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Daniel J. Friedman, Myles A. Steiner,
Emmett E. Perl, and John Simon
National Renewable Energy Laboratory

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Spectral and Concentration Sensitivity of Multijunction Solar Cells at High Temperature

Daniel J. Friedman[1], Myles A. Steiner[1], Emmett E. Perl[1,2], John Simon[1]

[1]National Renewable Energy Laboratory, Golden, Colorado, 80401, USA

[2]University of California at Santa Barbara, Santa Barbara, CA 93106, USA

Abstract — **We model the performance of two-junction solar cells at very high temperatures up to ~400°C for applications such as hybrid PV/solar-thermal power production. We show that high-temperature operation reduces the sensitivity of the cell efficiency to spectral content, but increases the sensitivity to concentration, both of which have implications for energy yield in terrestrial PV applications. For other high-temperature applications such as near-sun space missions, our findings indicate that concentration may be a useful tool to enhance cell efficiency.**

I. INTRODUCTION

Although conventional solar cell applications typically call for the cells to operate at temperatures less than ~100°C, there are potentially impactful applications for which the cell operating temperature would be far higher. There has been considerable recent interest in cells operating as a topping cycle in a hybrid solar-thermal concentrator system for terrestrial energy production with storage [1]. These cells would operate at temperatures of ~400°C or above, and as with all terrestrial solar applications would be subject to hourly and seasonal variation of the spectrum and intensity of the solar illumination. Another application of high-temperature solar cell operation would be photovoltaic-powered near-sun missions such as Mercury probes, for which cell operation at ~450°C would be desirable [2]. In this case, the spectrum seen by the cell would be a constant, but the concentration of the light could be treated as a design variable.

In this paper, we study the design of high-efficiency III-V two-junction cells for high-temperature operation, with 400°C chosen as a representative temperature, and identify areas in which the design and performance characteristics behave significantly differently than at more conventional near-room-temperature operating conditions. We show in particular that the sensitivity of the cell efficiency to spectrum and to intensity is notably different at high temperature than at room temperature, and we describe the consequences for solar cell and system design and power production.

II. DEVICE STRUCTURE AND CHARACTERISTICS

The solar cell structure we consider here is an (Al)GaInP/GaAs two-junction tandem cell with a tunnel junction providing a series connection. The top junction thickness, x_1, is adjusted to maximize the efficiency. Here, we consider only idealized junctions with long diffusion lengths and no parasitic absorption from layers such as the tunnel junction or window, but these can readily be accommodated using the same methods. This structure is being studied in the laboratory for high-temperature operation [3] to address the hybrid PV/solar-thermal application.

III. MODEL

To analyze analytically the dependence of the cell performance on temperature, we use a simple model that captures the essential physics. The voltage V of the series-connected tandem cell at a given current density J is the sum of voltages $V_1(J)$ and $V_2(J)$ of the top and bottom junctions,

$$V(J) = V_1(J) + V_2(J). \tag{1}$$

Each individual i^{th} junction is treated with the familiar single-diode model with ideality factor n=1 [4-6],

$$J(V_i) = J_{01,i}\left[\exp\left(\frac{eV_i}{k_BT}\right) - 1\right] - J_{SC,i}, \tag{2}$$

$$J_{01,i}(T) = C_{1,i}T^3 e^{-E_{g,i}/k_BT}. \tag{3}$$

Comparison with experiment in the next section shows this model to be an excellent qualitative description for high-quality junctions, especially at high concentration; effects of the n=2 dark current component will be discussed elsewhere. Series and shunt resistance are taken to be negligible.

Equations (2, 3) determine the open-circuit current, V_{OC}:

$$V_{OC} = \frac{k_BT}{e}\ln\left(\frac{J_{SC}}{J_{01}}\right). \tag{4}$$

The value of $C_{1,i}$ is determined empirically by comparison with high-quality experimental junction measurements at room temperature and considered to be temperature-independent. The temperature dependences of the bandgaps $E_{g,i}$ are accounted for via the Varshni coefficients for the respective materials [7]. The QEs are treated with the familiar Hovel equations [4]. The top junction, of thickness x_1 and absorption coefficient $\alpha_1(\lambda)$, filters the bottom junction reducing its QE by a factor $exp[-\alpha_1(\lambda)x_1]$. Other light-absorbing layers such as window layers and tunnel junctions are treated in the same manner.

