DETERMINATION OF OPTIMUM SUNLIGHT CONCENTRATION LEVEL IN SPACE FOR III-V CASCADE SOLAR CELLS

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ABSTRACT

The optimum range of concentration levels in space for III-V cascade cells has been calculated using a realistic solar cell diode equation. Temperature was varied with concentration using several models and ranged from 55° C at 1 sun to between 80° and 200° C at 100 suns. A variety of series resistance and internal resistances were used. Coefficients of the diffusion and recombination terms are strongly temperature dependent. The study indicates that the maximum efficiency of 30 percent occurs in the 50 to 100 sun concentration range provided series resistance is below 0.015 ohm-cm^2 and cell temperature is about 80° C at 100 suns.

INTRODUCTION

Cascade solar cells, especially those made using III-V materials, have the potential for much greater conversion efficiency than conventional single junction solar cells. The increased efficiency is mainly due to the better utilization of the solar spectrum by the two or three junctions of the cascade cell. An advantage of III-V material cascade cells is their low rate of decrease in power with increasing temperature. This indicates that III-V cascade cells should benefit from concentrated sunlight and be able to operate without forced cooling. The concentration level where the cell efficiency peaks depends on several factors, such as resistance losses and cell temperature as a function of concentration. Previous studies have calculated the efficiency of two and three junction cascade cells at various temperatures and concentrations (refs. 1 and 2), however, there was no definite relation between cell temperature and concentration. In an earlier study (ref. 3), the performance of gallium arsenide cells was calculated as cell temperature increased with concentration in specific difference functional relationships. The purpose of this effort is to expand the work of reference 3 to the case of III-V cascade cells.

METHOD OF CALCULATION

Current voltage curves were calculated for each cell in the cascade structure using the solar cell diode equation and the principle of superposition. Terms for the light-generated current, diffusion current, space charge recombination current, and series and shunt resistances are included. Cell current density J (in A/cm^2) is given by

$$J = J_L - J_{01}\left(\exp\frac{V + JAR_s}{V_T} - 1\right) - J_{02}\left(\exp\frac{V + JAR_s}{2V_T} - 1\right) - \frac{V + JAR_s}{AR_{sh}} \qquad (1)$$

where

A	cell area, cm^2
J_L	light-generated current density, A/cm^2
J_{01}	coefficient of diffusion current term, A/cm^2
J_{02}	coefficient of space charge region recombination current term, A/cm^2
R_s	series resistance, ohm
R_{sh}	shunt resistance, ohm
V_T	$=kT/q = 25.85$ mV at T = 300 K
V	cell output voltage

The individual current-voltage curves are added in series with ohmic resistance losses for the cell interconnects to obtain the cascade cell performance.

Before any calculations are possible, we must do the following:

(1) Determine the initial values (at 300 K) for J_L, J_{01}, and J_{02} for each junction in the cascade cell structure.
(2) Determine the temperature dependence of the above quantities.
(3) Determine the relationship between cell temperature and concentration.

In a series connected cascade cell, the current in each junction must be equal. This constraint is met by proper choice of the band gaps of the individual cells. For this study it was assumed that a III-V direct gap cell of band gap E_g, used as the top cell in a cascade structure, has a light-generated current equal to 80 percent of a "perfect" cell of the same band gap (quantum yield = 1 above the band gap and zero below the gap). The 20 percent loss can be attributed to grid coverage, surface reflection, recombination, etc. Integrating the quantum yield of a perfect cell against the Labs and Neckel AMO spectrum, gives the data in figure 1, which shows light-generated current for a perfect 1-cm^2 cell as a function of cutoff wavelength, λ_c:

$$\lambda_c = \frac{1.24}{E_g}$$

For a gallium arsenide cell of 0.867 μm cutoff wavelength, the 80 percent assumption leads to a value of 31.1 mA/cm^2 for light-generated current, in good agreement with the literature (ref. 4). For the second and third junctions, it was assumed that the light-generated current was 85 percent of a perfect cell (adjusted for absorption in the upper cells). Lower losses are assumed in the lower junctions due to decreased reflection and recombination losses. Using the above assumptions, the equal light-generated currents in each junction and the band gaps corresponding to any top cell band gap are uniquely determined.

