NASA Technical Memorandum 82899

Determination of Optimum Sunlight Concentration Level in Space for III-V Cascade Solar Cells

Henry B. Curtis
Lewis Research Center
Cleveland, Ohio

Prepared for the
Third European Symposium on Photovoltaic Generators in Space
cosponsored by the Royal Aircraft Establishment,
U.K. Department of Industry, and European Space Agency
Bath, United Kingdom, May 4-6, 1982

NASA

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

Henry B. Curtis

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio, U.S.A.

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 one sun to between 80°C 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 100X sun concentration range provided series resistance is below 0.015 ohm-cm^2 and cell temperature is about 80°C at 100 suns.

INTRODUCTION

It is widely recognized that 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 relationships between cell temperature and concentration. In an earlier study at NASA Lewis (ref. 3), the performance of gallium arsenide cells was calculated as cell temperature increased with concentration in specific different functional relationships. The purpose of this effort is to expand the work of ref. 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 resistance are included. Cell current density J in amp/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 (amp/cm^2)

J_{01} = coefficient of diffusion current term (amp/cm^2)

J_{02} = coefficient of space charge region recombination current term (amp/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 bandgaps of the individual cells. For the purpose of this study, it was assumed that a III-V direct gap cell of bandgap Eg, 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 bandgap (guantum yield = 1 above the bandgap and zero below the gap). The 20 percent loss can be attributed to grid coverage, surface reflection and recombination, etc. Integrating the quantum yield of a perfect cell against the Labs & Neckel AMO spectrum, gives the data in Figure 1. Figure 1 shows light generated current for a perfect 1 cm^2 cell as a function of cutoff wavelength, $\lambda_c \left(\lambda_c = \frac{1.24}{Eg}\right)$.

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 bandgaps corresponding to any top cell bandgap are uniquely determined.

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

1) The diode quality factor n = 1.2 at a 1 sun concentration level at 300 K
2) V_{oc} (volts) is 70 percent of the bandgap (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 one sun illumination leads to an n value 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 the V_{oc} equal to 0.7 times bandgap. 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 bandgap is one volt, typical of a good GaAs cell.

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

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

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

and

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

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 bandgap means more photons are collected, and 2) material properties such as lifetime improve with increasing temperatures (Ref. 8). It is assumed that the bandgap change accounts for most of the increase of 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 bandgaps are varied with temperature in this study, the calculated light generated current already reflects this effect. For a gallium arsenide cell, the above results in a 25 μa/cm^2-K temperature coefficient which is in substantial agreement with published results (Ref. 9).

ORIGINAL PAGE IS
OF POOR QUALITY

Dependence of Cell Temperature on Concentration Level

The operating temperature of a solar cell in space is dependent upon 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 is beyond the scope of this paper to calculate temperature variations with concentration for a nearly infinite set of starting assumptions. We will rely on actual data for one sun operation, and other studies for data at concentrated sunlight levels.

For one 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 are no actual data available for cell temperature at elevated concentration levels in space, so the results of two studies will be utilized to determine the range of operating temperatures expected. The first study does not limit cell size and has no active cooling, and a cell temperature of 398 K (125°C) at 50 suns was computed. A margin for error of nearly 14 K is included and this value (125°C) can be considered conservative. A second study (Ref. 12) indicates that much lower temperatures are possible for space solar cells. The latter study utilizes very small cells (4 mm diameter) in order to maximize the heat transfer from cell to radiator. A cell temperature of 353 K (80°C) is calculated for a 100 sun irradiance level.

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 is 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 ($T^4 = A_1CR + A_2$) was fitted to the 328 K - 1 sun point and to each of the higher concentration points. This leads 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.

ORIGINAL PAGE IS OF POOR QUALITY

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 bandgap 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 we shall treat series resistance, shunt resistance and interconnect resistance on ohm-cm^2 terms.

