Photovoltaic Fiber as a Building Block for Flexible Space Solar Power

Johns Hopkins Applied Physics Laboratory

Michael H.-C. Jin, Richard A. Korneisel, Richard J. Ung, and Konstantinos Gerasopoulos

Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland 20723, USA

Michael.Jin@jhuapl.edu (technical PoC)
Konstantinos.Gerasopoulos@jhuapl.edu (programmatic PoC)

Abstract

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has developed photovoltaic fibers (PVFs) including interdigitated back contact (IBC) crystalline silicon (c-Si) solar cells as small as 0.35 mm^2. The fiber was built on a flexible circuit strip as narrow as 400 µm and the solar cell was surface mounted on the strip. The solar cells were cut out of the state-of-the-art IBC Si solar cell with power conversion efficiency (PCE) of about 22 % under AM1.5 irradiation. The PCE of the fiber has reached up to 11 % under AM1.5 after encapsulation and PCE is expected to improve with further optimization in solar cell dicing. The fiber did not show any performance loss after 8000 bending cycles with a bending radius down to 1 cm. The bending test was not performed until failure and the minimum bending radius is expected be on the order of millimeters. To demonstrate the practicality of the fiber technology, the fibers were woven into textiles powering a light-emitting diode. The c-Si PVF has been tested under AM0 irradiation and showed slightly higher PCE than when measured under AM1.5 irradiation. Together with its potential for flexible space solar power, the technology aligns well with current interest in Si solar cell technology for space power.

Flexible Space Solar Power

- Flexible photovoltaic textiles enable:
  - Smart inflatable space structures with solar energy harvesting capability
    - Space stations
    - Lunar surface habitats – textile solar energy complements NASA's vertical solar array technology development roadmap
  - Multifunctional electronics-integrated textiles (textronics)
  - Low stowed launch volume

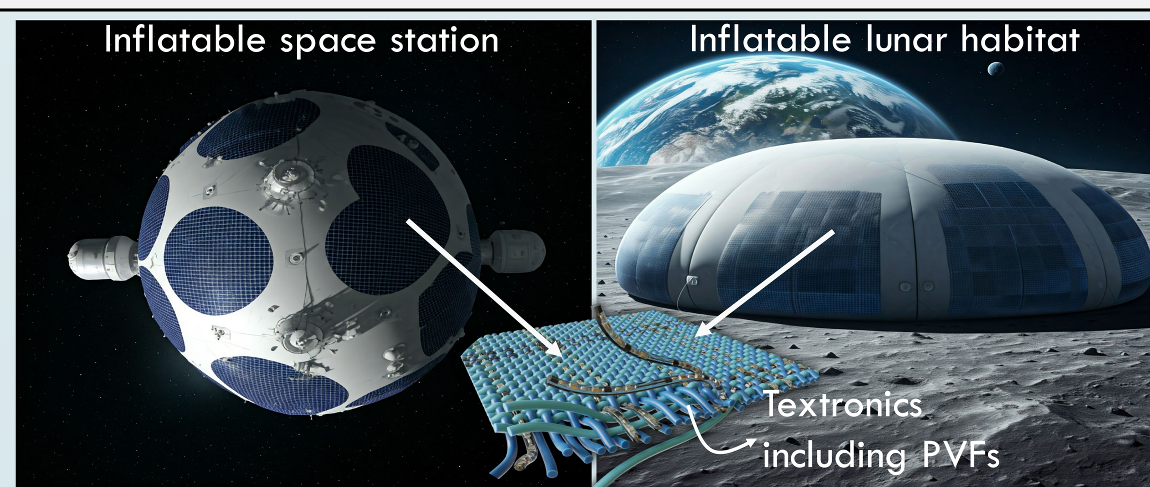
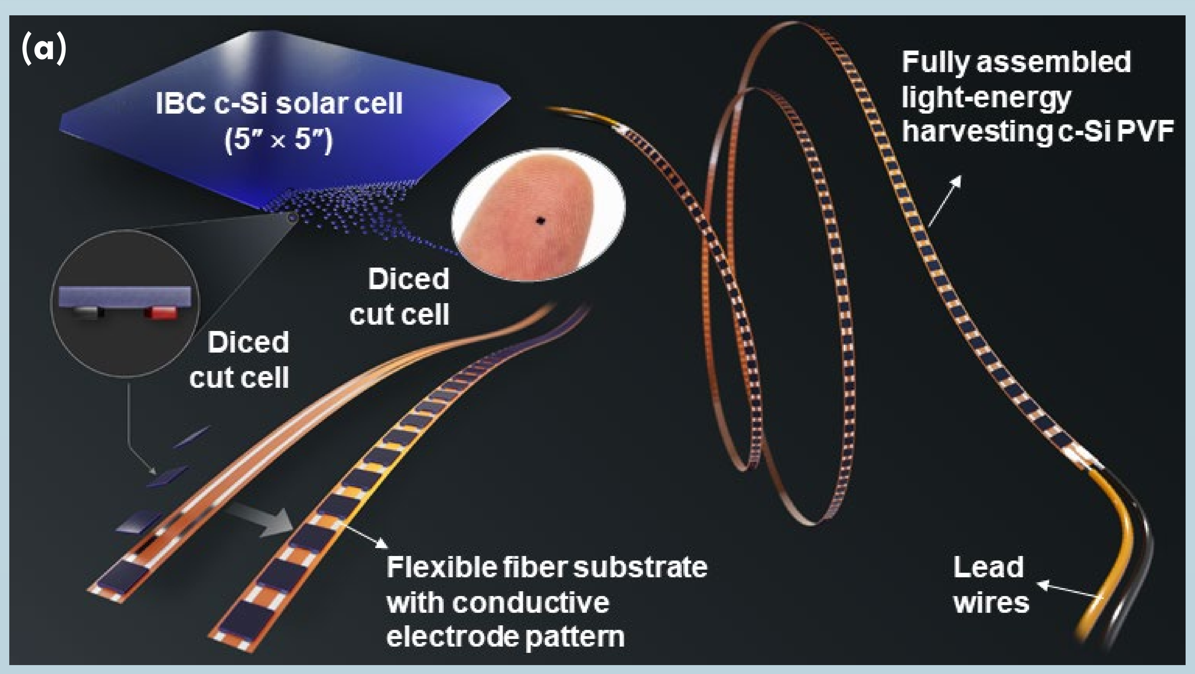


