Full Recovery of Radiation Damage in Silicon Solar Cells at 80°C Under Light

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Abstract

We report effective recovery of radiation damage in electron and proton irradiated 20-micron-thick silicon heterojunction solar cells using annealing at 65°C, 80°C and 100°C under light with 0.5 Sun intensity conducted at open circuit. The cells with 18% AM1.5 efficiency were shown to fully recover after irradiation with 1 MeV 1e15 cm^{-2} electrons and 300 KeV 1e10 cm^{-2} protons within 8 hours of curing at 80°C under light.

It was shown that annealing rate was a function of wafer thickness, wafer type, annealing temperature and irradiation conditions.

Providing solar cell in space can achieve 80°C periodically, this opens a possibility of self-curing solar cells with substantially lowered radiation-induced degradation. Coupled with other advantages of ultrathin silicon solar cell technology developed by Solestial such as low cost, competitive efficiency, robust electroplated metallization, low temperature coefficient, compatibility with automated production and no scaling bottlenecks, this can solve the challenge of powering LEO satellite mega constellations that require 10s of MW of space-stable solar panels and enable future in-space power infrastructure.

Experiment

- Silicon heterojunction solar cells with thicknesses 20, 40 and 80 microns have been prepared on the wafers with different combination of impurities. Cell area was 4 cm^2 for proton and 30-73.5 cm^2 for electron irradiation.
- Annealing was conducted in atmosphere under 500 W/m^2 white light produced by a halogen bulb. Cell temperature was maintained using metal chuck with Peltier elements. Annealing was conducted at open circuit. Voltage was measured in-situ.

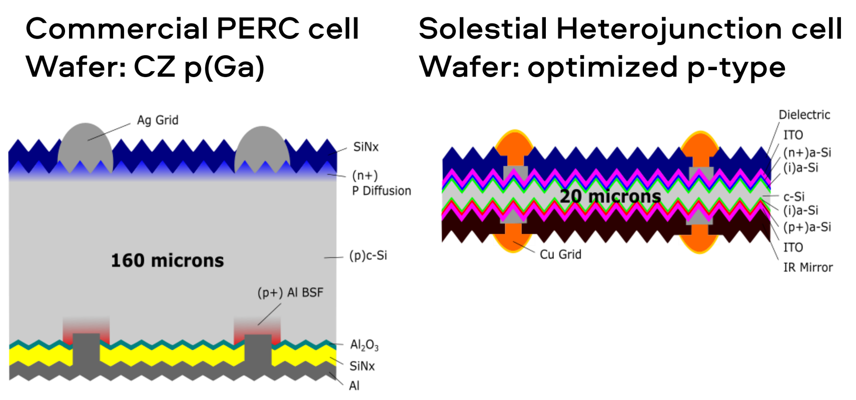

Figure 1. Schematic picture of a PERC solar cell and Solestial Ultrathin Si Heterojunction solar cell.

