6th European Space Power Conference, Oporto Portugal, May 6-11 2002.

THE NEXT-GENERATION OF SPACE CELLS FOR DIVERSE ENVIRONMENTS

[1]Sheila Bailey, [1]Geoffrey Landis, and [2]Ryne Raffaelle

[1]NASA Glenn Research Center, MS 302-1, Brookpark, OH 44135
Sheila.bailey@grc.nasa.gov, geoffrey.landis@grc.nasa.gov
[2]Rochester Institute of Technology, Dept. of Physics, 85 Lomb Memorial Drive, Rochester, NY 14623-5603
RPRSPS@rit.edu

ABSTRACT

Future science, military and commercial space missions are incredibly diverse. Military and commercial missions range from large arrays of hundreds of kilowatt to small arrays of ten watts in various Earth orbits. While science missions also have small to very large power needs there are additional unique requirements to provide power for near-sun missions and planetary exploration including orbiters, landers and rovers both to the inner planets and the outer planets with a major emphasis in the near term on Mars. These mission requirements demand cells for low intensity, low temperature applications, high intensity, high temperature applications, dusty environments and often high radiation environments. This paper discusses mission requirements, the current state of the art of space solar cells, and a variety of both evolving thin-film cells as well as new technologies that may impact the future choice of space solar cells for a specific mission application.

1. MISSION REQUIREMENTS

The major strategic goals of the NASA Space Science Enterprise are to: 1) understand the evolution of the universe from origins to destiny and understand its galaxies, stars and planets, 2) support human exploration and 3) develop new technologies that will enable the exploration of the universe.

Some of the specific goals of the Space Science enterprise are: 1) understand the nature and history of our Solar System, and what makes Earth similar to and different from its planetary neighbors; 2) understand the origin and evolution of life on Earth; 3) understand the external forces, including comet and asteroid impacts, that affect life and the habitability of Earth; 4) identify locales and resources for future human habitation within the solar system; 5) understand how life may originate and persist beyond Earth and 6) support human space flight.

A number of challenging missions are being considered to realize these goals. These future missions are organized according to the following themes. The themes are:

Solar System Exploration (SSE),
Sun-Earth Connection (SEC),
Astronomical Search for Origins (ASO), and
Structure and Evolution of the Universe (SEU).

Since the very first satellite launched by NASA, photovoltaic have provided primary power for all but a small fraction of NASA science missions. A number of far-term missions under study require advanced solar cell and array technologies to meet their power requirements. Most of these missions require advanced solar cell/array technologies with high efficiency, low mass, low stowed volume, high reliability and low cost. Some missions may emphasize some of these characteristics over others due to unique requirements and/or environments [1].

Some of the Solar System Exploration and Sun-Earth connection missions have additional unique requirements such as: solar cells and arrays that function in low solar intensities and at low temperatures (outer planetary missions), highly radiation resistant solar cells and arrays (Jovian missions), solar cells/arrays that function at high temperatures and high solar fluxes (missions to Mercury and the Sun), solar cells and arrays that produce >10 kW (solar electric propulsion (SEP) missions), and electrostatically clean arrays (Solar-terrestrial probe missions of Sun-Earth connection).[2]

1.1 Outer Planets

Some of the outer planetary missions under study for launch later than 2007 include Europa Orbiter, Pluto/Kuiper Express, Europa Lander, Neptune Orbiter, Titan Explorer, Saturn Ring Observer, and Jupiter Polar Orbiter.

All of these missions have a common requirement of operating for the most part at significant distances from the sun. The solar intensities for the outer planets, compared to Earth (AM0) intensity, are:

- Jupiter (5.1 AU): 3.7% of AM0
- Saturn (9.5 AU): 1.1%
- Uranus (19.2 AU): 0.28%
- Neptune (30 AU): 0.1%
- Pluto (29.7 - 49.4 AU): 0.04 - 0.11%

In view of this, solar power was not considered in early planning for these missions. In the past, missions that travel far from the sun have used radioisotope thermoelectric generators, but there may be programmatic, economic and political reasons to consider using solar power for some missions in the future. As a minimum, it is required that missions that plan to use radioisotope power must demonstrate that a mission cannot be done effectively with solar power. Therefore all missions must examine the possibility of using solar power, even those that operate far from the sun.

