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THE NASA SPACE SOLAR CELL ADVANCED RESEARCH PROGRAM

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SUMMARY

While both space and terrestrial applications of photovoltaic energy conversion can benefit from higher efficiency devices, space solar cells must also survive the effects of the naturally occurring space radiation environment. Although recent advances in our understanding of the factors that control the performance of silicon solar cells have led to efficiency breakthroughs in laboratory devices, the potential radiation damage susceptibility of such devices is a serious drawback. Our understanding of the underlying mechanisms which cause radiation damage in silicon solar cells has improved steadily over the years, with the result that in principle we can prescribe the cell and material parameters needed to achieve an outer space efficiency of 20 percent while potentially maintaining current, or even slightly improved, levels of radiation resistance. It is now apparent that to achieve a significant improvement in radiation resistance will require development of solar cells from materials other than silicon. In some cases, such as GaAs and InP, the alternate materials have the potential for higher efficiency along with greatly improved radiation resistance. In other cases, such as amorphous silicon and $CuInSe_2$, the materials exhibit potential for dramatic improvement in radiation resistance, but with predicted efficiencies at best equal to that of present commercially available silicon space cells. This paper will discuss the content and direction of the NASA space solar cell advanced research program, and describe its relationship to the issues mentioned above. Recent results will be presented on both radiation resistance and efficiency of space cell designs from the various materials under investigation in the program.

INTRODUCTION

While both space and terrestrial applications of photovoltaic energy conversion can benefit from higher efficiency devices, space solar cells must also survive the effects of the naturally occurring charged particle space radiation environment. A great deal of effort has been directed toward developing an understanding of the underlying mechanisms which cause radiation damage in space silicon solar cells (ref. 1). In principle we can now prescribe the cell and material parameters needed to achieve improved levels of radiation resistance, while potentially maintaining present, or even slightly higher space (i.e., at AMO) efficiencies [ibid.]. Recent achievements in controlling the performance limiting factors of silicon solar cells have led to efficiency breakthroughs in laboratory devices (refs. 2 and 3). The apparent susceptibility to radiation damage of these latter devices, however, is a potentially serious drawback which could limit their usefulness in space applications.

It has been clear for some time that any major improvement in radiation resistance will require development of cells from new materials. In some cases, such as GaAs and InP, the materials offer the potential for higher efficiency along with greatly improved radiation resistance. In other cases, such as amorphous silicon and $CuInSe_2$, the materials exhibit potential for dramatically improved radiation resistance, but with efficiencies predicted at best to be equal to space cells currently in use. It is necessary to pursue several cell technology options, however, since future photovoltaic space power systems will have more specialized environmental and operational requirements than has been the case thus far. The result is that a wide variety of space solar cells, each with its own set of customized performance properties (and associated costs), will be needed.

ADVANCED CELL TECHNOLOGY

The solar cell technologies under investigation in the NASA program include planar and concentrator cells, multiple junction cells and ultrathin cells. Recent work on thin silicon single crystal cells, GaAs cells, and InP cells on foreign substrates will be presented here.

Thin Silicon Single Crystal Cells

It is well known that decreasing the thickness of single crystal silicon solar cells improves their radiation resistance; hence the so-called "2 mil" cell (actually 62 μm in practice) is almost as tolerant to charged particle radiation as a standard GaAs cell though less efficient. The primary reason for the increased radiation resistance in thin Si cells is that the diffusion length remains greater than the base thickness of the cell for larger levels of fluence than in a conventional cell. Unfortunately, decreasing the thickness also causes some loss of efficiency. The indirect absorption in silicon allows the optical pathlength in thin cells to exceed cell thickness at long wavelengths, with an attendant loss of photogenerated current. In an attempt to address this problem, NASA's Jet Propulsion Laboratory initiated an effort (ref. 4) to develop cells as thin as 25 μm that would have efficiencies equal to or greater than 13 percent AMO. Though not as efficient as their thicker counterparts (commercially available Si space cells are available with efficiencies above 14 percent), the anticipated improvement in end-of-life performance (i.e., after a 10 year exposure to the radiation environment in geosynchronous Earth orbit, or GEO) is expected to be superior to all other Si cells. The single most important factor contributing to the improved efficiency of these new thin cells is the incorporation of light trapping in the ultrathin structure. Figure 1 (ibid.) shows the calculated efficiency of cells both with (R = LT) and without (R = 0.8) light trapping, for two different assumed values of back surface recombination velocity. R is the appropriate reflection coefficient for each cell type. It was assumed to be 0.8 for a double pass of light at normal incidence through a "standard" cell. In the case of light trapping, 10 passes of light were assumed with a 95 percent reflection at each internal interface. The results show that 13 percent should indeed be feasible in a 25 μm thick cell.

