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Advanced Solar Cells for Satellite Power Systems

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ADVANCED SOLAR CELLS FOR SATELLITE POWER SYSTEMS

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Abstract

The multiple natures of today's space missions with regard to operational lifetime, orbital environment, cost and size of spacecraft, to name just a few, present such a broad range of performance requirements to be met by the solar array that no single design can suffice to meet them all. The result is a demand for development of specialized solar cell types that help to optimize overall satellite performance within a specified cost range for any given space mission. Historically, space solar array performance has been optimized for a given mission by tailoring the features of silicon solar cells to account for the orbital environment and average operating conditions expected during the mission. It has become necessary to turn to entirely new photovoltaic materials and device designs to meet the requirements of future missions, both in the near and far term. This paper will outline some of the mission drivers and resulting performance requirements that must be met by advanced solar cells, and provide an overview of some of the advanced cell technologies under development to meet them. The discussion will include high efficiency, radiation hard single junction cells; monolithic and mechanically stacked multiple bandgap cells; and thin film cells.

I. INTRODUCTION

Although the overwhelming majority of satellites are powered by silicon solar cells, a few now obtain their primary power from gallium arsenide. Use of this latter cell type is necessitated by the need for additional power and increased radiation resistance in a particular space environment. For example, consider missions in low earth orbit (LEO) which includes spacecraft altitudes from approximately 150 to 800 nautical miles (NM). Except for polar orbits, missions in LEO are in a relatively benign radiation environment. In this case the major requirement is for cells with high beginning of life efficiency. For most other orbits, radiation damage is an important factor and high end of life efficiency is a dominate requirement in cell selection. As spacecraft altitude is increased from the LEO range, one encounters more intense radiation environments. The most severe radiation environments occur in the so called mid-altitude orbits (MAO), where satellite heights vary between approximately 1000 and 10000 nautical miles. As a result, most satellites which fly in MAO are designed for a limited lifetime. Extending satellite lifetime will require a breakthrough in cell radiation resistance. At present, an alternative is to apply thick cover

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glass shielding to the cells. This also implies a thicker array support structure which introduces additional launch weight and costs. As shown in the first figure, global communication systems would benefit from an extended operational capability in MAO. The figure illustrates the dramatic reduction in satellite numbers required to achieve total global telecommunications as altitude is increased (Ref. 1). Reducing the number of satellites tends to lower life cycle costs for the system, both in terms of launch and ground control costs.

Satellites in geosynchronous orbit (GEO), with altitudes of approximately 22000 nautical miles, are primarily used in communication systems and are presently designed for at least seven years of operation. However, future communication satellites are being planned requiring 15-20 years of operational lifetime. Radiation induced cell degradation, although not as severe as in MAO is a primary concern here. Hence the primary characteristic required for solar cells in GEO is high end of life efficiency. This can be achieved by improved resistance to radiation damage. Advanced cells such as InP and GaAs are superior to Si in this respect.

One issue not addressed in the preceding discussion is the cost of solar cells for space application. It is easy to see that cell cost by itself is not a major factor in determining total mission cost. For example, a typical space qualified silicon solar cell now sells for an equivalent cost of about $100 per watt. A fully assembled space solar array typically costs between $1000 and $1,500 per watt. Satellite costs vary widely, depending on the mission, but in general the array represents less than 20% of the total. The result is that cell costs are only a few percent of the total. Since the total increase in mission cost is still minimal, a new cell with mission-enabling characteristics can be considered, even at several times the cost of currently available cells. This has proven to be the case for the GaAs on Ge cell now in commercial production in the U.S. Such cells start out at 5 or 6 times the cost of Si cells. However, the advantage they provide (more power per unit area, higher radiation resistance), makes them cost effective for all missions with high radiation damage, or where power requirements could not be met with the array area available on the satellite.

On the other hand, no matter what the orbital environment in which the mission will fly, reductions in satellite stowage volume needed on the launch vehicle can lead to substantial mission cost reductions by permitting use of a smaller launch vehicle class. Although higher efficiency cells can reduce array size while maintaining array output, there is a limit to the volume into which arrays with such cells can be packed on the launch vehicle. The primary problem is in the nature of any single crystal solar cell: it is not flexible, and therefore requires mechanical support to withstand the extreme acoustic environments encountered during launch. In some cases, this is a more important variable than the size of the array when deployed, and leads to an alternate approach for optimizing mission performance and cost: the use of thin film solar cells and arrays. We shall touch on this technology in a later section of the paper.

