

HIGH TEMPERATURE SOLAR CELL DEVELOPMENT

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ABSTRACT: The majority of satellites and near-earth probes developed to date have used photovoltaic arrays for power generation. If future missions to probe environments close to the sun will be able to use photovoltaic power, solar cells that can function at high temperatures, under high light intensity, and high radiation conditions must be developed. In this paper, we derive the optimum bandgap as a function of the operating temperature.

Keywords: Thermal Performance, Fundamentals, Space Cells

1 BACKGROUND

The vast majority of satellites and near-earth probes developed to date have used photovoltaic arrays for power generation. If future missions to probe environments close to the sun will be able to use photovoltaic power, solar cells that can function at high temperatures, under high light intensity, and high radiation conditions must be developed [1,2]. For example, the equilibrium temperature of a Mercury surface station will be about 450 °C, and the temperature of solar arrays on the proposed "Solar Probe" mission (Figure 1) will extend to temperatures as high as 2000°C, although it is likely that the craft will operate on nuclear power, or using stored (battery) power rather than solar energy during the closest approach to the sun [3].

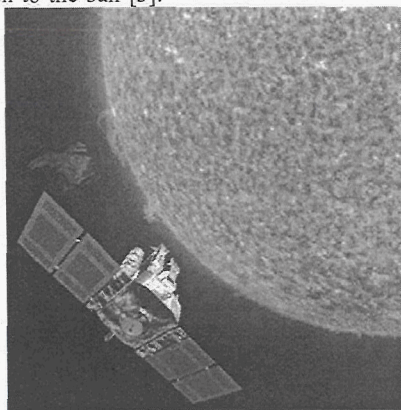


Figure 1: a proposed future mission to investigate the plasma environment near the sun.

Advanced thermal design principles can be used to reduce the solar flux on the arrays. Such techniques include replacing some of the solar array area with mirror panels or reflectors, such as is done on the MESSENGER spacecraft. The solar array for the MESSENGER mission to Mercury incorporates reflective panels over 2/3 of the solar array area, replacing active solar cells with mirrors to minimize the solar heating of the array at a solar intensity of 10.6 times AM0. Other techniques for reducing solar flux include pointing the array normal away from the direction to the sun, and designing the cells to reflect rather than absorb light out of the band of peak

response. These techniques can reduce the operating temperature somewhat. Nevertheless, it is desirable to develop approaches to high-temperature solar cell design that can operate under temperature extremes far greater than today's cells.

2 HIGH TEMPERATURE SOLAR CELL DEVELOPMENT

Solar cells decrease in efficiency with temperature [4, 5]. Loss of open circuit voltage with increasing temperature, due to increase in dark current [5], contributes the majority of the change in efficiency. Fill factor variation in general follows the open circuit variation. A small variation of short circuit current with temperature is primarily due to the change in bandgap energy with temperature. As the cell heats up, the bandgap decreases, and hence the cell responds to longer wavelength portions of the spectrum, and therefore the short circuit current actually increases with temperature. Hence, the J_{sc} variation term is roughly proportional to the incident spectral intensity at wavelengths near the band edge.

Since the V_{oc} variation with temperature is roughly the same for cells of different bandgap, while the actual V_{oc} increases with bandgap, the normalized temperature coefficient, $1/\eta d\eta/dT$, increases directly with bandgap. From this a theoretical maximum operating temperature can be computed as a function of bandgap, where the maximum operating temperature is defined as the temperature at which the efficiency, extrapolated from the linear temperature coefficient, drops to zero. This is shown in figure 2. Clearly, high bandgap materials are needed to operate at elevated operating temperatures [6].

However, since the photon flux from the sun decreases at high photon energies, an optimum bandgap exists for each temperature.

Solar cells made from wide bandgap compound semiconductors are an obvious choice for such an application. In order to aid in the experimental development of high-temperature solar cells, we have initiated a program studying the theoretical and experimental photovoltaic performance of wide bandgap materials. In particular, we have been investigating the use of GaP [7], SiC [8,9], and GaN

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materials for space solar cells. We present theoretical results on the limitations on current cell technologies and the photovoltaic performance of these wide-bandgap solar cells in a variety of space conditions.

