ENERGY PRODUCTION FROM HIGH-EFFICIENCY 5-JUNCTION CONCENTRATOR SOLAR CELLS

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ABSTRACT: Solar cells with a greater number of junctions are likely to be required to continue the rapid efficiency increases of 3-junction concentrator photovoltaic (CPV) cells over the last 8 years, spurring research in 4-, 5-, and 6-junction solar cells. The effects of: varying air mass through the day and year; aerosol optical depth (AOD); cell temperature; and non-normal incidence of light on solar spectrum and current balance in 5-junction (5J) terrestrial concentrator cells are examined separately, to assess the magnitude of the effect for each mechanism. The advantages of the higher efficiency design of 5-junction cells, such as AlGaInP/ AlGaInAs/ GaInAs/ GaInNAsSb/ Ge 5J cells with a dilute nitride ~1-eV GaInNAsSb subcell 4, are found to substantially outweigh the effects of varying spectrum from atmospheric variations on the energy production of 5J cells.

Keywords: III-V, concentrator, CPV, 5-junction, high-efficiency, energy production

1 INTRODUCTION

III-V multijunction concentrator photovoltaic (CPV) cells are the highest efficiency solar cell technology yet demonstrated, and have experienced the most rapid rise in absolute efficiency over recent years. Since the advent of 40% solar cells in 2006 [1], production CPV cells with efficiencies of 39-40% have become available in high volumes, and researchers have continued to push the limits of efficiency in prototype devices, to prove what is physically achievable [2-7]. The relatively high costs of III-V epitaxy and growth substrates on a per unit area basis are mitigated by the high optical concentrations, in excess of 500 suns (50.0 W/cm^2), at which most multijunction CPV cells are designed to operate. Solid engineering work in cell processing and in the design and manufacture of CPV optics, trackers, and overall systems continue to bring the cost of CPV solar electricity generation closer to even the heavily-subsidized price of conventional power generation, with its many hidden health, environmental, and societal costs.

Against this rosy backdrop, questions remain about the actual energy production from multijunction CPV cells in the field, where the spectral content of incident sunlight and temperature of the solar cell vary widely with time and weather conditions [8-14]. In contrast to single-junction cells, two-terminal multijunction cells carry a requirement that each subcell in the stack have roughly the same photogenerated current density to have the highest conversion efficiency. Since the input spectrum varies, there will certainly be current imbalance among the subcells at many times each day and throughout the year, due to changing air mass and other atmospheric conditions. Cell temperature also changes the wavelength dependence of quantum efficiency in each subcell, providing another mechanism for current imbalance. The key question is how much of the very high efficiency demonstrated by multijunction solar cells under standard test conditions will translate into kilowatt-hours produced in actual field conditions.

These questions are raised even more when the number of junctions in the CPV cell is increased. A certain amount of comfort with energy production has been gained from experience with 3-junction GaInP/GaInAs/Ge solar cells in fielded CPV systems, but cells with 4, 5, 6, or more junctions divide the solar spectrum up into narrower slices. Figure 1 shows the calculated light I-V curves and schematic cross-section for a 5-junction AlGaInP/ AlGaInAs/ GaInAs/ GaInNAsSb/ Ge cell, with subcell bandgap combination of 2.0/ 1.68/ 1.41/ 1.12/ 0.67 eV, and projected average production light I-V parameters of V_{oc} = 5.48 V, J_{sc}/intensity = 0.0933 A/W, FF = 0.883, and efficiency of 45.2% at 500 suns (50 W/cm^2) under standard test conditions (STC): AM1.5D (ASTM G173-03) spectrum, 25°C.

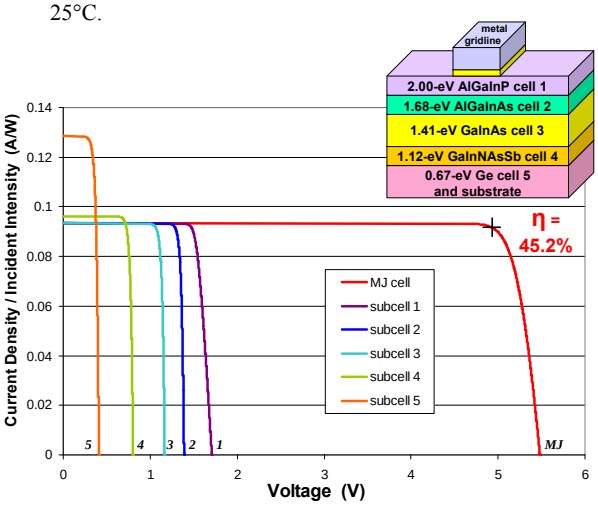

Figure 1: Illuminated I-V curves and schematic cross-section of a 5-junction concentrator solar cell with >45% projected average efficiency in production.

