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GaAs and III-V Compound Solar Cells Status and Prospects for Use in Space

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Dennis J. Flood and David J. Brinker
Lewis Research Center
Cleveland, Ohio

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GaAs AND III-V COMPOUND SOLAR CELLS STATUS
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Dennis J. Flood and David J. Brinker
National Aeronautics and Space Administration
Cleveland, Ohio 44135

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SUMMARY

Gallium Arsenide solar cells now equal or surpass the best silicon solar cells in efficiency, radiation resistance, annealability, and in the capability to produce usable power output at elevated temperatures. NASA has been involved in a long range research and development program to capitalize on these manifold advantages, and to explore alternative III-V compounds for additional potential improvements. This paper will review the current status and future prospects for research and development in this area, and will indicate the progress being made toward development of GaAs cells suitable for variety of space missions. Cell types under various stages of development include n^+/p shallow homojunction thin film GaAs cells, x100 concentration ratio p/n and n/p GaAs small area concentrator cells, mechanically-stacked, two-junction tandem cells, and three-junction monolithic cascade cells, among various other cell types.

INTRODUCTION

The requirements placed on space power systems in the coming decade are expected to grow, not only in terms of delivered power, but also in terms of their complexity. Solar arrays will be expected to be larger, lighter, more constant in their output over longer periods of time, and able to function in more demanding space environments than at present. In addition, the cost/watt of such arrays will be expected to fall from present levels. Major advances in solar cell performance and fabrication technology must occur if these broad space power system needs are to be satisfied as they are translated into mission requirements. Accordingly, the NASA Lewis Research Center has formulated a program in GaAs and III-V compound solar cell research and development that is intended not only to respond to presently perceived agency mission requirements, but also to create totally new mission opportunities as well. The program ranges from basic materials science to prepilot cell production. The activities fall roughly into three categories: (1) GaAs concentrator cells, (2) thin film cells, and (3) multijunction cells. Tolerance for the damage caused by charged particle irradiation in the natural space environment is a major consideration in the III-V cell area, and along with the potential for high efficiency forms an important part of the justification for it.

GaAs CONCENTRATOR CELL

Interest in GaAs concentrator cells stems not only from their potential for higher efficiency and radiation resistance, but also from their potential for lowering the cost of very large solar arrays. Figure 1 summarizes the results of a NASA study of multihundred kilowatt array designs (ref. 1). The plot of combined cell and component costs versus concentration ratio shows the existence of a broad minimum between ~x20 and x200. Figure 2 illustrates a concentrator design currently under NASA development at the Marshall Space Flight Center. Specifications for this miniature Cassegrainian system call for a cell capable of 20 percent AMO at x125 and 85 °C. Results of measurements made at Lewis Research Center on one of the early cell designs are shown in figure 3. With 19 percent already demonstrated, there appear to be no apparent technical "show-stoppers" which will prevent realization of the above goals. This application dramatically illustrates the higher efficiency and higher temperature capabilities of GaAs compared to silicon. GaAs concentrator cells will have over twice the efficiency of silicon at the operating temperatures projected for this array design. The physical dimensions of the cell are a key to its potential cost-reducing benefits. The diameter of the illuminated area is 4 mm, while the length of one edge is 5 mm. The ~60 to 1 reduction in processed semiconductor area compared to a planar array of equal output is the primary reason for the projected lower cost of this array design. (An additional assumption, of course, is that the cost per unit area of the concentrator optics will be significantly lower than the equivalent area of processed semiconductor material.) The anticipated cell output at operating conditions is ~0.4 W. Based on informal estimates, the projected cost of such cells should be on the order of 30 to 50 dollars/W.

Improved radiation resistance for such an array is expected because of the inherent shielding provided by the concentrator element against the natural radiation environment encountered in many orbits. Although radiation resistance is not of major importance for LEO applications, the design may make possible the use of photvoltaic power generators in some of the mid-altitude orbits that have previously been dismissed because of their high density radiation environment. Beyond that, if high efficiency can be coupled with lightweight concentrator optics, such arrays could eventually be advantageously flown in GEO.

