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P/N InP SOLAR CELLS ON Ge WAFERS

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SUMMARY

Indium phosphide (InP) P-on-N one-sun solar cells were epitaxially grown using a metalorganic chemical vapor deposition process on germanium (Ge) wafers. The motivation for this work is to replace expensive InP wafers, which are fragile and must be thick and therefore heavy, with less expensive Ge wafers, which are stronger, allowing use of thinner, lighter weight wafers. An intermediate $In_xGa_{1-x}P$ grading layer starting as $In_{0.49}Ga_{0.51}P$ at the GaAs-coated Ge wafer surface and ending as InP at the top of the grading layer (backside of the InP cell) was used to attempt to bend some of the threading dislocations generated by lattice-mismatch between the Ge wafer and InP cell so they would be harmlessly confined in this grading layer. The best InP/Ge cell was independently measured by NASA-Lewis with a one-sun 25°C AM0 efficiency of 9.1%, open-circuit voltage of 790 mV, fill-factor of 70%, and short-circuit photocurrent 22.6 mA/cm^2. We believe this is the first published report of an InP cell grown on a Ge wafer.

Why get excited over a 9% InP/Ge cell? If we look at the cell weight and efficiency, a 9% InP cell on an 8 mil Ge wafer has about the same <u>cell</u> power density, 118 W/kg (BOL), as the best InP cell ever made, a 19% InP cell on a 18 mil InP wafer, because of the lighter Ge wafer weight. As cell panel materials become lighter, the cell weight becomes more important, and the advantage of lightweight cells to the <u>panel</u> power density becomes more important.

In addition, although InP/Ge cells have a low beginning-of-life (BOL) efficiency due to dislocation defects, the InP/Ge cells are very radiation hard (end-of-life power similar to beginning-of-life). We have irradiated an InP/Ge cell with alpha particles to an equivalent fluence of 1.6 x 10^{16} 1 MeV electrons/cm^2 and the efficiency is still 83% of its BOL value. At this fluence level, the power output of these InP/Ge cells match the GaAs/Ge cell data tabulated in the JPL handbook. Data are presented indicating InP/Ge has more power output than GaAs/Ge cells at fluences in excess of this value.

INTRODUCTION

The cost, weight, and fragility of InP wafers have impeded InP cell use in space. Therefore, InP cells on light, strong, inexpensive silicon (Si) or Ge wafers are of great interest (ref. 1). This paper reports the results of a Phase I Small Business Innovative Research program seeking to replace the InP wafer on which the InP solar cell is epitaxially grown with a Ge wafer which has better properties (Table I). Since InP is fragile, thick ~16 to 20 mil wafers are required for strength. Ge has become a leading substrate for GaAs space solar cells, and is inexpensive if bought in large quantities. Although the density of Ge (5.3 g/cm^3) is similar to InP, Ge is stronger and therefore a thinner Ge wafer than InP wafer can be used to increase the power density (W/kg) and lower the launch weight.

Table I *Comparison of III-V Space Cells on InP and Ge wafers.*

	InP Cell on Ge Wafer	InP Cell on InP Wafer	GaAs Cell on Ge Wafer
High-Volume Wafer Cost ($/2" wafer)	20-50	180-250	20-50
Wafer Density (g/cm^3)	5.32	4.81	5.32
Wafer Strength	Strong	Fragile	Strong
Typical Thickness (mils)	8	18	8
Wafer Weight (g/cm^2)	0.108	0.220	0.108
One-sun AM0 BOL Efficiency	9% (NASA)	18% (Typical)	18% (Typical)
BOL Cell Power Density (W/kg)	114 (Phase I)	112	229
AM0 EOL (10^{16} 1MeV e/cm^2) Efficiency	8% (Spire data)	12% (Spire data)	6% (JPL Handbook)
EOL Cell Power Density (W/kg)	102	75	76

InP cells have more defects when grown on Ge wafers, due to differences in crystal lattice constants of InP (5.87Å) and Ge (5.66Å). This lattice constant mismatch is 3.7% between InP and Ge. Mechanical stress in the InP film grown on the substrate is relieved through the formation of dislocation defects in the InP film. The dislocations act as recombination centers, and resulting in a lower beginning-of-life (BOL) efficiency for InP heteroepitaxial cells (~10%) on Ge wafers than InP cells (~20%) on InP wafers. However, the lower BOL efficiency of InP heteroepitaxial cells is compensated by the lighter weight of Ge wafers compared to InP wafers (Table I), so that the BOL power densities for InP/Ge and InP/InP are similar, and we expect a higher end-of-life (EOL) power density from these InP/Ge cells compared to GaAs or Si cells at high fluences.

