Indium Phosphide Solar Cells—Status and Prospects for Use in Space

Irving Weinberg and David J. Brinker

Lewis Research Center
Cleveland, Ohio

Prepared for the
21st Intersociety Energy Conversion Engineering Conference (IECEC)
cosponsored by the ACS, SAE, ANS, ASME, IEEE, AIAA, and AIChE
San Diego, California, August 25–29, 1986
ABSTRACT

The current status of indium phosphide cell research is reviewed and state of the art efficiencies compared to those of GaAs and Si. It is shown that the radiation resistance of InP cells is superior to that of either GaAs or Si under 1 MeV electron and 10 MeV proton irradiation. Using lightweight blank technology, a SEP array structure and projected cell efficiencies, array specific powers are obtained for all three cell types. Array performance is calculated as a function of time in orbit. The results indicate that arrays using InP cells can outperform those using GaAs or Si in orbits where radiation is a significant cell degradation factor. It is concluded that InP solar cells are excellent prospects for future use in the space radiation environment.

IN THE PAST, indium phosphide solar cells have been of interest largely because of their potential for terrestrial applications. Research activity was primarily directed towards structures such as n-type indium tin oxide on p-type InP (n-ITO/p-InP) (1) and n-type CdS on p-type InP (n-CdS/p-InP) (2). Recently, however, it has been demonstrated that monolithic indium phosphide homojunction cells have properties which make them candidates for use in the space radiation environment (3,4). For example, it has been shown that InP cells have significantly more radiation resistance than either GaAs or silicon cells under 1 MeV electron and 10 MeV proton irradiations (3,4). In addition it has been observed that exposure to light tends to partially remove radiation induced degradation in InP (5). Furthermore the degradation can be removed by annealing at the relatively low temperature of 115 °C. Also since CdS has a band gap of 2.41 eV, a major portion of the solar spectrum is transmitted to the InP. Active area efficiencies as high as 15 percent at air mass 2 have been reported for the n-CdS/p-InP heterojunction cell (9). With respect to ITO/InP, the highest efficiency cell has been produced by Courta and his coworkers (10). Total area efficiencies of 16.2 percent have been reported at AM 1.5 and light intensities of 100 mW/cm². These latter cells were produced by RF sputter deposition of ITO onto a p-type substrate (10). Rather than being a heterojunction ITO/InP cell, it is believed that the cell is an n/p buried homojunction resulting from diffusion of tin into the zinc doped p-type substrate during the sputter deposition process (10). Prior to this, a monolithic InP homojunction cell with reasonable efficiencies was produced by Turner and Fan (11). These latter cells were n++p and were produced by liquid phase epitaxy with total area efficiencies as high as 15 percent. In addition to the preceding, MIS Schottky barrier cells have been fabricated on p-type InP with AM1 efficiencies of 14.5 percent (12).

No air mass zero efficiencies or radiation damage data were reported for the preceding cells. This follows from a primary interest in terrestrial applications. Recently, however, radiation damage data were reported for n/p homojunction cells with excellent results (3,4). These latter cells have achieved AM 1.5 efficiencies of 15 percent (13), and have exhibited radiation resistance superior to both GaAs and silicon under both electron and proton irradiations (3,4). The AMO efficiencies of these n/p homojunction cells have been determined at NASA Lewis (Table 1). Figures 1 and 2 show the I-V curve and spectral response of the highest efficiency cell. Measurements for the various cell types, from other sources, are summarized in Table 2.

The wide variety of solar simulators used and the propensity of some investigators to use active rather than total areas sometimes makes it difficult to compare cell performance. We have found, for example that in converting air mass 1.5 data to air mass zero, cell efficiencies are reduced by 25 percent. Since, for space applications, our interest lies in air mass zero, total area measurements, all of the cell parameters quoted in the remainder of this report will adhere to these conditions.