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II. HIGH EFFICIENCY SINGLE CRYSTAL CELLS

A. Single Junction Cells

At present, the only new single crystal, single junction cell under development for space application is the InP cell, which has been shown to have significantly improved radiation resistance compared to either GaAs or Si (Refs. 2, 3, 4). This is illustrated in the second figure where a comparison is made between InP, GaAs and Si cells under 1 MeV laboratory irradiations (Ref. 4). Similar results are obtained under 10 MeV proton irradiations (Ref. 4). For completeness, Table I lists the preirradiaton performance parameters of the cells shown in the figure. Although the InP cells, for which data is shown, had efficiencies considerably lower than the highest achieved for this cell (see below), their efficiencies at the highest fluence were considerably higher than those of the GaAs or Si cells. The GaAs solar cell is now a commercial product in the space satellite industry, and is available on a thin germanium substrate with average efficiencies in excess of 18.5% AM0. Its average cost is about 5 times that of the equivalent area space silicon cell, but it has been shown to be cost effective at the array level when radiation damage is a significant mission driver (Ref. 5)). For InP, current development is aimed at improving cell ruggedness (and to a lesser extent to reduce cost) by growing it on alternate substrates, such as Si or Ge (Ref. 6, 7). At present the highest efficiencies for InP have been obtained in the n^+-p structure, and exceed 19% AM0 in a 2cm by 2cm device (Ref. 8). However, both Si and Ge are n-type dopants in InP, so when the n^+-p structure is grown on either one, a rectifying diode is formed at the interface which severely limits cell performance. Attempts to eliminate the autodoping have not been successful. As a result, attention has been turned to achieving high performance in a p^+-n-n^+ structure, which would take advantage of the autodoping that occurs from the substrate. The large lattice mismatch between InP and either substrate (about 4% for Ge, and 8% for Si) is still a major obstacle which limits device performance, but potentially successful lattice grading or buffer layer techniques have been demonstrated (Ref. 9, 10).

Recent work on the use of hydrogen passivation of dislocations produced in the heteroepitaxial growth of InP on GaAs has shown great promise (Ref. 11). The effect of the hydrogen passivation is evidently to alter the charge-trapping kinetics of the dislocations, causing them to exhibit more point defect-like behavior. A more than two order of magnitude reduction in electrical activity of dislocations has been observed (ibid). Although GaAs is not a preferred substrate, the technique, if shown to be fully successful, should be applicable to any heteroepitaxially grown InP cell. The technique has also been shown to substantially increase the efficiency of homojunction InP cells (Ref. 12).

Though scarce, data on the radiation damage characteristics of n/p InP solar cells are beginning to emerge, along with a better understanding of the defects created by both electron and proton irradiations of the cells. Recent work has shown an interesting radiation-induced carrier enhancement in p/n cells, which has been related it to the lattice defect structure of these cells (Ref. 13). It is usually the case that carrier concentrations in n^+p InP cells decrease upon irradiation (Ref. 14). However, for an irradiated p^+n cell with zinc as

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the p-dopant, an increased carrier concentration is observed in the cell's n-region (Ref. 13). It is believed that zinc, diffusing into the n-region, forms a deep donor complex with either a radiation induced phosphorus interstitial or vacancy. The increased, or enhanced carrier concentration is attributed to the action of this complex (Ref. 13, 15). Similarly, the radiation-induced defect structure of InP cells is becoming more clearly understood, as is the behavior of the defects when the cells are annealed at relatively low temperatures (Ref.16).

B. Multijunction Cells

There have been several proposed multibandgap (MBG) cell structures over the years, both for space and terrestrial use. They have had two basic forms: one is essentially a single monolithic crystal throughout, although lattice grading or other lattice matching techniques are required, and the other is a simple mechanical stack of two cells with the appropriate bandgaps. Both types have their advantages and disadvantages in terms of actual usefulness on an array, and no clear choice has yet emerged between them. At the present time the only mechanically stacked cell still undergoing development is the GaAs/GaSb concentrator cell first reported by Boeing (Ref. 17). The limitation with this device is that it exists only as a concentrator cell, and its size is restricted by the area of presently available commercial GaSb substrates. There are no inherent restrictions which would prevent it from competing as a large area planar device, but as yet no development along those lines has taken place. The concentrator structure has achieved 30% AM0 efficiency at about 100 suns in laboratory measurements (Ref. 17). Radiation damage data are not yet widely available on GaSb, with or without a GaAs top cell for partial shielding, but the flexibility and ease of arranging four terminal contacts with the mechanically stacked devices in general helps their performance in radiation environments by eliminating the need for current matching between the two cells in the structure.