Solar power can be used for future missions in two ways. One use is for operation of the spacecraft and instruments at the planetary target, while the spacecraft is at large distances from the sun . The other use is to power solar electric propulsion to accelerate the probe toward the planetary target while still in the inner solar system, with radioisotope power used for operations far from the sun.

Solar electric propulsion (SEP) is attractive for many outer planetary missions because it either significantly reduces the cruise time (time of flight) required to reach the outer planets or increases the payload mass by reducing the on-board fuel required.

Some of the generic solar array requirements of the SEP missions are:

1. Power levels: 10-20 kW near-term; 20-40 kW mid-term, 40-100 kW far-term
2. Operating range 0.6 to 5 AU
3. Specific Power: 150 W/kg minimum; 300 W/kg or higher desired (beginning of life (BOL) at 1 AU)
4. Output voltage constant to factor of 2 over solar range
5. High radiation tolerance
6. Output voltage > 100 V (BOL at 1 AU)
7. Small stowed/packaging volume: 20 kW/m^3 minimum; 40 kW/m^3 desired
8. High natural frequency (> 0.5Hz)
9. Cost: Less than $500/watt

The use of solar power to operate the spacecraft and instruments while the spacecraft is at a distant target planet must operate efficiently in a low-intensity, low temperature (LILT) environment. At low solar intensities, arrays must operate at very low-temperatures. Actual temperatures depend on various thermal parameters, but as a rule, a cell that operates at 30°C at 1 AU, will operate at about -60°C at 2 AU, and about -140°C at 5 AU. A variety of phenomena may be experienced under LILT conditions, all of which have the potential to produce detrimental effects on the solar cell performance.

Missions to the Jovian system (Europa Orbiter, Europa Lander, and Jupiter Polar Orbiter) will also experience high radiation doses. The definition of a high radiation environment for our purposes is a total exposure that exceeds that of a typical low altitude or geosynchronous Earth orbit mission. Figure 1 shows the energy spectrum of particles in the trapped radiation belts of Jupiter, compared with the environment in the Earth's radiation belts [3]. As is seen from the picture, compared to Earth, the Jupiter radiation belts have a considerably higher number of very high energy electrons, and comparatively fewer protons. The overall radiation intensity at Jupiter is approximately fifty times higher than that experienced in Earth's radiation belts.

Advanced solar cell and array technologies for spacecraft power will be considered for Jovian missions. However, spacecraft solar power for missions to Saturn and beyond are major challenges due to mass and area requirements and become impractical at some point even with the use of concentrators.

Some of the solar cell/array requirements for all of the outer planet missions include:

Power levels: 200-500 watts
Operating range 0.6 to 5 AU
Specific Power: 200 W/kg; 300-500 W/kg desired (BOL at 1 AU)
Output voltage constant to factor of 2 over solar range
High radiation tolerance
Output voltage > 28-30V (BOL at 1 AU)
Cost: Less than $500/watt

1.3 <u>Inner planets</u>

MESSENGER (mission to Mercury currently in final design stage) solar array operates at a high temperature of 130°C, can be pointed directly at the sun for a minimum of 1 hour and is able to withstand temperatures of 260°C before irreversible solar array failure occurs.

Other proposed future solar missions include the following: Solar Sentinels missions, scheduled to fly as close as 0.3 AU in about 2010; the Interstellar Probe mission, proposed to reach 0.25 AU in 2015; the Solar Orbiter mission (a European Space Agency Spacecraft), planned to reach 0.21 AU in 2012; and the Particle Accelerator and Solar Orbiter (PASO) mission, proposed to fly to 0.17 AU in about 2015.

Approaches to high-temperature solar cell design are listed in section 2.5. Existing solar array technology with reduced performance and increased risk meets the requirements for the MESSENGER mission that approaches the sun to about 0.3 AU. Future sun encounters at less than or equal to 0.3 AU requires advanced solar cell and array technologies.

Concurrent with the solar cell development, work is needed on solar array substrates that can survive high temperatures. The maximum survival temperature of existing solar cells and the graphite epoxy substrate face sheets is approximately 300-350°C. Replacement of the composite face-sheets and aluminum honeycomb core with titanium sheet and foil respectively should result in panels that can survive 600°C.