Figure 1: Examples of space application equipped with multifunctional textronics; the two application images were generated using Google Gemini from the prompt of an inflatable space station and an inflatable lunar habitat with flexible solar modules, respectively.

Fiber Technologies Developed by JHU/APL (Prior Work [1,2])

Crystalline Silicon (c-Si) PVFs [1]

- Best PCE reported for c-Si PVFs: ~10%
- Scalable fabrication on 400 µm-wide, 1.5′-long, flexible fiber substrates
- Leveraged mature IBC c-Si solar cell technology (SunPower C60 with PCE of 22%)
- Device-agnostic (any surface-mountable devices including PVs, batteries, LEDs, sensors, etc.)
- No performance loss after 8000 bending cycles at a bending radius down to 1 cm



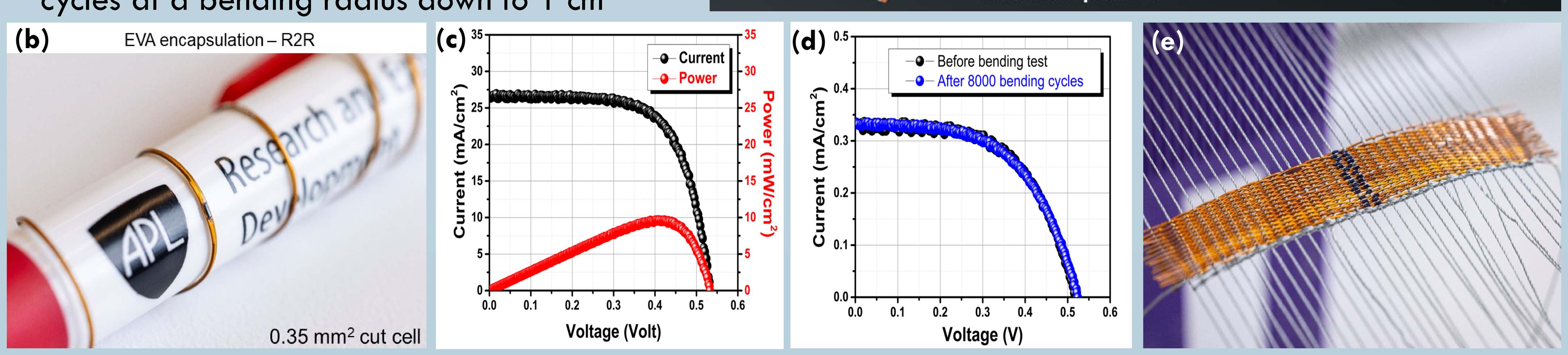
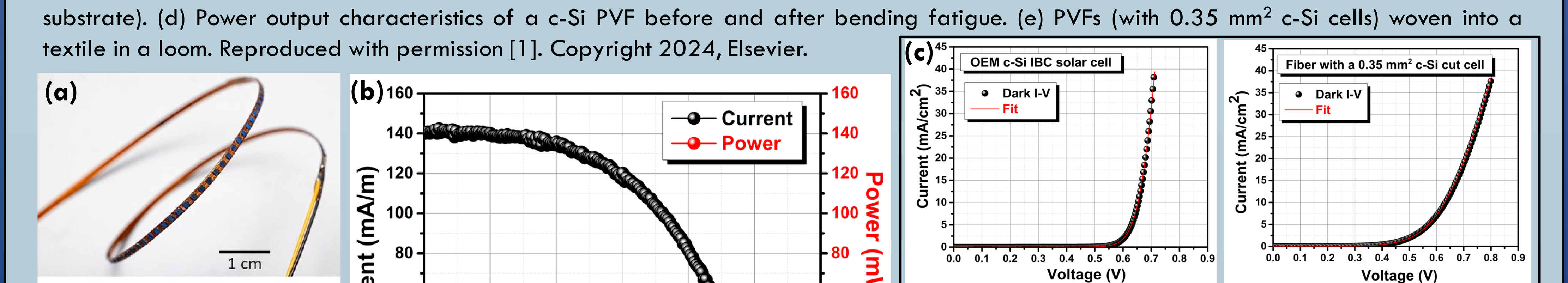


Figure 2: (a) Illustration of the c-Si PVF fabrication. (b) PVF with a single 0.35 mm^2 c-Si cell on a 400 µm-wide fiber substrate, encapsulated with ethylene vinyl acetate (EVA) using a roll-to-roll (R2R) process. (c) Best PCE reported for c-Si PVF (1mm² c-Si cell on a 1.5 mm-wide fiber substrate). (d) Power output characteristics of a c-Si PVF before and after bending fatigue. (e) PVFs (with 0.35 mm^2 c-Si cells) woven into a textile in a loom. Reproduced with permission [1]. Copyright 2024, Elsevier.



Sample	J_{01} [mA/cm²]	n_1	J_{02} [mA/cm²]	n_2	R_{sh} [kΩ·cm²]	R_s [Ω·cm²]
OEM solar cell (5″×5″)	5.8E-11	1	6.9E-09	1.3	34.3	0.8
Fiber with a 0.35 mm² c-Si cut cell	7.2E-11	1	6.6E-03	2.5	1.5	0.3

J_{01}: saturation current density due to recombination at the surfaces and the bulk of the device; J_{02}: saturation current density due to recombination in the space charge region of the device; n_1 and n_2: diode ideality factors; R_{sh} and R_s: shunt resistance and series resistance, respectively

Figure 3: (a) A 1.5′-long PVF with 84 units of 1mm² c-Si cell on a 1.5 mm-wide fiber substrate. (b) Power output characteristics of (a). (c) Dark I–V characteristics of a 153 cm² original equipment manufacturer (OEM) IBC solar cell and a fiber with a 0.35 mm^2 c-Si cell, fitted using a classic two-diode model, showing significant decrease in R_{sh} of the diced c-Si cell. Reproduced with permission [1]. Copyright 2024, Elsevier.

