

SOLAR ARRAY TRADES BETWEEN VERY HIGH-EFFICIENCY MULTI-JUNCTION AND Si SPACE SOLAR CELLS

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ABSTRACT

This paper describes a trade study between state-of-the-art, commercially-available very high-efficiency III-V multi-junction solar cells and advanced high-efficiency silicon cells at the bare cell and panel levels. The solar cell technologies in this comparison will be high-efficiency rad-hard 3-mil Si, dual-junction InGaP/GaAs (on Ge), and triple-junction InGaP/GaAs/Ge, with the beginning-of-life (BOL) efficiencies of 17%, 23%, and 26%, respectively. Two different typical orbits will be considered: geosynchronous (GEO) and low-earth (LEO) orbits. It will be assumed that the end-of-life (EOL) conditions for GEO and LEO will be equivalent to degradation due to 1-MeV electrons at $5E14$ and $1E15$ e/cm^2 , respectively. Parameters critical to conventional rigid solar arrays such as specific power/mass (W/Kg), specific mass/area (Kg/m^2), specific power/area (W/m^2), and normalized end-of-life (EOL) $\$/W$ will be compared for these cell technologies.

INTRODUCTION

Historically, the need for power in space has been dominantly provided by silicon solar cells. In the past several years, however, high-volume manufacturing of high-efficiency multi-junction solar cells has enabled the use of this alternative technology for space power generation [1-3]. Compared to Si, multi-junction cells are more radiation resistant and have greater energy conversion efficiencies, but they are also heavier (higher density and thickness) and cost more. When the need for very high power or smaller solar arrays are paramount in a spacecraft, multi-junction cells are often used instead of, or in hybrid combinations with, Si to reduce the array size. Very large solar arrays, for example, pose a difficult challenge for the attitude control systems onboard a typical satellite.

Several trade studies have been published in the past comparing the performance, cost, weight, area, etc. of different solar cell technologies for space applications [4-7]. Since then however, both multi-junction and silicon cell technologies have improved in three significant ways: conversion efficiency, radiation resistance, and cost. High-efficiency rad-hard 3-mil Si solar cells, for example, exhibit beginning-of-life (BOL)

efficiencies averaging about 17%, under one-sun, air-mass zero (AM0) illumination conditions [8-9]. Commercially-available dual- and triple-junction InGaP/GaAs/Ge solar cells, on the other hand, have demonstrated minimum average BOL AM0 efficiencies, as high as, 23% and 26%, respectively [1,10]. These cell technologies are also more radiation hard than Si space cells, and their cost has decreased significantly in the past two years. In fact, the EOL cost per unit power ($\$/W$) for the multi-junction cell technologies are only now becoming competitive with high-efficiency Si technologies.

The following is a trade comparison at the cell and panel levels between high-efficiency Si and multi-junction space solar cells.

SOLAR CELL TECHNOLOGY COMPARISONS

The solar cell technologies that are considered in this paper are state-of-the-art 3-mil high-efficiency Si, InGaP/GaAs-on-Ge dual-junction (2J), and InGaP/GaAs/Ge-on-Ge triple-junction (3J) solar cells. Only solar cells that are currently in volume production and are available for commercial sales were considered for this study [9-10]. The solar cell characteristics that primarily determine EOL power are particle irradiation and temperature coefficient degradation mechanisms. Other secondary effects such as ultra-violet (UV) and thermal cycling degradation mechanisms also affect EOL power in space. As a rule, the degradation rates for multi-junction cells under particle irradiation are significantly lower (better) than for Si cells.

As mentioned earlier, the multi-junction cell technologies offer higher BOL and EOL electrical performance than their Si counterpart. This is illustrated in Table 1, where the BOL minimum average AM0 (one-sun) solar cell efficiency, EOL temperature coefficients, and power remaining factors (P/P_0) after 1-MeV electron irradiation under $5E14$ and $1E15$ e/cm^2 fluences for these cells are presented. It should be noted that the electrical performance of these cells normally do not degrade after they are made into CICs (coverglass-interconnected-cells). The data presented in Table 1, therefore, also applies to CICs. Blue-red reflector (BRR) coverglass is sometimes used with Si cells to lower their operating

temperature in space. BRR glass, however, also diminishes the in-band useful light transmission to the cell, reducing the cell's output power by 2-3% (relative).

III-V compound semiconductor multi-junction solar cell layers are normally grown via metal-organic chemical vapor deposition (MOCVD) on Ge substrates. The use of the Ge substrate has two advantages over III-V compound semiconductor substrates such as GaAs: lower cost and higher structural breakage strength. These advantages make the manufacturing of these solar cells cost effective.

On the other hand, both GaAs and Ge substrates have a higher material density than Si substrates by a factor of about 1.8. Consequently, at the bare cell level, Si cells are lighter in weight. In addition, Si cells are typically thinner than cells grown on Ge. This is due to the fact that Si substrates are less brittle than Ge, and have the greater strength to be safely manufactured at thickness values, as small as, 75 μm . In contrast, Ge wafers used for solar cell manufacturing have thickness values that range from 140 to 180 μm . The combination of lower density and higher material strength enables Si cells to have a low mass per unit area (Kg/m^2) figure of merit. A comparison of typical cell thickness and Kg/m^2 values for Si and multi-junction solar cells is shown in Table 2.