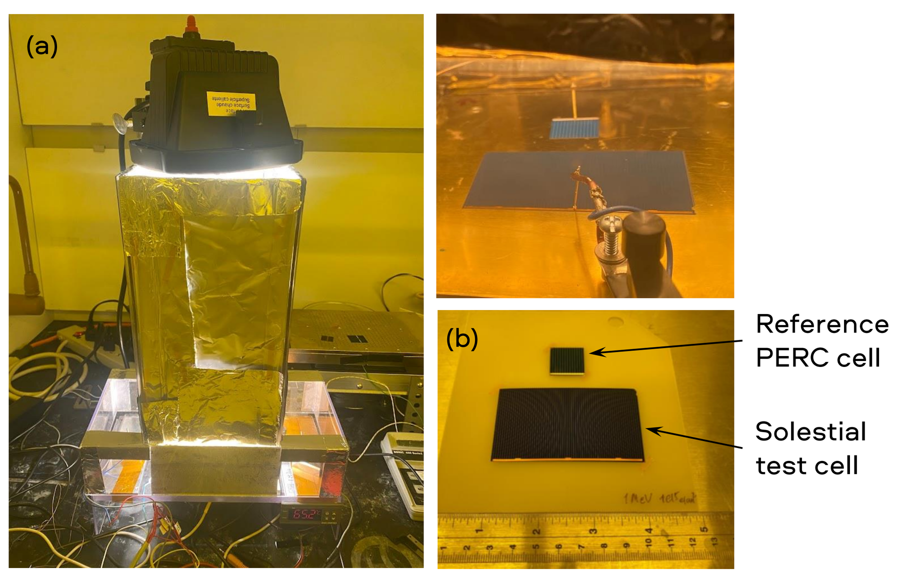

Figure 2. (a) Curing setup with a light source and a temperature control stage. (b) Sample that was used for electron irradiation.

Results

- **Dependence of annealing rate on wafer thickness.** For both 1 MeV electrons and 3 MeV protons annealing rate was a function of wafer thickness, 80-micron-thick cell having almost zero annealing. 20-micron-thick cells had 120 mV/hr and 7.5 mV/hr annealing rate for 1 MeV 1e15 cm^{-2} electron and 3 MeV 1e11 cm^{-2} proton irradiation respectively.
- **Dependence of annealing rate on wafer impurities.** At SPW 2019 we reported that 90% V_{OC} can be recovered at 100°C in CZ p(B) wafers whereas no annealing was observed for CZ n(P) wafers. In this work we further optimized wafer choice to achieve 100% recovery. Further, additional impurities have been added to the wafer as an extra process step. This enabled to reduce annealing temperature to 80°C and increase annealing rate to 120 mV/hr.

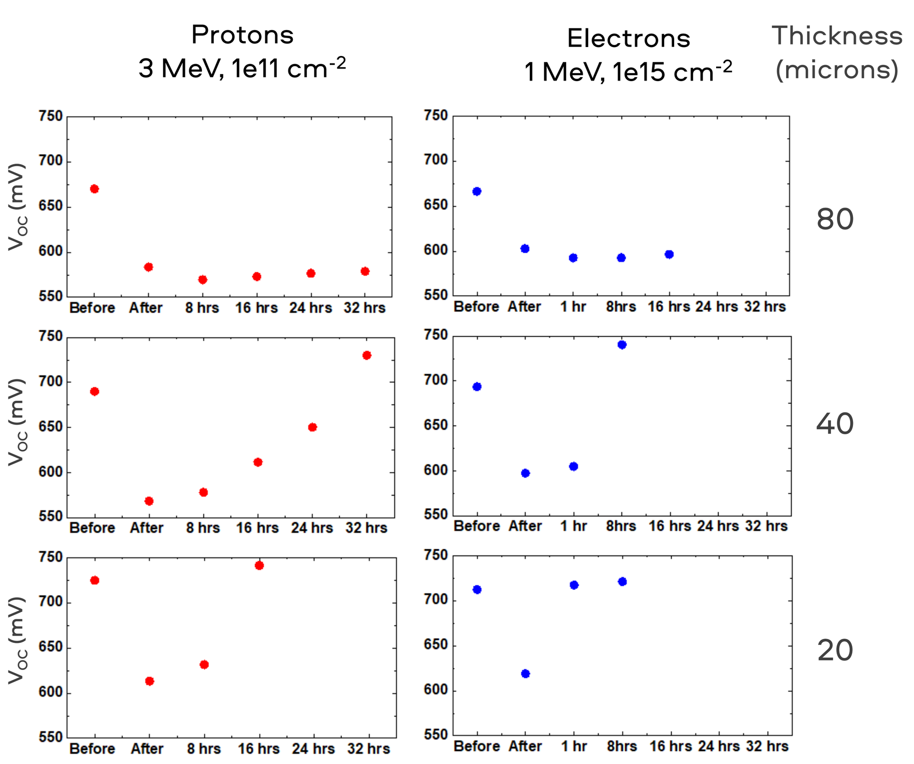

Figure 3. Cell thickness dependence of curing rate for 1 MeV, 1e15 cm^{-2} electron and 3 MeV, 1e11 cm^{-2} proton damage. Curing temperature 100°C.

