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Performance, Size, Mass and Cost Estimates for Projected 1KW EOL Si, InP and GaAs Arrays

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Introduction

One method of evaluating the potential of emerging solar cell and array technologies is to compare their projected capabilities in space flight applications to those of established Si solar cells and arrays. Such an application-oriented comparison provides an integrated view of the elemental comparisons of efficiency, radiation resistance, temperature sensitivity, size, mass and cost in combination. In addition, the assumptions necessary to make the comparisons provide insights helpful toward determining necessary areas of development or evaluation. Finally, as developments and evaluations progress, the results can be used in more precisely defining the overall potential of the new technologies in comparison to existing technologies. This paper compares the projected capabilities of Si, InP and GaAs cells and arrays.

Cell Characteristics

Si, InP and GaAs cell efficiencies are compared in Table I. A small range is given for the theoretical limit and for typical production since various sources give slightly different values. The projected efficiencies are those used for the calculations in this paper. It was assumed that there will be more near-term improvement in the InP cells than in the others because it is a less mature technology.

Radiation effects on current cells are shown in Table II. The results are calculated from Reference 1 for the proton irradiation and for the 1×10^{15} electron irradiation. The 3×10^{15} electron irradiation data are from Reference 2.

Table III shows the projected EOL efficiencies for radiation of 3×10^{15} e/cm^2 (1 Mev equivalent) calculated from Tables I and II. This assumes that relative damage coefficients are similar for the three cell types. This fluence level was selected to take advantage of the radiation resistance characteristics of the InP and GaAs cells.

The variation of peak power (P) with temperature (T) for the cells is shown in Table IV. The calculations were based on data from Reference 2. The InP and GaAs cells show less sensitivity to temperature than the Si cells primarily because their open circuit voltages are significantly higher while their temperature coefficients are similar.

The mass for 2×4 cm cells is shown in Table V. The cell thickness used for the cells is different because of differences in fragility. As a result the mass of the cells reflects both the differences in material density and the differences in cell thickness. As can be seen, the cell mass for InP and GaAs cells is projected to be significantly higher than for Si cells.

Cell costs for 2 × 4 cm cells in quantities necessary to produce 1 kw EOL power were estimated using typical, proprietary production cost estimating procedures, including effects of mechanical and electrical yield. The results are shown in Table VI. As shown, the wafer or substrate price for InP and GaAs cells is a significant fraction of the cell cost.

Array Characteristics

The projected cell characteristics were used to estimate the size, weight and cost for Si, InP and GaAs solar arrays with a 1 kw EOL power capability. Details are shown in Table VII. It was assumed that the arrays were oriented and that the degraded Si array temperature was 60°C. The temperatures of the InP and GaAs arrays were then calculated according to the equation:

[1] $$(T_1/T_2)^4 = (\alpha_1 - F_1\eta_1)/(\alpha_2 - F_2\eta_2).$$

where
T is the absolute operating temperature
α is the absorptivity
F is the packing factor (assumed to be 0.9)
η is the operating (EOL) efficiency
and subscripts 1 and 2 refer to the two cell types.

For these calculations the absorptivity was taken as 0.75 for Si and 0.78 for GaAs as given in Reference 3. The absorptivity for InP was assumed to be 0.78, the same as for GaAs. Array temperatures of 55°C and 58°C were calculated for the InP and GaAs arrays respectively as shown in Table VII.

The estimate of orbital degradation included radiation degradation due to 3 × 10^{15} e/cm^2 (1 Mev equivalent), ten year ultraviolet degradation of 4% and thermal cycle losses, expected to increase with cell fragility. Assembly losses of 3%, 2% for cell mismatch and 1% for interconnection, were also included. Glassing losses were assumed to be negligible.

From these, the beginning of life (BOL) power requirements were calculated and the cell requirements were determined. The array area was determined for an assumed packing factor of 0.9. Array mass was then calculated for flexible arrays assuming a mass of 1.0 kg/m^2 excluding cells, and for a rigid array assuming a mass of 2.5 kg/m^2 excluding cells.

Finally, array costs were estimated for the rigid arrays using typical proprietary production cost estimating procedures. Again, effects of mechanical and electrical yield were included. Cost estimates were not made for the flexible arrays because of the paucity of available background data. The cost estimates for the rigid arrays are shown as relative costs in Table VIII to protect their proprietary nature.

Discussion and Conclusion

The overall results are summarized in Table VIII. It is projected that array area requirements will be significantly lower, by almost a factor of 2, for InP and GaAs arrays compared to Si arrays. This could result in significant reductions in requirements for spacecraft orientation and station keeping propulsion systems. The savings in array mass due to the smaller area; however, is largely lost for lightweight flexible arrays because of the higher cell mass of InP and GaAs cells compared to Si cells. Nevertheless, there is some savings, about 15%, anticipated for InP arrays. For rigid arrays, where the cell mass is a smaller fraction of the array mass, the savings become more significant, about 30% for InP and 20% for GaAs compared to Si. These factors are important to launch capability and cost, or, alternatively, the savings can be passed on to spacecraft instruments.

The cost per EOL watt is estimated to be higher by a factor of 6 for the InP array and by a factor of 3 for the GaAs array than for the Si array. These are major considerations since cost is a driving factor in most solar array procurements. Justification for these costs would have to come at the spacecraft and mission level which is beyond the scope of this paper.