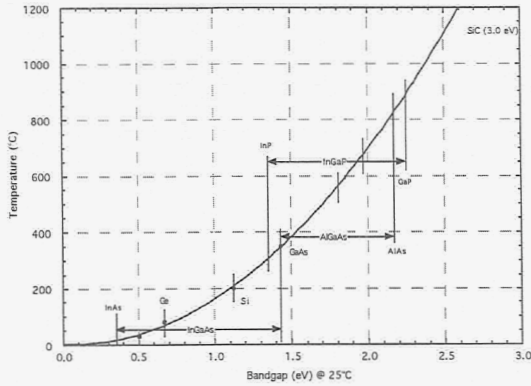


Figure 2: theoretical maximum operating temperature as a function of bandgap.

3 EFFECT OF BANDGAP OF CELLS OPERATING AT HIGH TEMPERATURE

To choose the optimum solar cell material for high temperature operation, the theoretical efficiency was derived from the fundamental physics of operation as a function of temperature [10].

3.1 Short circuit current vs. Bandgap

The open circuit voltage for an ideal semiconductor increases with bandgap. Solar irradiance was calculated as a function of wavelength for AM0 and AM1.5, and the photon flux vs. wavelength was derived, where

• Photon Flux = (Irradiance per wavelength)/(Energy per individual photon of that wavelength)

From this the limiting I_{sc} (Short Circuit Current) can be determined as a function of the cell bandgap. For a given bandgap, we integrate the Photon Flux over the distribution from low wavelengths to the maximum wavelength for which electron-hole pairs can be made for that bandgap. The maximum wavelength can be calculated by: $\lambda_m = 1.24/E[eV]$. This integration is then multiplied by the electron charge. The short circuit current is only a weak function of the temperature.

3.2 Open Circuit Voltage vs. Bandgap

The open circuit voltage for an ideal semiconductor is:

$$V_{oc} = \left(\frac{kT}{q}\right) \ln\left(\frac{I_{sc}}{I_0} + 1\right)$$

To give an approximation of the temperature dependence, I_0 (saturation current) can be assumed to be

$$I_0 = 1.5 \times 10^5 \exp(-E_g/kT) \text{ [A/cm}^2\text{]}$$

where E_g is bandgap energy and k , the Boltzmann constant, is $= 8.61423 \times 10^{-5} \text{ (eV/K)}$.

3.3 Efficiency vs. Bandgap

The efficiency was calculated with both a constant

Fill Factor ($FF = 0.8$) and the ideal Fill Factor (IFF). The ideal fill factor is calculated by:

$$IFF = \frac{V_{oc} - \ln(V_{oc} + 0.72)}{V_{oc} + 1}$$

The ideal fill factor is calculated as only a function of scaled V_{oc} , where scaled $v_{oc} = V_{oc}/(kT/q)$. The ideal fill factor increases toward unity as the bandgap approaches infinity. Since this may not be realistic for experimental solar cells, efficiency was also computed with a fixed fill factor of 0.8, in order to separate out the fill-factor portion of the temperature dependence. As seen in the following graphs, there are only slight differences in the results seen with constant fill factor and with variable fill-factor.

3.4 Results

The following graphs show the relevant photovoltaic parameters as a function of temperature and bandgap.

Figure 3 shows the conversion efficiency of a solar cell as a function of bandgap, for a standard temperature of 300 K (top curve), and for elevated temperatures up to 900C. Figure 4 shows the value of the peak of the efficiency curve as a function of wavelength, and figure 5 shows the bandgap at which the efficiency is maximum.

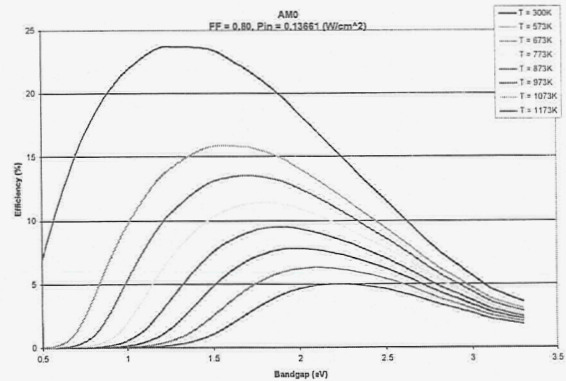


Figure 3: theoretical performance as a function of bandgap for standard (300K) operation, and for high temperature operation from 300 to 900C.