Fig. 2 plots the calculated external and internal quantum efficiencies (EQE and IQE) of this 5-junction cell, showing its finer partition of the solar spectrum relative to conventional 3-junction cells. This reduces carrier thermalization losses, making each subcell a more efficient converter of the portion of the spectrum for which it is designed, in principle. However, this can also magnify the effect of changing spectrum on the current of one subcell. For an atmospheric variation that affects

primarily the short solar wavelengths, the top cell current change is greater for the narrower spectral response range of the top cell in a 5-junction cell than in a 3-junction cell. Since it only takes inadequate current in one subcell of the series-interconnected stack to limit current of the whole multijunction cell, the 5-junction cell would be expected to show a stronger sensitivity to spectrum variation than the 3-junction cell. This is a crucial issue for continuing the rapid rise in multijunction cell efficiency, because many proposed future designs make use of 4, 5, 6 or more junctions to achieve their projected average efficiencies of 45% or even 50%. Solar cell efficiency is important only because it is an excellent predictor of energy production; if this correlation between cell efficiency and kilowatt-hours of electricity produced is lessened, it is important to quantify and understand that change thoroughly to gauge the effectiveness of future 4, 5, and 6-junction cell designs.

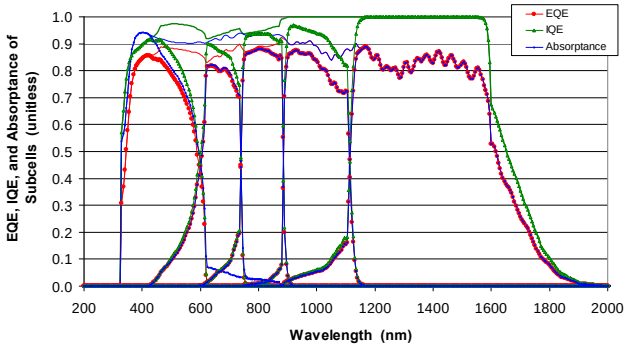

Figure 2: Calculated external and internal quantum efficiencies, and total absorptance including current loss mechanisms, for a 5-junction cell, showing its relatively fine wavelength partition of the solar spectrum.

In this paper, rather than examining selected geographical locations, we aim at a more fundamental understanding of the effects that different types of spectrum changes can have on multijunction cells, such as the quite different effects of air mass and aerosol optical depth of the atmosphere. We seek to provide a sense of how large each of these effects is, comparing them to each other and to the effects of cell temperature on energy produced, and further compare the magnitudes of these effects in 5-junction (5J), 3-junction (3J), and 1-junction (1J) solar cells. The influence of the angle of light incidence on current balance in multijunction cells is also examined. In this way, the crucial question of how much advantage is retained in the energy production of 5-junction cells, not just in their efficiency at the design point, can be answered.

2 NON-IDEAL EFFECTS IN MULTIJUNCTION SOLAR CELLS

A fairly complete physical model for multijunction cells, with temperature-dependent bandgaps, absorption coefficients, and diode saturation current densities, has been developed, and is used to predict the performance of 5J, 3J, and 1J concentrator solar cells under various real world conditions in this study. The SMARTS solar irradiance model [15,16] is used to generate the solar spectra resulting from different atmospheric conditions. The 5-junction AlGaInP/ AlGaInAs/ GaInAs/ GaInNAsSb/ Ge lattice-matched cell configuration of Figs. 1 and 2 is used in the charts below, with >45% efficiency under standard test conditions (STC). 3-junction cells are represented by a fairly conventional upright GaInP/ GaInAs/ Ge configuration with 1.885/ 1.41/ 0.67 eV bandgap combination, with 39.2% efficiency at 500 suns, 25°C, matching the performance of C3MJ+ solar cells in high-volume production. For 1-junction cells, silicon base solar cells are used, with a bandgap of 1.12 eV, and 26.0% efficiency at 500 suns, 25°C STC.

