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Solar spectral variations and their influence on concentrator solar cell performance

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ABSTRACT

A comparative study is performed to quantify the difference in efficiency and spectral sensitivity between a tandem junction and its spectrum splitting parallel junction counterpart. Direct normal solar spectra in a representative sunny site, Tucson, Arizona are calculated using the SPCTRAL2 model at 15-minute intervals throughout a year with real-time meteorological data input. The corresponding efficiencies of the two junctions under 500X concentration at cell temperatures deduced from thermal modeling with real-time ambient temperatures are computed. Both junction structures comprise the same materials, InGaP, GaAs and Ge, and are each optimized to the AM1.5D standard spectrum and cell temperature of 25°C, under which the parallel junction achieves a 1.0% absolute (and 2.5% relative) higher efficiency than the tandem junction. The two junctions are compared for their hourly, daily, and yearly average efficiencies. It is found that the yearly average efficiency of the parallel junction is 2.65% absolute (and 7.31% relative) higher than that of the tandem junction.

Keywords: solar spectrum, spectral variation, tandem junction, parallel junction, efficiency, spectral sensitivity, solar cell temperature

1. INTRODUCTION

Traditional concentrator photovoltaics (CPV) uses a vertically stacked tandem junction configuration. In recent years, parallel junctions, where laterally aligned solar cells with differing bandgaps are used along with spectrum splitting optical elements have stimulated renewed interest1-6. Compared to tandem junctions, using parallel junctions allows subcells to be optimized independently and eliminates the current matching constraint, thereby rendering higher efficiency. Additionally, since the subcells do not need to be epitaxially grown on top of one another, the lattice matching requirement is eliminated, rendering great flexibility in junction and substrate materials choices, potentially eliminating the expensive III-V or Ge substrates that tandem junctions traditionally utilize. Furthermore, for tandem junctions, when the incident solar spectrum varies due to changing meteorological conditions, the currents in the subjunctions may no longer match, causing efficiency degradation. By contrast, in parallel junctions, no current matching is required, and therefore it is expected that solar spectral variations will have less influence on their performance compared to tandem cells.

Quantifying spectral effects on solar cell efficiency is important for predicting solar cell energy production in a particular climate for certain time durations, and for devising site specific optimal solar cell designs7. With the emergence of smart grid integration, the capability to predict solar energy production and accordingly the amount of electricity that must be provided by the utility grid for particular applications becomes increasingly crucial8. Although spectral effects are expected to have less influence on parallel junctions than on tandem junctions, the availability of practical quantitative data on this difference for CPV applications is very limited. Most research about the influence of solar spectral variation on solar cell performance has been limited to one sun condition under the global spectrum9,10, while concentrator solar cells can only utilize the direct normal spectrum. Quite often, the solar spectrum is calculated not using real sets of meteorological data, but by varying only one parameter at a time, such as the aerosol optical depth11. Simulation studies often treat solar cell materials as imaginary with arbitrary bandgaps11, and work attempting to quantify the difference of solar spectral sensitivity between series and independently connected multijunctions often assumes the two cell designs have the same vertically stacked structure (including the same subjunction thicknesses), with the only difference being that the in-series connected cell has to match the current for efficiency calculations9,11. Usually, no reflection losses are...
considered, and the cell quantum efficiency is often assumed to be 100% for all wavelengths below the specified bandgap wavelength\textsuperscript{8,11}. Very few papers have considered realistic solar cell temperatures\textsuperscript{10,12}, which can significantly influence CPV performance. This research quantifies the difference of efficiency and spectral sensitivity between a tandem junction and its spectrum splitting parallel junction counterpart with all these deficiencies addressed.

Direct normal solar spectra for concentrator solar cells in a typical sunny site, Tucson, Arizona at 15-minute intervals throughout a whole year are calculated using the SPCTRAL2 model\textsuperscript{13}. Real-time meteorological data for the year 2000, and geographical parameters of Tucson are used as input for the spectral calculations. The corresponding efficiencies of tandem and parallel junctions under 500X concentration with realistic cell temperatures deduced from thermal modeling with real-time ambient temperature are computed for each spectrum. Both junction structures comprise the same materials, InGaP, GaAs and Ge, commonly used for CPV, and are each optimized to the standard operating condition (SOC), i.e., air mass 1.5 direct normal (AM1.5D) spectrum and a cell temperature of 25°C. The two junctions are compared for their hourly, daily, and yearly average efficiencies. The spectral effects are analyzed.