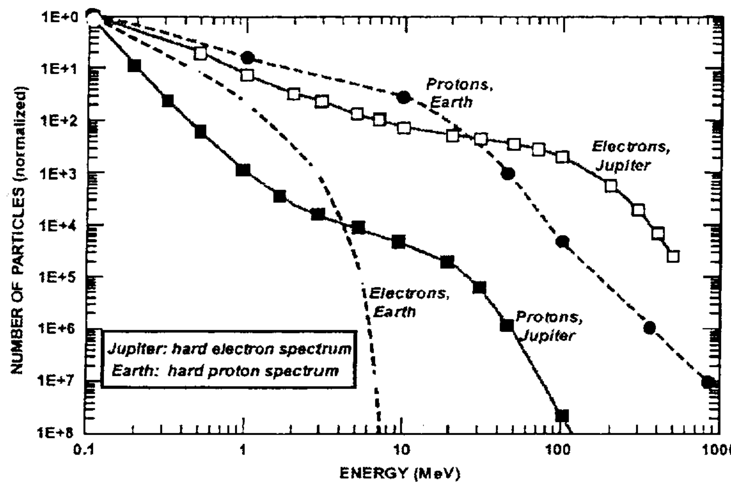

Fig. 1: Normalized energy spectrum of trapped electron and proton radiation environment at Jupiter, compared to Earth (from Kayali [3])

1.4 Sun-Earth connection

The Sun-Earth Connection (SEC) Program seeks to understand our changing Sun, and its effects on the solar system, life, and society. The SEC Program includes several Earth-orbiting missions, inner and outer planetary missions, and missions to Sun. Some of the major planned SEC missions concepts are: Magnetospheric Multi Scale (MMS), Geospace Electro-Dynamic-Connections (GEC), Magnetospheric Constellation (MagCon), Solar Probe, Living with the Star, Solar Farside Observer, and Solar Polar Imager.

Solar cell and array requirements for SEC missions vary significantly depending on the mission type. Some of the key solar cell and array technology requirements are: electrostatically clean "conductive" arrays, high-efficiency cells and low cost arrays, high temperature solar cell/arrays, solar cells and arrays that can function under LILT conditions and high power arrays for Solar Electric Propulsion.

1.5 Mars Solar Cells

NASA plans a series of ambitious missions to explore the planet Mars. The primary technological drivers for these missions are: long-distance surface mobility improved imaging, subsurface exploration, and life-detection technologies. The Mars exploration plan calls for a series of missions on two-year centers, alternating between landers and orbiters.

Photovoltaic needs for future Mars orbiters are not fundamentally different from those for Earth orbiters, i.e. lower cost, lighter weight, higher efficiency and higher reliability. Solar-powered landers and rovers need the highest possible efficiency cells to minimize the deployed area of the arrays at any power level. Since the effective solar spectrum at the surface of Mars is depleted at short wavelengths, a cell designed to maximize the efficiency in the red-shifted spectrum on Mars would be very valuable for Mars surface applications. The other issue for surface power is dust accumulation on the arrays. It is not yet understood how serious a problem this is, or what can be done to mitigate it.

The Mars surface environment is quite different from the orbital environment in which space solar arrays normally operate. Major differences of the Martian surface from operating conditions of Earth orbit are:

- suspended atmospheric dust
- low operating temperatures
- deposition of dust on the arrays
- wind loading
- peroxide components of the soil
- low radiation
- low atmospheric pressure

A discussion of solar cell issues specific to Mars operation is presented in [4].

The atmosphere of Mars carries a considerable amount of suspended dust. This dust reduces the intensity of sunlight on the surface. The amount of dust in the atmosphere is characterized by the optical depth τ, which can vary from less than 0.4 to values greater than 4, depending on the season, the latitude, and the presence of dust storms. The effect of dust on the solar intensity at the surface has been analyzed by several researchers [5], indicating that at low optical depths the atmospheric dust is not opaque, but does result in a large fraction of the incident intensity on the surface originating from indirect (scattered) sunlight. At high sun angles-- that is, in early morning operation and late afternoon operation, or for near-polar missions-- the atmospheric pathlength increases, and the solar intensity is correspondingly lower. The performance of test solar cells on the Pathfinder mission tends to confirm these calculations.

The spectrum at the surface of Mars is modified by the passage of light through the dust layer. The dust reduces the amount of short wavelengths light penetrating to the surface. The effect on longer wavelengths is less. A reduction in the blue light shifts the optimum choice of solar cell materials to favor lower bandgap semiconductors, which respond better to the red and IR.