The coefficients of the diffusion and recombination terms, J_{01}, and J_{02}, are determined for each band gap by assuming the following:

(1) The diode quality factor n is equal to 1.2 at 1-sun concentration and at 300 K
(2) Voltage V_{oc} is 70 percent of the band gap (eV).

The diode quality factor can be determined by using equation (1) and plotting an I_{sc} - V_{oc} curve. The slope of this curve at 300 K and at current levels corresponding to 1-sun illumination leads to an n value that is dependent on the relative values for J_{01} and J_{02}. For example, if J_{02} is zero, then the cell is completely diffusion limited, and n = 1.0. By adjusting the relative value of J_{01} and J_{02}, an n value of 1.2 can be obtained. The final value of the two constants is determined by V_{oc} = 0.7 E_g. The value of n = 1.2 is assumed to be typical of current III-V cells (refs. 5 and 6). For GaAs 70 percent of E_g is 1 V, which value is typical of a good GaAs cell.

The temperature dependence of the various band gaps was assumed to be similar to that of gallium arsenide. The gallium arsenide temperature dependence can be obtained from the literature (ref. 7).

The J_{01} and J_{02} vary with the square of the intrinsic concentration and the intrinsic concentration, respectively. Hence,

$$J_{01} \propto T^3 \exp(-E_g/kT) \tag{2}$$

and

$$J_{02} \propto T^{3/2} \exp(-E_g/2kT) \tag{3}$$

The temperature dependences of J_{01} and J_{02} are calculated from equations (2) and (3).

The light-generated current of a solar cell increases with increasing temperature for two reasons: (1) the smaller band gap means more photons are collected, and (2) material properties such as lifetime improve with increasing temperatures (ref. 8). It was assumed that the band gap change accounted for most of the increase in light-generated current with temperature, and a value of 0.020 percent/K was assigned to the "better material properties" portion of increased current. Since band gaps were varied with temperature in this study, the calculated light-generated current already reflects this effect. For a gallium arsenide cell, this resulted in a 25 $\mu A/cm^2$-K temperature coefficient, which is in substantial agreement with published results (ref. 9).

The operating temperature of a solar cell in space is dependent on many factors. These include the incident irradiance, the absorptance and emittance of the cell and radiator surface, the thermal transfer between cell and radiator, the size and orientation of the radiator, and the orbit of the spacecraft. It was beyond the scope of this study to calculate temperature variations with concentration for a nearly infinite set of starting assumptions. Instead actual data for 1-sun operation and other studies for data at concentrated sunlight levels were used.

For 1-sun operation in space, a cell temperature of 328 K (55° C) is typical of present photovoltaic arrays (ref. 10). These arrays use passive cooling, and the cells are producing power. There were no actual data available for cell temperature at elevated concentration levels in space, so the results of two studies were used to determine the range of operating temperatures expected. For the first study, which did not limit cell size and had no active cooling, a cell temperature of 398 K (125° C) at 50 suns was computed. A nearly 14-K margin for error is included, making this cell tmeperature value conservative. For the second study (ref. 12) much lower cell temperatures were computed for space solar cells: 353 K (80° C) for a 100-sun irradiance level. This study used very small cells (4 mm diam) to maximize the heat transfer from cell to radiator.

These low cell temperatures at concentration are similar to earlier work on small silicon cells at several hundred AM1 concentrations for terrestrial purposes. (ref. 13) Passive cooling was assumed in all the above work. Because of the usual dependences observed in space between irradiance and temperature, a T^4 relationship to concentration ratio ($T^4 = A_1 CR + A_2$) was fitted to the 328 K - 1-sun point and to each of the higher concentration points. This lead to two different temperature dependences with concentration, a high temperature dependence and a low temperature dependence. A third, intermediate dependence curve is obtained by arbitrarily using a temperature level of 398 K (125° C) at 100 suns. The three temperature dependences are summarized below.

	Temperature, K	CR
High temperature	398	50
Intermediate temperature	398	100
Low temperature	353	100

Figure 2 shows temperature as a function of concentration for these three temperature dependences.

RESULTS AND DISCUSSION

Current-voltage curves were generated for cascade cell structures for sunlight concentration levels up to 250x (AMO). Figure 3 shows a typical three-junction cascade cell curve as well as the individual curves for each junction. Cell temperature was varied with concentration as described above, and efficiencies were calculated as a function of concentration level for a variety of series resistance, cell interconnection resistance, and top band gap values.