Figure 1 shows the measured V_{OC} of GaAs and AlGaInP junctions under low and high concentrations as a function of temperature from 25–400°C. Details of the fabrication and measurement of the devices are given in [3, 8]. The figure also shows the fit of the model to the data. The one adjustable parameter, the J_{01} coefficient C_1, is determined by self-consistently fitting to the entire V_{OC} vs. temperature and concentration data set. The figure shows good agreement of Eqs. (2,3) with the measured data, including reproducing the effect of concentration on dV_{OC}/dT.

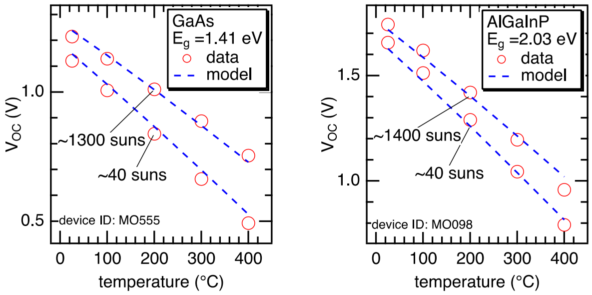

Fig. 1. Measured V_{OC} of GaAs and AlGaInP junctions under low and high concentrations as a function of temperature from 25-400°C from [3], compared with the fit to the model.

IV. CURRENT MATCHING AND SPECTRAL SENSITIVITY

A critical parameter in the design of series-connected multijunction cells is the thickness of each junction, with the thickness chosen to optimize the efficiency of the cell [9]. Figure 2(a) shows the modeled efficiency of an idealized GaInP / GaAs cell with junction bandgaps {1.85eV, 1.41 eV} as a function of the top junction thickness, at 400°C at 1000 suns.

The figure illustrates the well-known behavior that the top-junction photocurrent $J_{SC,1}$ increases and the bottom-junction photocurrent $J_{SC,2}$ decreases with top-junction thickness, leading to an efficiency maximum at roughly the point where $J_{SC,1}$ and $J_{SC,2}$ are matched. This efficiency is re-plotted against the current mismatch $J_{SC,1} - J_{SC,2}$ in Fig. 2(b), and compared to the efficiency at 25°C. The efficiencies are normalized to 1 at their maximum values to facilitate the comparison of the rate of decrease of efficiency with current mismatch. The comparison shows that the efficiency is much less sensitive to current mismatch at 400°C than at 25°C. This difference arises because junction dark currents increase rapidly with temperature, which decreases fill factors and increases the difference between the short-circuit and maximum-power-point values of the current.

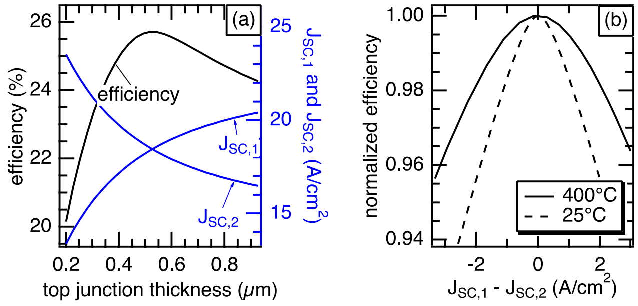

Fig. 2. (a) Cell efficiency and the top- and bottom-junction currents $J_{SC,1}$ and $J_{SC,2}$ as a function of top junction thickness for an idealized 1.85 eV / 1.41 eV two-junction cell, at 400°C, under the ASTM G173 AM1.5 Direct spectrum at 1000 suns. (b) Efficiency vs. current mismatch $J_{SC,1} - J_{SC,2}$ at 400°C as in (a), and at 25°C. The efficiencies are normalized to 1 at their maximum values.

