High-Temperature Solar Cell Development

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Missions for High Temperature Solar Cells

The vast majority of space probes to date have relied upon photovoltaic power generation. If future missions designed to probe environments close to the sun (Figure 1) will be able to use such power generation, solar cells that can function at high temperatures, under high light intensity, and high radiation conditions must be developed. The significant problem is that solar cells lose performance at high temperatures.

Approaches to solar arrays for near-sun missions include:

- High epsilon/low alpha coatings
- Array off-pointing: array points at angle to sun
- Partially-populated array (with missing cells replaced with mirrors)
- Reflective coatings
- Solar cells designed to operate at high temperature

Active cooling techniques, such as use of solid-state refrigerators, in general require more power to operate than the resultant gain in efficiency.

For example, current plans for Mercury missions reflect away most of the incident solar energy to limit the operating temperature and avoid destroying the array (figure 2). While this is one solution to the problem, this does not optimally use the solar energy, and it would be desirable to develop solar cells that can perform well at high temperatures, rather than developing techniques to reduce the temperature at the price of reduced performance.

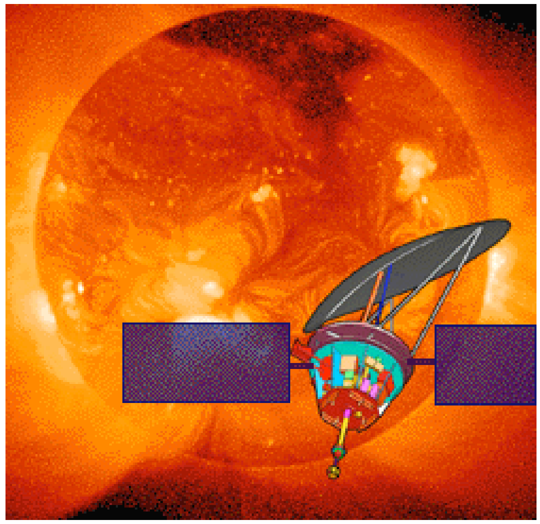

Figure 1: Artist's concept of the Solar Probe mission, proposed to reach a distance of 4 solar radii from the sun.