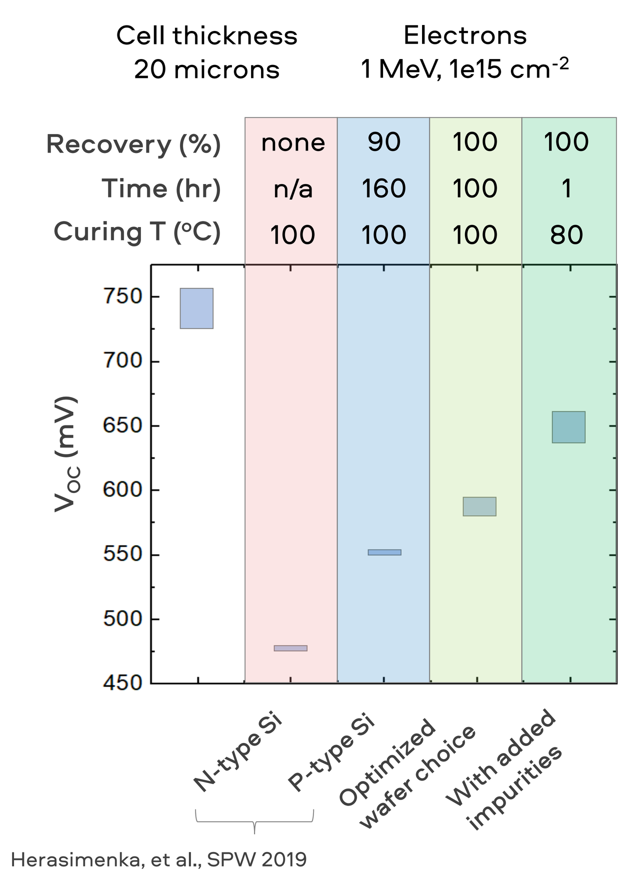

Figure 4. Dependence of curing rate in 20-micron-thick Si Heterojunction solar cells on wafer type (set of impurities in c-Si wafer).

- **Dependence of annealing rate on temperature.** It was shown that optimized 20-micron-thick solar cells experience annealing of 1 MeV electron damage at temperatures as low as 65°C. Annealing rates were 120 mV/°C, 11.4 mV/°C and 2.5 mV/°C for 100°C, 80°C and 65°C annealing temperature respectively.
- **Annealing of low energy proton damage.** It was shown that annealing was also effective for cluster defects formed by fully stopped protons (100 KeV protons have <1 micron stopping range in silicon).

