Thermal Performance of Perovskite-Based Photovoltaics for Operation in Low Earth Orbit

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Abstract

Perovskite-based photovoltaics are attractive for applications in space. The space environment is harsh with ionizing radiation, atomic oxygen, UV radiation, extreme temperatures, and thermal cycling. Herein, the thermal performance of perovskite active layer and perovskite photovoltaic devices in low earth orbit is analyzed. A 1 μm silicon oxide layer coupled with 500 nm zirconia thin film aid in cell thermal management is determined. The residual stresses between various layers in a device are modeled and it is proved that thermally induced mechanical failure of the perovskite (time > 460 years) is unlikely during operating lifetime of any mission. Target power conversion efficiencies are also shared to manage maximum operating temperature of a perovskite-based device.
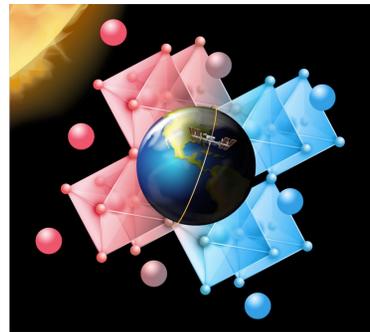
Figure 1. Artist rendering of thermal cycling of a perovskite based photovoltaic in LEO

Impact of Device Efficiency on Temperature

Figure 3 is a contour plot of temperature over the range of efficiencies during the sunlit portion of the orbit. As more energy is converted to electricity the temperature will decrease. The solar cell efficiency only affects the temperature during periods of solar illumination. When the solar cell is in shadow, the temperatures converge to a constant of about −90 °C. The temperature decreases from a peak above 73 °C at 0% efficiency to a peak of about 46 °C at maximum efficiency. By increasing the cell efficiency, substantial gains in thermal mitigation can be achieved.
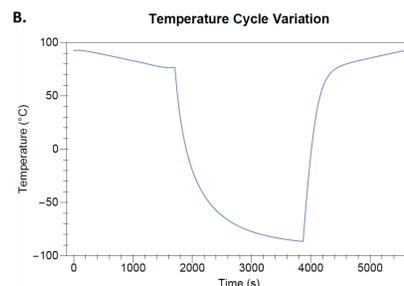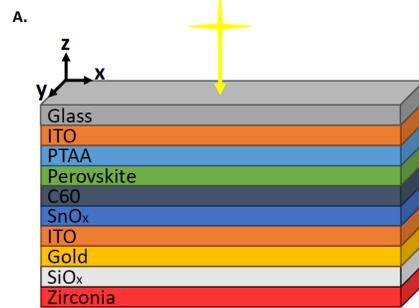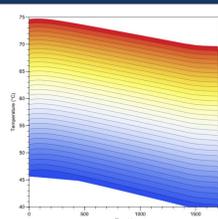
Calculation of Perovskite Temperature

Figure 2. A) Layered model for calculation of temperature in the perovskite layer. The yellow star corresponds to the incident sunlight. B) Perovskite active layer temperature variation throughout LEO with no electrical conversion efficiency.

To investigate the temperature throughout a LEO cycle, a thermal model is derived. The model uses the layered structure of a nine-layer, single junction triple-cation $(Cs_x(MA_{0.17}FA_{0.83})_{(100-x)}Pb(I_{0.83}Br_{0.17})_3)$ p-i-n perovskite solar cell determined to be promising for implementation in space [1]. Cell operation is in superstrate configuration as shown in **Figure 2A**. The incident area of the cell is 10 x 10 mm. The cell was onboard the International Space Station (ISS) which is at an orbital distance of 420 km from the Earth's surface. This gives an orbital period of 5578.22 s or approximately 93 min. The cell is modeled with the glass layer (z-direction) sun facing throughout the orbit. The cell is assumed to be thermally isolated from any surrounding bodies. The goal is to determine the feasibility of maintaining operating temperatures below the critical temperature and identify modifications that can be made to the cell to improve thermal performance.

