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Recent Results From Advanced Research on Space Solar Cells at NASA

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RECENT RESULTS FROM ADVANCED RESEARCH ON SPACE SOLAR CELLS AT NASA

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SUMMARY

The NASA program in space photovoltaic research and development encompasses a wide range of emerging options for future space power systems, and includes both cell and array technology development. The long range goals are to develop technology capable of achieving 300 W/kg for planar arrays, and 300 W/m^2 for concentrator arrays. InP and GaAs planar and concentrator cell technologies are under investigation for their potential high efficiency and good radiation resistance. The Advanced Photovoltaic Solar Array (APSA) program is a near term effort aimed at demonstrating 130 W/kg beginning of life specific power using thin (62 μm) silicon cells. It is intended to be technology transparent to future high efficiency cells and provides the baseline for development of the 300 W/kg array.

INTRODUCTION

NASA, through its Office of Propulsion Power and Energy, conducts a continuing space energy conversion research and technology program of wide ranging scope and content. The primary objective of the program is to provide a broad technology base to meet power system requirements for future space missions, including growth space station, advanced Earth orbiting satellites, lunar and planetary bases, and solar system exploration. Power system requirements for those future missions will span the range from a few kilowatts to megawatts, and operating lifetimes will vary from 2 years to perhaps multiple decades. In some mission scenarios, such as a lunar or Mars base, a new planning element will be introduced: the mission capabilities will evolve over time from the initial outpost with intermittent operation to a permanent base with continuous operation. The impact on power system requirements and capabilities is just beginning to be assessed, but it is clear that an evolutionary technology development strategy will be needed to address this most ambitious of all manned space mission scenarios. As in any program of limited resources, it is essential to address those technologies that represent mission critical capabilities, and which have the broadest application across the entire mission set.

The photovoltaic element of the space energy conversion program is designed to provide the technology for improved conversion efficiency, reduced mass, reduced cost, and increased operating life of solar cells and arrays. At present the program is divided into a generic base R&T effort and a more focused effort for lunar or Mars surface power systems under Project Pathfinder. This paper will primarily discuss some of the key technologies under development in the base R&T program and how they are expected to benefit future Agency missions.

A specific long range goal of the base R&T program is to develop the technology base for planar photovoltaic arrays with a specific power of 300 W/kg at beginning of life (BOL) and 300 W/m^2 for concentrator arrays at BOL. Achievement of these technology goals will improve the payload fraction of future earth orbiting spacecraft, and extend the potentially useful range of photovoltaic power systems on interplanetary spacecraft. The increased sophistication and long lead time of future missions, along with anticipated launch vehicle constraints, will place a premium on system reliability, lifetime and mass. For many current spacecraft almost half of the total spacecraft mass is taken up by the auxiliary propulsion and power sub-systems, while the payload accounts for about one-fourth of the total. As a result, reducing the mass of the nonpayload portion of the spacecraft by one-third would permit a doubling of the mass allocation for the payload. The extra mass allocation could be used for the addition of equipment to enhance operations, autonomy, reliability, redundancy and lifetime of the payload.

The overall thrust of the NASA space energy conversion research and technology program is aimed at achieving these mass and reliability benefits. For example, current solar arrays have specific powers in the range from 15 to 30 W/kg. NASA-sponsored technology has already shown that 66 W/kg is achievable, and the program is now aimed toward a proposed demonstration of 130 W/kg, using the NASA-developed 62 μm thick high efficiency silicon solar cell. Achievement of the 300 W/kg goal mentioned at the outset, especially when coupled with improved radiation resistance, will require new, ultrahigh specific power solar cells. Some of the work on advanced cell technology is described in the next section of the paper. The successful realization of all the required technology elements will provide spacecraft designers with a ten-fold increase in solar array specific power compared to present practice, and open up new mission opportunities previously thought inaccessible to photovoltaic power systems.

