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Evolution of Multijunction Solar Cell Technology for Concentrating Photovoltaics

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Multijunction solar cells have evolved from their original development for space missions to displace silicon cells in high concentrating photovoltaic (CPV) systems. Today's three-junction lattice-matched production cells have efficiency of 39–39.5% under high concentration, and there appears to be little opportunity for further efficiency gain with this three-junction technology. Future generations of CPV cells will exploit more than three junctions, with metamorphic subcells, or both technical approaches to achieve efficiencies >45%. As new designs seek closer current matching and further spectral splitting, atmospheric variability will necessitate careful modeling to optimize energy output. These new cells will also be higher cost, which will favor higher CPV system concentration.

1. Historical Perspective

Optical concentration has been explored since the earliest days of the photovoltaic (PV) industry, as a means to both boost cell efficiency and leverage the high cost of solar cells. Early concentrating photovoltaic (CPV) systems used the technology of the day, i.e., almost exclusively silicon, although the potential of multijunction cells, including the structure that was ultimately successfully commercialized in today's technology, was recognized by the late 1970's.[1)]

Strong interest in GaAs from the space community for its radiation hardness motivated the development of GaAs devices, on lightweight Ge substrates. Bedair *et al.* demonstrated the first multijunction solar cell with epitaxially-grown subcells monolithically interconnected with an epitaxially grown tunnel junction, the basic approach used today, with an AlGaAs/GaAs two-junction cell in 1979.[2)] Several years later, Olsen *et al.*[3)] demonstrated the dual junction GaInP/GaAs cell, and this technology was deployed on space missions in the mid-1990's. An active Ge bottom subcell was developed, using the Ge growth substrate, resulting in three-junction (3J) GaInP/GaInAs/Ge cells which were first launched on spacecraft in 2000.

These successes sparked immediate interest in the terrestrial CPV community. Numerous experiments were tried using the new multijunction cells,[4,5)] and to development of cells optimized for terrestrial use, leading to a series of record terrestrial concentrator cell efficiencies,[6–9)] including the first solar cell of any type to reach over 40% efficiency[8)] in 2006. These achievements led to incorporation of multijunction cells in place of silicon cells in the leading CPV systems,[10,11)] and to the development of numerous new systems. Commercialization of the cell technology has steadily progressed. Figure 1 shows the progression of production efficiency distributions for commercial CPV products made by Spectrolab to date, with steadily increasing performance.[12,13)]

Until the introduction of the "C4MJ" technology in 2011, all production cells had been lattice-matched. The C4MJ technology, by contrast, has an upright metamorphic structure (see Fig. 2).

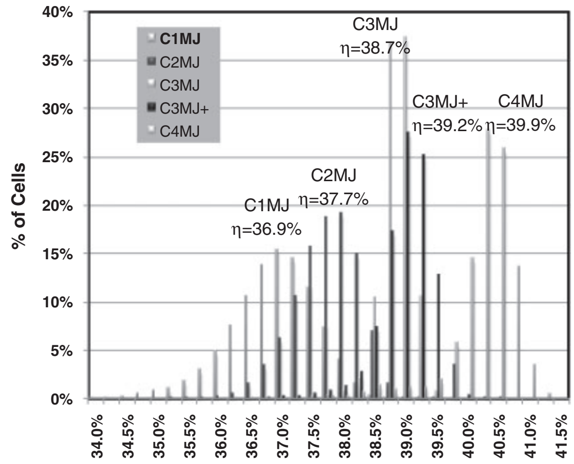

Fig. 1. Spectrolab production efficiency history.

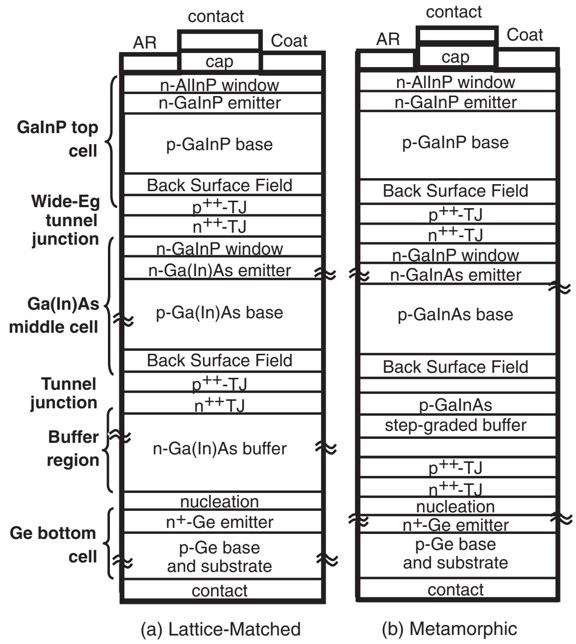

Fig. 2. Lattice matched and metamorphic epitaxial structure.