As seen from equation (1), the quantities AR_s and AR_{sh} may be treated as independent variables. The same holds true for AR_c, where R_c

is the interconnect resistance between cells, whose ohmic voltage drop is subtracted from the cascade cell performance. Hence, for the remainder of the study series resistance, shunt resistance, and interconnect resistance were treated in terms of ohm-cm^2.

As in the previous work (ref. 3) the effect of shunt resistance at higher concentration levels was negligible. Because the main focus of this study is on higher concentration ratios, a value of 2500 ohm-cm^2 for shunt resistance was used throughout.

Figure 4 shows efficiency as a function of concentration for three interconnect resistance values for a three junction cascade cell with a top band gap of 2.07 eV. The low-temperature dependence was used and AR_S = 0.015 ohm-cm^2. Note the falloff in efficiency above about 100 concentration and the fairly broad maximum over the 30 to 100 range. The value of 50 m ohm-cm^2 (the center curve) for cell interconnect resistance resulted in a voltage drop of 75 mV at each interconnection at 100 AM0. This was somewhat less than the 100-mV drop assumed in reference 1, but probably within future technology. The top band gap was 2.07 eV. The corresponding band gaps for the second and third cells are 1.55 and 1.17 eV. This is <u>not</u> the optimum choice of band gaps; however, for direct gap materials of the same lattice constant, data from references 14 and 15 indicate that it is the only choice. Since the ability to grow individual cells in a monolithic stack of different lattice constants is considered improbable (ref. 1), the more realistic choice is 2.07 eV as top band gap, even though efficiencies could be about 3 percentage points higher with a more optimum band gap combination.

The effect of varying series resistance of the individual junctions is shown in figure 5. The effect of series resistance is less than the interconnect resistance due to the smaller values used in the calculation. The value of 15 m ohm-cm^2 should be readily achievable since similar and lower values have already been produced in single gallium arsenide cells (refs. 16 and 17).

Figure 6 shows efficiency as a function of concentration for the three temperature dependences. The efficiencies are equal at 1 sun and change as concentration and temperature are increased. The benefit of operating the cell at lower temperatures at concentration is readily evident. At 100 suns, the high temperature dependence results in an efficiency value lower than at 1 sun, due to the high operating temperature. Also at 100 suns, the difference in efficiency between the high- and low-temperature dependence curves is about 5.7 percentage points (29.67 and 23.97 percent). This is considerably more than the change in efficiencies in figures 4 and 5 due to the range of series and interconnect resistances studied. Hence, the effect of decreasing the operating temperature is the most important factor in raising the efficiency of cascade cells operating at high concentration levels.

The effect of mismatch in the currents of the individual cells is shown in table I. The first source of mismatch arises from the band gaps being chosen at one temperature and the cell being operated at a different temperature. For temperature differences of 30 to 40 K, this mismatch effect was negligible, with changes in efficiency of 0.1 percentage point. Since any cascade cell will be designed for the concentrator it will be used in, this mismatch error can be neglected. The second mismatch error results from the uncertainty of our knowledge of the AMO spectrum. The Labs and Neckel spectrum was used throughout this study to determine light-generated currents and band gaps. The other recognized AMO spectrum was that of Thekaekara. Data were generated using band gaps chosen by the Labs and Neckel spectrum and light-generated currents chosen using the Thekaekara spectrum. The differences were small, about 0.4 percentage point difference in efficiency, which resulted in approximately a 1.3 percent drop in maximum power.

The third mismatch arises from radiation damage in space. For protron irradiation of sufficiently low energy we can assume that the current in the top cell is reduced by 10 percent. This results in approximately a 7-1/2 percent drop in efficiency of the cascade cell.

CONCLUSIONS

The optimum concentration level for III-V cascade cells is about 50 suns (with a range of 10 to 100 suns), where the efficiency falls off by less than 1 percentage point, provided the following conditions are met:

(1) An optical concentrator-passive cooling system must be provided which maintains cell temperature as low as possible. Some concepts presently under study indicate temperatures of 80° C at 100-sun concentration appear feasible through use of small cells to obtain good heat transfer to a radiating surface. The small cell concept has already been demonstrated in terrestrial concentrators to yield low operating temperatures.