ADVANCED SOLAR CELL TECHNOLOGY

Research on high performance solar cells conducted by NASA Lewis Research Center is focused on radiation tolerance and high efficiency, with special emphasis on indium phosphide (InP) and gallium arsenide (GaAs) devices. The InP work has three major thrusts: (1) demonstrating a cell structure capable of achieving 20 percent AMO efficiency with 1 percent or less degradation in power after 10 years in GEO; (2) heteroepitaxial growth of InP on alternate substrates such as silicon or germanium; and (3) demonstration of high efficiency, ultrathin InP cells with improved radiation resistance compared to GaAs and silicon. The papers by Weinberg, et al. (ref. 1) and by Brinker, et al. (ref. 2) provide an excellent update on some recent results and the potential of this exciting new cell technology. Other details appear in the paragraphs below. Work on GaAs cells similarly has three major thrusts: (1) development of high efficiency concentrator cells; (2) demonstrating feasibility of the point contact junction geometry in GaAs; and (3) development of a V-grooved cell geometry with improved efficiency and radiation resistance compared to the standard cell geometry. The paper by Bailey, et al. (ref. 3) describes the latter in more detail.

InP Cells

Work on InP solar cells has resulted in an achieved efficiency of 18.8 percent in laboratory devices (ref. 4) in an n/p homojunction structure. A second cell type, produced by sputtering ITO onto InP (ref. 5) has produced efficiencies in excess of 16 percent and with a level of radiation resistance equivalent to that observed in the OMCVD-produced homojunction device (ref. 6).

Efforts are also underway to fabricate InP cells on alternate substrates. The initial efforts have used Si as the substrate. The feasibility of this approach has been demonstrated and n+/p structures have been fabricated that have achieved 7.2 percent AMO efficiency (ref. 7). A GaAs buffer layer was used between the Si and InP because of the large lattice mismatch between the latter two. In addition, a 9.4 percent AMO InP n+/p cell has been grown directly on a GaAs substrate. Both results were achieved without benefit of optimization of the growth process, and both cell types were plagued by high defect densities (in excess of $10^8/cm^2$) caused by lattice mismatch between the substrate and the unoptimized growing InP film. Growth directly on GaAs substrates was undertaken to eliminate the effects of defects which may arise from the GaAs/Si interface. It also serves as an impetus to investigate the growth of InP directly on Ge substrates, since Ge is so closely lattice matched to GaAs. Figure 4 shows the internal quantum efficiency of InP cells on InP substrates, GaAs substrates, and GaAs/Si substrates. The effect of the high defect density in the cells with foreign substrates is easily seen in the severely lowered red response in each case. The poor blue response of the heteroepitaxial cells compared to the InP only cell is attributed to a thicker than desired emitter for the cells with the foreign substrates. A host of problems yet remain, but the early results are encouraging. Epitaxial growth should be achievable with sufficiently high epitaxial layer quality that efficiencies above 19 percent can be realized.

Work in the third area, the ultrathin InP cell, has just begun, and will utilize the CLEFT process developed by John Fan and coworkers to produce high specific power GaAs cells (ref. 8). A cleaved film with 4 cm^2 area has been demonstrated. Once achieved, the CLEFT device will be mechanically bonded to a low cost, rugged, lightweight substrate and tested for its spaceflight worthiness. Both planar and concentrator cell structures will be investigated in all of the above work.

GaAs Cells

Efficiencies approaching 22 percent AMO in planar GaAs cells have been reported (ref. 9). Radiation resistance has also been shown to be better than in silicon on both a normalized and an absolute basis (ibid.). The impressive gains in this cell type have come about primarily by paying careful attention to material properties, and applying good analytical models to the development of device designs. While some performance gains in standard planar structures can yet be made by continuing this approach, more dramatic improvement appears possible through various geometrical enhancements. Three approaches are under investigation: V-grooved cells, point contact cells, and concentrator geometries.

V-grooved GaAs cells. - The primary advantage of the V-groove cell illustrated in figure 1 lies in its potential for increased radiation resistance. A properly dimensioned sawtoothed junction geometry, coupled with the high optical absorption coefficient of GaAs, should also result in higher current collection than the planar structure. There are two primary effects: (1) a higher fraction of minority carrier generation takes place within a diffusion length of the pn junction compared to the planar geometry, and (2) the V-groove texture reduces reflectivity losses from the surface of the cell. The first effect implies higher radiation resistance. The second should result in higher photocurrent generation. A competing effect is that the increased junction area may result in a higher dark current and correspondingly lower open circuit voltage. Initial device characteristics have been promising (ref. 10). Radiation damage testing awaits further device development.