2. Multijunction Technology Roadmap

The record cell efficiency for "conventional" lattice-matched 3J cells is 41.6%.[7)] This record has been matched by 3J upright metamorphic cells,[14)] and has been surpassed by two different approaches:

- A 42.3% efficiency 3J cell with metamorphic bottom cell achieved with bifacial growth;[15)] and
- A 3J lattice-matched cell with an undisclosed lattice-matched technology has achieved 43.5% efficiency.[16)]

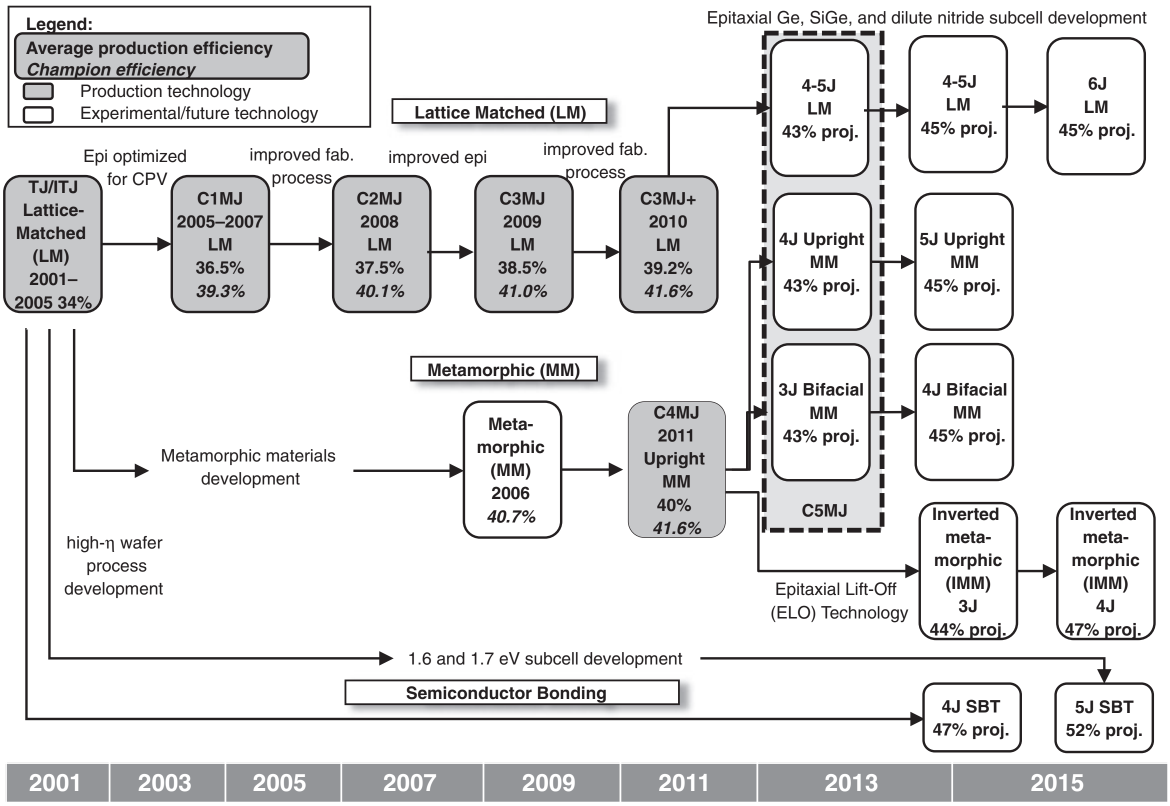

Fig. 3. Multijunction cell technology roadmap.

In addition, recent record AM0 efficiency results for a 4J inverted metamorphic (IMM) have surpassed the best efficiencies of any 3J cells,[17] demonstrating for the first time a device with more than three junctions surpassing the best 3J devices. Taken together, these record devices demonstrate that promising avenues for improvement exist with both lattice-matched and metamorphic structures.

Spectrolab has a broad research program pursuing a variety of development paths toward improved efficiency (see Fig. 3). This program includes the above structures, as well as semiconductor bonding.