Scalable Fiber Fabrication

- Scalable fiber fabrication is possible with conventional industry tools such as a solder jet printer, a pick-and-place tool, and a laser cutter
- Parallel assembly processes such as micro-transfer printing, fluid assembly, chiplet printing, and laser-induced forward transfer can be explored to lower the cost of fabrication and to increase the throughput

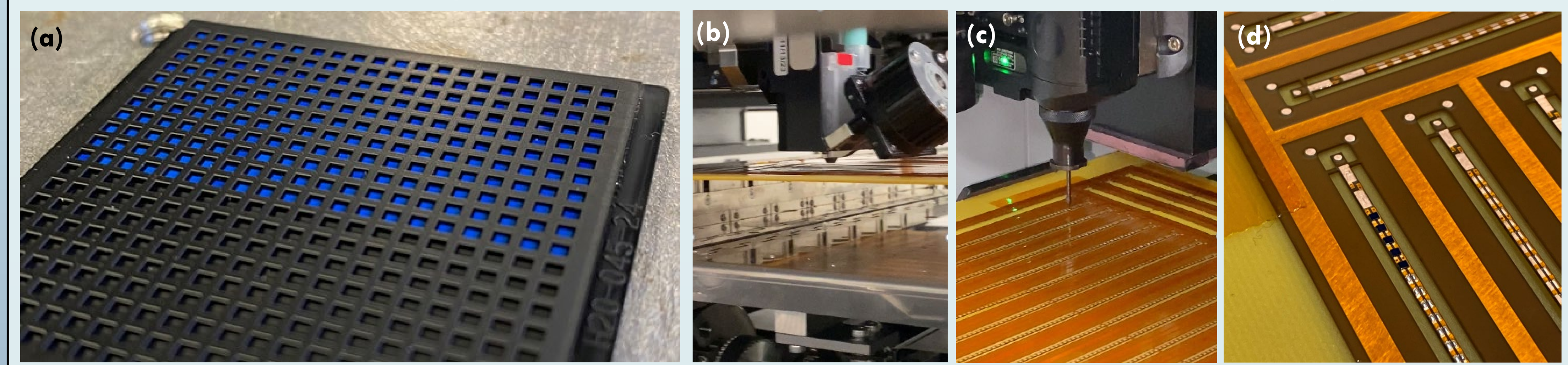
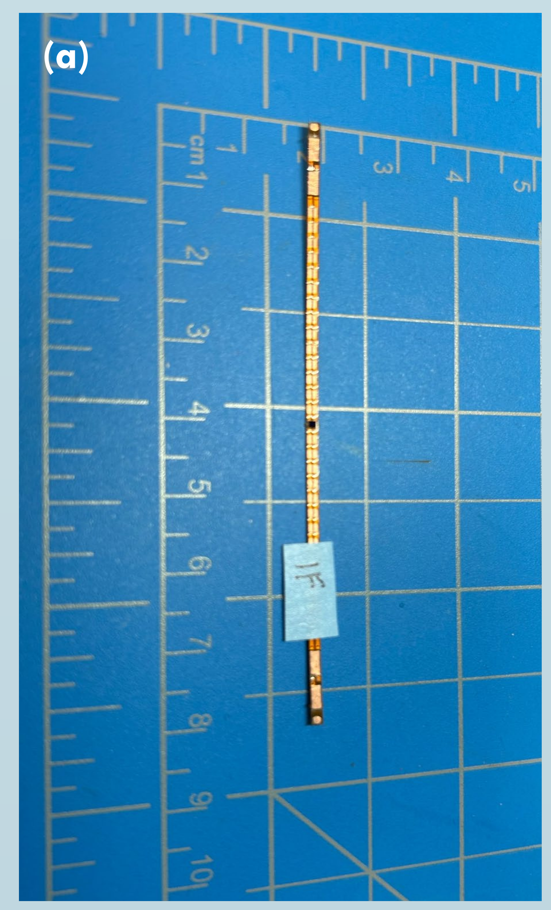
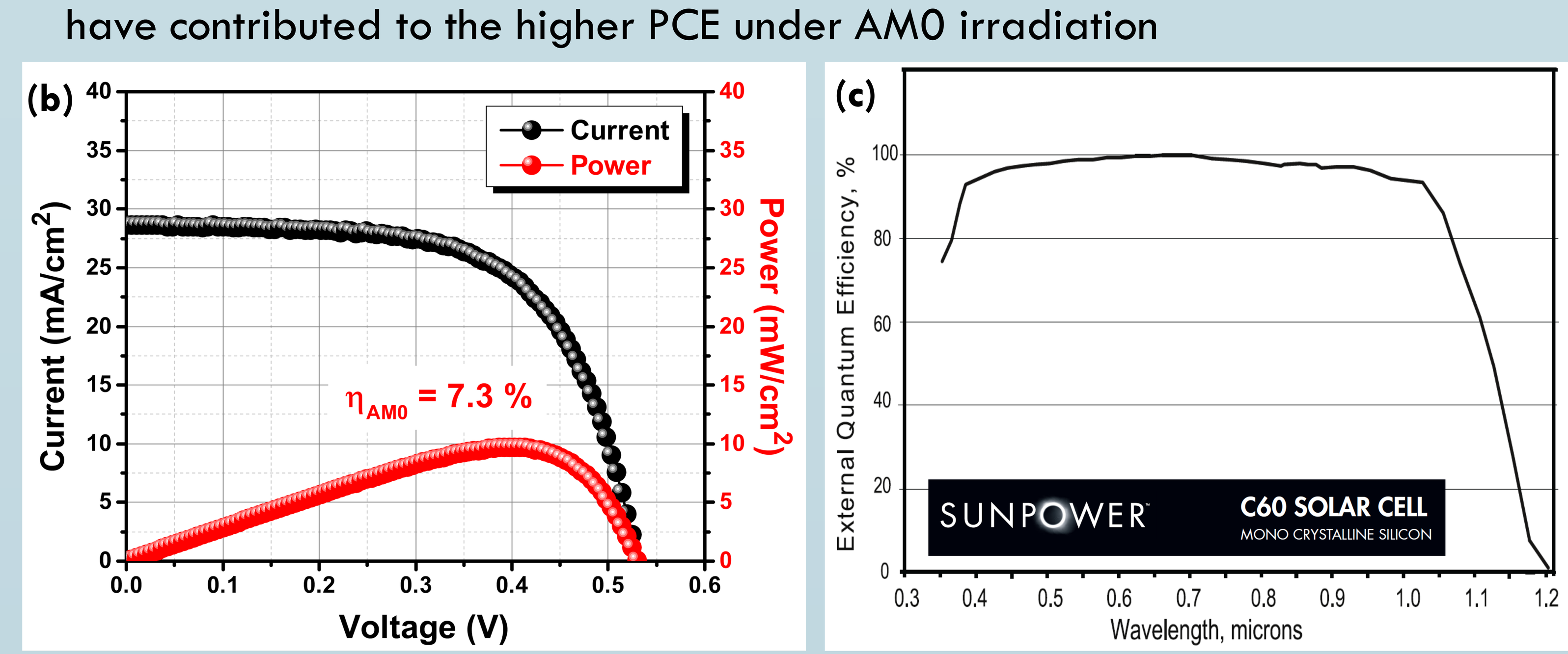