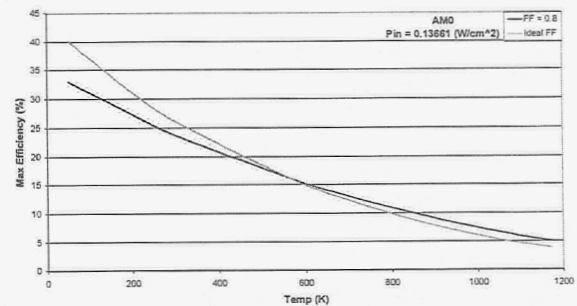


Figure 4. Theoretical efficiency for a cell of optimum bandgap as a function of operating temperature, according to theoretical models with fixed and variable fill-factor

3.5 Irreversible degradation

In addition to the reversible loss of theoretical performance with temperature, solar array operation at high temperature needs to avoid irreversible degradation leading to destruction of the arrays.

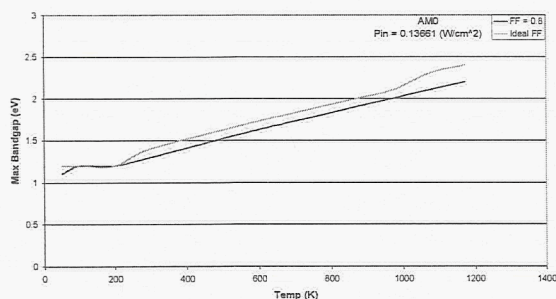


Figure 5. Theoretical efficiency of cell of optimum bandgap as a function of operating temperature, for models with fixed and variable fill-factor

Effects that produce irreversible performance loss include:

- Ohmic contact degradation [11, 12]
- Dopant diffusion
- Compound semiconductor degradation
- Interconnect-related failure
- Coverglass debonding [13]
- Array structural degradation.

Technologies to deal with these problems have been developed under other programs [11-13].

4 SiC SOLAR CELLS

We are continuing to develop solar cells from the wide bandgap material silicon carbide [8,9]. A major challenge with producing high temperature photovoltaics using SiC is the fabrication of contacts to the substrate material. The contacts must be able to withstand the same operating conditions as that of the device. Since the SiC solar cells to be fabricated are designed for use at 600 °C, the contacts must be stable at high temperatures.

A TiSi₂ process was developed whereby 2300 Å of polysilicon is deposited using chemical vapor deposition followed by a 1000 Å film of evaporated titanium to produce a suitable grid contact. The silicon and titanium are reacted by thermal annealing to form TiSi₂ and create an intimate contact capable of operating at 900 °C. A similar process using Pt instead of Ti was also developed to produce ohmic backside contact for producing prototype devices.

A completed cell is shown in figure 6.

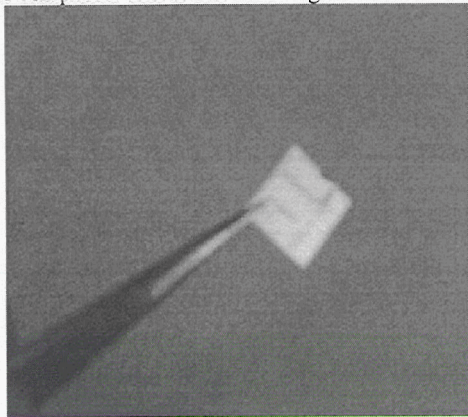


Figure 6. Experimental silicon carbide solar cell, with TiSi top grid contact.

5 CONCLUSIONS

Operation of solar cells at high temperature requires development of solar cells from wide bandgap materials. For the first time, we have derived explicitly the optimum bandgap of solar cells as a function of temperature, and show that the bandgap for optimum energy conversion increases from slightly less than 1.5 eV for standard temperatures near 300 K, to about 2 eV for operation at 1000 K.

6 ACKNOWLEDGEMENT

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