A common strategy for all the proposed improved device structures is to more closely match the currents between subcells. In both of the record cells cited above, the bottom Ge cell has been replaced by a wider bandgap material which is current matched (or nearly so) to the top two cells and provides a higher voltage than Ge. Cells with more junctions seek to further split the solar spectrum and inherently rely on current matching over a broader range of sub-bands.

3. Implications of Advanced Designs

The trend toward more junctions, and more closely matched currents between multiple subcells, has potential performance implications as discussed below. In addition, all of the technology options on the roadmap can be expected to increase production cost.

3.1 Performance

The current balance for a given cell varies with both atmospheric variations and the temperature of the cell.[13,18] Indeed, the effect of cell temperature has been shown to degrade performance in bifacial growth cells with a closely matched bottom cell current.[15] On the other hand, King *et al.* have shown by analysis that, at least considering air mass variation only, a 6J cell outperforms 3J, 4J, and 5J cells throughout the day except within 30 min of sunrise or sunset, when the available energy is low.[5,19] This finding is useful in that it shows the added junctions deliver higher energy over a broad range of spectral content from changing air mass throughout the day.

Figures 4 and 5 provide a simplified look at the variation in current balance due to major atmospheric variables. The SMARTS model[20] was used to model the solar spectrum at Daggett, California at 3 pm on the autumnal equinox (as a representative CPV location and spectral condition) based on TMY3 site data.[21] The TMY3 data were examined to find the minimum and maximum broadband AOD and precipitable water, and SMARTS spectra were generated with the minimum and maximum values to represent extreme bounds of atmospheric conditions at a typical CPV site. The broadband aerosol optical density (AOD) was converted to a spectral AOD value as described by Myers.[22]

Figure 4 illustrates that AOD has a broadband effect that is most pronounced in the shorter wavelength region, whereas precipitable water (W) affects the longer wavelength portions of the spectrum with very little effect on the short wavelengths. Thus both influence the current balance but in different ways.

Figure 5 shows that this is indeed the case. The relative currents are shown for C3MJ+ (1.88 eV/1.4 eV/0.67 eV) and a 5J lattice-matched cell with GaInNAs

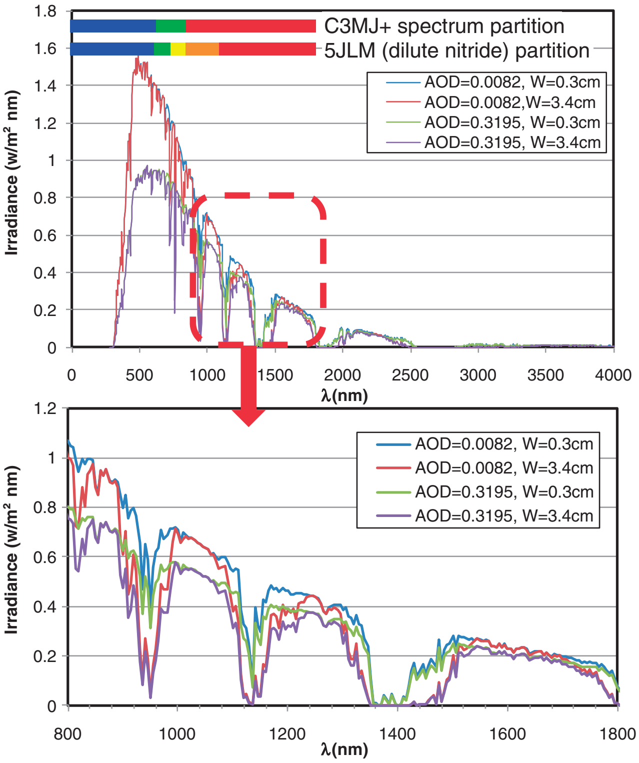

Fig. 4. (Color) SMARTS simulated spectra for AOD and precipitable water extremes. The model parameters are based on TMY3 data for Daggett, CA at 3 pm on the autumnal equinox, except the AOD and precipitable water inputs are varied by the extremes for the site.