2.1 Varying air mass through day and year

Figure 3 plots the efficiencies of 5J, 3J, and 1J cells, and air mass for the hours after 12 noon on the fall equinox near Los Angeles, California. At 5:30 to 6:00 pm near sunset, when little solar energy is available, the multijunction cells do suffer from current imbalance. The efficiencies of all 3 types of cells are roughly the same at 5:30 pm. However, the higher efficiency at STC of 3J cells compared to 1J cells translates to higher efficiency and energy production for the 3J cells over the vast majority of energy-producing hours during the day. Similarly, the higher efficiency of 5J cells at STC results in higher efficiency and higher energy production for 5J cells than for 3J cells over the most important part of the day when high solar intensity is available.

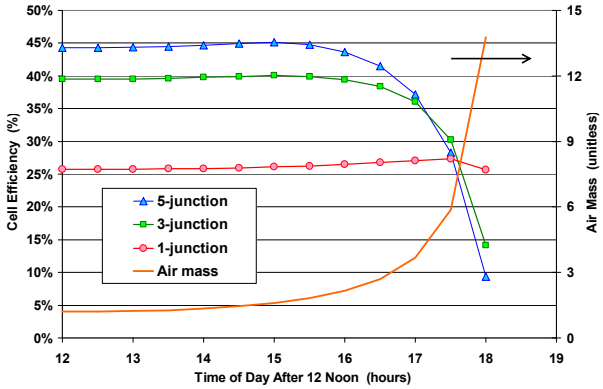

Figure 3: Efficiencies of 5J, 3J, and 1J cells, and air mass after noon on the fall equinox near Los Angeles.

This can be seen clearly in Fig. 4, which plots a measure of energy production, the product of cell efficiency and available solar intensity available at each time of the day. The efficiency advantages of the cells with higher efficiency at STC clearly persist through out the day in terms of energy production with 5J, 3J, and 1J performance converging only near 6:00 pm.

2.2 Aerosol optical depth (AOD)

The aerosol optical depth is another parameter affecting transmittance of the atmosphere, which quantifies haze or one type of light scattering. AOD can vary significantly with geographic location, weather conditions, and human activity. The SMARTS solar radiation model was used to generate a series of irradiance curves as a function of AOD, and their effect on 5J, 3J and 1J solar cells can be seen in Fig. 5. For reference, the data point at 0.084 AOD corresponds to the standard ASTM AM1.5 Direct spectrum. The multijunction cells do lose a few efficiency points at the

highest AOD values considered here, which are at the upper end of observed values throughout the year from typical meteorological year (TMY) data in the U.S. desert southwest [17]. Although 1J Si efficiencies have almost no dependence on AOD, the large efficiency advantage of 5J cells over 3J, and of 3J over 1J cells, is retained through the AOD values encountered in a typical year.

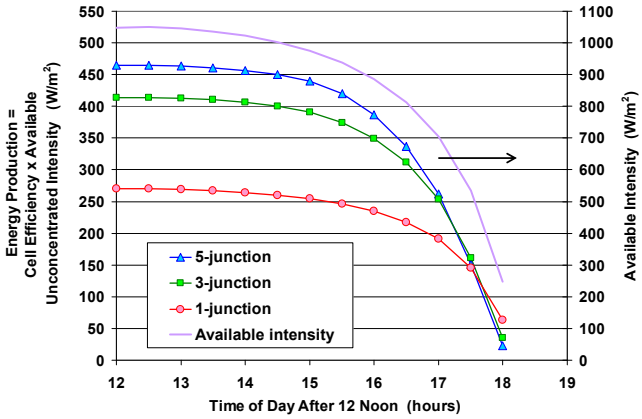

Figure 4: The product of 5J, 3J, and 1J cell efficiency and available solar intensity, plotted versus time of day.

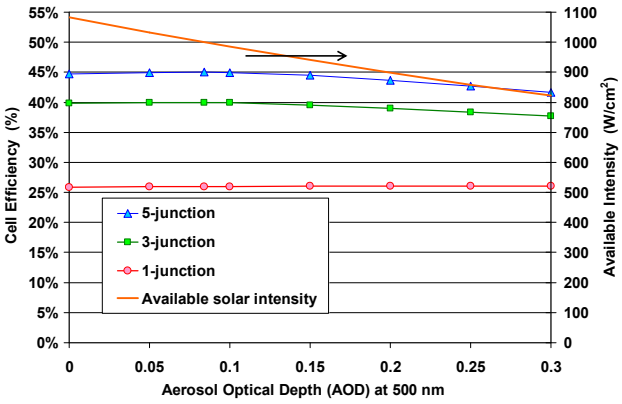

Figure 5: 5J, 3J, and 1J solar cell efficiencies as a function of aerosol optical depth (AOD).