Point contact GaAs cells. - An earlier analysis by Weizer and Godlewski (ref. 11) of the effect of alternate junction geometries in GaAs showed that a point contact geometry, similar in principle to that developed by Swanson et al., (ref. 12), in silicon, could result in AMO efficiencies in excess of 25 percent. Achieving such performance is predicated on reducing the junction area to 1 percent of the total cell area. The reduced junction area reduces the dark current to the low levels required by the calculations. Key requirements for the successful fabrication and operation of such a device are an extremely low back surface recombination velocity (<100 cm/sec), a thin cell structure (<10 μm thick), and bulk diffusion lengths in p-type material approaching several tens of microns. The latter is required to keep the individual point contact areas within reason: at 1 percent coverage, point contacts 1 μm^2 in area will need to be placed in a square lattice pattern on 10 μm centers. If the structure is to be radiation resistant, diffusion lengths several times greater than the junction separations are required. The challenge is to bring all the elements together into a single device.

GaAs concentrator cells. - Concentrator solar arrays for space application may provide a way to achieve higher efficiency and better radiation resistance, compared to conventional silicon arrays, at a reasonable cost. Improved radiation resistance could come not only from the more radiation tolerant GaAs cell material, but also from the additional shielding provided by the individual optical elements which focus the light on each small area cell. Inexpensive optical elements and small area cells are the keys to reasonable cost for such an array. A major component of the NASA program, therefore, has been the development of concentrator cells with higher efficiency at the expected operating conditions of 80C and 100 suns now under consideration.

Figure 2 contains a plot of efficiency as a function of concentration ratio for a miniature (4 mm diam active area) GaAs concentrator solar cell produced for NASA by Varian Associates (ref. 13). A maximum efficiency of 25.1 percent in an n/p configuration was achieved near 300 suns AMO at 28C. Based on the measured temperature coefficients of similar devices (ibid.)., the expected efficiency at the operating conditions mentioned above should approach 22.5 percent AMO. A key factor in achieving the higher performance was maintaining careful control over the series resistance and grid line fabrication. An alternate approach for achieving high output from GaAs concentrator cells is shown in figure 3.

Instead of using an intricate, carefully designed grid structure to reduce series resistance, a simple, thick, straight line pattern with heavy surface coverage has been employed, as shown by the cell on the left. A similar cell is shown on the right, except that is has had added to it a "prism cover" which effectively eliminates the gridline obscuration by reflecting the incident light away from the metallization lines into the cell surface (ref. 14). This approach has resulted in a measured efficiency of 22.3 percent at 100 suns AMO and 100C. Ultimately, replacement of the GaAs concentrator cell by a multi-bandgap device approaching 30 percent efficiency will be required to achieve the 300 W/m^2 goal, but the technology described above is capable of over 200 W/m^2 in an appropriate array design.

In addition to the areas mentioned above, the Agency has a growing interest in the so-called thin-film cell technologies such as amorphous silicon and copper indium diselenide. There are two primary reasons for such interest: (1) the potential radiation resistance of the ultra-thin devices, and (2) the possibility of their extremely low cost. Internal Agency assessments indicate that these cell types will only be a value if they can be incorporated on very lightweight, flexible solar array blankets (such as Kapton) that can be easily deployed or erected, and which have a large volumetric power density when stowed on a spacecraft during launch and transport.

CONCLUSION

Improved radiation resistance is as important to many future space missions as is increased efficiency, and must be accounted for in all solar cell designs for potential space application. Efforts in the NASA Program to reduce radiation damage, while maintaining high efficiency, range from geometrical alteration of cell structures (light trapping, V-groove and dot junction GaAs), to development of cells from materials with potentially better inherent radiation resistance (InP), to high output concentrator cells with at least partial shielding from concentrator optical elements. Early results in all three areas are promising.