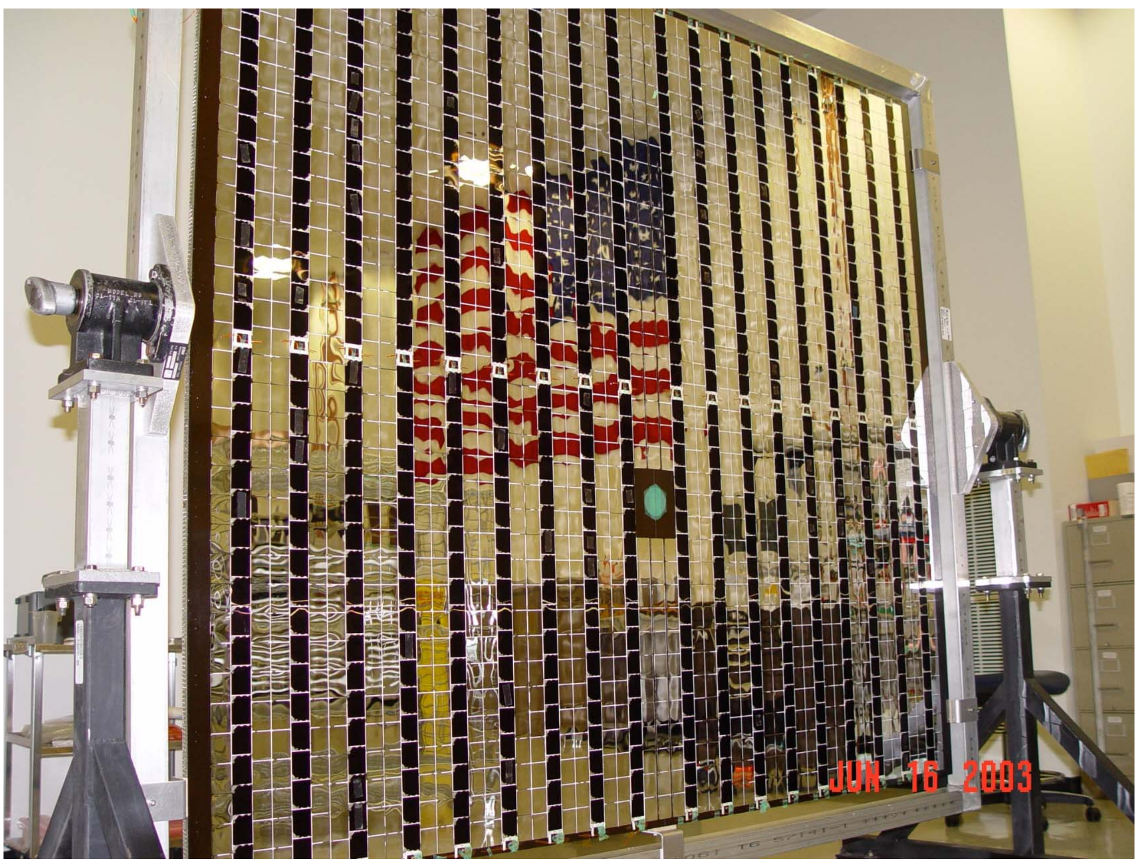

Figure 2: Solar array for the MESSENGER mission to Mercury (Johns Hopkins Applied Physics Laboratories). The majority of the sun-facing surface consists of mirrors to reflect the incident solar radiation and limit temperature.

NASA requirements for solar power systems for high temperature near-sun operation has the goals [1]:

Improved efficiency at high temperature

Improved lifetime at high temperature

Solar cells are desirable for elevated operating temperatures ranging from the Mercury orbiter, in which the solar array equilibrium temperature (assuming a sun-facing array with no reflectors) would be 450 C, to the proposed Solar Probe mission [2], for which, at 4 solar-radii, a sun-facing array with no reflectors would reach an equilibrium temperature of approximately 2300 C. Solar cells made from wide bandgap compound semiconductors are an obvious choice for such an application, since the higher voltage of wide bandgap solar cells results in less degradation [3,4]. For example, silicon solar cells (1.1 eV) lose about 0.45% of their power per degree C increase in operating temperature. GaAs cells (1.4 eV) lose about 0.21% per degree C [5].

The normalized temperature coefficient ($1/\eta \, d\eta/dT$) can be resolved into the sum of the variations of the open circuit voltage, Voc, the short circuit current, Jsc, and the fill factor, FF:

$$1/\eta \, d\eta/dT = 1/Voc \, dVoc/dT + 1/Jsc \, dJsc/dT + 1/FF \, dFF/dT \qquad (2)$$

The Voc variation contributes the majority of the change in efficiency. Fill factor variation in general tracks the open circuit variation. 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 Jsc variation term is roughly proportional to the incident spectral intensity at wavelengths near the band edge [5].

Since the Voc variation with temperature is roughly the same for cells of different bandgap, while the actual Voc increases with bandgap, the normalized temperature coefficient, $1/\eta \, d\eta/dT$ increases directly with bandgap. However, since the photon flux from the sun decreases at high photon energies, an optimum bandgap exists for each temperature.

To verify the efficiency of wide bandgap solar cells at high temperatures, we measured a GaInP solar cell (1.6) as a function of temperature from room temperature up to 400 C. As shown in figure 3, open circuit voltage and fill factor decrease with temperature, while the short circuit current shows a slight increase. Power loss [$1/P \, dP/dT$] is about 0.177% per degree, with irreversible degradation due to shunting occurring slightly above 350C.

The theoretical performance of solar cells as a function of bandgap and temperature is shown in figure 4. As can be seen, the optimum bandgap shifts from about 1.4 volts at room temperature (27C) to about 2.3 volts at 900C.