\section{METHODOLODY}

\subsection{Solar spectrum calculation}

CPV outperforms other solar technologies in desert-like climates with abundance of sunshine throughout the year. Among such locations in the U.S., including Arizona, California, Nevada, New Mexico, and Texas, we choose Tucson, Arizona (AZ) in the Year 2000 for our study due to the availability of complete meteorological data. Direct normal solar spectra at 15-minute intervals throughout the whole year are calculated using the clear day SPCTRAL2 model. Real-time meteorological data including aerosol optical depth and precipitable water vapor provided by AERONET\textsuperscript{14} for Year 2000, ozone amount obtained using the van Heuklon model\textsuperscript{15}, and geographical parameters of Tucson (latitude=32.23°, longitude=-110.95° and elevation=779 meters) are used as input for the spectral calculations. The wavelength resolution is 5 nm.

\subsection{Multijunction solar cell design and efficiency computation}

Our parallel and tandem junctions are both made of the same materials, InGaP, GaAs and Ge, with the individual bandgaps being 1.87, 1.42 and 0.67 eV, respectively. For a certain solar cell structure, the cell efficiency is determined by two factors: solar spectrum and cell temperature. The efficiency of each type of junction is computed for each of the spectra calculated above, under 500X concentration. Solar cell temperature is simulated based on real-time hourly ambient temperature as detailed in section 2.3. The efficiency calculation of multijunctions at a certain cell temperature is performed with MATLAB and presented below.

\subsubsection{Parallel junction}

For spectrum splitting parallel junctions, subcells with different bandgaps are laterally aligned and electrically isolated from each other, each receiving a certain part of the solar spectrum directed to it by spectrum splitting optics. Light can be first concentrated and then spectrally split, or concentrated and spectrally split simultaneously using compact optical elements. If a separate spectrum splitter is used, extra optical loss may be introduced compared to a tandem junction which splits the spectrum naturally. Since the quality of optical components keeps improving, for simplicity, in this paper, we do not consider the loss from optical elements for either parallel or tandem junctions.

The subcells in our parallel triple junction InGaP-GaAs-Ge are considered to be grown on inexpensive Si substrates, either monolithically integrated on the same Si substrate\textsuperscript{3} or each having its own substrate. Due to the well-matched lattice constants between the III-V materials (In\textsubscript{0.49}Ga\textsubscript{0.51}P and GaAs) and Ge, the subcells can be epitaxially grown on a single crystalline Ge buffer layer on top of a Si substrate\textsuperscript{16}. Realistic design of the subcells on Si substrates is made, optimized to SOC mentioned previously. The absorber thicknesses are chosen to be 2.0, 2.0, 2.5 µm for InGaP, GaAs, and Ge subcells, respectively. A typical antireflection coating (ARC) is applied for each subcell (MgF\textsubscript{2}/ZnS double layer ARC for the two III-V subcells and Si\textsubscript{3}N\textsubscript{4} for Ge). No light trapping structures are included. The efficiency of each subcell with a specific split of a certain solar spectrum is calculated as follows. First, the absorption spectrum $A(\lambda)$ is
obtained using the transfer matrix method for optical waves in multilayer structures\textsuperscript{17,18}, and the subcell short circuit current density \( J_{sc} \) is then acquired from

\[
J_{sc} = qX \int_{\lambda_1}^{\lambda_2} A(\lambda) s(\lambda) d\lambda
\]

where \( q \) is the electronic charge, \( X \) is the concentration factor taken as 500 in this study, \( s(\lambda) \) is the incident solar photon flux under a certain one sun solar spectrum, and \( \lambda_1 \) and \( \lambda_2 \) define the wavelength range allocated to that subcell. The open circuit voltage \( V_{oc} \) is then obtained from

\[
V_{oc} = \frac{kT}{q} \ln \left( \frac{J_{sc}}{J_0} + 1 \right)
\]

where \( k \) is the Boltzmann constant, \( T \) is solar cell temperature, and \( J_0 \) is the reverse bias saturation current density of the diode, which strongly depends on cell temperature\textsuperscript{19}, with