COMPARISON WITH OTHER CELLS

As mentioned previously, the band gap of InP lies between that of Si and GaAs, hence its theoretical efficiency should lie between the efficiencies of these two cells. This can be seen in Fig. 3 where we have used Loferski’s calculation of efficiency as a function of band gap (7). The figure also includes the highest efficiencies achieved to date for cells shown, i.e., 21 percent for GaAs (14), and 13.6 percent for InP from Table 1. The two values shown for silicon are 18 percent for the low resistivity
maximum power. In this figure, the InP data is present state after 30 yr of R&D while the present efficiency to date should not discourage continued pared to the 2 mil, 10 cm cell. This makes the higher efficiency cell a doubtful candidate for use electron irradiation is shown in Fig. 4, where the R&D on this cell. Silicon cells have reached their thickness and low resistivity, the higher efficiency inherently greater radiation resistance. The fact that InP has the lowest achieved efficiency to date should not discourage continued R&D on this cell. Silicon cells have reached their present state after 30 yr of R&D while the present GaAs cells have been under development for 16 yr. On the other hand, the homojunction 4/0 cell has been the object of 6 yr of extremely low keyed R&D. With increased effort, it is believed that InP cells will achieve efficiencies in the vicinity of 20 percent.

RADIATION EFFECTS

The performance of InP, GaAs and Si under 1 MeV electron irradiation is shown in Fig. 4, where the comparison is made on the basis of normalized cell maximum power. In this figure, the InP data is obtained from Ref. 3, GaAs from Ref. 17, and 2 mil silicon from the radiation handbook (18). The figure clearly shows the superior radiation resistance of InP over the remaining cells. Similar data for 10 MeV proton irradiations are also shown where the InP data is obtained from Ref. 4, the GaAs data from Ref. 19 and the 2 mil silicon data from previously unreported data obtained at NASA Lewis. From the figure, under 10 MeV proton irradiations, the InP cell exhibits radiation resistance which is superior to the remaining cell types.

The data of Fig. 4, for InP, includes the effects of incident light on cell performance, an effect which is illustrated in Fig. 6. The increased output under illumination follows from the cell recovery, due to minority carrier injection, which has been observed under forward bias conditions (20). Since the effect increases with light intensity one would expect greater recovery at air mass zero than was observed in Ref. 5.

The recovery noted under minority carrier injection is one form of annealing. Additional recovery, by heating is also observed at a conveniently low temperature (Fig. 7) (21). In this case, complete recovery at 115 °C is observed after a radiation dose which has reduced cell output essentially to zero. This temperature is low enough so that no irreversible damage to array components would occur if thermal annealing in space were attempted. If thermal annealing in space is impractical, annealing could be accomplished by passing current through the cell under forward bias conditions. On the other hand, thermal annealing becomes practical in space if the cell were used under concentration, an application where the increased light intensity results in cell heating. In this case, the heating could be used to advantage in keeping the cell at a temperature where complete recovery is obtained. Thus, thermal annealing combined with the additional shielding afforded by the concentrator structure could conceivably result in a cell showing no degradation in the space radiation environment.

PROJECTED PERFORMANCE IN SPACE

Considering the present state of the art, GaAs cells would outperform InP in the space radiation environment. However, with an increased R&D effort, InP solar cells can reasonably be expected to achieve efficiencies well above those exhibited by the present day cells. By analogy with the progress attained for GaAs, we assume a projected efficiency of 20 percent for InP under research conditions in the laboratory. Under these conditions, GaAs cells have already achieved AMO efficiencies of 21 percent (14). Noting that these efficiencies are 2 percent below the theoretical values shown in Fig. 3, we assume a projected efficiency of 17 percent for the 2 mil silicon cell. Since these are the projected efficiencies of the best laboratory cells, one anticipates that lower efficiencies will be achieved in production. It is our intent to compare the cells in a solar array where the cells are fabricated on a production rather than a laboratory basis. Hence, in comparing the cells in the space radiation environment we assume projected production efficiencies of 19 percent for GaAs, 18 percent for InP and 15 percent for Si.