The P/N InP/Ge cells have lower BOL efficiencies than Spire's InP cell record efficiency 19% N/P InP cells grown on InP wafers. However, we predict EOL efficiencies after high fluences will be similar for these two InP cell types, since radiation damage will dominate the diffusion lengths in both cell types, instead of dislocations dominating the diffusion length in InP/Ge cells, leading to similar EOL efficiencies in both types. Therefore, because of their lighter weight, InP/Ge cells should have an EOL power density about twice that of InP homojunction cells.

N-on-P InP-on-Si cells were investigated by Spire (ref. 2) with one-sun AM0 efficiencies of 9.9% the highest reported to date (ref. 3). Our Phase II goal in this program is to achieve 15% BOL efficiencies for P-on-N InP-on-Ge cells. We plan to work on lowering the dislocation density through an improved $In_xGa_{1-x}P$ grading technique between the Ge wafer and the InP cell. By using a P/N design, the need for a tunnel junction in N/P heteroepitaxial InP cell designs is eliminated. The

tunnel junction is necessary in N/P designs due to outdiffusion of Si or Ge, N-type MOCVD dopants, from the Si or Ge wafers into the back P-layers of the N/P cell. P-on-N InP cells may more radiation resistant than even InP N-on-P cells, leading to higher EOL efficiencies (ref. 4). InP cells were grown on GaAs (ref. 5) at NREL with efficiencies of 14% BOL at one-sun AM0 (ref. 6).
The NREL work shows that a 14% BOL efficiency can be achieved in a heteroepitaxial cell with significant dislocations. The dislocation density in the 9.9% AM0 Spire InP/Si cells is 10x higher than in the NREL work. If we can reduce the dislocation density in our InP-on-Ge cells to the level achieved by NREL in its InP-on-GaAs work, a similar efficiency to the NREL work should be achieved, since Ge (5.66Å) and GaAs (5.65Å) have similar lattice constants. The 15% Phase II InP/Ge goal therefore seems reasonable.

The power density of P-on-N InP/Ge cells at this early stage is already similar to the best N-on-P InP cells on InP wafers, which have undergone much more development. Beginning-of-life efficiency (9% AM0) of the P/N InP/Ge cells is limited partly by the new P-on-N InP cell technology used for the first time in Phase I. We are now making 17% P/N InP cells on InP wafers, but at the time of this program effort the P-on-N InP control cells on InP wafers, our first, had reached only 12% efficiency, mainly due to too thick (~2000Å) an emitter layer, compared to the 19% N-on-P InP cells on InP wafers with 300Å emitters achieved after long development. As the performance of the P/N InP cell on InP wafer baseline technology increases, so should the InP/Ge cell performance since we would be starting out with a higher efficiency InP cell on the Ge wafer. It is important to realize that the best efficiency the Phase I InP/Ge cells could possibly have is the ~12% efficiency of the control P/N InP cells on InP wafers. The BOL efficiency of the InP/Ge cell at time of the program was substantially limited by the P/N InP cell technology. This P/N InP cell technology should be improvable to levels approaching 20%.

CELL STRUCTURE

Table II shows the target epilayer structure used for the Phase I InP/Ge cells.

Table II *Epilayer structure of P-on-N InP cell on Ge substrate.*

Layer	Material	Doping cm^{-3}	Thickness μm	Comments
Contact Cap	InGaAs	P, $\sim 10^{19}$, Zn	0.3	InGaAs is selectively etched from photoarea, but left under front grid metal to form ohmic contact
Emitter	InP	P, $\sim 10^{18}$, Zn	0.2	Thickness tradeoff - thin better for QE; thick better for low resistance
Base	InP	N, $\sim 10^{17}$, Si	1.5	1.5 μm absorbs > 95% of AM0 light
Back Surf. Field	InP	N, $\sim 10^{19}$, Si	0.5	Reflects minority carrier holes, enhances QE
$In_xGa_{1-x}P$ Grading	InP to $In_{0.49}Ga_{0.51}P$	N, 10^{19}, Si	8	Lowers dislocation density due to InP/Ge lattice-mismatch
Nucleation	GaAs	N, 10^{19}, Si	1	Easier to grow on GaAs
Substrate	Ge	N, 10^{17}, Sb	300	Eagle-Picher epi-ready Ge wafers