Table 1. – Electrical performance comparisons for high-efficiency 3-mil Si, dual-junction (2J), and triple-junction (3J) bare solar cells.

Solar Cell Technology	BOL Min. Ave. η (%)	EOL Temp. Coefficient (abs.%/°C)	P/Po (5E14 e/cm ²)	P/Po (1E15 e/cm ²)
3-mil High-Efficiency Si	17.0	-0.053	0.83	0.79
2J	23.5	-0.030	0.89	0.84
3J	26.0	-0.045	0.92	0.87

Table 2. – Thickness and mass per unit area comparisons for Si and multi-junction bare solar cells.

Solar Cell Technology	Thickness (μm)	Kg/m^2
High-Efficiency Si	75	0.23
2J	140	0.85
3J	140	0.85

As shown in Table 1, both the radiation hardness and the temperature coefficients for the multi-junction cells are significantly better than Si cells. These primary degradation factors lead to much higher EOL power levels for the multi-junction cells.

From the data presented in Tables I and II, the EOL performance of these cell technologies can be calculated. This is shown in Table 3, where the EOL cell efficiencies at room temperature and at typical LEO and GEO operating temperatures and radiation environments are presented.

Table 3. – EOL electrical performance comparisons for high-efficiency 3-mil Si, dual-junction (2J), and triple-junction (3J) bare solar cells for typical GEO and LEO temperatures and radiation environments.

Solar Cell Technology	EOL Efficiency @ 28°C (%)	EOL Efficiency on Orbit (%)
GEO Conditions (60°C) – 1-MeV, 5E14 e/cm ²		
High-Efficiency Si	14.1	12.5
2J	20.9	20.0
3J	23.9	22.6
LEO Conditions (80°C) – 1-MeV, 1E15 e/cm ²		
High-Efficiency Si	13.4	10.6
2J	19.7	18.1
3J	22.6	20.3

As shown in table 3, under EOL orbital conditions, the multi-junction cells significantly outperform high-efficiency Si cells. For example, the area for a typical rigid panel is approximately 8 m². For a typical solar cell area of 24 cm², and a panel packing factor of 0.90, the panel can house 3,000 cells. Under GEO conditions, this panel populated with high efficiency Si will produce an EOL power level of approximately 1.2 kWe of power. In contrast, the same panel populated with triple-junction cells will produce an EOL power of about 2.2 kWe.

Alternatively, comparing the solar array size for these cell technologies, for the same EOL power requirements in GEO (15 year mission), solar arrays populated with high-efficiency Si cells will be 57% and 77% larger than arrays populated with dual- and triple-junction cells, respectively. Under LEO conditions, the Si solar arrays will be larger than dual- and triple-junction arrays by 69% and 92%, respectively.

The large difference in size between solar arrays populated with Si and multi-junction cells is very significant from the system's point of view. This is specially true for very high powered GEO communication satellites where Si solar array area can exceed 100 m². For a GEO satellite that requires an EOL power level of 15 kWe, for example, the high-efficiency Si solar array area will be greater than 104 m². In contrast, for the same EOL power

level, a triple-junction solar array will have an area of approximately 59 m², or about a factor of 1.8 smaller than the Si array.

The impact of the array size on the functions and economics of the spacecraft are three folds. In general, smaller arrays desirably reduce the satellite weight, array stowage volume, and system requirements on spacecraft attitude control systems including the rate of chemical fuel usage. Three other important figures of merit for a solar cell are EOL area power density (W/m²), specific weight (W/Kg), and cost (\$/W). These figures address different advantages/disadvantages of various cell technologies. They are listed in Table 4.

Table 4. – EOL area power density (W/m²), specific weight (W/Kg), and normalized cost (\$/W) for high-efficiency Si, dual-junction (2J), and triple-junction (3J) bare solar cells.

Solar Cell Technology	W/m ²	W/Kg	Normalized Cost (\$/W)
GEO Conditions (60°C) – 1-MeV, 5E14 e/cm ²			
3-mil High-Efficiency Si	169	676	1.00
2J	271	319	1.38
3J	306	360	1.22
LEO Conditions (80°C) – 1-MeV, 1E15 e/cm ²			
3-mil High-Efficiency Si	143	574	1.00
2J	245	288	1.29
3J	275	323	1.15

As expected, at the bare cell level, the EOL power per unit area is far greater for multi-junction cells than it is for Si cells. The EOL specific weight for Si, however, is nearly a factor of two greater than the specific weight for multi-junction cells. Surprisingly, the EOL cost of power for bare high-efficiency Si is only 15-22% less than the triple-junction cell. This relatively small difference in cost is mainly due to two factors: the significantly greater EOL efficiency and the much reduced cost of the triple-junction cells as compared to only a few years earlier.