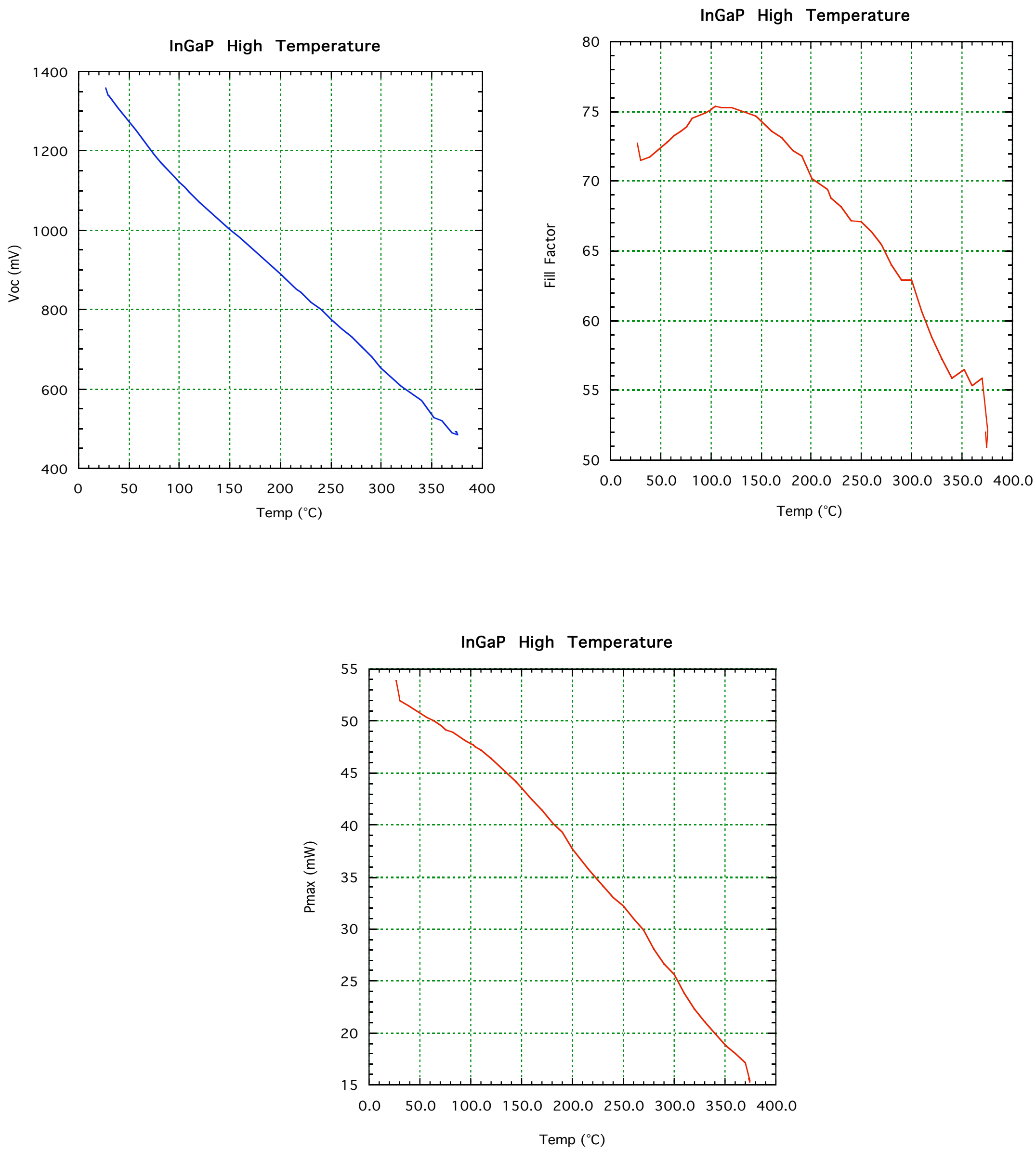

Figure 3: Open circuit current, fill factor, and efficiency of a GaInP solar cell measured as a function of temperature, from 0 to 400 C.

