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Materials perspectives for next-generation low-cost tandem solar cells

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ABSTRACT

Recent progress in commercial single-junction photovoltaic (PV) technologies has brought device efficiency closer to their practical limits. Module prices are dropping rapidly and solar energy has already reached grid parity in many areas. Solar module costs now constitute a small fraction of the total systems costs and to continue system cost reduction, increasing efficiency becomes even more critical. Multi-junction solar cells are the most logical path to increase PV module performance beyond 25%, but the varieties available today are still are out-performed in efficiency or cost by the main stream single-junction technologies: crystalline Si, CdTe and CIGS. Finding a solution for this problem is attracting a growing research interest. We review the latest developments in the field with particular focus on thin-film high band gap candidates such as perovskites on commercial bottom cells including silicon, CdTe and CIGS. We also review the current state of all-chalcopyrite tandems, and promising concepts using CdTe-alloys as a top cell on silicon.

1. Introduction

Thin film photovoltaics (PV) has come a long way since 1883 when Charles Fritts made the first solar cell on a metal foil coated with selenium and a thin layer of gold [1]. For more than 130 years numerous other materials and devices have been explored with the ultimate goal to make photovoltaic energy widely available. Pioneered in 1950s, crystalline silicon faced significant challenges such as an indirect band gap necessitating large quantities of ultra-pure material, and a multi-step fabrication process intense in energy consumption, technical facilities and labor. Research on direct band gap thin-film PV technologies aimed to provide a solution to these challenges and lower fabrication cost. Today grid parity is a reality, not only with thin-film front-runners CdTe and CIGS, but also with crystalline silicon that dominates the PV market [2]. The exponential reductions in PV module costs resemble the improvements in semiconductors, and although the physics of photovoltaics do not follow the size-scaling which underpins Moore's Law, the rapid technological improvements in all aspects of PV fabrication have led to a 23% reduction in cost for every doubling of manufacturing capacity [3]. This rate is faster than any other energy technology and has accelerated even more in recent years. The cost reduction stems from a variety of sources including: reduced material costs, reduced material usage, lower processing costs, and increased efficiency.

Today the costs per watt of the actual solar cells has dropped so rapidly that the cell manufacturing constitutes just a small fraction of the total PV expense, and increasingly the balance of system cost, or a commodity material such as the glass panel, drive the cost of producing solar energy [4]. Due to the shifting cost structure, increasing efficiency has become one of the most powerful levers for overall cost reduction.

Employing multiple absorbers with different band gaps in tandem or multi-junction devices is the most viable way to push the efficiency limit significantly beyond the practical limit for single-junction modules of about 25% [5]. Despite a multitude of possible material sets and structures for multi-junction solar cells, only two have made it to the market: III-V multi-junctions for concentrated light or space applications, and amorphous silicon. III-V multi-junctions currently surpass the efficiency of any other solar cell technology, however the high costs of production have relegated them to systems using optical concentration which necessitate both direct sunlight and tracking systems not suitable for building integration. Amorphous silicon is versatile, compact, and cheap allowing it to become a standard power solution for a variety of consumer products, however the efficiency of the record triple junction A-Si cell has only modestly improved in the last 30 years despite significant research and stands at 14% which is less than a typical commercial single junction multi-crystalline Si module [6]. There is an urgent need to develop efficient planar tandem PV technologies that can be implemented broadly in both utility and commercial or residential installations similar to mainstream PV today. Developing a completely new multi-junction device structure remains a possibility on the long term however a more practical and quicker solution may be instead of competing with silicon and a well-established manufacturing

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base, to upgrade these already large-volume technologies by integrating tandem partners on top. Taking advantage of existing infrastructure along the whole supply chain could offer a fast track for these technologies.

The largest principal distinction across all multi-junction solar cells is the way the sub-cells are interconnected. Of the multiple device architectures and interconnection schemes that can be employed for tandem solar cells [7], the only one established for commercial application is a two terminal (2-T) monolithically integrated device. This architecture has significant benefits such as requiring only one transparent conductive layer (TCL) which can be a serious source of series-resistance and light transmission losses for large-area thin-film modules. TCL losses at the module scale also help explain the large efficiency difference between lab-scale and full-scale thin-film devices. Alternative device architectures such as mechanically stacked 4-terminal, 3-terminal, and spectrum-split cells have in some cases outperformed 2-T-monolithic devices [8] however increased complexity in wiring, voltage conversion, and panel level electronics for maximum power point tracking (MPPT) for each terminal add potential costs. Due to these complications, a clear path to cost-efficient commercial application for these alternative architectures has yet to be demonstrated.

2. Common challenges for monolithic tandem integration

Beyond optimizing each individual sub-cell, there are a number of unique challenges to developing an efficient monolithic multi-junction solar cell. The two largest challenges and design criteria are: 1) proper sub-cell selection for current matching, and 2) layer process compatibility during fabrication; each of which will be described in more detail here.