The amount of dust in the Martian atmosphere varies with the presence of dust storms. Dust storms can be local, lasting only hours to days, can be regional, or can be global in extend, extending for up to a hundred days in duration. The global dust storms are seasonal, and occur only during the southern hemisphere summer (although not every summer will have such a dust storm.)

Since the sky of Mars scatters light, the sunlight comes from a range of angles, rather than in a straight line from the sun. Concentration devices such as mirrors or lenses will be much less effective, and the efficiency of concentration devices will be worst at the highest dust loading. It also means that physical spectrum-splitting devices such as prisms or gratings will probably be not be effective on Mars.

Mars temperatures are lower than the standard test temperature. The effect of this is to shift the technology choice toward lower bandgap semiconductors. The temperature coefficient of a solar cell depends on the detailed shape of the spectrum near the energy bandgap of the material. This effect is important to current-matched multijunction cells, since the current matching will be sensitive to spectrum and to temperature. The spectral dependence makes temperature coefficients difficult to measure with simulated sunlight.

A particular difficulty is encountered with low temperature operation of some types of multijunction solar cells, including cascade cells and multi-junction amorphous cells. The interconnection between the individual elements of the cascade is typically done by use of a tunnel junction, which requires high doping levels to operate. Since dopant levels typically freeze out at low temperatures, the tunnel junction resistance can have a strong dependence on temperature, and in some cases can increase significantly at low temperature, resulting in lower performance.

The atmospheric dust does not remain suspended in the atmosphere indefinitely, but deposits out of the atmosphere onto any horizontal surfaces. This dust deposits out of the atmosphere and onto any flat surface; the time scale for this settling is on the order of 100 days. A measurement on the Pathfinder mission (Fig. 2) indicated dust coverage rate of 0.3% power loss per day [6]. This degradation rate probably levels off with time, but the long-term trend is still highly debated.

This is potentially the factor which limits the operating lifetime of a solar array on Mars, unless a technique is developed to periodically remove the dust. The worst-case scenario is that the lander is in the settling phase of a global dust storm. There can be one, and possibly two, global dust storms per Martian year, typically occurring near perihelion. In some years there are no global storms.

The dust deposition adds an additional red-shift to the insolation received by the solar cell.

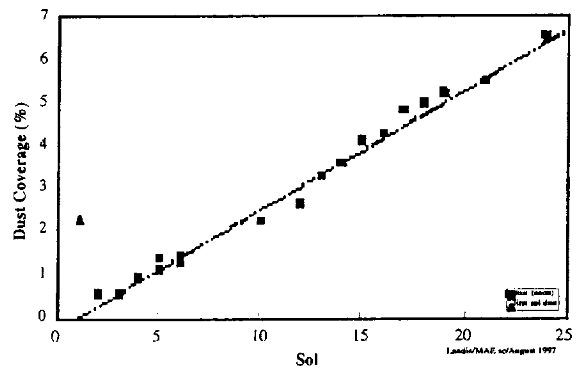

Fig. 2. Dust coverage of the Sojourner Rover solar array. Data measured from the MAE experiment on the rover.

2. ADVANCED SOLAR CELLS

Until the '90s single-crystal silicon solar cells had been used for electrical power on almost all space satellites. Their scalability, reliability, and predictability have made Si solar cell/array the prime choice for spacecraft designers. Early silicon solar cells were typically ~11% efficient, and the conversion efficiency of silicon cells currently flown varies between 12.7% and 14.8%.

2.1 Commercial solar cells

Advanced solar cells with improved efficiency developed over the past fifteen years include 1) single junction GaAs solar cells, 2) dual junction III-V compound semiconductor solar cells, and 3) triple-junction III-V compound semiconductor solar cells. GaAs/Ge cells currently available on the market have an average conversion efficiency of 19% at AM0. The GaAs-type solar cells have higher radiation resistance than silicon solar cells. Dual-junction and triple-junction solar cells are presently available from several vendors. Commercially available dual-junction solar cells are 21-22% efficient. Currently, triple-junction cells (comprising GaInP, GaAs, and Ge layers) are grown in tunnel-junction connected layers, and are 26-28% efficient in production lots. Table 1 provides a summary of some of the important characteristics of commercially available space solar cells.