Figure 4: (a) 1 mm^2 c-Si cells in a pick-and-place compatible tray. (b) Solder jet printing process. (c) Pick-and-place process. (d) Fiber substrate board after the solder paste was reflowed in an oven and the fibers were mostly isolated from the board using a laser cutter.

c-Si PVF under AM0 Illumination

- PCE under AM0 irradiation was slightly higher than PCE under AM1.5 irradiation
- Slightly higher external quantum efficiency (EQE) at shorter wavelengths might have contributed to the higher PCE under AM0 irradiation





Solar Irradiation	V_{OC} (V)	J_{SC} (mA/cm²)	FF	PCE (%)
AM1.5	0.50	26.5	0.51	6.8
AM0	0.53	28.6	0.64	7.3

Figure 5: (a) c-Si PVF with a 1 mm^2 c-Si cell. (b) Power output characteristics of the PVF under AM0 irradiation; Rocket Lab's Z4J cell was used as a reference cell. (c) External quantum efficiency of SunPower's C60 solar cell from the vendor datasheet (https://solarmuseum.org/cells/284_sunpower/)

Stability of c-Si PVFs

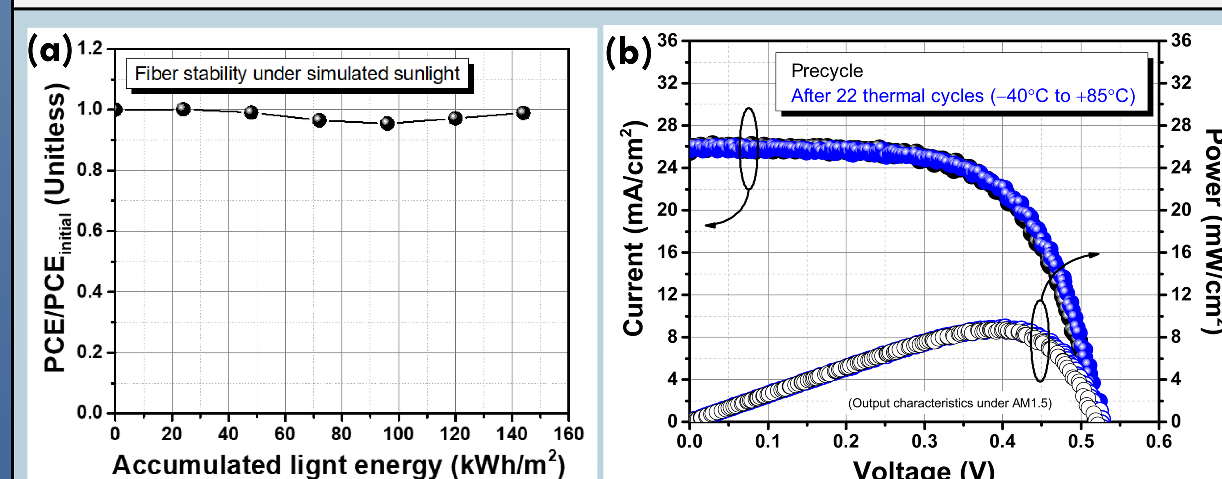


Figure 6: (a) Stability of a c-Si PVF exposed to a halogen lamp (100 mW/cm²) in a laboratory environment for six days. Reproduced with permission [1]. Copyright 2024, Elsevier. (b) Thermal cycle data collected from a c-Si PVF following a method outlined in IEC 61215.

- No performance loss from preliminary long-term stability and thermal cycling tests, reaffirming the maturity of the c-Si solar cell technology
- Fig. 6a: total energy the fiber received was 144 kWh/m², comparable to insolation expected for entire month of March at the Washington Dulles International Airport in US

Summary

- This work demonstrates an approach for achieving flexible space solar power using textile-based photovoltaic (PV) devices. This technology could enable new space structures such as inflatable space stations and inflatable lunar surface habitats with an integrated solar energy harvesting capability
- Device-agnostic fiber technologies developed by the Johns Hopkins University Applied Physics Laboratory can serve as the cornerstone of multijunctional textronics
- In this study, crystalline silicon PV fibers fabricated using a scalable process were characterized under AM0 irradiation and demonstrated no performance loss after thermal cycling testing

Acknowledgements

This work was supported by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) Independent Research and Development Program. The authors would like to thank Louis Bettwy and Nathan Fairbanks of the JHU/APL for their assistance in fabricating c-Si PVFs and dicing solar cells, respectively. The authors also thank Paul Gush of the JHU/APL for printing this poster. Finally, the authors acknowledge David Scheiman of the Naval Research Laboratory for providing the SunPower C60 IBC c-Si solar cells.

The 42nd Space Power Workshop (2025)

[1] M. H.-C. Jin, L. J. Currano, V. O. Rojas, E. D. Jacque, R. A. Korneisel, N. J. Fairbanks, A. W. Freeman, B. R. Trethewey, B. H. Glaros, B. G. Carkhuff, K. Gerasopoulos, "Scalable Crystalline Silicon Photovoltaic Fibers for Electronic Textile Applications", *Adv. Funct. Mater.* 2024, 2402350

[2] R. A. Altmaier, J. E. Tiffany, A. G. Simmonds, C. A. McHale, D. O. Fernandes, T. R. Hamann, D. E. Hoover, S. A. E. Mittelman, J. R. Meseke, J. O. Sharp, N. A. Knowlton, K. Gerasopoulos, "High-Linear-Energy Layered Fiber Batteries Using Roll-to-Roll Lamination and Laser Cutting", *Adv. Mater. Technol.* 2024, 2400417