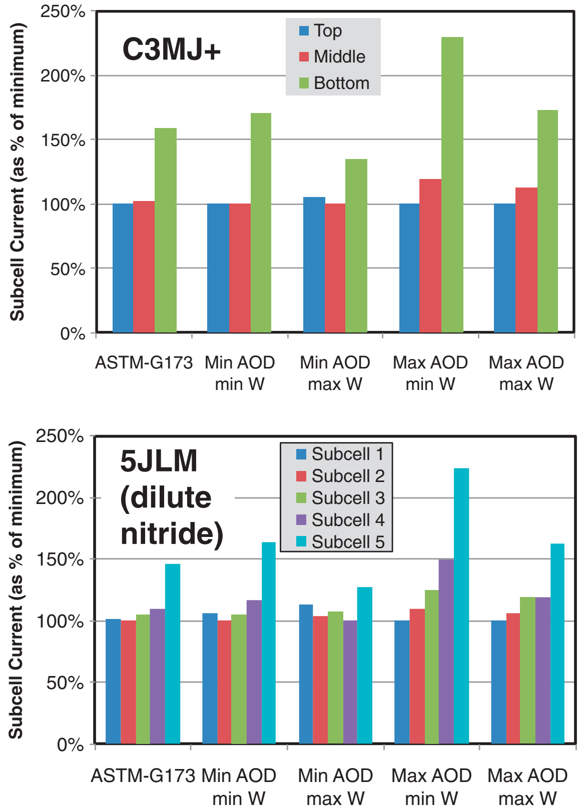

Fig. 5. (Color) Current balance under varying simulated atmospheric conditions for C3MJ+ and a five-junction lattice-matched cell with a dilute nitride fourth junction.

for the fourth subcell (2.1 eV/1.71 eV/1.4 eV/1.12 eV/0.67 eV). The C3MJ+ cell is top-cell-limited in all conditions except low AOD, high W. The 5J cell, with the top two cells closely current-matched under the standard (ASTM-173G) direct spectrum, fares rather well with these atmospheric extremes, with subcell 1, 2, or 4 limiting performance depending on the condition.

It should be noted that this analysis neglects the band edge shifts due to temperature. The fact that cell temperature is somewhat correlated with atmospheric conditions (e.g., high air mass occurs near twilight when cell temperature is lower) highlights the need for full annual modeling of cell and system performance, taking into account system optics transmittance, cell temperature, and spectral variability in order to arrive at optimal bandgap tailoring.

3.2 Cost

In the space industry, satellites and associated launch costs run to hundreds of millions of dollars, and for commercial satellites, the revenue potential is directly proportional to the power generated by the solar panels. High efficiency is therefore extremely leveraging in space applications. In CPV systems the cell efficiency similarly leverages the balance of systems cost. If the complete plant costs are known, one can easily calculate the impact on the overall project economics for different cell price and efficiency combinations.

Figure 6 illustrates this calculation using hypothetical cost and efficiency numbers for concentrating silicon, and "low-cost" and "high-cost" multijunction cells. Cell efficiencies are as noted, and are assumed to be a function of

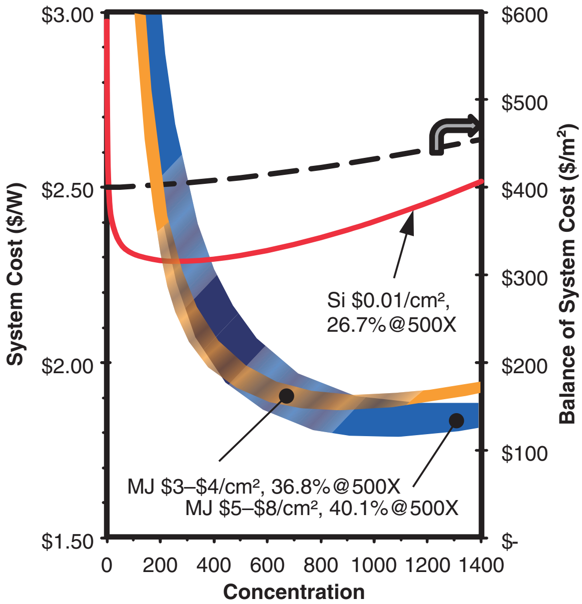

Fig. 6. (Color) Impact of cell efficiency and cost on system economics (assuming increasing system cost with concentration). Numbers for illustrative purposes only.

concentration based on empirical fit to 3J cell data. The balance of system cost is assumed to increase superlinearly with increasing concentration (secondary axis).

Assuming the balance of system cost is independent of concentration, the higher efficiency MJ cells will always result in a lower system cost ($/W) at sufficiently high concentration. By the same token, however, the roadmap to higher efficiency will most likely drive CPV systems to ever-increasing concentration.

4. Conclusions

Multiple avenues exist for further growth of multijunction solar cell efficiency. These avenues all necessitate much more careful and comprehensive modeling than has been the practice to date to ensure optimized performance in the field. To the extent the higher efficiency cells increase manufacturing cost, the trend to higher concentration systems will continue.

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