2.2 Advanced high efficiency cells

Improvements in the efficiency of multi-junction cells continue to be made. Large area triple junction cells of 29.3% have been achieved in the laboratory. There will probably be cells with 30% lot-average efficiency on germanium substrates within a few years.

Table 1. Commercial Space Solar Cells

Parameter	Silicon	High Efficiency Silicon	Single Junction GaAs	Dual Junction	Triple Junction
Status	Obsolete	SOA	Obsolete	Nearly Obsolete	SOA
STC Efficiency (%)	12.7 - 14.8	16.6	19	22	26.8
STC Operating Voltage (V)	0.5	.53	.90	2.06	2.26
Cell Weight (mg/cm^2)	13 - 50	13 - 50	80 - 100	80-100	80-100
Temp Coefficient at 28°C	-0.55%/C	-0.35%/C	-0.21%/C	-0.25%/C	-0.19%/C
Cell Thickness (μm)	50 - 200	76	140 to 175	140 to 175	140 to 175
Radiation Tolerance	.66 - .77		.75	.80	.84
Absorptance	.75		.89	.91	0.92

Table 2. Current Status of Thin-film Cell Efficiencies for AM1.5 and AM0.

Cells	**Efficiency(%)** AM 1.5 global	**Efficiency(%)** AM0	**Area** (cm^2)	**Description**
Cu(Ga,In)Se	18.8	16.4*	1.04	NREL, on glass
CdTe	16.4	14.7*	1.131	NREL, on glass
a-Si/a-Si/a-SiGe**	13.5	12.0	.27	USSC[7]
Photo-electrochemical	10.6	9.8*	.25	EPFL, nanocrystalline dye[11]

* Courtesy of Keith Emery, NREL. The efficiency and Jsc for global reference conditions (25°C, 1000 W/m², IEC 60904-3, ASTM E892 global) were taken from the references and translated to AM0 using the new ASTM E490-2000 reference spectrum. The calculated efficiency assumes that the fill factor does not change for the increased photocurrent. Quantum efficiencies corresponding to the table entries were used in the calculations.

**unstabilized.

There are three ways in which III-V cells are likely to be improved beyond this level:

1. A fourth junction can be added to the current lattice-matched GaInP/GaAs/Ge triple junction cell.

2. Use of a more optimal set of bandgaps that can be grown if the lattice matching problem is solved.

3. Development of a manufacturing process that uses a lighter, stronger, less expensive substrate than germanium. Silicon is the obvious choice but there is a large lattice mismatch that must be accommodated. Ceramics represent another possible option.

2.3 Thin-film solar cells

A new technology for solar cells that is developing rapidly is the thin-film cell, consisting of a thin (typically one micro-meter) semiconductor layer, deposited on a substrate. For terrestrial applications, the thin-film substrates are typically either glass or stainless-steel foil. Recently, amorphous silicon thin-film solar array has been space qualified by flight on the Mir space station [7]. Table 2 shows the current status of thin-film cell efficiencies.

The potential for space applications comes with the substitution of a thin foil or of a plastic substrate. Such thin-film cells could potentially have an specific power of a thousand watts per kilogram, or even higher, if the efficiency can reach reasonable values on thin substrates, and if array technology can also be improved. An additional advantage of thin-film technology is that the radiation tolerance of thin-film cells is extremely high, as much as an order of magnitude higher than the radiation tolerance of single-crystal cells.

Thin-film cells for space are currently being developed by a number of researchers, and are the subject of several recent review articles, however, the technology is not currently ready for mission application. Thin-film cells require substantially less material and have promised the advantage of large area, low cost manufacturing. Much progress has been made to date on thin-film cells based on materials such as CdSe, $Cu(In,Ga)Se_2$, and amorphous silicon.