Two monolithic cells receiving considerable attention are the InP/GaInAs cell (Ref. 18) and the GaInP$_2$/GaAs cell (Ref. 19). The latter has the potential to be grown directly on Ge substrates with high efficiency in a very straightforward manner, since no lattice matching is required. The former requires an InP substrate, but the same lattice matching and/or buffer layer techniques being developed for InP on Si or Ge can be used here as well. Both devices are produced by organometallic chemical vapor deposition (OMCVD).

A major issue for both cells is their performance after irradiation by electrons and protons. Little or no data has appeared in the open literature, although it is presumed that both cell structures should show reasonable resistance based on the basic materials from which they are made. As with any MBG structure, however, they can be expected to show more rapid degradation than either of their component cells. For example, the InP/GaInAs cell when subjected to 1 MeV electron irradiation exhibits a radiation resistance as high as an InP homojunction cell for fluences up to 10^{14} cm^{-2} (Ref. 20). For higher fluences the bottom cell limits the cell current and degrades the tandem cell efficiency (Ref. 20). In general, this occurs because of the critical importance of maintaining current matching through both cells, and the likely event that radiation degradation will be different in each. The result is rapidly

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developing current mismatch in the component cells and loss of performance. In the case of the InP/GaInAs cell, the radiation results suggest that the base dopant level of the bottom cell is critical in achieving current matching. In fact, it is concluded that a base doping level around 2-5 X 10^{16} cm^{-3} in the bottom cell would result in current matching for the tandem configuration (Ref. 20). In general, if radiation damage is expected to be significant during the mission, it is necessary to consider designing the cell for optimum performance near its expected end of life (EOL); doing so may actually provide a higher overall output for the duration of the mission.

The primary value of the MBG cell may well be in its application to missions for which little or no radiation damage is anticipated. Here again, reductions in the satellite balance of system costs are expected to outweigh any increases in cell cost, although the definitive answer must await commercial availability of such cells.

III. THIN FILM CELLS AND ARRAYS

The principal advantages to be gained from the use of thin film solar cells are lighter weight, flexibility and in the case of polycrystalline thin films (PTF) cells, a demonstrated high radiation resistance.

Although the majority of thin film cells are of the PTF variety, single crystal films are presently the most viable candidates for use in space. In particular, peeled films of single crystal GaAs cells, 5 microns thick, have been produced in small quantities with maximum AMO efficiencies of 18% (Ref. 21). Hence, it is not unreasonable to expect that with additional effort, AMO total area efficiencies of 19% will be achieved in production. At these efficiencies, with a 2 mil cover glass, the JPL Advanced Photovoltaic Solar Array (APSA) would achieve a specific power of 190 W/Kg (Ref. 21). This should be compared to the specific power of 130 W/Kg achieved with 55 micron silicon and 115 micron GaAs on Ge cells using the same cover glass thickness (Ref. 21). Since the peeled films are deposited on a 5 mil glass superstrate, cell handling in module processing is a potential problem. However, for a module consisting of 42, 8 cm^2, peeled film GaAs cells high efficiency strings were assembled with an acceptable cell loss of 5% (Ref. 21).

Considering polycrystalline thin film (PTF) solar cells, the greatest activity has occurred in CuInSe2, CdTe and amorphous Si. The cells are typically a few microns thick. In considering these cells for space it is noted that efficiencies are usually listed at air mass 1.5 and 100 mW/cm^2 (global) and often in terms of active rather than total area. In the absence of direct measurement, when translating the global efficiencies to AMO, a loss of 20% appears conservative and we shall use this factor in converting efficiencies (Ref. 22). To date, the highest reported total area global efficiency achieved for a PTF cell is 15.9% (16.5% active area) (Ref. 25). This was achieved for a CuIn$_x$Ga$_{1-x}$Se$_2$ (CIGS) cell whose total area was 0.437 cm^2 (Ref. 23). This translates to an AMO total area efficiency of 12.7%.