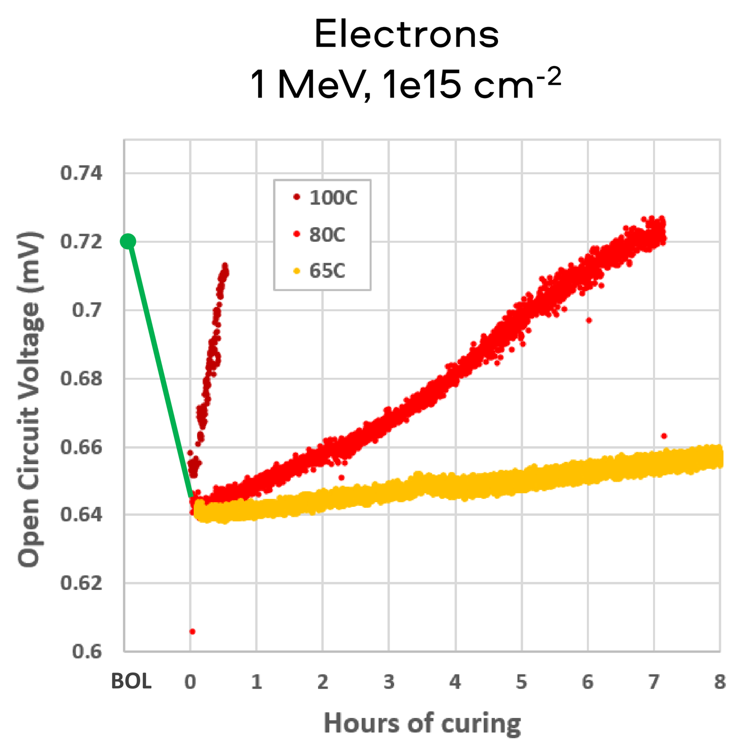

Figure 5. Annealing of 1 MeV, 1e15 cm^{-2} electron damage.

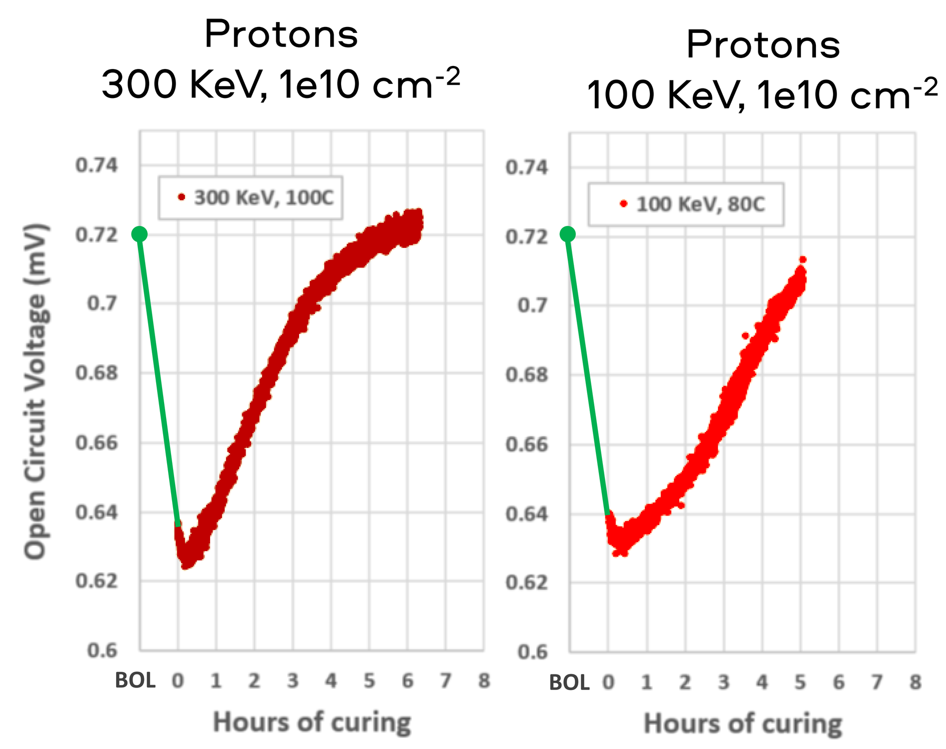

Figure 6. Annealing of 100 KeV and 300 KeV, 1e10 cm^{-2} proton damage.

