Thermal Performance of Singlet Fission and Tandem Solar Cells

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Abstract

The economic value of a photovoltaic installation depends upon both its lifetime and power conversion efficiency. Progress towards the latter includes mechanisms to circumvent the Shockley-Queisser limit, such as tandem designs and multiple exciton generation (MEG). Here we explain how both silicon tandem and MEG enhanced silicon cell architectures result in lower cell operating temperatures, increasing the device lifetime compared to standard c-Si cells. Also demonstrated are further advantages from MEG enhanced silicon cells: (i) the device architecture can completely circumvent the need for current-matching; and (ii) upon degradation, tetracene, a candidate singlet fission (a form of MEG) material, is transparent to the solar spectrum. The combination of (i) and (ii) mean that the primary silicon device will continue to operate with reasonable efficiency even if the singlet fission layer degrades. The lifespan advantages of singlet fission enhanced silicon cells, from a module perspective, are compared favorably alongside the highly regarded perovskite/silicon tandem and conventional c-Si modules.

Introduction

At present, wafer-based silicon modules are the dominant PV technology. These modules are currently provided with warrantied lifetimes usually of 25 years. Progress in all areas of PV module manufacturing will reduce costs, but there remains significant scope to reduce the cost of PV electricity through improved power conversion efficiency and by increasing the module lifespan beyond the present 25 years.

The power conversion efficiency of conventional cells are approaching the single threshold Shockley-Queisser (SQ) efficiency limit [1, 2]. Efforts to circumvent this limit include the introduction of multiple absorbing thresholds, which can take several forms. Tandem cells incorporate a second junction with a larger bandgap material (such as perovskites or III-Vs), and excitonic methods exploit multiple-exciton generation processes, such as singlet fission. The process of singlet fission in molecular semiconductors is well established, whereby a photo-excited singlet exciton undergoes fission into two triplet excitons, producing twice the electronic charge carriers for each absorbed photon.

While both these approaches increase efficiency, little thought has been given to their impact on thermal load, particularly when considering the degradation present in realistic devices. Here, we provide a model for understanding the impact of multiple absorbing thresholds on thermal load. We investigate the thermal load reduction from both tandem and singlet fission cells, and estimate the resulting improvement to the lifespan of a module made from those cells.

Solar module thermal analyses

In our thermal model for c-Si based devices, solar photons absorbed above the bandgap ($\lambda <$ 1200nm) convert their energy to both electricity and excess heat generation, while all photons absorbed below the bandgap contribute to heat only [3]. Applying these assumptions to our thermal model, the solar module operating temperature was determined to be 46.1°C, in line with the rule of thumb that modules operate 20-30°C above the ambient temperature.

We next apply the model to two well-studied approaches to multiple threshold devices: a perovskite on silicon tandem and a tetracene-based singlet fission device. For the perovskite/Si tandem cell, the working voltage is taken as 1.4V (0.8V and 0.6V for the perovskite and Si junctions, respectively) [4]. Singlet fission in the molecular semiconductor tetracene is well-known to generate two triplet excitons that are energetically matched to the silicon bandgap. The singlet fission energy threshold is assumed to be at 530nm, slightly endothermic with ΔE=0.2eV [5]. The thermal load spectra for the different cell architectures is shown in Fig. 1.
The operating temperature of these two configurations are calculated as $T_{PSK/Si}$ = 44.4°C and $T_{SF/Si}$ = 43.7°C, showing a reduction in temperature ΔT= 1.7°C and ΔT = 2.4°C compared with the conventional Si module, respectively. c-Si module lifetime is generally found to double for every 10°C reduction in temperature [6], for a thermally activated process this corresponds to an activation energy E_a = 0.63eV at a module temperature of 46.1°C. The lifespan of a module can therefore be expressed using an Arrhenius equation $\mathrm{lifespan} = A \times e^{\frac{E_a}{kT}}$, with A = 3.1×10^{-9} years. This equates to an increase in lifetime of 3.1 years (12%) for the perovskite tandem and 4.5 years (18%) for the tetracene-based SF cell. A comparison of key parameters for these three structures discussed above are shown in Table 1.