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

Figure 4 shows efficiency as a function of concentration for three different interconnect resistance values for a three junction cascade cell with a top bandgap of 2.07 eV. The low temperature dependence is used and AR_s = 0.015 ohm-cm^2. Note the falloff of efficiency above about 100X concentration and the fairly broad maximum over the 30 to 100X range. The value of 50 m ohm-cm^2, the center curve in figure 4, for cell interconnect resistance results in a voltage drop of 75 mV at each interconnection at 100 AMO. This is somewhat less than the 100 mV drop assumed in ref. 1, but probably within future technology. In figure 4, the top bandgap is 2.07 eV. The corresponding bandgaps for the second and third cells are 1.55 eV and 1.17 eV. This is not the optimum choice of bandgaps, however if we constrain ourselves to direct gap materials of the same lattice constant, data from references 14 and 15 indicate 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), we will limit ourselves to the more realistic choice of 2.07 eV as top bandgap, even though efficiencies could be about 3 percentage points higher with a more optimum bandgap 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 (Ref. 16 and 17).

Figure 6 shows efficiency as a function of concentration as the three different temperature dependences are used. The efficiencies are equal at one sun and change as concentration and temperature are increased.

The benefit of operating the cell at lower temperatures at concentration is readily evident. At 100X, the high temperature dependence results in an efficiency value lower than at one sun, due to the high operating tempera-

ORIGINAL PAGE IS
OF POOR QUALITY

ture. 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%). 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 bandgaps 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 is negligible with changes in efficiency of 0.1 percentage points. 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 & Neckel spectrum was used throughout this study to determine light generated currents and bandgaps. The other recognized AMO spectrum is that of Thekaekara. Data was generated using bandgaps chosen by the Labs & Neckel spectrum and light generated currents chosen using the Thekaekara spectrum. The differences were small, about 0.4 percentage points difference in efficiency, which resulted in approximately a 1.3% 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%. This results in approximately a 7-1/2% drop in efficiency of the cascade cell.

CONCLUSIONS

The optimum concentration level for III-V cascade cells is about 50X with a range of 10 to 100X where the efficiency falls off by less than one 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 100X concentration appear feasible by utilizing 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 100X concentration is considerably less than the loss due to higher operating temperatures, shown in figure 6.

ORIGINAL PAGE IS
OF POOR QUALITY

REFERENCES

1. Maloney T J 1981, Projected performance of III-V epitaxial multijunction solar cells in space, Sol. Energy Mater. 4, 1981, pp. 359-372.

2. Lamorte M F and Abbott D H 1980, Computer modeling of a two-junction, monolithic cascade solar cell, IEEE Trans Electron Devices 27 (1), 231-249.

3. Curtis H B 1981, Determination of optimum sunlight concentration level in Space for gallium arsenide solar cells, 15th Photovoltaic Specialists Conference, Kissimmee, Florida, 12-15 May 1981, 52-56.

4. Kamath S et al 1979, Fabrication of high efficiency and radiation resistance GaAs solar cells, Solar Cell High Efficiency and Radiation Damage, Cleveland, OH, 13-14 June 1979, NASA-CP-2097, 209-216.

5. Fan J C C et al 1980, GaAs shallow-homojunction solar cells, 14th. Photovoltaic Specialists Conference, San Diego, CA, 7-10 Jan. 1980. 1102-1105.

6. Turner C W et al 1980, Indium phosphide homojunction solar cells, 14th. Photovoltaic Specialists Conference, San Diego, CA, 7-10 Jan. 1980, 351-353.

7. Yang E S 1978, Fundamentals of semiconductor devices, New York, McGraw-Hill.

8. Hovel H J 1975, Solar cells, New York, Academic Press.

9. Swartz C K and Hart R E Jr 1979, Temperature and intensity dependence of the performance of an electron-irradiated (AlGa)As/GaAs solar cell, Solar Cell High Efficiency and Radiation Damage, Cleveland, Oh, 13-14 June 1979, 217-226.

10. J. Scott-Monck, J A 1980, "Prospects for Enhancing SEP Array Performance," Space Photovoltaic research and technology 1980, Cleveland, OH, 15-17 Oct. 1980, 351-361.

11. GDC-AST-81-019-VOL-2 (General Dynamics/Convair) 1981, Study of multi-megawatt technology needs for photovoltaic space power systems, vol. 2, by Peterson D M and Pleasant R L.

12. Patterson R E et al 1981, Low cost, high concentration ratio solar cell array for space applications, Intersociety Energy Conversion Engineering Conference, 16th., Atlanta, GA, 9-14 Aug. 1981, 383-389.