The epilayers are grown by MOCVD using trimethylindium, triethylgallium, and phosphine at 76 torr and a low temperature, 600°C, to limit zinc diffusion and emitter junction depth. Dimethylzinc is being used for all P-type and silane for N-type doping, respectively. With an InP P/N cell design, we desire a thin emitter to limit surface recombination loss and increase photocurrent; on the other hand, the emitter must be thick enough so that along with increased cell gridline coverage (4% shadow loss), a reasonable emitter sheet resistance I^2R loss is obtained, compensating for the low maximum P-InP emitter doping (~10^{18} cm^{-3}, ~10X lower than N-InP) and mobility (~20X lower than N-InP) of the P-InP emitter.

A P/N design is used to avoid a tunnel junction present in N/P designs. Germanium is an N-type dopant in III-V semiconductors in the metalorganic chemical vapor deposition (MOCVD) process, outdiffuses from the Ge wafer during epigrowth into the back of the cell. In an N/P design, Ge would create an opposing P/N junction in the P-type back layers of the cell. This parasitic junction must be a tunnel junction for the cell to pass current, increasing complexity in N/P cell designs. In a P/N design, the back N-type doping is simply increased by the Ge diffusion and is of little concern; no tunnel junction is needed. In addition, various NASA-Lewis papers indicate P/N InP cells may eventually be more efficient than N/P cells due to higher obtainable open-circuit voltages and amenability to surface passivation.

A high density of defects, mainly dislocations, form in the material to accommodate the lattice-mismatch (3.7%) between InP and Ge. If these defects thread upward into the cell through the junction, they increase the dark current and act as minority carrier recombination sites, lowering the cell efficiency. For lattice-mismatched heteroepitaxial cells, grading layers are used to attempt to bend the threading dislocations harmlessly away parallel to the plane of the cell junction. In this program we used an $In_xGa_{1-x}P$ grading layer starting with $In_{0.49}Ga_{0.51}P$ lattice-matched to the GaAs-coated Ge wafer and ending with InP. This grading layer will be discussed more fully in future publications concerning InP/Si solar cells.

PRE-IRRADIATION CELL DATA

Table III shows verified (courtesy of I. Weinberg and D. Brinker of NASA-Lewis) preirradiation InP/Ge cell data of similar P/N InP cells on InP, GaAs, and Ge wafers. The 11.9% control cells on InP wafers represent an upper limit of what the InP cells on Ge could achieve at the time of the program. Recently 17% P/N InP cells on InP were made, so that if the new InP cell growth parameters were used, a higher InP/Ge cell efficiency would be obtained than presented in this paper. Series resistance from I-V data for all Phase I cells was ~0.5 Ω-cm², causing ~10 mV drop in V_{MAX} for the ~20 mA/cm² photocurrent. The series resistance is dominated by the emitter sheet resistance. If we half the emitter thickness, we will double the series resistance.

Table III *AM0 one-sun data of Spire Phase I cells.*

All one-sun AM0 25°C pre-irradiation Comments	η %	V_{OC} mV	J_{SC} mA/cm²	FF %	Cell ID
P/N InP cell on InP wafer (control)	11.9	848	22.9	84.2	5668-2626-2-8
P/N InP cell on 8 µm InGaP grade on GaAs-coated Ge wafer (NASA-Lewis verified measurement)	9.1	792	22.6	69.8	5714-2795-1-8