THIN FILM CELLS

Research on thin film solar cells is directed toward improving their performance, not only in terms of their efficiency, but also in terms of their radiation resistance. An important thrust for the NASA space power program is the development of technology for the next generation of GEO communications spacecraft. At present, about 23 percent of the satellite mass launched to orbit must be dedicated to the power system, which is approximately the same fraction that is available for the payload itself. The benefits derivable from reducing the power system mass are directly translatable into revenue for commercial satellites, and into increased capability for noncommercial satellites. An approach under investigation at the present time for producing ultralightweight solar cells is the CLEFT (Cleaved Lateral Epitaxial Film Transfer) process developed at the Lincoln Laboratory by John Fan and co-workers (refs. 2 to 5). Progress in this area is well known, and a detailed discussion need not be included here. The NASA goal is to demonstrate a 4 μm thick GaAs cell with at least 20 percent AMO efficiency, which suffers no more than a 10 percent loss of power after 10 yr of exposure to the GEO radiation environment. The goal is ambitious, but achieving it could result in significant reductions in the mass of the solar array for GEO systems. The best cell specific power demonstrated to date is 5400 W/kg, achieved with a 5.5 μm thick cell with gridded back contacts. A cross section of the cell is shown in figure 4. Measured efficiency is 14.3 percent at AMO. The illuminated area is 0.51 cm^2.

There are many technological challenges to overcome before the CLEFT cell can be considered a viable candidate for use in space. Chief among them are the following: development of a uv-resistant adhesive to use in the film transfer process; improving the open circuit voltage and fill-factor; establishing the radiation tolerance of the cell; and perhaps the most formidable among them, developing a suitable interconnect technology for joining 4 or 5 μm thick cells together in an array.

MULTIJUNCTION CELLS

As is well-known, the efficiency of a typical single junction solar cell is limited fundamentally by the location of its bandgap within the solar spectrum. Cascading two more bandgaps can produce a significant increase in output power for such a device compared to a single p-n junction. Calculations of multibandgap cell efficiencies at AMO indicate that a total conversion efficiency of ~30 percent could be achieved in a three-cell stack under x100 illumination (ref. 6). The cell structure initially selected by NASA is shown in the first column of table I, and was driven by the earlier assumed requirement that the structure had to be lattice-matched throughout. The second column shows the current distribution of desired bandgaps for the structure, and is a result of the successful demonstration of composition grading between the various active layers of the cell. Relaxing the requirements for the strict lattice-matching allows for greater flexibility in the choice of bandgaps to achieve short-circuit current matching from each constituent cell in the stack. The second set of bandgaps should produce a slightly higher efficiency than those of column one, and should make fabrication of the tunnel junction between the bottom and middle cells somewhat easier. (The high doping densities required for a tunnel junction interconnect are easier to achieve in a lower bandgap material.) The interconnect between the middle and top cells can be some sort of metal interconnect, such as that developed by Varian Associates (ref. 7). The lower cell of the stack has been fabricated from GaInAs, and has a measured efficiency at 100 suns of 17.6 percent. Middle and upper bandgap cells have been fabricated and have measured quantum efficiencies in excess of 90 percent. The complete monolithic structure has not yet been fabricated. Further progress in this area depends on the development of a low resistance ohmic interconnect between cells that is either transparent or produces minimal blockage.

An interesting alternative to the above structure is to use just two junctions, and to mechanically stack them. As has been pointed out by Fan (ref. 8), such a structure can be either a two, three, or four terminal device. The monolithic stack, on the other hand, is most easily made into a two terminal device. There is some loss of efficiency in the AMO spectrum for a two junction cell, but there may also be a trade-off in the radiation hardness of the two structures which favors a two-junction, four terminal device. If the end-of-life performance of a series-connected multijunction cell is to be maintained at reasonable levels, it becomes necessary to develop constituent cells which degrade by matched amounts in a radiation environment. Although possible in principle, it promises to be a challenge to achieve. A four terminal device, on the other hand, does not require current matching, and is, therefore, not susceptible to the potentially rapid output deterioration of the monolithic series-connected device.