13. SAND-78-7027 (Wisconsin Univ.) 1978, Design and development of a 300-Watt solar photovoltaic concentrator, by Napoli L S and Swartz G A.

14. Glisson T H et al 1978, Energy bandgap and lattice constant contours of III-V quaternary alloys, J. Elec. Mater. 7 (1), 1-16.

15. Williams C K et al 1978, Energy band gap and lattice constant contours of III-V quaternary alloys of the form AxByCzD or ABxCyDz, J. Elec. Mater. 7 (5), 639-646.

16. Sahai R. et al 1978, High efficiency AlGaAs/GaAs concentrator solar development, 13th. Photovoltaic Specialists Conference, Washington, D. C., 5-8 June 1978, 946-952. Efficiency AlGaAs/GaAs

17. Ewan J et al 1978, GaAs solar cells for high solar concentration applications, 13th. Photovoltaic Specialists Conference, Washington, D.C., 5-8 June 1978, 941-945.

ORIGINAL PAGE IS
OF POOR QUALITY

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

Source of mismatch	% Drop in P_{max}
$\Delta T \sim 30^{\circ}$ between cell operation and bandgap optimization	Negligible 0.3%
Uncertainty of AMO spectrum Labs & Neckel/Thekaekara	Small 1.3%
Radiation damage 10% drop in one cell current	6-7.5%

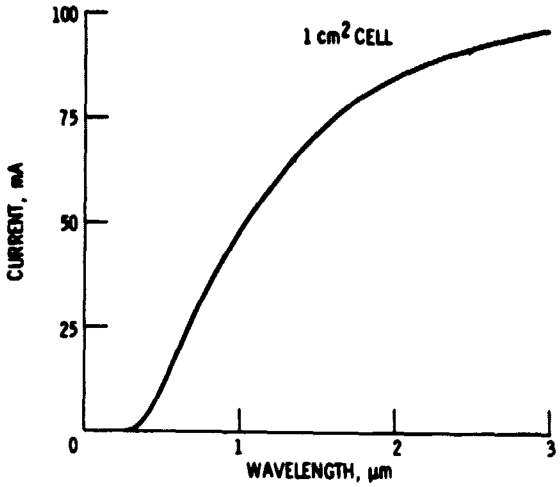

Figure 1. - Variation of short-circuit current of perfect cell with cutoff wavelength.

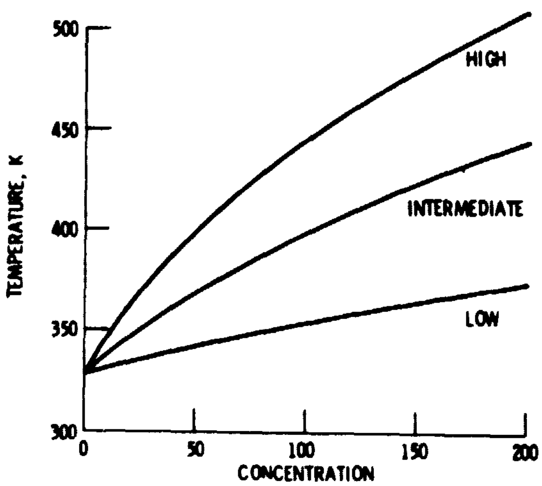

Figure 2. - Variation of temperature with concentration for different temperature dependences.

ORIGINAL PAGE IS OF POOR QUALITY

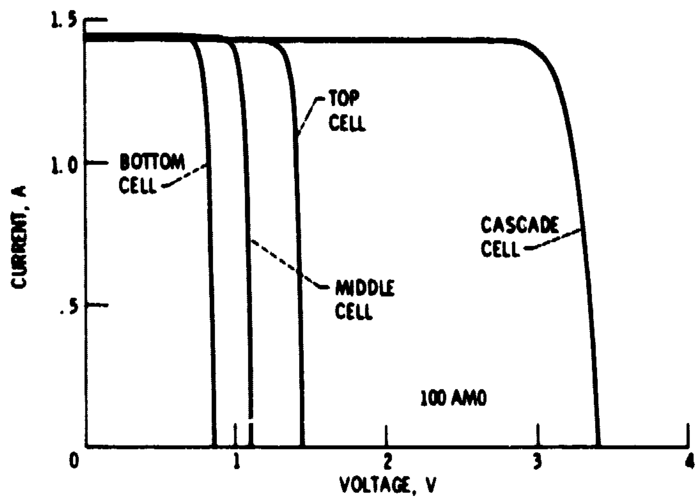

Figure 3. - Series addition of individual I-V curves.