In the process of developing these estimates, the need for several areas of technology development and evaluation became apparent. These include:

1. Development of cells to meet projected performance levels,
2. Increase in strength and reduction of mass of InP and GaAs cells by using alternative substrates such as GaAs on Ge as is underway,
3. Reduction of wafer cost, especially for InP,
4. Broad radiation damage studies for InP and GaAs cells to permit accurate engineering calculations of in-flight degradation,
5. Experimental determination of InP and GaAs solar cell temperature characteristics for both new and degraded cells,
6. Development and characterization of stable contacts and coatings, especially for InP cells,
7. Determination of absorptivity and emissivity of InP cells.

References

[1.] I. Weinberg, C.K. Swartz, and R.E. Hart, *Conference Record of the 18th IEEE Photovoltaic Specialists Conference*, 1722, IEEE, New York (1985).

[2.] I. Weinberg, C.K. Swartz, R.E. Hart, and R.L. Statler, *Record of the 19th Photovoltaic Specialists Conference*, 548, IEEE, New York (1987).

[3.] Michael W. Mills and Richard M. Kurland, *Proc. Space Photovoltaic Research and Technology Conference*, 117 (1988).

TABLE I. CELL EFFICIENCY (% AT AMO, 25° C)

Cell Type	Theoretical Limit	Typical Production	Projected Production
Si	18-21	15-15.5	15.5
InP	21-22	16-17	19.0
GaAs	23-25	19-20	20.0

TABLE II. RADIATION EFFECTS ON CURRENT CELLS
(Eff./Initial Eff. at AMO, 25° C)

Cell Type	After 10^{12}p/cm^2	After 10^{15}e/cm^2	After 3x10^{15}e/cm^2
Si	.593	.673	.57
InP	.922	.939	.85
GaAs	.805	.779	.68

Note: Protons (p) 10 Mev
Electrons (e) 1 Mev

TABLE III. PROJECTED END OF LIFE EFFICIENCY
(% AT AMO, 25° C)

Cell Type	Initial Efficiency	EOL After 3x10^{15}e/cm^{2}eq.
Si	15.5	8.8
InP	19.0	16.2
GaAs	20.0	13.6

Note: Assumes similar 1 Mev electron equivalencies.

TABLE IV. VARIATION OF PEAK POWER WITH TEMPERATURE

Cell Type	Efficiency (%)	P/A (mw/cm^2)	dP/AdT ($mw/cm^{2}°C$)	dP/PdT (%/°C)
Si	15.5	21.0	- 0.092	- 0.438
InP	19.0	25.7	- 0.053	- 0.206
GaAs	20.0	27.1	- 0.044	- 0.162

TABLE V. MASS OF TYPICAL 2 CM X 4 CM CELLS

Wafer Material	Density (gm/cm^3)	Thickness (cm)	Substrate Mass (gm)	Cell Mass(gm)[1]
Si	2.328	0.0203	0.378	0.438
InP	4.787	0.0356	1.363	1.423
GaAs	5.316	0.0305	1.297	1.357

[1] Metallization and coating = 0.060 gm/cell.

TABLE VI. ESTIMATE OF 2 CM X 4 CM CELL COST

Cell Type	Wafer Size(mm)	Wafer Price($)	Substrates Per Wafer	Price per Substrate($)	Cost per Cell ($)
Si	100(d.)	5.50	6	0.92	12
InP	60(d.)	256.00	2	128.00	440
GaAs	45(sq.)	60.00	2	30.00	155

TABLE VII. PERFORMANCE, SIZE AND MASS ESTIMATES FOR 1KW EOL ARRAYS

	Si	InP	GaAs
EOL Power (w)	1000	1000	1000
EOL Temperature (°C)	60	55	58
EOL Power at 25° C (w)	1181	1066	1056
Orbital Losses (%)			
Radiation Damage	43	15	32
UV Degradation	4	4	4
Thermal Cycle Effects	2	5	4
Total	49	24	40
BOL Power at 25° C(w)	2316	1403	1760
Assembly Losses (%)	3	3	3
Total Cell Power (w)	2388	1446	1814
Cell Efficiency (%)	15.5	19.0	20.0
Cell Output (mw)	167.8	205.6	216.4
Cells Required	14231	7033	8383
Array Area (m^2)	12.65	6.25	7.45
Cell Mass (kg)	6.233	10.008	11.375
Flexible Array Mass (kg)	18.88	16.26	18.83
Rigid Array Mass (kg)	37.86	25.63	30.00

TABLE VIII. SUMMARY OF RESULTS

	Si	InP	GaAs
EOL Power at T (w)	1000	1000	1000
BOL Power at 25° C (w)	2316	1403	1760
Array Area (m^2)	12.65	6.25	7.45
EOL Power Density (w/m^2)	79	160	134
BOL Power Density (w/m^2)	183	224	236
Flexible Array:			
Mass (kg)	18.88	16.26	18.83
EOL Specific Power (w/kg)	53	62	53
BOL Specific Power (w/kg)	123	86	93
Rigid Array:			
Mass (kg)	37.86	25.63	30.00
EOL Specific Power (w/kg)	26	39	33
BOL Specific Power (w/kg)	61	54	59
Relative Cost Per Watt EOL	1.00	6.14	2.88
Relative Cost Per Watt BOL	1.00	10.14	3.79