RADIATION DAMAGE

Accounting for the effects of the natural space radiation environment is a major factor in space solar array design, particularly when long lifetime missions are planned. What is required at the cell level is an improved understanding of the nature of the damage caused by such an environment, and development of methods to either limit it or to repair it. Figure 5 illustrates recent developments in the general area of defect behavior in GaAs solar cells. The addition of hydrogen to the crystal lattice results in passivation of the anti-site defect in boat-grown single crystal GaAs. It is tempting to assume that this result is analogous to that on lithium counter-doping in Si reported elsewhere in this conference. (See the paper by Weinberg et al.) Work in this area is relatively new in GaAs, and significant gains in our understanding of defect formation and control can be expected in the near future. As mentioned, also of potential importance is the ability to anneal the effects of radiation damage. Figure 6 shows the fraction of output power restored by low temperature annealing of shallow homojunction $n^+/p/p^+$ GaAs solar cells following irradiation by 1 MeV electrons to a fluence of 10^{15} cm^{-2}. The ability to recover a significant fraction of BOL output by thermally annealing the array at temperatures that may actually be realizable on orbit could extend the useful life of a satellite in a cost-effective way. Improvements in this area can be expected as our understanding of the entire question of radiation damage improves.

An important component of that understanding is the situation regarding radiation damage equivalence in GaAs. Figure 7 illustrates some of the complexity encountered when attempting to establish the relative performance of GaAs cells relative to Si cells. It becomes necessary to investigate not only the behavior under 1 MeV electron irradiation, but also under proton irradiations of various energies and fluences. The data in figure 7 are for 2 MeV protons. As shown, however, when performances of the cell types are compared at the operating temperature expected on orbit, GaAs cells appear superior. Data in this figure are for a $p/n/n^+$ cell structure with a 0.5 µm deep junction. Similar data at other energies show similar behavior, with the result that confidence in the radiation resistance of GaAs solar cells continues to increase. The laboratory data presented here will be supplemented in the future by flight data from a variety of sources, including NASA and military missions.

POTENTIAL IMPACT ON SPACE MISSIONS

Figure 8 is a plot of array cost as a function of mission duration for both silicon and GaAs solar arrays in a geosynchronous orbit (ref. 9). The study included estimated launch costs based on then-available models for direct launch to GEO, as well as an assumed Shuttle/upper stage launch scenario. Details of the launch model are not important for the present discussion, since we are interested only in comparisons for the same launch method. The figure presents the result of one aspect of the trade studies - the total array cost, including launch costs, as a function of mission duration, with cell costs used as an adjustable parameter. The curves shown include what are considered reasonable costs for the two cell types: GaAs at 300 dollars/W, and silicon at 100 dollars/W, as well as one low cost projection for each. The results are clear: GaAs cells at 300 dollars/W are competitive with silicon at 100 dollars/W. The study assumed the same BOL power for each array, and incorporated the best radiation damage and efficiency data available at the time. The results are not limited to GaAs, but could include any high efficiency III-V cell type for which similar radiation damage behavior might occur. The essential point is that although GaAs and other III-V materials have higher densities than silicon, and, therefore, make heavier cells at the same cell thickness, mission costs can still be lower because of their potential for higher efficiency and increased radiation hardness. Both of the latter attributes will work to lower the total mission cost because of their impact on EOL power and array area. The total cost is a strong function of the balance-of-system mass (array mass less cell mass), and BOS mass is a strong function of cell efficiency. The last point is illustrated in figure 9, which shows a comparison of the variation of array mass reduction with efficiency for III-V cells compared to 14 percent AMO Si cells. The array size was determined in both cases by the same BOL power requirements, and no allowances were made for any differences in radiation hardness between Si and GaAs or any other III-V materials. The calculation also assumed an advanced, ultralightweight array design as baseline (ref. 10), and cell thicknesses were assumed to be 50 μm in all cases. As is clearly shown, the reduction in BOS mass which results from higher efficiency more than offsets the effect of the greater individual cell masses. The net effect should be reduction in total mission costs based on this factor alone.