CELL IRRADIATION

A second P/N InP/Ge cell, of a slightly lower BOL efficiency (7.5%) than the best cell shown in Table III was mounted in a special test fixture for the destructive alpha irradiation test (equipment courtesy of C. Blatchley and C. Colerico of Spire). An Am-241 alpha particle source was used to irradiate the cells to explore how performance varies with radiation damage. Equivalent 1 MeV electron exposures were determined by a non-ionizing energy loss (NIEL) calculation (ref. 7) for the alpha source for a 1.5 cm separation between the 1 cm^2 InP/Ge cell centered under the alpha source in vacuum. The calculation included effects of the angular incidence of particles at the cell edges offset from the centerline, so that the divergence of the alpha particle beam from its 0.5 cm aperture was taken into account. The alpha particle energy in the InP at the depth of interest is 3.643 MeV and the calculated NIEL value is 0.29 MeV-cm^2/g. The equivalent 10 MeV proton flux is 4.18×10^7 protons/ cm^2-s. The equivalent 1 MeV electron flux is 3.55×10^{10} electrons/cm^2-s or 1.28×10^{14} electrons/ cm^2-hour. AM0 efficiency data and quantum efficiency data were taken before irradiation, and after 1, 8, 32, and 126 hours. The final 126 hour data set was equivalent to a fluence of 1.6×10^{16} 1 MeV electrons/ cm^2. One of the advantages of using the alpha source for these experiments is that it is possible to obtain high equivalent electron fluences in short times due to higher damage rate of the four heavy nuclei (two proton, two neutron) of the alpha particles versus the lighter electrons. AM0 data for this cell is at various fluences is shown in Table IV and Figure 1.

Table IV *InP/Ge cell (7.5% BOL) one-sun 25°C AM0 data at various equivalent electron fluences.*

(Alpha particle irradiation) Equivalent # of 1 MeV electrons/cm^2	η %	V_{OC} mV	J_{SC} mA/cm^2	FF %
1.3×10^{14}	7.5	774	23.4	57.1
1.0×10^{15}	7.4	768	23.5	56.2
4.1×10^{15}	7.0	751	22.7	56.8
1.6×10^{16}	6.3	708	21.6	56.8

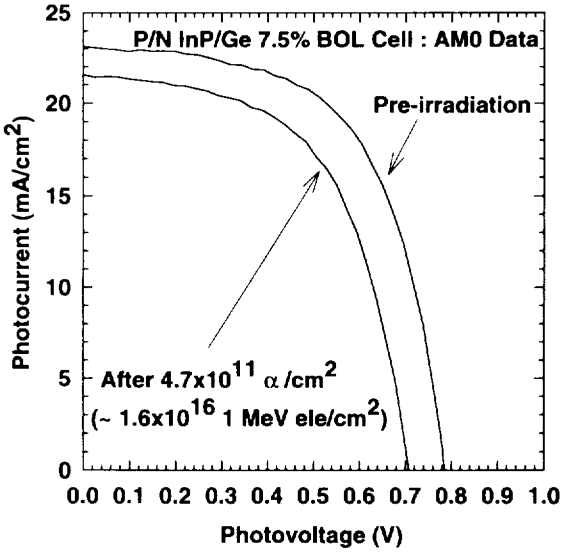

Figure 1 *AM0 I-V curves of an InP/Ge cell before and after alpha irradiation.*

Figure 2 shows measured absolute quantum efficiency of the cell before irradiation and after the maximum irradiation. As expected, most of the photocurrent loss seen in Figures 1 and 2 is due to lower quantum efficiency at the longer wavelengths, which are absorbed further from the cell junction and must diffuse to the junction to be collected. The radiation damage lowers the base (hole) diffusion lengths in these P/N cells slightly, as seen in Figure 2 near the InP cutoff wavelength (920 nm). The quantum efficiency at shorter wavelengths is affected very little, since, even though the diffusion lengths are lower in the emitter also, the emitter thickness (0.2 μm) is still small compared to the emitter (electron) diffusion lengths (~1 μm).