\[
J_0(T) = CT^{-3} \exp \left( -\frac{E_g(T)}{kT} \right)
\]

where \( C \) is an empirical constant which we deduced from the experimental \( J_0 \) values of InGaP, GaAs and Ge solar cells at 300 K, and \( E_g \) is the bandgap of the semiconductor material comprising the solar cell. The temperature-dependent fill factor and the resulting subcell efficiency are determined by following Ref. 19, assuming ideal diode behavior and neglecting parasitic resistances. The total efficiency of the parallel junction is simply the sum of the efficiency of each subcell. The optimal spectrum splitting wavelengths are found by searching for the values rendering the highest parallel junction efficiency. Note that for simplicity and in order to estimate the efficiency limit, no shadowing is considered, and 100\% carrier collection is assumed for both parallel and tandem junctions. After the initial spectrum splitting optimization under the AM1.5D spectrum, the thickness of the ARC for each subcell is further optimized for the wavelength range allocated to it to achieve the highest \( J_{sc} \), rendering a parallel junction efficiency of 42.28\%.

### 2.2.2 Tandem junction

A Ge substrate is used for the tandem junction InGaP/GaAs/Ge, which has a MgF\textsubscript{2}/ZnS ARC. The thickness of the top subjunction, InGaP, is reduced from 2.0 \( \mu \)m and adjusted to match the current from the middle subjunction, 2.0 \( \mu \)m thick GaAs, under the AM1.5D spectrum. The first step to calculate the tandem junction efficiency under a certain solar spectrum is to obtain the absorption spectrum \( A(\lambda) \) in each subjunction (layer) using the transfer matrix method, and then the \( J_{sc} \) for each subjunction is acquired using Eq. (1) where \( \lambda_1 \text{=}300 \text{ nm and } \lambda_2 \text{=}1800 \text{ nm. The remaining steps follow Ref. 20. Specifically, at a certain tandem junction current \( J \), the \( J-V \) relation for subjunction \( i \) is described by}

\[
V_i(J) = \frac{kT}{q} \ln \left( \frac{J_{sci} - J_0}{J_{o0}} + 1 \right)
\]

where \( J_{sci} \) and \( J_{o0} \) are that subjunction's short circuit current density and reverse bias saturation current density determined by Eq. (3). The optimum operating point \( (J_{mo}, \Sigma_{m=1} V_{mo}) \) and tandem junction efficiency is again found assuming ideal diode behavior and lack of parasitic resistances. Under SOC, the tandem junction has an efficiency of 41.45\%. For comparison, the parallel junction efficiency is higher than that of the tandem junction by 1.03\% absolute and 2.48\% relative. Time-averaged efficiencies reported below are calculated by taking the ratio of the total output power over a given period to the total input power over that same period.

### 2.3 Multijunction solar cell temperature simulation

Solar cell temperature is determined by the ambient temperature and incident solar power, and influenced by the cell efficiency. With the same ambient temperature and incident power, a higher efficiency cell will operate at a lower temperature because more incident solar energy is converted to electricity instead of heat. Additionally, a higher cell temperature reduces cell efficiency, and as a result, more heat will be generated from the incident solar energy, which in turn further increases the cell temperature. Therefore, the steady state solar cell temperature for a certain ambient temperature and incident solar power must be determined for final solar cell efficiency calculations detailed in Section 2.2. We simulate the steady state CPV temperature with a combination of COMSOL Multiphysics and MATLAB programming software for each calculated solar spectrum, with the input of incident solar power and ambient
temperature. Hourly ambient temperature in the year 2000 recorded at the KTUS airport in Tucson, AZ, and certified by
the National Weather Service (NWS) is acquired from Weather Underground\textsuperscript{21}. A finned aluminum heat sink with
commonly used dimensions\textsuperscript{22} is designed and passive air cooling is considered. The cell temperature converges with a
relative error of less than 0.1%. The final solar cell efficiency is computed with the steady state cell temperature.