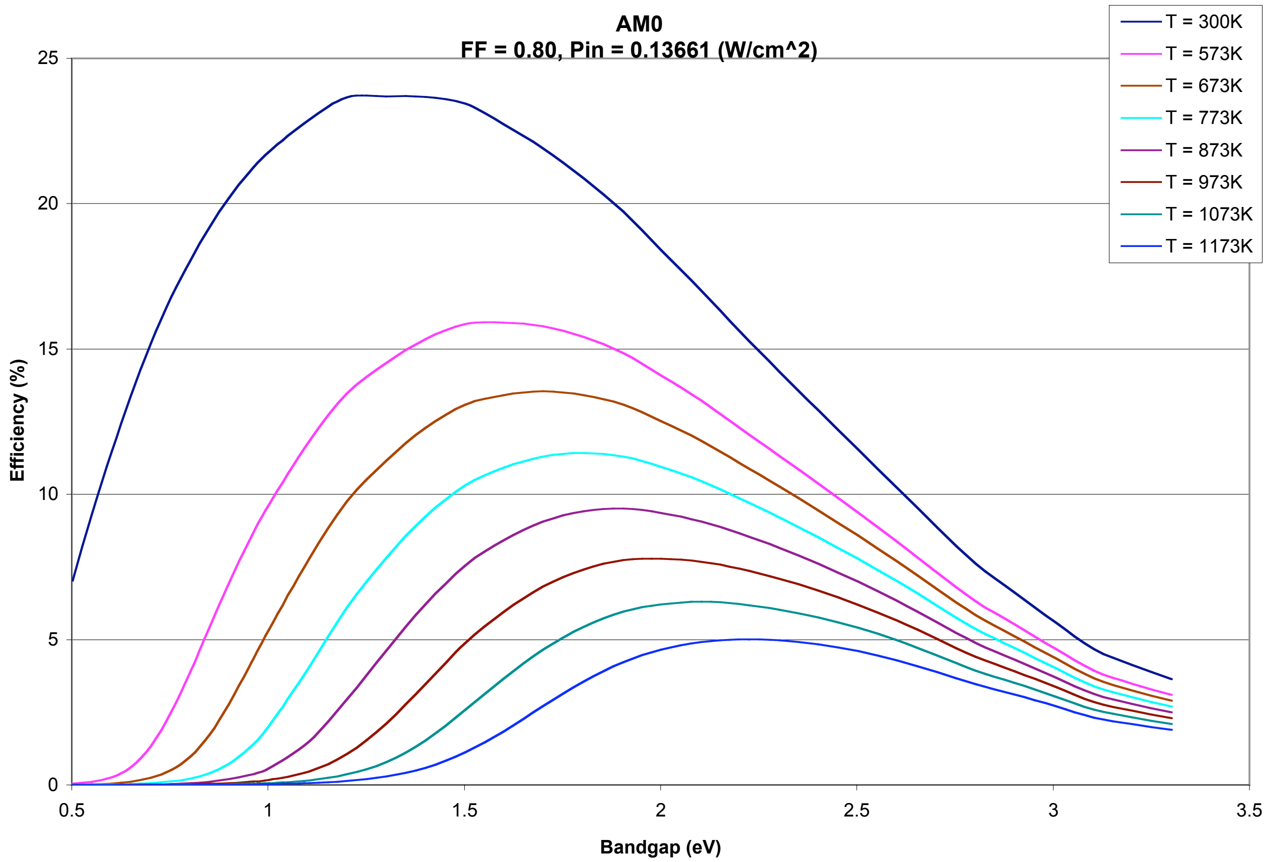

Figure 4: Theoretical efficiency of a solar cell as a function of bandgap, showing the shift of optimum bandgap from about 1.4 volts at room temperature (27C) to about 2.3 volts at 900C.

In order develop solar cells for such applications, we have initiated a program to manufacture and measure the photovoltaic performance of wide bandgap solar cells, including cells from GaInP, GaP [6], GaN, and SiC [7]. Figure 5 shows a SiC solar cell developed at NASA Glenn in collaboration with the Rochester Institute of Technology and Cree Semiconductors [8].