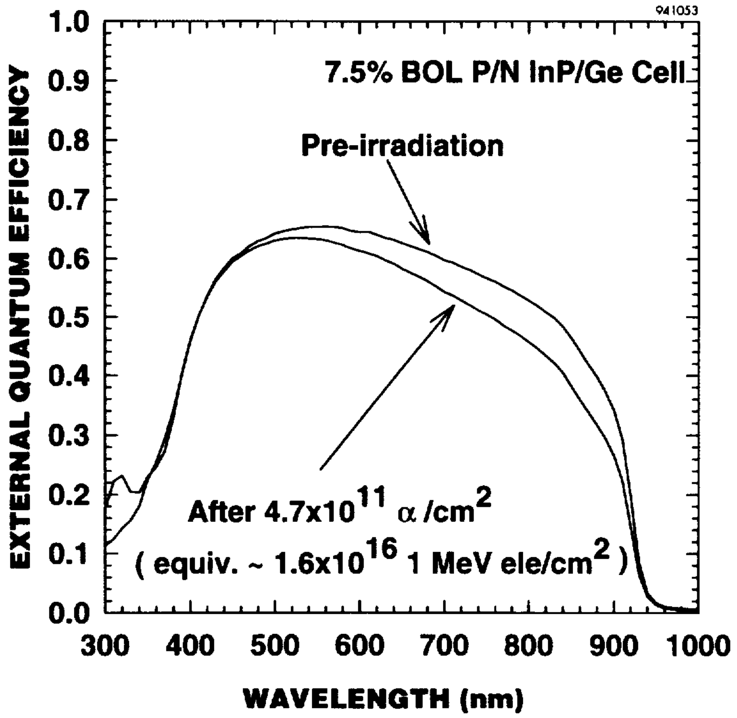

Figure 2 *Absolute quantum efficiency of 7.5% BOL InP/Ge cell before and after irradiation. Drop in longer wavelength QE indicates lower base diffusion lengths.*

CONCLUSIONS

We have presented experimental data on P/N InP/Ge solar cells which indicate that this technology is promising for space power use in long space missions or in very high radiation orbits. The use of Ge wafers eliminates the need for costly, fragile, heavy, InP wafers. Even in its primitive current state of development, these 9% BOL InP/Ge cells appear to have higher power output and cell power density than either 19% BOL InP cells on InP wafers or 18% BOL GaAs cells on Ge wafers after a fluence of ~10^{16} electrons/cm^2 (Figure 3). Future work would center on increasing the InP/Ge cell performance so that it could compete with GaAs/Ge cells for space missions that do not require extreme radiation resistance.

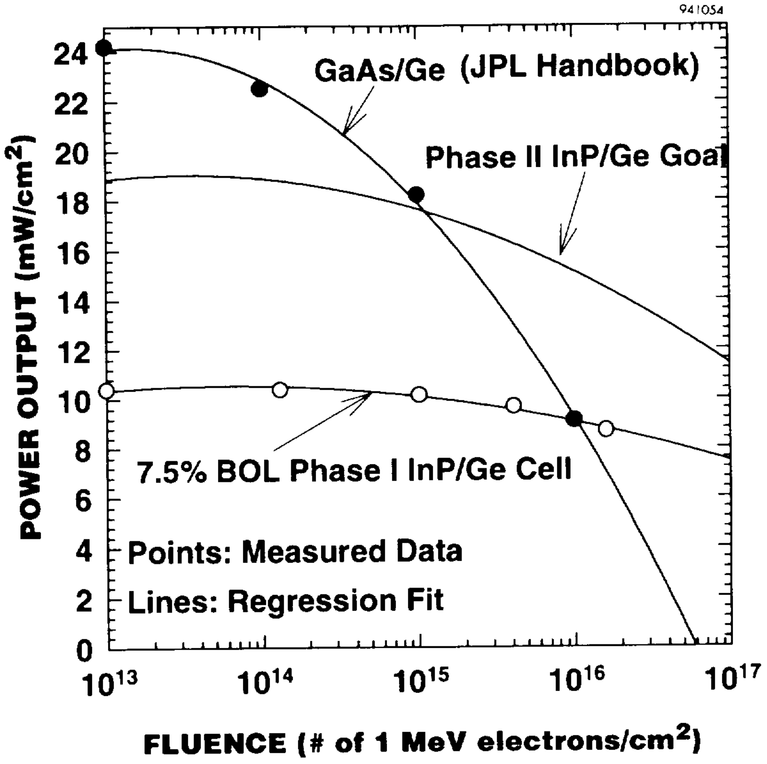

Figure 3 *Measured AM0 power output versus electron fluence for P/N GaAs/Ge cells (from JPL Solar Cell Handbook) and P/N InP/Ge cells (this work). Points are measured data; lines through points are simple 2nd-order polynomial regression fit. Line labeled Phase II is simply a goal and is not measured data. This plot shows that even the primitive Phase I InP/Ge cells have more power output after a fluence of 10^{16} electrons/cm^2 than the current mainstay GaAs/Ge cells. However, this fluence is very high, and is likely only in high radiation (van Allen belt) orbits or for very long (~10 year or more) missions in more standard orbits. The Phase II goal shown indicates the point where these InP/Ge cells could compete with GaAs/Ge for more standard, low radiation missions.*

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SESSION II

THIN-FILM AND HIGH EFFICIENCY CELL DEVELOPMENT