2.3 Effect of temperature

Increasing cell temperature reduces cell voltage, and tends to increase current output due to a reduction in bandgap which allows more low energy photons to be collected. On balance, the reduction in voltage is the larger of the two effects, resulting in a loss of overall efficiency. The temperature dependence of 5J, 3J, and 1J cell efficiency is modeled in Fig. 6, and the reduction in efficiency with temperature is seen clearly for 3J and 1J cells. CPV cells in concentrator systems typically operate between 50 and 75°C. For 5J cells, the lowering of the top cell bandgap results in significantly more current in the top cell as temperature rises, increasing the J-ratio, and increasing the fill factor of the 5J cell substantially due to the current imbalance. Interestingly, though the voltage drops in each subcell as expected, the overall efficiency of the 5J cell has a remarkably low dependence on temperature, due in part to the compensating effect of the increased fill factor in 5J cells that comes with higher top cell current and greater current imbalance at higher cell temperatures.

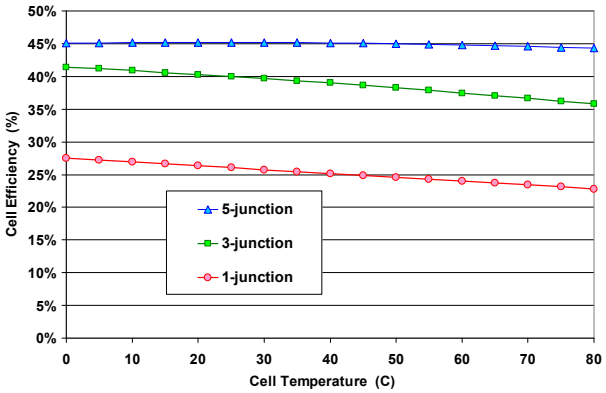

Figure 6: Temperature dependence of 5J, 3J, and 1J cell efficiency. Note the relative insensitivity of 5J cell performance on temperature.

2.4 Non-normal incidence of light

In concentrator systems, the primary optics and particularly the secondary optics project light onto the cell at non-zero angles with respect to the surface normal. This results in a somewhat longer path length through the subcell absorbers than if all light were at normal incidence. However, the refractive indices of semiconductors like GaInP and GaInAs are very high, causing obliquely incident light to be coupled into the cells at an angle close to the surface normal inside the semiconductor. The refractive indices for both these materials are 3.5 or higher for photon energies above their bandgaps. For a Fresnel lens concentrator with an energy-weighted average angle of $\theta_1 = 30°$ from the normal for light incident from air ($n_1 = 1.0$), Snell's law shows that light is coupled into the semiconductors at an angle of only $\theta_2 = \sin^{-1}[(n_1/n_2)\sin(\theta_1)] = 8°$. Thus the path length of light is $1/\cos(\theta_2) = 1.01$ times that for normal incidence, or 1% longer. Even for a large energy-weighted average angle of 45° from the normal, incident on the cell from a secondary optical element with refractive index $n_1 = 1.5$, light is coupled into the semiconductors at only 18°, giving a 5% longer path length in this more extreme second example. This results in J-ratios between the top two subcells (cells 1 and 2) of only 1.5% and 0.3% higher for the 5J and 3J cells considered here, respectively. So although the effect of non-normal incidence on path length through the semiconductor can be significant for 5J cells, and is important to understand, it is a relatively small effect for multijunction cell performance, and can be corrected for a desired energy-weighted average angle by slight adjustments in subcell thickness. Other effects of non-normal incidence such a higher front surface reflectance can have a greater impact.

3 SUMMARY

The overall message from careful analysis of non-ideal effects encountered by multijunction cells in the field is that although the effects of varying spectrum can be readily seen, and it is important to optimize the MJ cell for average operating temperature, AOD, angle of incident light, and other conditions, these effects are actually quite small in terms of energy production. The efficiency measured at standard test conditions (STC)

remains an excellent predictor of energy production under variable field conditions. 5-junction cells do show these effects more than 3-junction cells, which in turn are more susceptible to varying spectrum than 1-junction cells. However, these differences are much less significant than the STC efficiency gains of 3J cells over 1J cells, and the gains of 5J cells over 3J cells. Five-junction terrestrial concentrator cells are capable of reaching over 50% efficiency with >45% production average efficiency. The >45% efficiencies achievable by 5-junction cells, and the higher energy production that goes along with efficiency, hold the promise to take concentrator photovoltaics past the economic tipping point toward cost-effective solar electricity without subsidies.

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