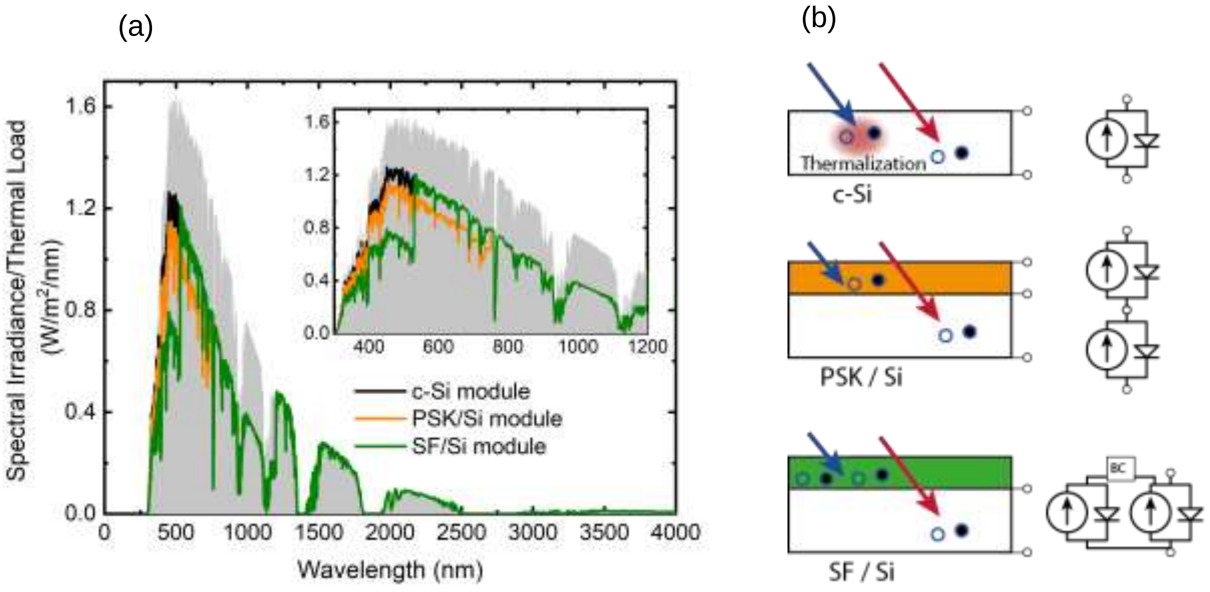


Fig. 1 Comparing conventional and tandem devices. (a) Solar spectral irradiance AM1.5G overlaid with the heat load spectra for various cell architectures. The inset shows the relevant 300-1200nm wavelength range. (b) The carrier generation process in each configuration and the equivalent circuit. BC denotes a buck converter which is a power converter that halves the voltage and doubles the current, representative of the singlet fission process.

Table 1 | The energy distribution of a solar device for conventional c-Si module, monolithic perovskite/Si module, and singlet fission/Si module.

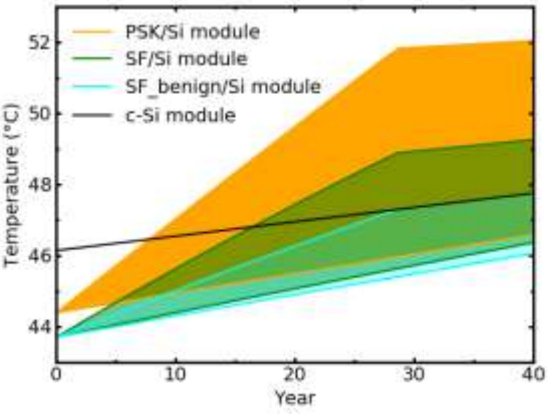
Structure	Initial Efficiency (%)	$P_{elelctr.}$ (W)	$P_{rad.}$ (W)	$P_{conv.}$ (W)	Temperature (°C)	Lifespan (years)
c-Si module	26.5	211.7	198.7	349.9	46.1	25
PSK/Si module	31.0	248.1	188.0	324.3	44.4	28.1
SF/Si module	32.8	262.3	183.8	314.2	43.7	29.5

Degradation

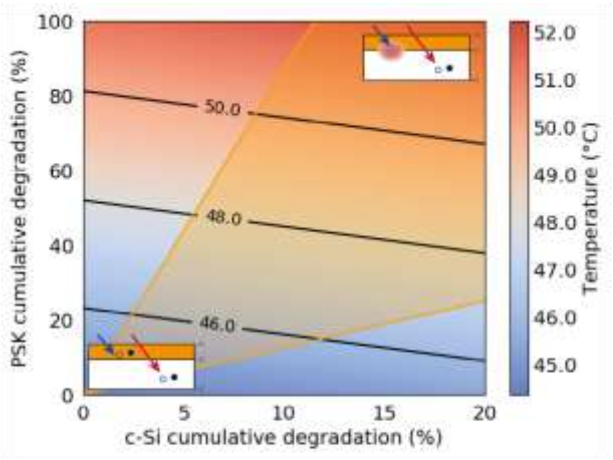
Degradation is inevitable in all components of a PV module. Conventional silicon modules operating in the field typically suffer a 0.4% per annum degradation rate; commercial thin-film technologies (CdTe, CIGS) typically degrade roughly twice as quickly [7]. In Fig. 2(a) we show the effect of degradation on module temperature for conventional silicon, perovskite/silicon, and singlet fission/silicon solar modules with a lower bound for degradation at 0.5%/year and an upper bound of 3.5%/year [8] for the perovskite and singlet fission components. At the beginning of life, all cells would sit at the lowest temperature points, corresponding to the lower left-hand side of Fig. 2(a). As time progresses, these cells will degrade at variable rates, but not exceeding the bounds of the shaded region to some end of life state. Since the degradation product of tetracene singlet fission film is transparent to solar radiation, although degradation occurs, a singlet fission/silicon solar cell will return to the primary underlying silicon solar cell.