3. RESULTS AND DISCUSSIONS

3.1 Solar spectrum

As a typical example, Figure 1 depicts the computed direct normal solar spectra at seven different times for Day 172, the
summer solstice, in the year 2000 in Tucson, between sunrise at around 4:45 and sunset at near 18:30. The standard
spectrum AM1.5D is shown for reference. The y-axis is chosen to be the incident solar photon flux instead of energy
flux because the number of incident photons at each wavelength is directly related to the solar cell efficiency, as
evidenced from Eq. (1). Clearly, from sunrise to midday, the total solar irradiance increases first rapidly and then at a
slower speed, from 296 W/m\textsuperscript{2} at 5:00 to 943 W/m\textsuperscript{2} at 11:30. At 8:00, the total irradiance and spectral shape are already
close to those of the AM1.5D spectrum. Meanwhile, the peak wavelength blue shifts from 860 nm at 5:00 to 630 nm at 11:30.
From midday to sunset, the trends reverse. This is because near sunset and sunrise, solar zenith angles are high,
rendering a bigger air mass (effective optical path length), which causes more attenuation of the solar radiation,
especially in the short wavelength range. On other days, a similar trend is observed.

![Figure 1. Direct normal solar spectra on Day 172 in Year 2000, Tucson, AZ. Peak wavelength $\lambda_p$ and total irradiance $I$ for each spectrum are also shown. Aerosol optical depth $\tau$, precipitable water vapor $W$ and ozone amount $O_3$ for that day are listed. Also depicted is the AM1.5D standard solar spectrum for reference.](image)

3.2 Solar cell efficiency

For the parallel junction, it is found that the optimal spectrum splitting wavelengths barely change with the solar
spectrum and ambient temperature, and they are always near the band edges of the subcells, i.e., almost always at 670
nm and 840 nm.

3.2.1 Hourly multijunction efficiency

Figure 2 compares the parallel and tandem junction efficiencies at 15 minute intervals on four days with special solar
events, i.e., the solstices and equinoxes. A quick inspection of Figure 3 reveals that the evolution of parallel and tandem
junction efficiencies is quite similar during the course of a day, although tandem junction efficiency is always lower
than that of parallel junction at the same time on the same day. Every day, the efficiency of each multijunction rises rapidly at sunrise, and then becomes almost constant at around 40%, followed by a rapid drop near sunset.

Figure 2. Solar cell efficiency variation on four special days in the year 2000, Tucson, AZ at 15 minute intervals. PJ represents parallel junction and TJ stands for tandem junction.

3.2.2 Daily and yearly average solar cell efficiencies

Figure 3 illustrates daily and yearly average solar cell efficiencies. The variation from day to day is significantly reduced compared to hourly variation shown in Figure 2, and the daily efficiencies range from 37% to near 41% for parallel junction, and from 33.5% to 38% for tandem junction. The two curves look very similar, except that the one for parallel junction is increased by about 3% from that of tandem junction. The fluctuation is slightly higher near the beginning of the year.

Figure 3. Daily and yearly average multijunction solar cell efficiency in the year 2000 in Tucson, AZ. PJ represents parallel junction and TJ stands for tandem junction.
The yearly average efficiency is 38.87% for parallel junction and 36.23% for tandem junction, different by 2.65% absolute and 7.31% relative. Compared to the efficiencies under SOC that they are optimized for, the yearly average efficiency for parallel junction is reduced by 3.41% absolute and 8.06% relative, while that for tandem junction is reduced by 5.22% absolute and 12.61% relative. For both absolute and relative reduction, parallel junction is around 64 to 65% of that for tandem junction. However, this difference may not be significant given that the parallel junction may encounter extra losses from the optical spectrum splitter. To make parallel junctions really excel, it is important to take full advantage of the flexibility in materials choice to optimize the combination of bandgaps and to incorporate subcells with favorable bandgaps, such as replacing the Ge junction with a material that has a bandgap near 1 eV, for example, Si$^5$ or dilute nitride III-V compounds$^{23}$, or by adding other materials with bandgaps higher than that of InGaP.

4. CONCLUSION

Under SOC, for tandem and spectrum splitting parallel junctions made of the same materials, InGaP, GaAs and Ge, with realistic cell parameters and optimized design, parallel junction efficiency is higher than that of tandem junction by 1.03% absolute and 2.48% relative. The yearly average efficiency difference between parallel junction and tandem junction is 2.65% absolute and 7.31% relative when both the spectrum and solar cell temperature deviate from the SOC. To reach the full potential of parallel junction devices, one should fully take advantage of the flexibility in materials choice and optimize the combination of bandgaps.

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