Had space-quality GaAs solar cells been available at the time of the Helios mission, the impact of incorporating them would have been quite dramatic. Figure 10 is a plot of calculated array output for that mission for both silicon and GaAs cells. Mission planners would have been able to reduce the size of the array to one-fourth its original size to achieve the same power at 0.25 au, the planned point of closest approach. Alternatively, they could have flown even closer to the sun, had that been desirable. (The latter assumes that thermal requirements for the rest of the spacecraft could have been accommodated during the closer approach.) At any rate, the availability of GaAs solar cells would have provided mission planners with additional flexibility in mission design, which is one of the goals of the NASA research and technology program.

CONCLUSION

The intent of the preceeding discussion has been to provide a brief overview of the NASA research and technology program in GaAs and other III-V compound solar cells, and to assess the prospect for using such cells in future space missions. Sufficient advances have occurred to assure their eventual incorporation into a variety of missions. They will do so on a cost-effective basis, and, in many cases, will represent mission-enabling technologies for decades beyond the present.

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TABLE I. - MULTI-JUNCTION CELL BANDGAS

Cell	L-M	C-G
Lower	1.15	1.15
Middle	1.55	1.43
Upper	2.05	1.95

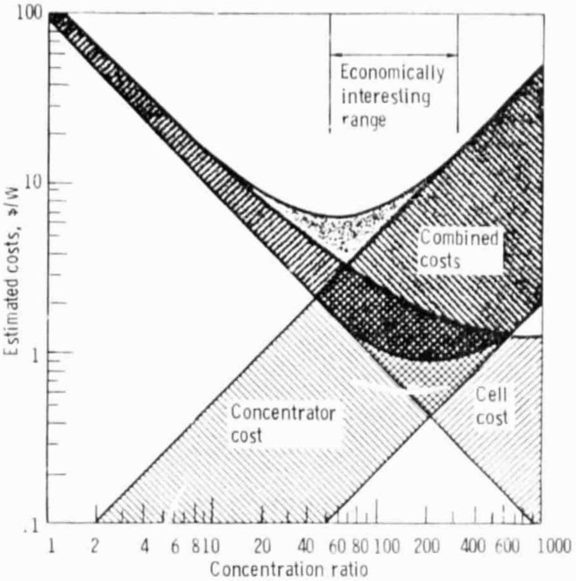


Figure 1. - Estimated concentrator array costs vs concentration ratio for multi-hundred kilowatt space power systems.

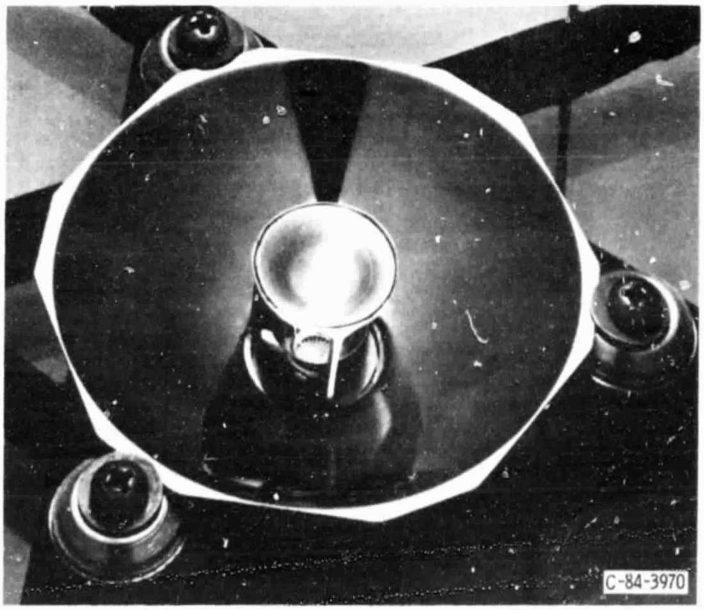


Figure 2. - Miniature cassegrainian concentrator design currently under development.