Figure 2 (ibid.) plots measured efficiency versus thickness for both polished and textured (i.e., light trapping) cells. Two types of surface texture were used: one which left pits in the surface, and one which left pyramids on the surface. As can be seen in the figure, both surfaces are effective at increasing the current collected in the devices. The data in the figure also show that 25 μm thick cells with light trapping can approach 14 percent AM0 efficiency, a significant improvement over thin cells with polished surfaces. Data on the radiation resistance of these cells are not yet available.

GaAs Cells

Efficiencies approaching 22 percent AM0 in planar GaAs cells have been reported (ref. 5). Radiation resistance has also been shown to be better than in silicon on both a normalized and an absolute basis (ref. 6). 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 3 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. 7). Radiation damage testing awaits further device development.

Point contact GaAs cells. - A recent analysis by Weizer and Godlewski (ref. 8) 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. 3), in silicon, could result in AM0 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, and 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 high efficiency at the expected operating conditions of 80C and 100 suns now under consideration by NASA.

Figure 4 contains a plot of efficiency as a function of concentration ratio for a miniature (4 mm diameter active area) GaAs concentrator solar cell produced for NASA by Varian, Associates (ref. 9). A maximum efficiency of 25.1 percent in an n/p configuration was achieved near 300 suns AM0 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 AM0. A key factor in achieving the high 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 5. 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 it 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. 10). This approach has resulted in a measured efficiency of 22.3 percent at 100 suns AM0 and 80C.

InP Cells

Considerable progress has been made in developing a high efficiency InP cell structure, and in ascertaining its radiation damage characteristics. The papers by Coutts et al. (ref. 11), and Weinberg et al. (ref. 12), presented in this volume summarize the status of this emerging and important cell technology on both aspects. Efficiencies of laboratory devices produced by organometallic chemical vapor deposition (OMCVD) are routinely over 18 percent AM0, with the record currently set at 18.8 percent (ref. 13).

An important thrust in the current NASA program is to produce an InP cell on foreign substrates using OMCVD. The initial efforts have used Si as the substrate. Spire Corporation, under contract to NASA Lewis Research Center, has demonstrated the feasibility of this approach by producing n+/p structures on Si, with a GaAs buffer layer, that have achieved 7.2 percent AM0 efficiency (ref. 14). In addition, they have also produced a 9.4 percent AM0 InP n+/p cell 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 growing InP film. Growth directly on GaAs substrates was undertaken to eliminate the effects of defects which might 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 6 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.

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 thin Si, 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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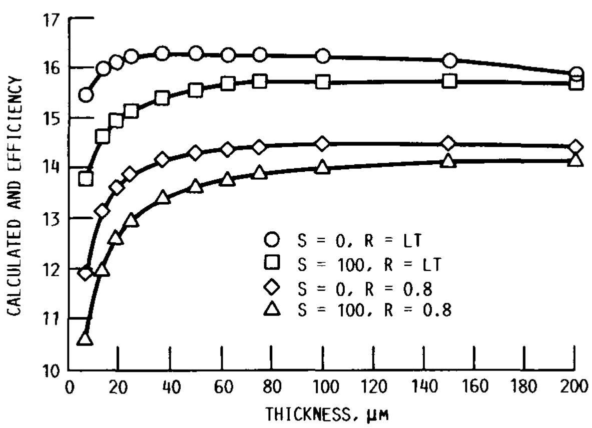

FIGURE 1. - EFFECT OF LIGHT TRAPPING AND BACK SURFACE RECOMBINATION VELOCITY ON CELL EFFICIENCY.

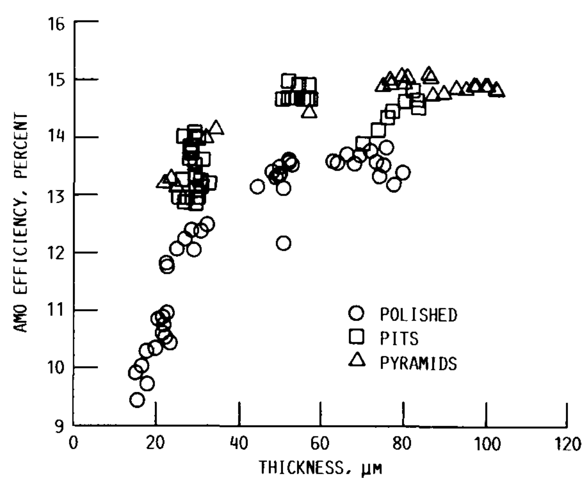

FIGURE 2. - EFFICIENCY VERSUS THICKNESS FOR DEVICES WITH AND WITHOUT LIGHT TRAPPING.