As a basis for comparison, we use array specific power, where

\[ P_a = \frac{(n_p \times I \times D)}{n_{BA}} \]

where \( P_a \) is array specific power in W/kg, \( n_p \) is cell efficiency at the temperature \( T \), \( I \) is solar intensity at AMO in W/m², \( D \) is a derating factor which accounts for losses due to packing factor, cell mismatch, diode losses etc. and \( n_{BA} \) is array specific mass in kg/m². Using a lightweight solar cell blanket and a SEP structure (21), we obtain the BOL array specific powers shown in Table 3. In computing these results, we used in all cases, 2 mil silicon cell thickness, 10 mil cover glass, a packing factor of 0.9, a derating factor of 0.8 and 1372 W/m² for the AMO solar intensity. Cell efficiencies at 60 °C were computed using the temperature dependency factor -9.1x10⁻² for Si, -6.4x10⁻² for GaAs and -6.3x10⁻² for InP.

For silicon, estimates of expected performance in space environments are obtained in the usual manner, using the 1 MeV electron damage equivalent fluences from the radiation handbook (18). Although a beginning has been made in obtaining similar 1 MeV damage equivalents for GaAs, the data is incomplete inasmuch as only proton irradiation effects have been considered (22). In the case of InP there is no damage equivalence data available. In view of this, in estimating the effects of radiation on InP and GaAs, for specific space orbits, we use the silicon 1 MeV damage equivalent fluences. This is admittedly an approximation. However, considering the results shown in Figs. 4 and 5, we assume that this procedure yields an upper limit for the 1 MeV electron damage equivalent fluences of the latter two cell types. The results of these calculations, at temperatures of 60 °C for geosynchronous orbit, a mid altitude orbit at 0 °C inclination and an altitude of 6000 NM and a polar orbit at 800 NM are shown in Figs. 8 to 10, respectively. These orbits were chosen using the criterion that radiation induced degradation is a significant loss mechanism. In each case, the projected GaAs array specific power is higher than BOL. However, with increasing time in orbit, the projected InP array specific power becomes significantly greater than the arrays containing either GaAs or Si.

DISCUSSION

The preceding approximate calculations indicate the advantage inherent in using fully developed
ment, are excellent. At present there appears to be
cost reduction is an important factor. At this
point, it is difficult, if not impossible to estimate
ultimate cell costs. However, when used in concentrators, cell
cost is a secondary factor. As mentioned previously, the
reverse is true. In this respect, it is noted that the Ibaraki
cells are fabricated by a closed tube diffusion process while the RPI cells are fabricated by open
tube diffusion (23). It is anticipated that cells
processed in the latter program using base dopant concentrations close to the optimum will yield
efficiencies exceeding those shown in Table 1.

In addition to the need for increased efficiencies, cost reduction is an important factor. At this
stage, it is difficult, if not impossible to estimate
ultimate cell costs. However, past experience indicates that, with increased volume, costs will
decrease. However, when used in concentrators, cell cost is a secondary factor. As mentioned previously, this
could result in a cell which maintains its BOL efficiency in the space radiation environment.

In conclusion, it may be stated that the pros-
pects for use of InP, in the space radiation environ-
ment, are excellent. At present there appears to be no
fundamental barrier to the attainment of efficien-
cies significantly higher than those currently
attained.