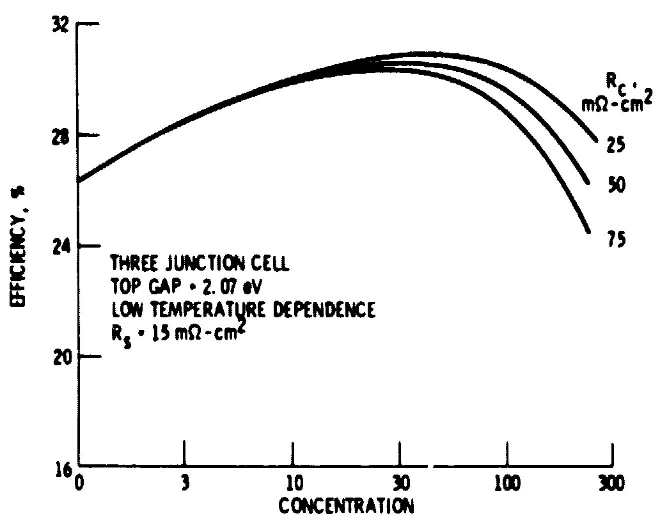

Figure 4. - Variation of efficiency with concentration for different interconnect resistances.

ORIGINAL PAGE IS
OF POOR QUALITY

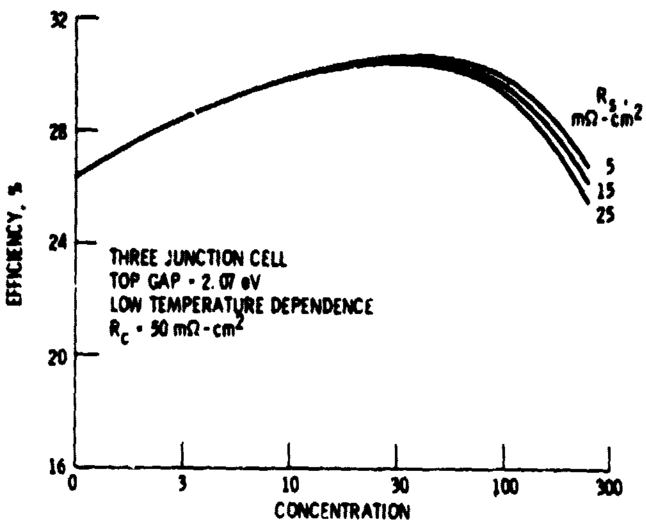

Figure 5. - Variation of efficiency with concentration for different series resistances.

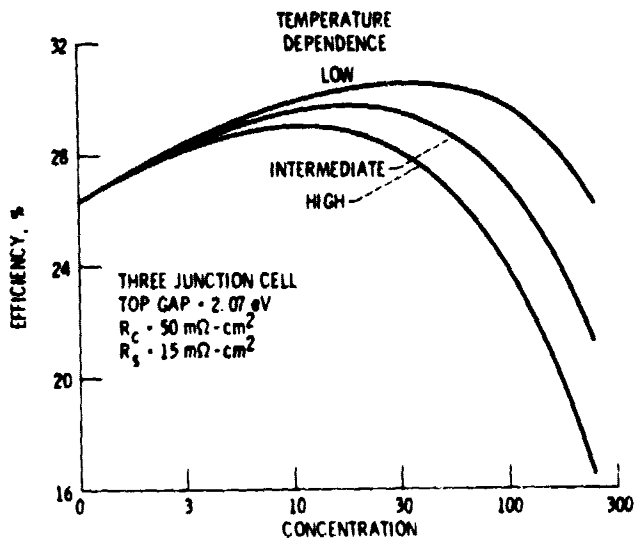

Figure 6. - Variation of efficiency with concentration for different temperature dependences.