This decreased sensitivity at high operating temperature to current mismatch implies that there should be a corresponding decreased sensitivity to the spectral content of the solar illumination, because the main effect of changes in spectral content is to change the current mismatch. There are many parameters besides air mass that determine a solar spectrum, but focusing on the air mass is a simple and useful proxy for arbitrary spectral fluctuations. To quantify sensitivity of the cell efficiency to spectral variations, we consider how the efficiency of a cell designed for the standard air mass 1.5 direct (AM1.5D) spectrum changes under varying air mass. For the cell under the AM1.5D spectrum at 400°C considered in Fig. 2(a), a top junction thickness of 0.53µm provides the optimal efficiency. Figure 3(a) shows how the efficiency of this AM1.5D-optimized cell varies with air mass. The efficiency peaks at AM=1.5 as expected and falls off at other AM values, but the falloff is quite slow. In comparison, a cell designed for AM1.5D at 25°C and operated at 25°C shows a much faster falloff of efficiency for AM≠1.5, i.e. a much greater spectral sensitivity. Figure 3(b) shows the same efficiencies normalized to their values at AM1.5. For air masses greater than 1.5, the 400°C cell efficiency falls off with increasing air mass at about 2/3 the rate of the 25°C cell efficiency falloff, confirming a significantly reduced spectral

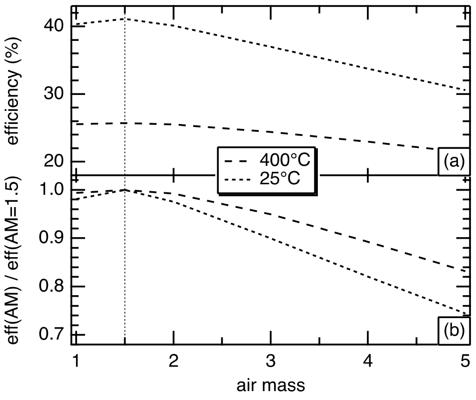

Fig. 3. (a) Modeled efficiencies at 400°C and 25°C at 100 W/cm^2 (1000 suns), and (b) the same efficiencies normalized to their AM=1.5 values, for the direct spectrum over a range of air masses for two-junction cells with top-junction thicknesses chosen for optimal performance at AM1.5D. The spectra were computed using the SMARTS2 code [10]. The spectrum at AM=1.5 is precisely the ASTM standard G173 AM1.5 direct spectrum. The spectra are normalized to 100 W/cm^2.

sensitivity at 400°C. Reduced spectral sensitivity results in increased energy harvesting in real-world conditions where the spectrum is not fixed, a promising observation for any application including the high-temperature topping-cycle concept which relies on operation of high-efficiency cells at high temperature under the terrestrial spectrum.

V. CONCENTRATION SENSITIVITY AT HIGH TEMPERATURE

From eq. (4), the rate of increase of V_{OC} with concentration increases with temperature, with the V_{OC} for each junction increasing ~59 mV/decade at 25°C and ~134 mV/decade at 400°C. This effect is accentuated in impact because V_{OC} itself decreases with temperature; both of these phenomena can be seen experimentally in the V_{OC} data of Fig. 1. As a result, the dependence of cell efficiency on concentration is much greater at high temperature than at room temperature. This difference is illustrated in Fig. 4, which shows the modeled relative efficiency of the two-junction cells of Fig. 3 as a function of concentration at 25°C and 400°C. This sensitivity could have a negative impact on energy yield for applications at high temperature under the terrestrial spectrum. Looked at another way, however, concentration may be desirable as a tool to enhance efficiency for high-temperature applications such as near-sun space missions.

VI. SUMMARY

We examined the expected performance of two-junction solar cells for applications at very high temperatures of ~400°C and beyond, under conditions of varying spectral content and concentration. High-temperature operation reduces the sensitivity to spectral content, but increases the sensitivity to concentration, conditions which both must be accounted for to properly assess energy yield under varying terrestrial illumination conditions. For other applications such as near-sun space missions, concentration may be a useful tool to enhance cell efficiency.

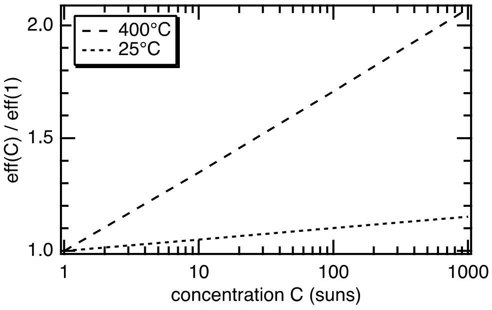

Fig. 4. Relative efficiency of the two-junction cells of Fig. 3 as a function of concentration at 25°C and 400°C.

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