REFERENCES

1. K.S. Sree Harsha, K.J. Rachmann, P.H. Schmidt,
E.G. Spencer and F.A. Thiel, "n-Indium Tin
Oxide/p-Indium Phosphide Solar Cells," Appl.
2. T. Wagner, J.L. Shay, K.J. Bachmann and E.
Buehler, "p-Inp/n-Cds Solar Cells and
Photovoltaic Detectors," Appl. Phys. Lett., 46,
3. M. Yamaguchi, C. Uemura, A. Yamamoto and A.
Shibukawa, "Electron Irradiation Damage in
"Potential for use of InP Solar Cells in the
Space Radiation Environment," Proceedings 18th
Photovoltaic Specialists Conf. Las Vegas Nev.
5. K. Ando and M. Yamaguchi, "Radiation Resistance of
6. M. Yamaguchi, C. Uemura and A. Yamamoto,
"Radiation Damage in n-InP Single Crystals and
7. J. Loferski, An Introduction to the Physics of
Solar Cells," pp. 25-49, in Solar Cells, Outlook
for Improved Efficiency, National Academy of
8. P. Rapoport, "Photovoltaic Effect and its
9. M. Bettini, K.J. Bachmann and J.L. Shay,
"CdS/CdTe and CdS/CdTe Heterojunctions by
Chemical-Vapor Deposition of CdS," J. Appl.
Phys., 52, 865-870 (1980).
10. T.J. Contts and S. Nasseem, "High Efficiency
Indium Tin Oxide/Indium Phosphide Solar Cells,"
11. G.W. Turner, J.C. Fan and J.J. Hsieh, "High-
Efficiency InP Homojunction Solar Cells," Appl.
12. K. Kamimura, T. Suzuki and A. Kunioka,
"Metal-Insulator Semiconductor Schottky-Barrier
13. K. Ando-Ibaraki Electrical Communication
Laboratories, Private Communication.
Lewis and R.C. Hamaker, "21% (One Sun, Air Mass
Zero) 4 cm GaAs Space Solar Cells," Appl.
15. M. Green, Private Communication: and A.W.
Blakers and M.A. Green, "20% Efficiency Silicon
(1985).
16. G. Storti, J. Wohlgemuth and C. Wrigley, "Thin
Cells For Space," pp. 81-94 in Solar Cell High
Efficiency and Radiation Damage, NASA CP-2059,
1979.
17. J.C. Fan, G.W. Turner, R.P. Gale and C.G.
Bozler, "GaAs Shallow-Homojunction Solar
Cells," pp. 1102-1105 in 14th IEEE Photovoltaic
Specialists Conference," San Diego, CA,
1980.
18. H.Y. Yada, J.R. Carter, Jr., B.E. Anspaugh and
R.C. Downing, Solar Cell Radiation Handbook, 3rd
Edition, JPL Publication 82-69, Jet Propulsion
Lab, Pasadena, CA, 1982.
"Performance and Temperature Dependencies of
Proton Irradiated n/p and p/n GaAs and n/p
Silicon Cells," 18th IEEE Photovoltaic
Specialist Conf. Las Vegas Nev. Oct, 21-25,
1985.
20. M. Yamaguchi, K. Ando, A. Yamamoto and C.
Uemura, "Minority-Carrier Injection Annealing of
Electron Irradiation-Induced Defects in InP
21. J. Scott-Monck, "Progress in Developing High
201-109, in Space Photovoltaic Research and
22. B.E. Anspaugh and R.C. Downing, "Radiation
Effects in Silicon and Gallium Arsenide Solar
Cells Using Isotropic and Normally Incident
IEEE Photovoltaic Specialists Conference,
1984.
23. S. Chandhi, P. Borrego and R.K. Parat, RPI,
Private Communication.
24. A. Yamamoto, M. Yamaguchi and C. Uemura,
"High Conversion Efficiency n-p Junction Indium
Digest of the 1st International Photovoltaic
Science and Engineering Conference, Secretariat of
the International PVSEC-1, Tokyo, Japan, 1984.
Table 1 - Air Mass Zero InP Cell Parameters-n/p Homojunction Cells

<table>
<thead>
<tr>
<th>Base dopant concentrations, cm⁻³</th>
<th>Efficiency, percent</th>
<th>Voc, mV</th>
<th>Jsc, ma/cm²</th>
<th>FF, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>4x10⁵</td>
<td>13.6</td>
<td>826</td>
<td>25.8</td>
<td>81.7</td>
</tr>
<tr>
<td>10¹⁶</td>
<td>11.4</td>
<td>818</td>
<td>24.5</td>
<td>78</td>
</tr>
<tr>
<td>10¹⁷</td>
<td>10.1</td>
<td>812</td>
<td>22.6</td>
<td>78</td>
</tr>
<tr>
<td>4.6x10¹⁶</td>
<td>12.9</td>
<td>815</td>
<td>26.3</td>
<td>82.6</td>
</tr>
</tbody>
</table>

aMeasurements performed at NASA Lewis.
bCells obtained from Ibaraki, ECL-Japan.
cCells obtained from S. Ghandi (RPI), Ref. 23.
dEfficiencies based on total cell area.