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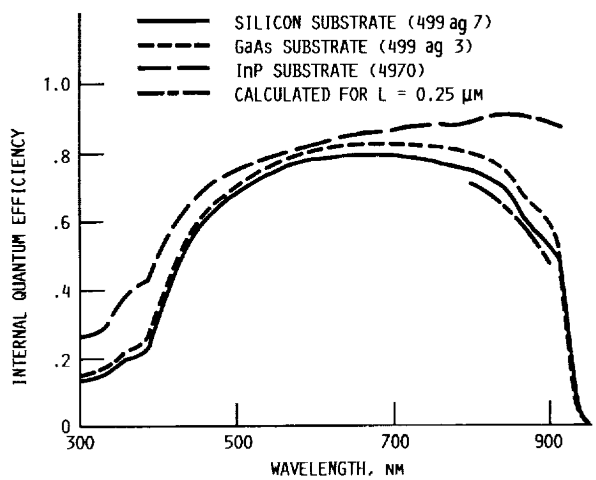

FIGURE 1. - INTERNAL QUANTUM EFFICIENCY OF InP CELLS ON VARIOUS SUBSTRATES.

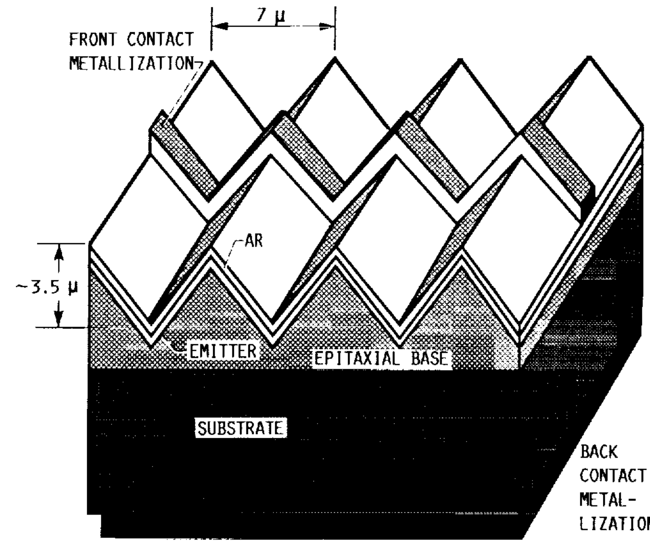

FIGURE 2. - SCHEMATIC OF V-GROOVED GALLIUM ARSENIDE SOLAR CELL (NOT TO SCALE).

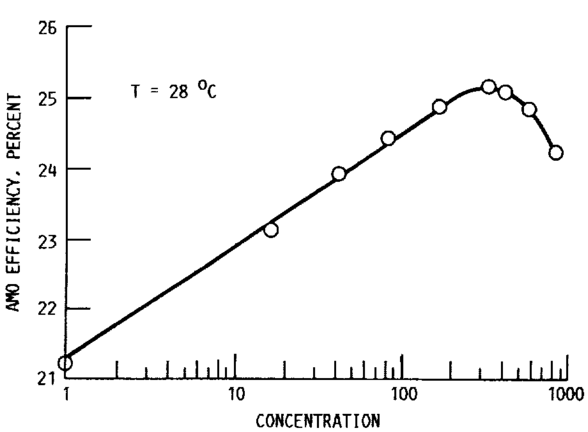

FIGURE 3. - AMO EFFICIENCY VERSUS SOLAR CONCENTRATION FOR THE n-p GaAs CELL.

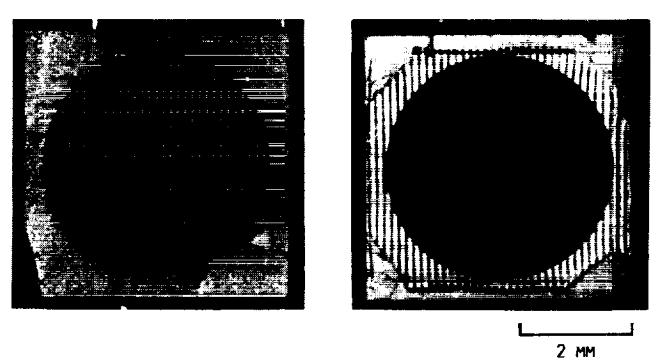

FIGURE 4. - GaAs CONCENTRATOR CELLS WITHOUT AND WITH PRISM COVER.

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16. Abstract

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