$$(1 - \eta_e)\alpha_f(\lambda)\dot{Q}_s''(\lambda, t) + \alpha_b\dot{Q}_a''(t) + \alpha_{b,f}\dot{Q}_p''(t)$$
$$- \left((\varepsilon_b + \varepsilon_f) + \frac{2h\varepsilon_s(l+w)}{A} \right)\sigma(T(t)^4 - T_\infty^4) = \rho h c_p \frac{dT}{dt} \qquad (1)$$

Equation 1 is solved numerically using backward differentiation formula method, and results are shown in **Figure 2B** for the case of perovskite active layer with 1 mm-thick glass and no electrical efficiency. The high temperature region reaches steady state, the low temperature region is still undergoing a transient response.

Backside Layer Variation

Careful selection of the backside material can optimize thermal performance of the array. The choice of backside layer can cause differences in cell temperatures of nearly 50 °C as shown in **Figure 4**. Zirconia provides the greatest reduction in temperature mainly due to low absorptivity at solar wavelengths and high emissivity at the cell temperatures. The critical factor for temperature is the outermost layer, other layers can be added for device performance as needed.
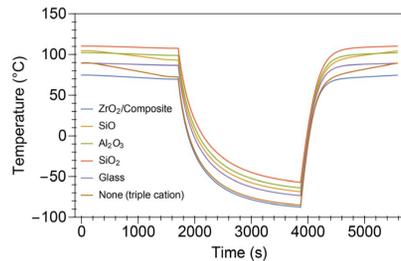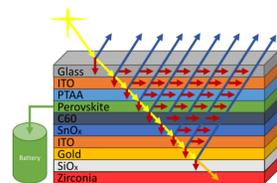

Figure 4. Perovskite temperature variation throughout LEO with varying backside materials.

Calculation of Absorbed Solar Irradiance

The absorbed solar irradiance is determined via the wavelength dependent optical constants for each layer in the solar cell stack. At any interface the energy can be reflected, converted to heat, converted to electricity, or transmitted through the layer. The absorbed energy is the energy absorbed by the layer that is not converted to electricity. In **Figure 5** the gray shaded portion indicates the quantum efficiency range of the solar cell. In Figure 4A-C lines indicate the amount of energy reflected (A), transmitted (B) or absorbed (C) at the layer and all prior layers and the shaded portion indicates the amount reflected, transmitted, or absorbed at the current layer.
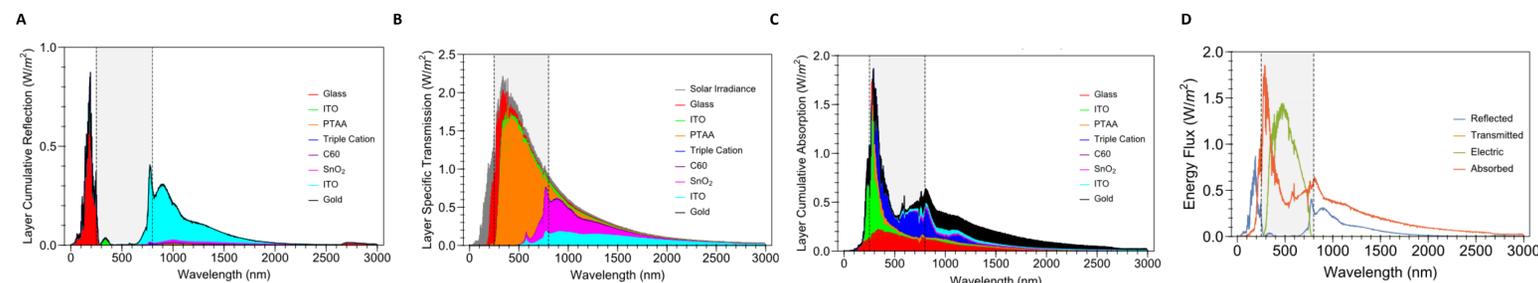