(2) The resistance losses due to series resistance in the individual cells and the cell interconnects are kept at reasonable values. A value of 15 m ohm-cm^2 for individual cell series resistance should be an achievable value since gallium arsenide cells have been made with this on lower series resistance values. A value of 50 m ohm-cm^2 represents a goal for cell interconnect resistance. There is no known experimental data on such values at present. In any event, the drop in efficiency due to increased resistance losses at 100-sun concentration is considerably less than the loss due to higher operating temperatures.

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TABLE I. - EFFECTS OF VARIOUS CURRENT MISMATCHES ON CASCADE CELL POWER OUTPUT

Source of mismatch	Percent drop in P_{max}
$\Delta T \sim 30^{\circ}$ between cell operation and band gap optimization	Negligible, 0.3 percent
Uncertainty of AMO spectrum Labs and Neckel/Thekaekara	Small, 1.3 percent
Radiation damage 10 percent drop in one cell current	6 to 7.5 percent

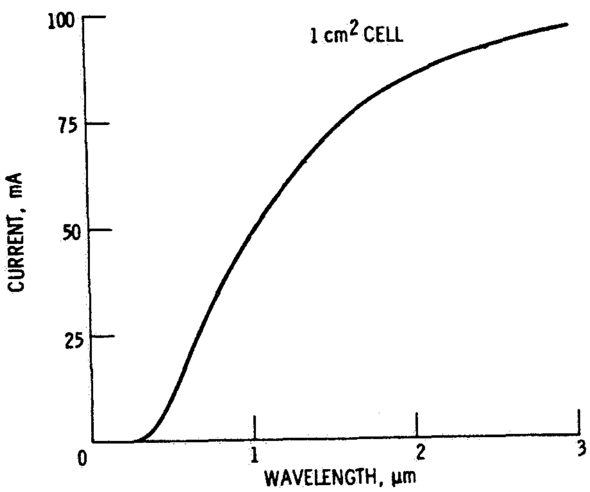

Figure 1. - Variation of short-circuit current of perfect cell with cutoff wavelength.

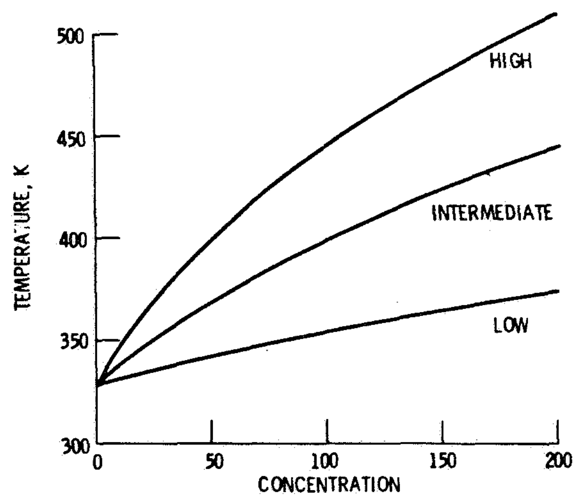

Figure 2. - Variation of temperature with concentration for different temperature dependences.

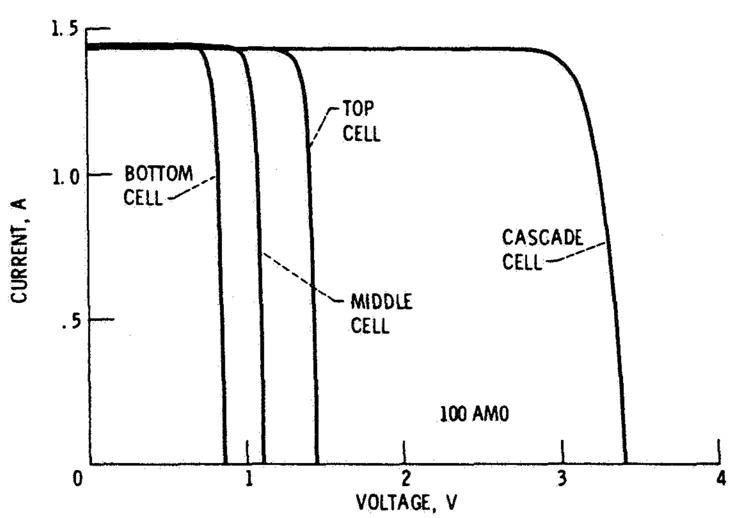

Figure 3. - Series addition of individual I-V curves.

