Multijunction Photovoltaic Cells: Efficiency and Cost-reduction for more Widespread Applications

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I. Introduction

Sunlight is a clean source of energy, naturally produced, and in quantity plentiful enough to provide a consistent source of power. Over the past century, there have been significant developments in technologies capable of harnessing such energy, making use of the extraordinary properties of semiconductor materials formed into photovoltaic (PV) solar cells. Though, even the most successful developments have their limitations, with the output efficiency of the most used terrestrial solar cell appliances residing at around 20% [1]. Many new developments have aimed to overcome these limitations, with much success, but often require high-cost materials and fabrication processes, therefore more is needed to see integration into more common-place applications.

II. Efficiency limitations

In their 1961 publication titled *'Detailed Balance Limit of Efficiency of p-n Junction Solar Cells'* [2], William Shockley and Hans J. Queisser calculated the theoretical maximum efficiency limit for a single p-n junction solar converter. The results showed, for an energy bandgap of 1.1eV, there is a maximum conversion efficiency of 30% [2]. Subsequent calculations considered light-absorption and scattering in the atmosphere using the AM 1.5G solar spectrum, which saw an increase to 33.7% for an energy gap of 1.4eV [3]. These limits arise from the material's intrinsic properties, the most significant being blackbody radiation, spectrum losses (incoming photons with too low energy), and electron-hole recombination [3]. These put restrictions on the discovery of solutions. Fig.1 shows the percentage of extractable energy (green & blue) for various materials at their optimum bandgap energies, compared to the various losses.

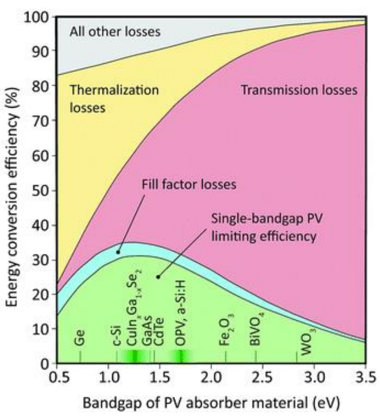

Fig. 1: Fundamental limitation of energy output for single p-n junction PV cells [4].

III. Efficiency improvements

The most successful method of increasing cell efficiency has been the development of multijunction solar cells (MJSC). These devices include multiple p-n junctions per cell and exceed the 33% limit by minimizing the spectrum losses. The layers have unique bandgap energies because they are each made using different materials, hence, each layer can absorb photons of different wavelengths. [5]. Fig.2 outlines an example of a popular III-V MJSC structure. The 'III-V' refers to the semiconductor compound containing elements from the third and fifth groups in the periodic table. In this case, there are three sub-cells comprised of Gallium Indium Phosphide (GaInP), Gallium Indium Arsenide (GaInAs), and Germanium (Ge). These are vertically stacked and separated by connecting tunnel diodes. The materials are suitable since they have comparable lattice constants [6]. Grouping materials in this manner is called lattice matching, which benefits the cell performance by limiting the number of dislocations that occur during the process of growing the layers directly on one another [7]. Too many dislocations will lead to excessive rates of recombination within those areas, in turn limiting the achievable current density [6].

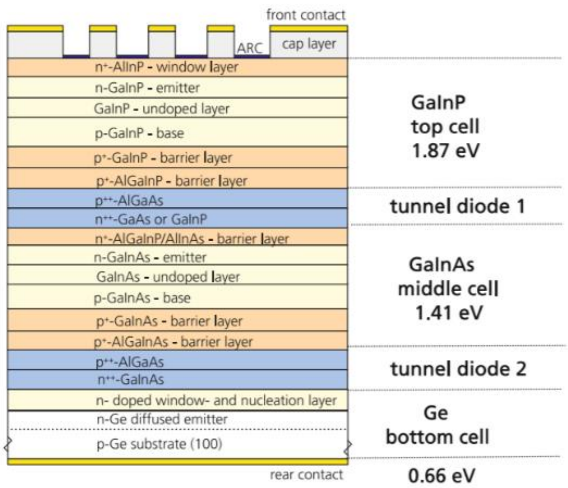

Fig.2 GaInP/GaInAs/Ge three-junction structure diagram [5].

The National Renewable Energy Laboratory has reported the market growth of solar cells for the past forty years. Their data shows that MSJC's have remained the highest performing cell designs since their creation. As of 2014, Three-Junction cells have achieved a peak efficiency of 44% [8], and more recent advancements in cells with four or more junctions have reached nearly 48% [8] when tested under optimal conditions.

IV. Applications

The cost of fabrication remains high due to the requirement of molecular epitaxy processes. As a result, the market for MJSC’s is typically limited to specialized sectors. The space industry's satellite and rover applications [9] is an example of where MJSC's are commonly implemented. Fig. 3 shows an image of MJSC's supplied to Airbus. Interestingly, the reason for this in part due to the suitability-metric for applications within the space industry being judged as the cost per unit mass (e.g. £/kg) [10], whereas for terrestrial uses it is the cost per nominal power rating (e.g. £/Wp) [10]. Since MJSC’s can be microfabricated, they tend to be small-scale with a high power-to-mass ratio. This is ideal for applications where the exact conversion efficiency isn’t a priority. This is not the case for terrestrial applications, where large-scale, high-power generation, that is sustained for long periods is essential. Certain new developments are making progress toward more widespread terrestrial use.

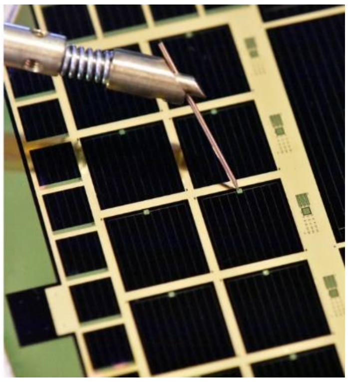

Fig. 3: A thin-film triple junction cell with a 33.7% efficiency supplied to Airbus by MicroLink Devices, Inc. for satellite applications [11].

Minimizing material cost is the simplest means of cost-reduction, examples of which have seen Silicon (Si) used as the base-cell material instead of the more expensive Ge [12]. By directly bonding the Si to the Gallium (Ga) based layer above *(The studies to which I now refer used Gallium Arsenide, GaAs, instead of the previously mentioned GaInAs),* lattice mismatching occurs. This is compensated for by replacing the direct-to-wafer-bonded tunnel junction with Indium coated intermetallic-bonded segments [12, 13]. The model provided successful performance results, allowing for cheaper substrates to be used along with reduced fabrication expenses. There was also the added advantage of being operationally compatible with ‘Thin-film’ silicon-based PV layers, which are the most cost-effective cells to manufacture [14].

V. Conclusion

There has been consistent growth in MJSC efficiency since the late nineties which is expected to continue, if not accelerate, into the foreseeable future. This is driven by the desire to integrate as many junctions per cell as is feasible [8]. These developments remain financially costly due to the need for expensive materials and molecular growth processes. This will likely continue to be necessary throughout the developmental stages. Only once new designs show confirmed success, typically demonstrated through integration into high-end specialist technologies, can monetary reductions begin to be incorporated. This is currently best achieved through the replacement of rarer materials with Si substitutes, maintaining the required need for a low-cost, high-power ratio in terrestrial applications, to ensure their long-term use in varying environments is sustainable.

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