Figure 5. The gray shaded portion in each figure indicates the quantum efficiency range of the solar cell. A) Cumulative layer-specific reflected energy flux throughout the solar energy spectrum. B) Cumulative layer-specific reflected energy flux throughout the solar energy spectrum. C) Cumulative layer-specific reflected energy flux throughout the solar energy spectrum. B) Cumulative layer-specific absorbed energy flux throughout the solar energy spectrum and D) Solar energy wavelength paths.

Strains Induced within the Photovoltaic

The solar cell will undergo thermal expansion as it heats and cools in orbit. In the z-direction this expansion is unconstrained. But the stack is bonded in the xy plane and will experience strains due to the coefficient of thermal expansion mismatch between the glass, perovskite, and backside layer. Macroscopic strains refer to length changes in the cell as compared to its original size, microscopic strains refer to strains in the crystal structure as shown in **Figure 6**.
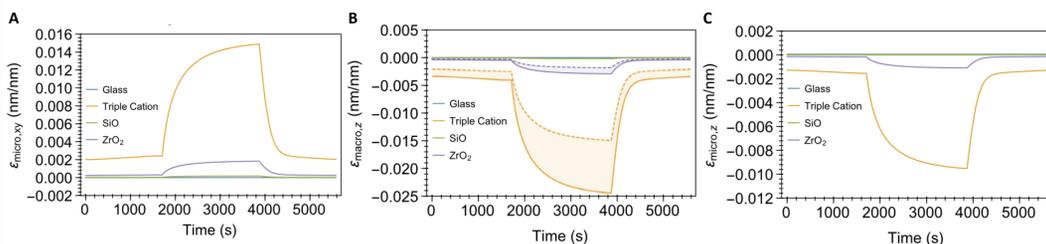

Figure 6. Strains introduced in the solar cell A) Microscopic strain in the x– and y–directions. B) Macroscopic strain in the z-direction where the based line indicates uniform triaxial deformation. and C) Microscopic strain in the z-direction.

Conclusions

- Perovskite-based photovoltaics have promise as a viable material for energy generation in LEO
- Careful selection of backside material and enhancement of PCE can help sustain temperature below critical value
- Recommend SiO/ZrO₂ composite backside layer to manage perovskite cell operating temperature in LEO
- Perovskite photoactive layer can endure 460 years before experiencing thermal fatigue
- Zirconia has limited performance in LEO with thermal fatigue predicted at 8 years
- Encourage further development to increase device PCE to yield substantial gains in thermal mitigation

Nomenclature

Symbol	Meaning	Symbol	Meaning	Symbol	Meaning	Symbol	Meaning
η_e	Electric efficiency	A	Incident area	σ	Stefan-Boltzmann Constant	λ	wavelength
α	Absorptivity of material	l	Cell length	f	Frontside layer	T	Temperature
Q_a''	Earth's albedo	w	Cell width	b	Backside layer	t	Time
Q_p''	Earth's planet flux irradiance	h	Cell thickness	s	Side layer	ρ	Material density
Q_s''	Solar spectral irradiance	ε	Emissivity of material	∞	Ambient properties	c_p	Specific heat

Acknowledgements

Full Text [2]

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References

[1] K. VanSant, L. McMillon-Brown, et al., "Combined Stress Testing of Perovskite Solar Cells for Stable Operation in Space", ACS Appl. Energy Mater., vol 6, no 20, pp 10319, 2023. https://doi.org/10.1021/acsaem.2c03972

[2] T. Krause, L. McMillon-Brown, et al., "Thermal Performance of Perovskite-Based Photovoltaics for Operation in Low Earth Orbit", Sol. RRL, vol 7, pp 2300468, 2023. https://doi.org/10.1002/solr.202300468