Space cell requirements dictate a more complicated trade space. Until recently the focus in space cells has been on efficiency rather than cost. In a several billion-dollar spacecraft the cell cost is relatively small at even a thousand dollars per watt (approximately the current array cost). This has primarily been true for spacecraft with power needs from a few hundred watts to tens of kilowatts. Deployment of a large earth orbiting space power system or arrays for SEP will require major advances in the photovoltaic array weight, stability in the space environment, efficiency, and ultimately the cost of production and deployment of such arrays. The development of large space power systems, and a host of other proposed space missions, will require the development of viable thin-film arrays. The specific power required for these applications is almost 40 times what is presently available in commercial arrays. While high-efficiency ultra lightweight arrays are not likely to become commercially available anytime soon, advances in thin-film photovoltaics may still impact other space technologies (i.e., thin-film integrated power supplies) and thus support a broad range of missions in the next decade. Mission examples include micro-air vehicles, ultra-long duration balloons (*e.g.* Olympus), deep-space solar electric propulsion (SEP) "Tug" Array, Mars SEP Array, and Mars surface power outpost.

2.4 Quantum dot solar cells

Quantum dot (QD) solar cells have the potential to increase the maximum attainable solar photon conversion efficiency to about 66% by utilizing hot photogenerated carriers to produce either higher photovoltages or higher photocurrents [8]. There have been several proposed configurations for creating a quantum dot solar cell which may be particularly applicable for thin-film cells.

The first is an intermediate band thin-film cell. If quantum dots are produced in an ordered array within in an insulating medium, the wavefunctions associated with the discrete electronic states of the quantum dots will overlap creating "mini-bands" within the insulating region. The lowest empty mini-band energy level should be roughly 1/3 of the bandgap energy of the semiconductor (of the n and p-type regions) above the valence band energy to maximize the device efficiency. For a Si based device ($E_g = 1.12$ eV and $\chi = 4.05$ eV), an array of dots whose sizes will yield an electron affinity of ~ 4.8 eV is required to maximize the efficiency. Quantum dot candidates for Si would therefore include such materials as $CuInSe_2$ and $CuInS_2$. Recent work shows appropriate quantum dots can be fabricated [9].

The second configuration is based on dye-sensitization of nanocrystalline TiO_2 layers [10]. Quantum dots are substituted for the dye molecules. Photovoltaic effects in such cells have been noted for semiconductors including InP, CdSe, CdS, and PbS [11-13].

The third configuration consists of structures in which quantum dots form junctions with organic-semiconductor polymers [14].

2.5 High solar intensities

Mission destinations with a need for high temperature, high intensity, and solar arrays include Mercury orbiters and landers, Venus orbital missions, and close encounters to the sun. For near-sun missions, solar power sources are ideal, since an abundant supply of solar energy is available. Paradoxically, however, the high solar intensity has a deleterious effect on solar cell performance, since the equilibrium temperatures of the solar arrays will also be high, and photovoltaic device performance typically decreases with temperature. For these missions it will be desirable to develop solar cells with a low temperature coefficient of efficiency [15].

GaInP cells should operate efficiently in the high temperature, high intensity environment of Mercury orbit. Fig. 3 plots normalized temperature coefficients of various solar cell types as a function of bandgap. From this curve, we expect a GaInP (1.85 eV) cell to have a normalized temperature coefficient of about 1 10^{-3} per degree K, half that of GaAs. Thus, at 425 C, the cell should produce 60% of nominal power. An 18% efficient GaInP cell will have 11% efficiency at 425C, or three times higher power than a GaAs solar cell.

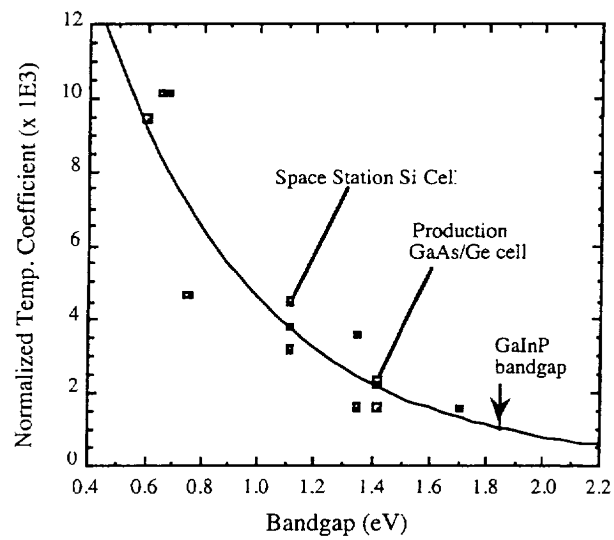

Fig. 3. Normalized temperature coefficient (1/P dP/dT) as a function of cell bandgap

Another approach for high-temperature operation is to develop new, high-stability, wide-bandgap materials. SiC is a wide-bandgap semiconductor now being commercialized for high-power, high-temperature power electronics. SiC material properties that make it attractive for these applications include a high bandgap, high thermal stability (> 700 °C); high breakdown field strength; good radiation tolerance; high thermal conductivity; and hardness.