PANEL LEVEL COMPARISONS

The specific weight and cost figures shown in Table 4 will be dramatically different when the solar cells are CIGed and laid down in conventional rigid panels. Many components contribute to the weight and cost of the panel. Some of these components are CIGed cells, panel substrate, face sheet (and adhesive), hinges, insulators, wiring, etc. In addition to the cost of panel components, the total cost of a panel includes the cost of the labor for lay-down, test, and engineering support.

At the panel level, the specific weight (W/Kg) figure of merit diminishes considerable for all cell types. In contrast to the bare cells, however, the multi-junction cells show greater W/Kg than do Si cells at the panel level. The EOL specific weight values at the CIC (with 100-μm ceria-doped microsheet coverglass) and panel levels for these cells are shown in Table 5.

Table 5. – EOL Specific weight (W/Kg) at the CIC and panel levels for 3-mil high-efficiency Si, dual-junction (2J), and triple-junction (3J) cells.

Solar Cell Technology	W/Kg	
	CIC	Panel
GEO Conditions (60°C) – 1-MeV, 5E14 e/cm ²		
3-mil High-Efficiency Si	261	75
2J	219	95
3J	248	108
LEO Conditions (80°C) – 1-MeV, 1E15 e/cm ²		
3-mil High-Efficiency Si	221	63
2J	199	86
3J	223	97

The data in Table 5 indicate that even at the CIC level, the specific power for the multi-junction cells is competitive with high-efficiency Si cells. For the same power level, at the panel level and in GEO, the dual- and triple-junction cells weigh 27% and 44% less than Si, respectively. Under LEO conditions, the dual- and triple-junction cells weigh 37% and 54% less than Si, respectively.

At the bare cell level, Si cells cost significantly less than multi-junction cells (see table 4). At the panel level, however, this cost advantage is reversed. Multi-junction cells still comprise a higher portion of the panel cost than do Si cells (Table 6), but because of their higher performance, their EOL \$/W is in fact or lower than 3-mil high-efficiency Si. This is the first time that Si cells no longer have a cost advantage over compound semiconductor solar cells.

Table 6. – The ratio of the cell cost to the panel cost for high-efficiency Si and multi-junction cells.

Solar Cell Technology	Cell/Panel Cost (%)
3-mil High-Efficiency Si	35%
2J	55%
3J	55%

The EOL normalized cost per unit power (\$/W) for the three cell technologies are presented in Table 7.

Table 7. – The EOL normalized cost per unit power (\$/W) for high-efficiency 3-mil Si, dual-junction (2J), and triple-junction (3J) solar cells at the panel level.

Solar Cell Technology	Normalized Cost (\$/W)
EOL GEO Conditions (60°C) – 1-MeV, 5E14 e/cm ²	
3-mil High-Efficiency Si	1.00
2J	0.90
3J	0.80
EOL LEO Conditions (80°C) – 1-MeV, 1E15 e/cm ²	
3-mil High-Efficiency Si	1.00
2J	0.84
3J	0.75

The cost advantage that is observed with multi-junction cells in Table 7 holds over even the somewhat less expensive 4-mil high-efficiency Si cells (at the panel level). 4-mil Si cells are less radiation hard and have lower specific power (W/Kg) than 3-mil Si cells, but they cost about 35% less. A comparison of normalized cost between 4-mil Si and multi-junction cells at the panel level is shown in Table 8.

Table 8. – The EOL normalized cost per unit power (\$/W) for high-efficiency 4-mil Si, dual-junction (2J), and triple-junction (3J) solar cells at the panel level.

Solar Cell Technology	Normalized Cost (\$/W)
EOL GEO Conditions (60°C) – 1-MeV, 5E14 e/cm ²	
4-mil High-Efficiency Si	1.00
2J	0.99
3J	0.87
EOL LEO Conditions (80°C) – 1-MeV, 1E15 e/cm ²	
4-mil High-Efficiency Si	1.00
2J	0.93
3J	0.83

As shown in both tables 7 and 8, at the panel level, the EOL cost of multi-junction cells is indeed lower than their Si counterpart for the same power level. At the same time, solar panels and arrays that are populated with multi-junction solar cells offer greater EOL power both for GEO and LEO environments.

At the panel and array levels, only conventional low efficiency space Si cells are presently less expensive than multi-junction cells. Their EOL power is, however, far lower than either the high-efficiency Si or the multi-junction cells. As well, their mass and area are far larger.

SUMMARY

A trade-off study was carried out between commercially-available state-of-the-art rad-hard high-efficiency 3-mil Si and multi-junction space solar cells at the bare cell and panel levels. It was demonstrated that satellite manufacturers can minimize solar array cost and size using the newly-available high-efficiency and radiation-hard triple-junction solar cells. For the same size panel, however, high-efficiency Si cells still afford a mass advantage (but with significantly lower power) over multi-junction cells. Finally, since the triple-junction cell particle radiation degradation is only in the 8-13% range (vs. 17-21% range for Si), the thermal and power management for the satellite is greatly enhanced at the system level.

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