Furthermore, the cumulative degradation effect over the lifespan of a solar module on its operating temperature for perovskite/silicon tandem, generic singlet fission/silicon (where the degradation product is not transparent to solar radiation), and tetracene singlet fission/silicon (where the degradation product is transparent to solar radiation) modules are also modelled and shown in Fig. 2(b)-(d) respectively. c-Si solar modules typically suffer < 20% cumulative degradation during a 25 year lifespan, while up to 100% degradation is modelled for perovskite and singlet fission materials in each configuration.

(a)



(b)



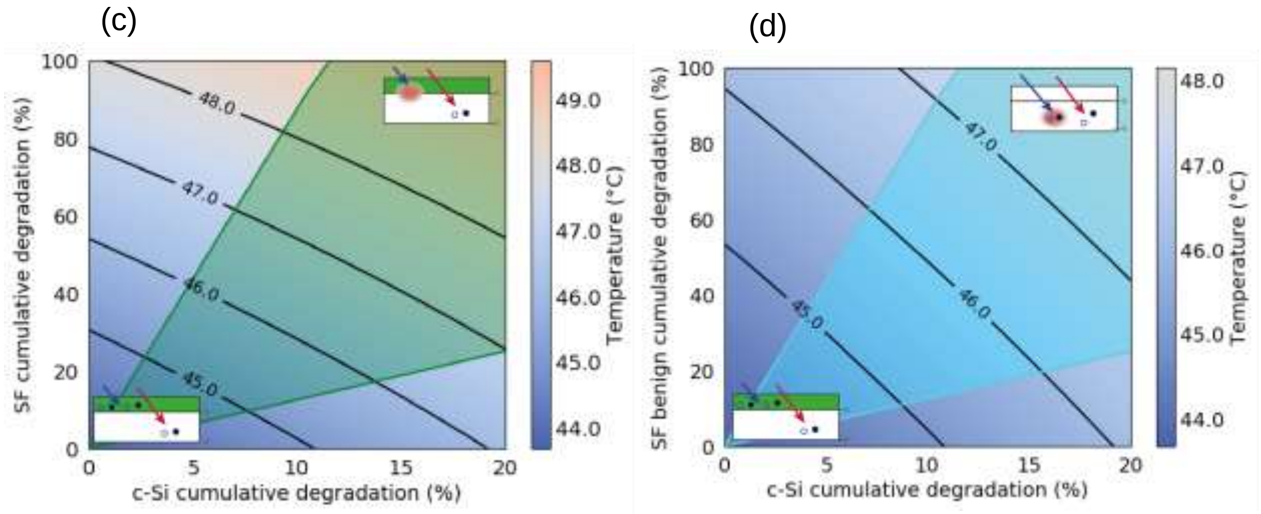


Fig. 2 The operating temperature of different device architectures. (a) Increase in module temperature plotted for modules composed of conventional c-Si, singlet fission/silicon, and perovskite/silicon modules. The c-Si degradation rate is 0.4% per annum; singlet fission/silicon and perovskite/silicon degradation rates have a lower bound of 0.5% per annum and an upper bound of 3.5% per annum. (b)-(d) module operating temperature resulting from cumulative degradation. The inset diagrams depict the carrier generation processes for beginning and end of life for (b) perovskite/silicon, (c) general singlet fission/silicon and (d) tetracene singlet fission/silicon modules respectively. The shaded region corresponds to the degradation rate of 0.5%-3.5% per annum.

Conclusions

The opportunity for multiple threshold silicon solar cells to increase the spectral efficiency compared with conventional silicon solar cells is well known. Here, we have shown that there are also ancillary benefits to the approach in terms of lower module temperature and resilience under degradation. At low degradation rates, both perovskite-based tandems and singlet-fission cells reduce thermal load and increase the lifetime of the primary silicon module. At larger degradation rates, tetracene-based singlet fission cells still outperform conventional cells as the benign nature of the degradation product is not detrimental to the performance of the primary silicon cell. In all these cases there exists the potential to significantly reduce the cost of energy produced by solar photovoltaic systems by both increasing efficiency and lifespan.

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