and protons. Electrons, as elementary charged particles, interact primarily through continuous scattering interactions with lattice electrons in the material. These interactions can lead to the creation of electron-hole pairs and atomic displacements. In this process, electrons lose energy and create PKAs more uniformly through the material due to their frequent electron-electron scattering and electron-phonon interactions. Protons, on the other hand, penetrate deeper into the material before losing most of their energy. As a result, PKAs generated by proton irradiation are concentrated in a specific area along the proton path, so-called displacement cascade. In conclusion, understanding how high-energy electrons and protons affect UT-Si solar cells is crucial for modelling and consequently mitigating radiation damage.

4. Conclusions

The assessment of solar cell performance in space relies on its key characteristics measurements under controlled conditions on the ground. This article outlines the procedure for processing and interpreting the data obtained from so-called ground-based testing. The central objective of this analysis is to predict the test structure response to radiation exposure using obtained test data acquired after subjecting them to reference particle irradiation. The proposed method benefits from its predictive capabilities in this context.

5. Acknowledgments

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