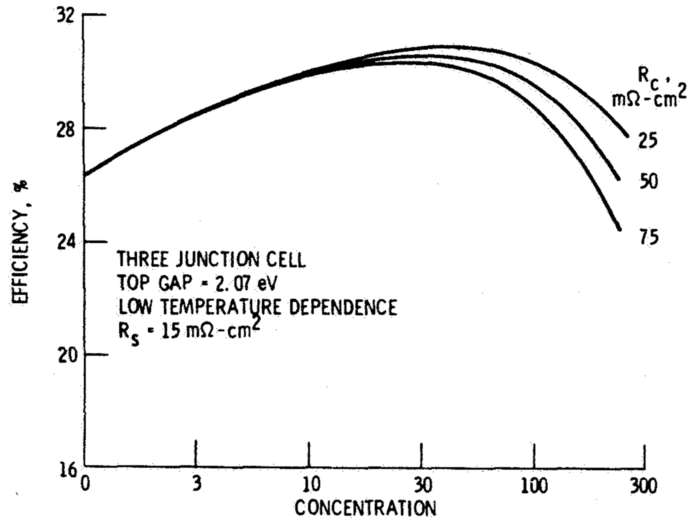

Figure 4. - Variation of efficiency with concentration for different interconnect resistances.

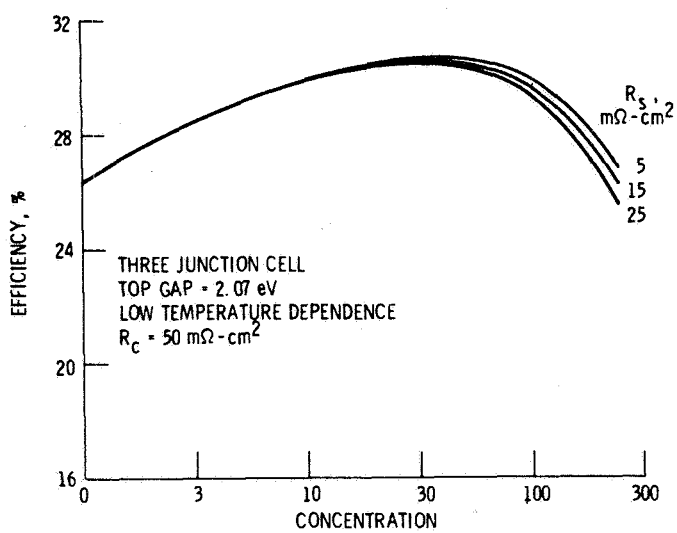

Figure 5. - Variation of efficiency with concentration for different series resistances.

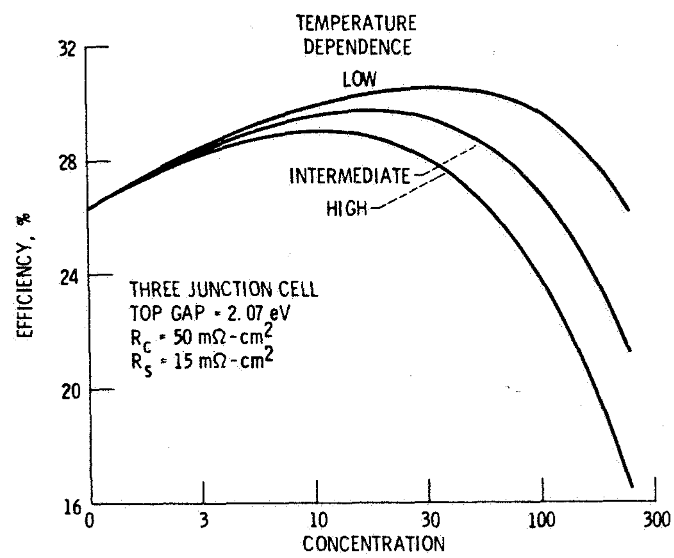

Figure 6. - Variation of efficiency with concentration for different temperature dependences.