The difficulties with SiC that exist presently are: micropipe defects; high dislocation densities, making the material unusable for solar cells; low carrier mobility; limited availability; and high cost. The high bandgap of SiC also limits the efficiency possible at low temperature.

Prototype SiC solar cells have been demonstrated at NASA Glenn [16], however, development of high efficiency SiC cells will require considerable effort.

SiC is clearly worthy of development investment due to its broad benefits in many areas of aircraft and space electronics.

3. CONCLUSIONS

Photovoltaics have achieved dramatic improvements in cell efficiency. Recently developed solar cells, "dual junction" or "cascade" solar cells, are presently available from several vendors with 21-22% efficiency. Triple-junction cells are up to 27% efficient in production lots.

Further development of photovoltaic technology is important if cell technology is to be developed for future NASA missions. Particular cells of interest include development of cells for high intensity environments (near-solar mission), low-intensity high radiation environments (Jupiter and outer solar system), and dusty, low-temperature environments (Mars).

4. REFERENCES

1. G. Landis and S. Bailey, "PV Power for Future NASA Missions," AIAA-2002-0718, AIAA 40th Aerospace Sci. Mtg, Reno NV, Jan. 14-17 2002.

2. S. Bailey, H. Curtis, M. Piszczor, R. Surampudi, T. Hamilton, D. Rapp, P. Stella, N. Mardesich, J. Mondt, R. Bunker, E. Gaddy, D. Marvin, and L. Kazmerzki, "Solar Cell and Array Technology for Future Space Science Missions", NASA Technical Report (unpublished).

3. S. Kayali, "Space Radiation Effects on Microelectronics", NASA Jet Propulsion Laboratories course: see material on JPL web site at: <http://nppp.jpl.nasa.gov/docs/Radcrs_Final2.pdf>

4. G. Landis, "Solar Cell Selection for Mars," *IEEE Aerospace and Electronic Systems Magazine,* Vol. 15, No. 1, 17-21 2000.

R. Haberle, C.P. McKay, O. Gwynne, D. Atkinson, G. Landis, R. Zurek, J. Pollack and J. Appelbaum, "Atmospheric Effects on the Utility of Solar Power on Mars," *Resources of Near Earth Space*, 799-818. U. Arizona Press Space Science Series , 1993.

5. G. Landis and P. Jenkins, "Measurement of the Settling Rate of Atmospheric Dust on Mars by the MAE Instrument on Mars Pathfinder," *J. Geophysical Res., 105,* No. E1, 1855-1857, 2000.

6. M. Kagan, V. Nadorov, S. Guha, J. Yang, and A. Banerjee, "Space Qualification of Amorphous Silicon Alloy Lightweight Modules," Proc. 28th IEEE Photovoltaic Spec. Conf., 1261-1264, 2000.

7. A. Luque and A. Marti, *Phys. Rev Lett. 78,* 5014, 1997.

8. R. Raffaelle, S. Castro, A. Hepp, and S. Bailey, "Quantum Dot Solar Cell", 17th Space Photovoltaic & Research Technology, to be published, 2001.

9. M. Gratzel, *Progress in Photovoltaics, 171,* 2000.

10. A. Hagfeldt and NM. Gratzel, *Acc. Chem. Res. 33*, 269, 2000.

11. P. Voget and H. Weller, *J. Phys. Chem, 98,* 3183, 1994.

12. P. Hoyer and R. Konenkamp, *Appl. Phys. Lett. 66,* 329, 1995.

13. N.C. Greenham, X Poeng, and A.P. Alivisatos, *Phys. Rev. B 54,* 17628, 1996.

14. D. Scheiman, G. Landis, D. Brinker, and V. Weizer, "High-Bandgap Solar Cells for Near-Sun Missions," Space Tech. & Applications International Forum, *AIP Conf. Proc. Vol. 458,* 616-620, 1999

15. R. Raffaelle, *et al.*, Proc. 28th IEEE Photovoltaic Specialists Conf., 1257-1260.