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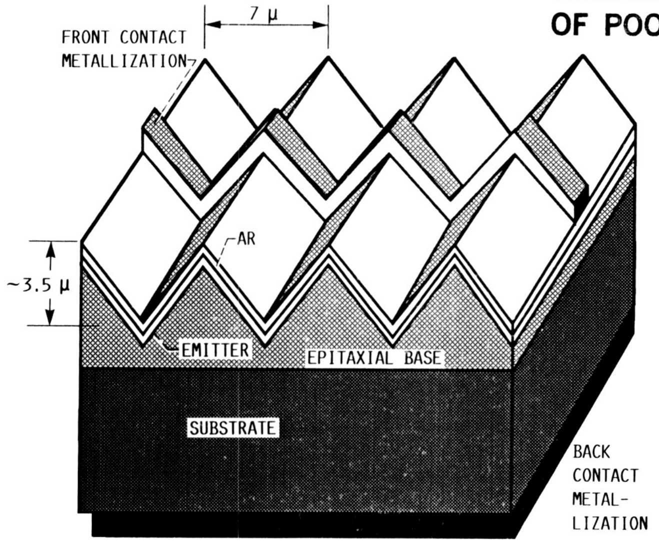

FIGURE 3. - SCHEMATIC OF V-GROOVED GALLIUM ARSENIDE SOLAR CELL (NOT TO SCALE).

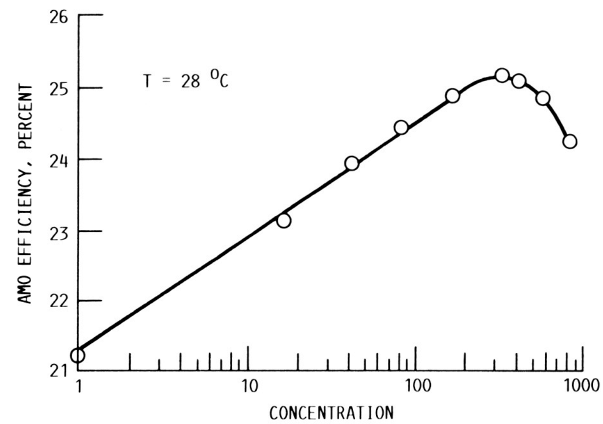

FIGURE 4. - AMO EFFICIENCY VERSUS SOLAR CONCENTRATION FOR THE n-p GaAs CELL.

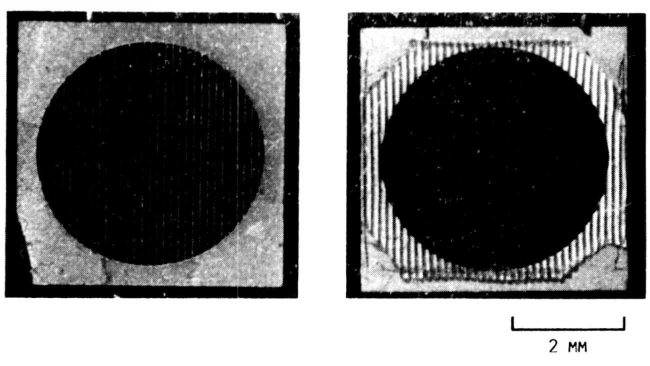

FIGURE 5. - GaAs CONCENTRATOR CELLS WITHOUT AND WITH PRISM COVER.

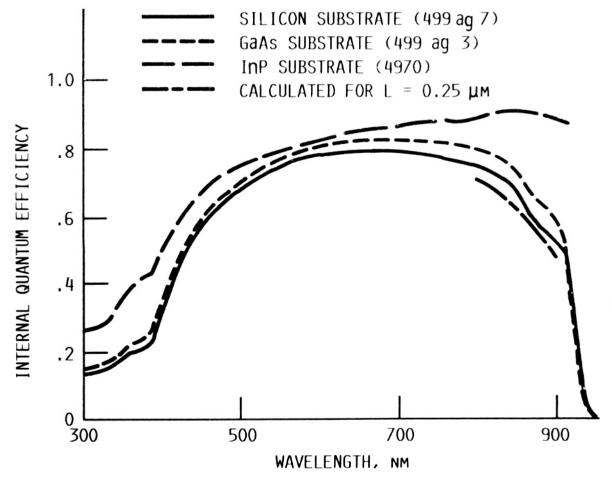

FIGURE 6. - INTERNAL QUANTUM EFFICIENCY OF InP CELLS ON VARIOUS SUBSTRATES.

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16. Abstract

Two major requirements for space solar cells are high efficiency and survivability in the naturally occurring charged particle space radiation environment. Performance limits for silicon space cells are well understood. Advanced cells using GaAs and InP are under development to provide significantly improved capability for the future.

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