	Before Irradiation	After Irradiation	After 8hrs at 80°C
Voc (mV)	718	614	714
Jsc (mA/cm²)	35.4	32.1	35.3
FF (%)	74.2	69.5	74
AM1.5 Eff. (%)	18.9	13.7	18.7

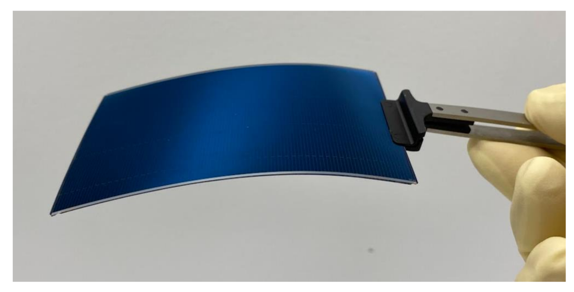

***Table I.** Efficiency of a large-area 20-micron-thick Si heterojunction solar cell before and after 1 MeV 1e15 cm^{-2} electron irradiation followed by 80°C curing under light.*

Discussion

- Effective annealing of radiation damage in thin silicon solar cells under light can enable lower radiation-induced degradation providing solar cells periodically experience temperatures close to 80°C while illuminated by the Sun.
- Note that annealing was demonstrated at open circuit, whereas solar cells in space will be at maximum pawer point with light generated current flowing. Future work will include annealing of the solar cell under load to better emulate real field conditions.
- Future work will also include expanding irradiation to other energies and fluences as well as using several solar cells per experiment instead of 1-2.
- Finally, future work will screen silicon wafers from different vendors to make sure annealing occurs for a variety of commercially available silicon wafers.

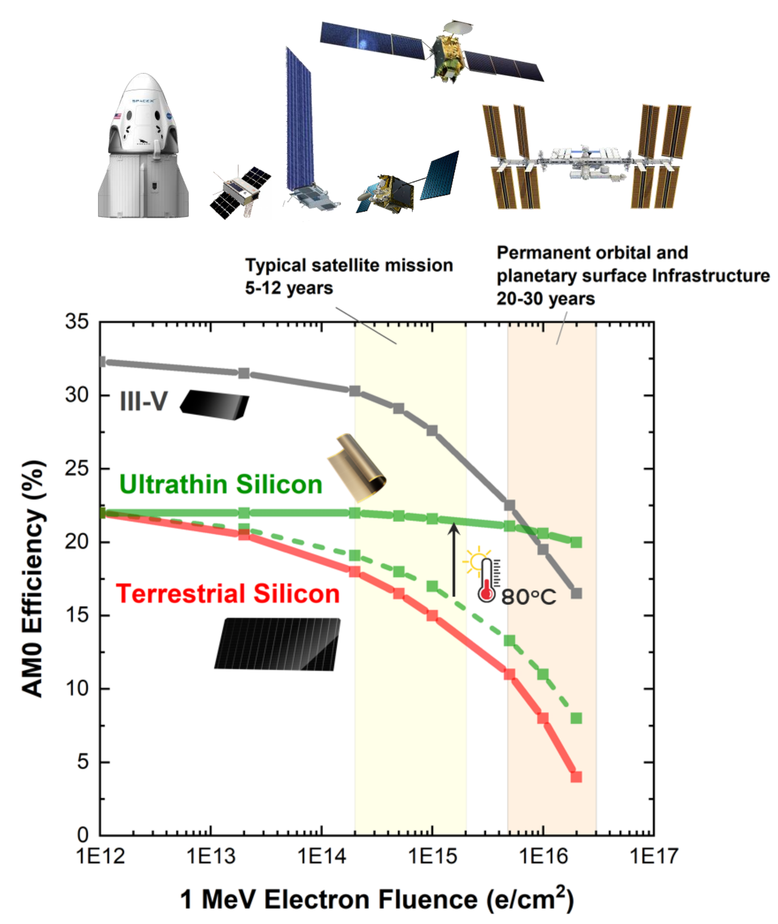

Figure 7. Projected end-of-life efficiency of ultrathin silicon solar cells providing solar cells routinely experience more than 80°C temperature in space.

Summary

- Low temperature annealing of ultrathin silicon solar cells under light was demonstrated. The dependence of annealing rate and temperature on cell thickness, wafer type and irradiation conditions was presented. Lowering degradation rate of solar cells enabled by self-curing was discussed.

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