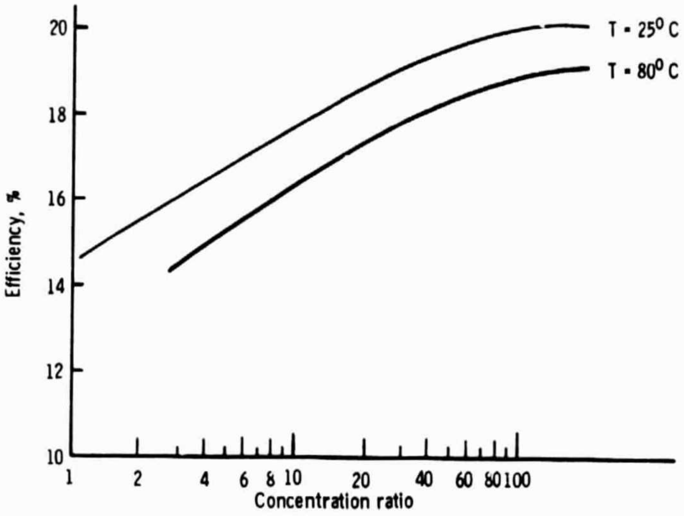


Figure 3. - Early GaAs concentrator cell efficiency.

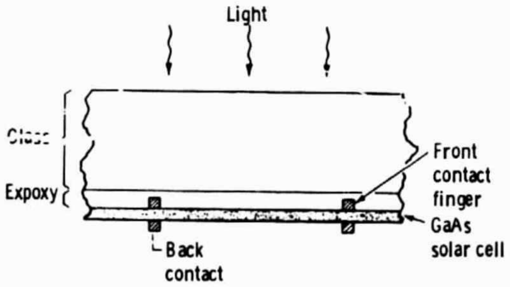
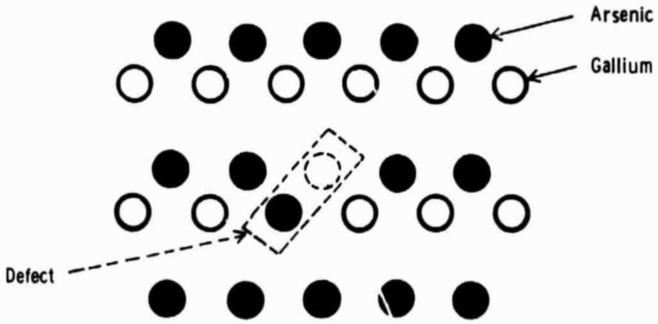


Figure 4. - Cross-section of the CLEFT GaAs cell.



Defect concentration decreased by adding atomic hydrogen

Figure 5. - Defect identification and passivation in GaAs.

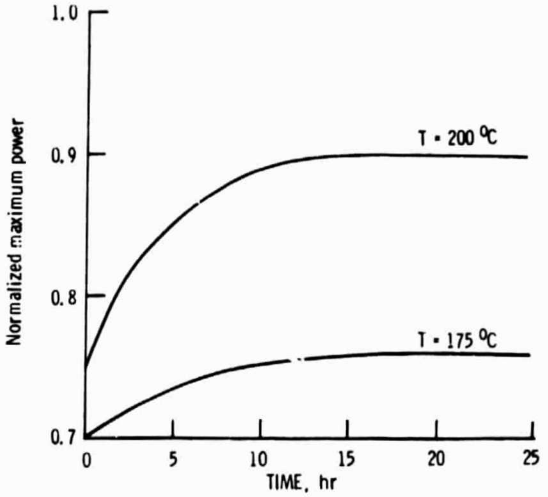


Figure 6. - Thermal annealing of radiation damage in GaAs shallow homojunction solar cells.