Table 2 - InP Cell Parameters Measured at Other Than Air Mass Zero

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Source</th>
<th>Air mass</th>
<th>Efficiency, percent</th>
<th>Voc, mV</th>
<th>Jsc, ma/cm²</th>
<th>FF, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>n/p homojunction</td>
<td>Ibaraki ECL</td>
<td>1.5</td>
<td>b18.6</td>
<td>833</td>
<td>27.7</td>
<td>81</td>
</tr>
<tr>
<td>ITO/InP (n/p)</td>
<td>Ref. 10</td>
<td>1</td>
<td>b15.8</td>
<td>768</td>
<td>26.9</td>
<td>76.7</td>
</tr>
<tr>
<td>n-CdS/p-InP</td>
<td>Ref. 9</td>
<td>2</td>
<td>c15</td>
<td>780</td>
<td>18.7</td>
<td>73.5</td>
</tr>
<tr>
<td>n⁺/p⁺/p⁺</td>
<td>Ref. 11</td>
<td>1</td>
<td>15</td>
<td>780</td>
<td>26.5</td>
<td>71.5</td>
</tr>
<tr>
<td>MIS</td>
<td>Ref. 12</td>
<td>2</td>
<td>14.5</td>
<td>739</td>
<td>17.8</td>
<td>79</td>
</tr>
</tbody>
</table>

aEfficiencies and short circuit currents based on total cell area except when otherwise noted.
bLight intensity = 100 mW/cm².
cBased on active area.

dEfficiencies based on total cell area.

dEfficiencies based on total cell area.

Table 3 - Projected Array Specific Powers at BOL

<table>
<thead>
<tr>
<th>Cell</th>
<th>Projected BOL cell efficiencies</th>
<th>Projected BOL array spec power, a W/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25 °C</td>
<td>60 °C</td>
</tr>
<tr>
<td>InP</td>
<td>18</td>
<td>16.4</td>
</tr>
<tr>
<td>Gas</td>
<td>19</td>
<td>17.9</td>
</tr>
<tr>
<td>Si</td>
<td>15</td>
<td>12.7</td>
</tr>
</tbody>
</table>

a2 mil cell, 10 mil cover glass.
Figure 1. - I-V curve of InP cell.

Figure 2. - Spectral response of InP cell.
Figure 3. - Predicted and achieved AM0 efficiencies.

Figure 4. - Normalized maximum power versus 1 MeV Electron Fluence.
Figure 5. - Normalized maximum power versus 10 MeV Proton Fluence.

Figure 6. - Radiation damage removal in InP by incident light.
Figure 7. - Radiation damage removal in InP by low temperature heating.

Figure 8. - Array specific power versus time in orbit.
Figure 9. - Array specific power versus time in orbit.

Figure 10. - Array specific power versus time in orbit.
**Title and Subtitle**

Indium Phosphide Solar Cells - Status and Prospects for Use in Space

**Author(s)**

Irving Weinberg and David J. Brinker

**Abstract**

The current status of indium phosphide cell research is reviewed and state of the art efficiencies compared to those of GaAs and Si. It is shown that the radiation resistance of InP cells is superior to that of either GaAs or Si under 1 MeV electron and 10 MeV proton irradiation. Using lightweight blanket technology, a SEF array structure and projected cell efficiencies, array specific powers are obtained for all three cell types. Array performance is calculated as a function of time in orbit. The results indicate that arrays using InP cells can outperform those using GaAs or Si in orbits where radiation is a significant cell degradation factor. It is concluded that InP solar cells are excellent prospects for future use in the space radiation environment.