The presence of high concentrations of grain boundaries and lattice defects in PTF cells implies that their efficiencies will be relatively low. This is offset by their light weight, potentially low cost and a demonstrated excellent radiation resistance. For example; a PTF $CuInSe_2$ (CIS) cell showed no degradation after irradiation by 1 MeV electrons to a fluence of 10^{16} cm^{-2} (Ref. 24). Furthermore, under 1 Mev proton irradiation to a fluence of 10^{12} cm^{-2} a 10% loss in efficiency was noted (Ref. 25). With respect to CdTe, little change in efficiency was observed after exposure to 1 MeV electron irradiation to a fluence of $3X10^{16}$ cm^{-2} (Ref. 26). However, amorphous silicon was observed to degrade to 69% of its preirradiation value after exposure to a 1 MeV electron fluence of 10^{16} cm^{-2} (Ref. 24). On the other hand, 97% recovery was observed after a 15 minute 175°C anneal (Ref.24). However, the observed degradation combined with their tendency to degrade when initially exposed to light make amorphous silicon cells the least attractive of the three PTF cells considered here for possible use in space.

With respect to specific power, a 15% AMO efficient (19.4% global) PTF cell, without cover glass would yield an APSA specific power of 210 W/Kg (Ref. 21). Considering the current state of this art, achievement of this relatively high efficiency does not appear achievable in the near term. Hence, for the near term, peeled film GaAs films appear to be the most viable candidates for this application. Amorphous silicon, for terrestrial use, is the subject of a large and active international research and development program with a manufacturing base which is enormous by space production standards. In fact, of the PTF cells, the manufacturing base for amorphous silicon cells is the most advanced. Aside from its terrestrial applications, the possible use of A-Si arrays, in carpet form, make them a viable candidate as start up power for a possible lunar base. However, the relatively low efficiency of small area A-Si devices (10%) and their well known instability tends to mitigate against the use of these cells as satellite power sources. In this connection, considering the present efficiencies of CIGS cells and the potential for CdTe, together with their observed high radiation resistance, these latter cells with further extensive development should be strong candidates for use in space solar cell arrays.

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TABLE 1.—AMO PERFORMANCE PARAMETERS BEFORE 1 MeV
ELECTRON IRRADIATION

Cell	Jsc, mA/cm^2	Voc, mV	FF, %	Efficiency, %
In P-n/p	32.1	822	82	16.0
GaAs/Ge	31	998	80	18.3
Si[a]	43.6	608	76	14.9
Si[b]	40	607	75	13.5

[a]8 mils thick, 10 Ω-cm base.
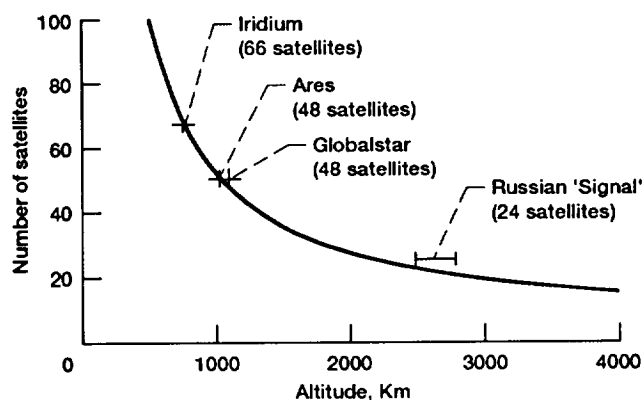[b]2.6-3.1 mils thick, 10 Ω-cm base.

Figure 1.—Satellite numbers required to achieve total global
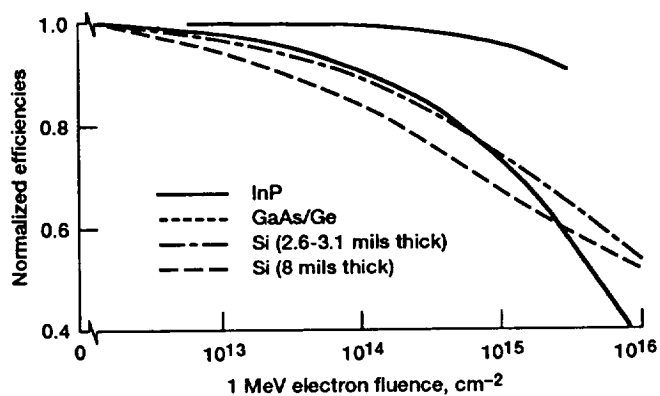coverage in circular polar orbits.

Figure 2.—Normalized efficiency after 1 MeV electron irradiation
(InP, GaAs and Si).

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