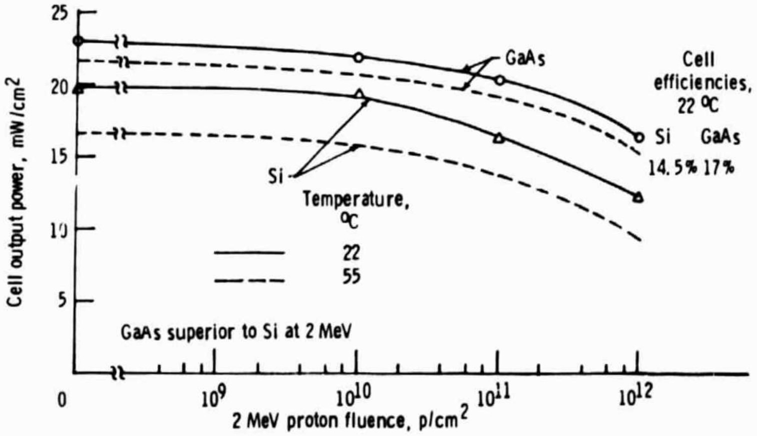


Figure 7. - Comparison of GaAs and Si under proton irradiation.

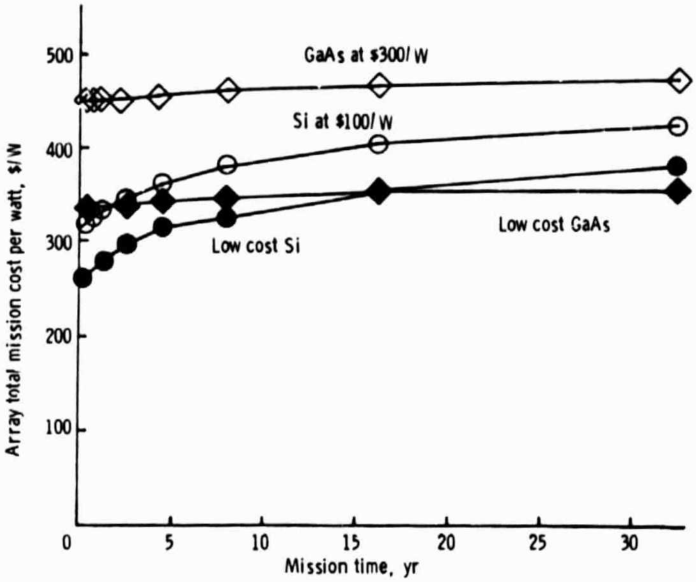


Figure 8. - Array cost vs mission duration for both GaAs and Si in geosynchronous earth orbit.

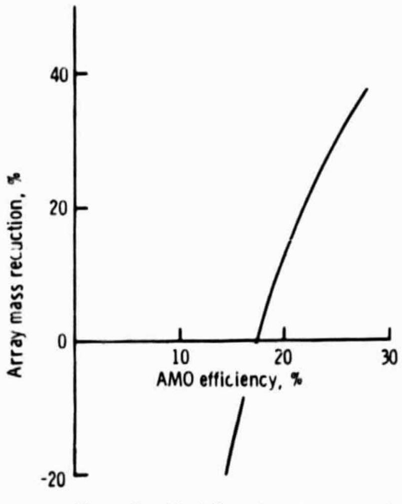


Figure 9. - Variation of array mass reduction with cell efficiency for III-V cells compared to 14% Si cells.

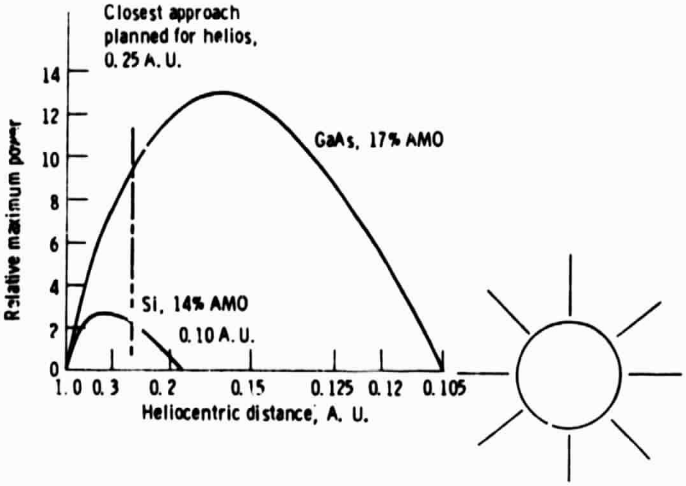


Figure 10. - Calculated array output for Helios mission for both GaAs and Si cells.