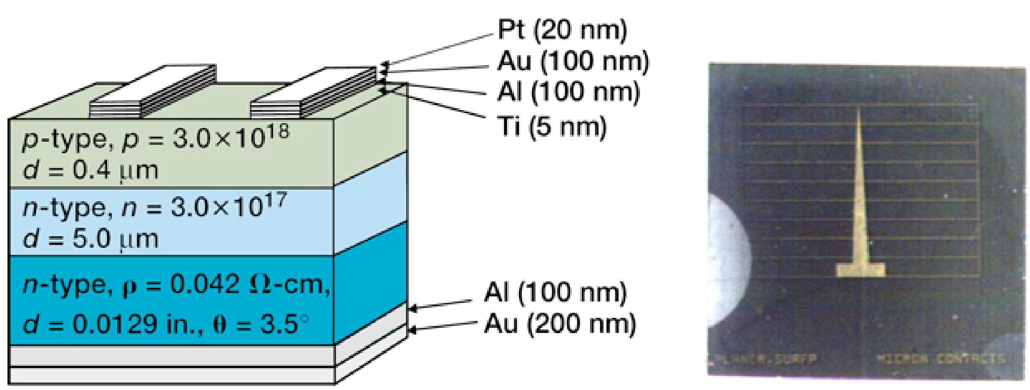

Figure 5: SiC solar cell. Left: schematic cross section. Right: photo of cell.

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. Effects that produce irreversible performance loss include:

- Ohmic contact degradation [9, 10]
- Dopant diffusion
- Compound semiconductor degradation
- Interconnect-related failure
- Coverglass debonding [11]
- Array structural degradation.

Technologies to deal with these problems have been developed under other programs [9, 10, 11].

Conclusions

High-temperature operation of solar cells is of interest to future NASA missions. Technology solutions such as off-pointing can reduce operating temperature, but also reduce power from the array. New solar cells that can operate at high temperature are desirable; this requires development of high bandgap semiconductors. A program to develop cells for high temperature operation, including GaInP, GaN, SiC and GaP cells, is in progress.

Achieving satisfactory operating lifetime at high temperature is an issue that has not yet been addressed in detail.

References

1. G. Landis and S. Bailey, "Photovoltaic Power for Future NASA Missions," paper AIAA-2002-0718, AIAA 40th Aerospace Sciences Meeting, Reno NV, January 14-17 2002.
2. S. Kerridge, *et al.* "Cost Effective Mission Design for a Small Solar Probe," *Acta Astronautica, Vol. 35, Suppl.,* pp. 257-266 (1995).
3. D. Scheiman, G. Landis, and V. Weizer, "High-Bandgap Solar Cells for Near-Sun Missions," presented at Space Technology & Applications International Forum (STAIF-99), Conf. on Global Virtual Presence, Albuquerque NM, 30 Jan.- 4 Feb. 1999; AIP Conference Proc. 458, 616-620.
4. J. Fan, "Theoretical Temperature Dependence of Solar Cell Parameters," *Solar Cells 17*, pp. 309-315 (1986).
5. G. Landis, "Review of Solar Cell Temperature Coefficients for Space," Proc. XIII Space Photovoltaic Research and Technology Conference, NASA CP-3278, NASA Lewis Research Center, June 1994, 385-400.

6. O. Sulima et al., “High Temperature AlGaP/GaP Solar Cells for NASA Space Missions,” presented at the 3rd World Conference on Photovoltaic Energy Conversion, Osaka Japan, May 11-18 2003.
7. R. Raffaelle, S. Bailey, P. Neudeck, R. Okojie, C. Schanabel, M. Tabib-Azar, D. Scheiman, P. Jenkins, and S. Hubbard, "Optical and Electrical Characterization of SiC Devices, *Proc. 28th IEEE Photovoltaic Specialists Conf.,* pp. 1257-1260 (2000).
8. S. Bailey and R. Rafaelle, "Silicon Carbide Solar Cells Investigated," *Research & Technology 2001,* NASA Technical Memorandum (2002),
9. S. P. Tobin *et al.* “Advanced Metallization for Highly Efficient Solar Cells,” *Proc. 19th IEEE Photovoltaic Specialists Conf.*, pp. 70-75 (1987).
10. M. B Spitzer., *et al.* "Gallium Arsenide Concentrator Solar Cells with Highly Stable Metallization,” *Proc. 20th IEEE Photovoltaic Specialists Conference*, pp. 930-933 (1988).
11. P. Younger, G. Landis and R.G. Tobin, "Integral Glass Covering of Spacecraft Solar Cells by Electrostatic Bonding," *Proceedings of the 14th IEEE Photovoltaic Specialists Conference,* San Diego, CA; 1240-1245 (1980).