- The first criteria for efficient 2-T multi-cell design is to match the current generated through each sub-cell with appropriate selection of band gaps. For a 2-T tandem cell the theoretical maximum efficiency of 46% is calculated for a band gap pairing of 0.94 eV and 1.60 eV, however only a small loss in efficiency is realized when constrained with the band gap of an established bottom cell technology such as Si or CIGS (E_g = 1.11 eV). The optimal top cell band gap for Si (or similar band gap CIGS) is approximately 1.73 eV, but a theoretical efficiency of greater than 40% can be achieved with a top cell band gap between 1.65 and 1.85 eV [9–11].

Even with the right band gap selection, to improve the efficiency of high-quality Si with a 2-T tandem junction is challenging. In 2-T devices, an efficient top cell is critical since the top cell provides a larger fraction of the total system power due to a higher voltage and the constraint of equal current imposed on both cells. The historical lack of highly efficient high-bandgap top-cells (outside of III-V growth) has made it challenging to exceed the single junction efficiency for champion silicon or CIGS.

Fig. 1 gives an example of optical distribution across a tandem structure on silicon, while Fig. 1b. shows the required efficiency for the top cell as a function of band gap to enable a 25% and 30% efficient tandem assuming a 20% efficient Si bottom cell [12].

- Process compatibility during layer fabrication is a second large restriction on the design and optimization of efficient tandems. In the case of substrate device fabrication, the bottom cell and pn-junction must withstand the maximum processing temperature of the top cell, while in the case of superstrate device the reverse must be true. One way to decouple the challenges of temperature compatibility is by bonding two complete devices [9], however the feasibility of such an approach in large scale commercial production remains to be demonstrated.

Additional challenges include providing ideal interlayers such as recombination layers or tunnel junctions to assure minimal added series resistance and parasitic optical absorption. Materials with a wide band gap, low sub-bandgap optical absorption, proper optical refractive index, proper work function, and high carrier density (> 10^{19} cm^{-3}) need to be used, but detailed discussion is beyond the scope of this paper.

This review will cover the status of different material sets for multi-junction and specifically prospects for commercial tandem solar cells. The sections are broken down by material category of the top cell, first briefly highlighting III-V materials (Section 2.1), then discussing prospects for chalcogenides in Section 2.2, CdTe and II-VI alloys in Section 2.3, and perovskites in Section 2.4. In Section 2.5, a small selection of alternative and new prospective materials are highlighted.

2.1. III-V Materials as top cell in silicon devices

High band gap III-V based solar cells have been an ideal option to create high performance tandem device on conventional solar cells. However, due to the difficulties in passivating the structural defects of III-V semiconductors, so far, the fabrication process has been limited to epitaxial growth on lattice matched single crystalline substrates. Epitaxial growth of III-V on Si substrates typically results in a high density of structural defects and degraded minority lifetime due to the mismatches in lattice constant as well as thermal expansion coefficient. By incorporating GaAs/$Al_{0.22}Ga_{0.78}As$ buffer layer, a two-terminal $Al_{0.15}Ga_{0.85}As$ (E_g = 1.6 eV) / Si tandem device with 21.2% efficiency (AM0, 1 sun) has been reported [13]. Alternatively, various approaches including epitaxial lift-off and spalling have been introduced to detach

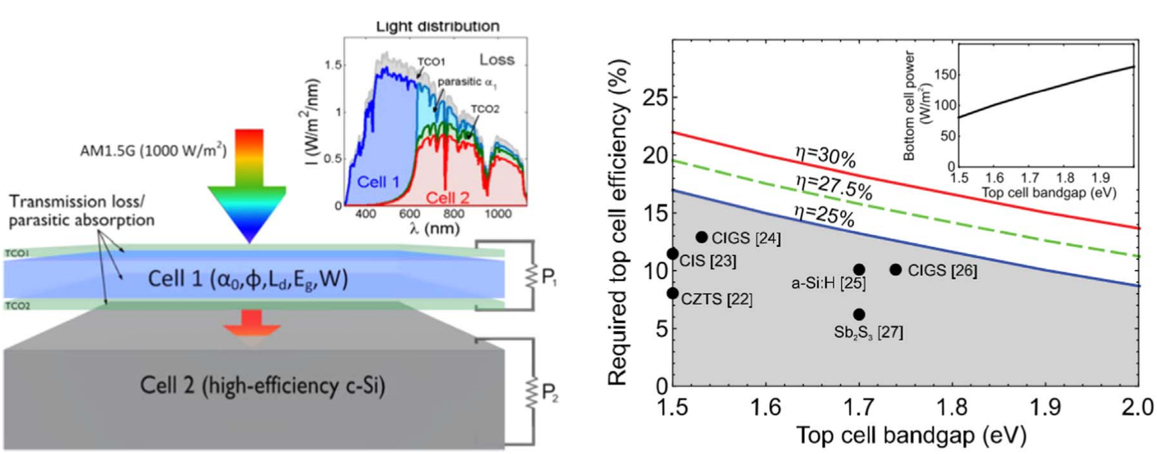

Fig. 1. Schematic representation of optical losses in a tandem solar cell. A 4-terminal example is used to show the additional loses of second TCO (a). Top cell conversion efficiency required for a top cell in a c-Si based tandem to reach 25–30% efficiency.
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