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Report

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A review of recent progress in heterogenous Silicon Tandem Solar Cells

Abstract— **Silicon solar cells are the most established solar cell technology and are expected to dominate the market in the near future. As state-of-the-art silicon solar cells are approaching the Shockley–Queisser limit, stacking silicon solar cells with other photovoltaic materials to form multi-junction devices is an obvious pathway to further raise the efficiency. However, many challenges stand in the way of fully realizing the potential of silicon tandem solar cells because heterogeneously integrating silicon with other materials often degrades their qualities. Recently, above or near 30% silicon tandem solar cell has been demonstrated, showing the promise of achieving high-efficiency and low-cost solar cells via silicon tandem. This paper reviews the recent progress of integrating solar cell with other mainstream solar cell materials. The first part of this review focuses on the integration of silicon with III–V semiconductor solar cells, which is a long-researched topic since the emergence of III–V semiconductors. We will describe the main approaches—heteroepitaxy, wafer bonding and mechanical stacking— as well as other novel approaches. The second part introduces the integration of silicon with polycrystalline thin-film solar cells, mainly perovskites on silicon solar cells because of its rapid progress recently. We will also use an analytical model to compare the material qualities of different types of silicon tandem solar cells and project their practical efficiency limits.**

Keywords— *solar cells, Si tandem, III–V compounds, II–VI compounds, chalcopyrite, perovskite*

I. Introduction

To achieve a sustainable energy future, solar electricity and solar thermal generation have to increase its share of global energy to 20% in 2050 and 70% in 2100, as projected by the German Advisory Council on Global Change [1]. As the 'engine' of the solar electricity conversion, the solar cell has to be more efficient and cheaper in order to realize this scenario. Silicon solar cells are by far the most dominant solar cell material in the photovoltaic (PV) market and are expected to stay dominant in the near future for several reasons. Firstly, the technology of manufacturing silicon solar cells is very mature and keeps advancing. State-of-the-art silicon solar cells can achieve more than 25% efficiency. In the meantime, the areal manufacturing cost of silicon solar cells keeps reducing and is closing its gap to the areal cost of other low-temperature deposited thin film solar cells. Secondly, silicon has been proven to be very reliable and meets the lifetime requirement of most PV applications. Thirdly, silicon is an earth-abundant element, making it free from the shortage of supply of raw materials.

The conversion efficiencies of mainstream solar cell materials were dramatically improved in the last few decades, but they are also converging to their limits. Figure 1 presents the historical record-efficiency of various types of solar cells along with their extrapolations. This analysis was originally presented in [2]. These curves were fitted by only the historical data and assumed that the advances of each technology are largely progressive rather than disruptive. The extrapolations show that the progress of the efficiencies is converging or will converge soon, which is mainly bounded by the Shockley–Queisser limit.

An important strategy to raise the efficiency of solar cells is stacking solar cell materials with different bandgaps to absorb different colors of the solar spectrum. This so-called 'multijunction' approach can reduce the thermalization loss due a high-energy photon absorbed by a small-bandgap material, and below-band-gap loss due to a low-energy photon failed to excite a high-bandgap material. This concept was most successfully implemented in a III–V compound semiconductor solar cell, since a compound semiconductor has a good range of lattice parameters and bandgaps to choose from. Thanks to the maturity of the III–V semiconductor industry, high quality III–V materials can be fabricated. Three-junction (3J) GaInP/InGaAs/Ge solar cell can achieve more than 40% efficiency under 500 suns. The world-record efficiency of a 3J cell comprises of lattice-mismatched GaInP, 1.42 eV-InGaAs and 1.0 eV-InGaAs, which can reach 44.4% efficiency under 302 suns, whereas a four-junction (4J) GaInP/GaAs;GaInAsP/ GaInAs could reach 46.0% at 508 suns [3]. Despite its superior performance, a III–V solar cell has a very small market share in solar electricity generation because of its high manufacturing cost. III–V solar cells are only adopted by the systems in which the cost of solar cells takes only a very small portion, such as satellites or high concentration photovoltaic systems. Replacing the epitaxial growth substrate by silicon is a promising pathway to reduce the manufacturing cost.

II. Design consideration and challenges of silicon tandem solar cells

Bandgap combination is one of the most important considerations when designing tandem solar cells. Figure 2 presents the efficiency contours of two-junction (2J) solar cells against top and bottom cell bandgaps [5, 6, 7]. The optimal bandgap combination of a 2J device is around 1.62 eV and 0.91 eV, which gives a limiting efficiency of 42.8%. Constraining the bottom cell to the bandgap of silicon (1.1 eV) gives a maximum limiting efficiency of 42.4% with a 1.72 eV top cell, which is close to the efficiency of optimal bandgap combi- nation. In the case of 3J tandem devices with silicon bottom cells, the optimal bandgap combination of top and middle cell is 2.01 eV and 1.5 eV. The efficiency contours of the 3J silicon tandem cell versus the top and middle cell bandgaps are plot- ted in figure 3. This combination deviates from the commonly used GaInP(1.87eV)/InGaAs(1.42eV) in III–V multi-junction solar cells. At present, since high quality solar cell materials of any type with bandgaps of 2.01 eV and 1.5 eV are difficult to fabricate, using GaInP(1.87eV)/InGaAs(1.42eV) as the top junctions on silicon is a good alternative.

There are three major ways to integrate silicon with other materials to implement a multi-junction device, which are illustrated in figure 4. The first one is two-terminal, series-

connected configuration, in which the sub cells are connected by conductive layers that can transport the carrier from one sub cell to another. The tandem device will then only have two terminals and can be simply operated as a standard single junction solar cell, which greatly simplifies its integration in a PV module and system. However, since the sub cells are connected in series, the requirement of current-match reduces the choices of materials in terms of bandgaps. In addition, the fabrication of highly conductive and optically-transparent conductive layers between each sub cell is also challenging. The second configuration is mechanical stacked tandem device, in which the sub cells are also vertically stacked but each sub cell has its own terminals to be operated individually to their own maximum power points. Compared with the two-terminal tan- dem configuration, this approach relieves the requirement of current-match and a conductive layer between sub cells, but it incurs other costs in modules and systems, such as cables and inverters. The third approach is using an optical spectrum splitter to redirect the different colors of the solar spectrum to each sub cell. The sub cells are just operated individually with- out any integration. The choice of sub cells is then very flexible. This configuration transfers the difficulty from the cell integration to the designs of the PV module. Our review will only focus on the first two configurations because the third approach is beyond the scope of solar cell fabrication.

III. SEMICONDUCTOR SOLAR CELLS ON SILICON

Integrating III−V compound semiconductors with silicon substrates has been studied extensively because it is a promising way to significantly reduce the cost of III−V semiconductor devices. The main challenge comes from the lattice mismatch between silicon and the commonly used III−V compound semiconductors. Monolithically epitaxial grown III−V multi-junction cells typically need all the epitaxial layers to have the same lattice constant to maintain high crystallinity, which is essential to attain high efficiency. Figure 5 shows the band- gaps versus lattice constants of commonly used III−V com- pound semiconductor versus their lattice constants. As shown in this figure, the choices of III−V compounds latticed match to silicon is very limited. Commercial GaInP/GaAs/Ge 3J solar cells composed of epitaxial layers lattice-matched to GaAs. Most of the research efforts that aim to achieve more junctions are also based on this material system.

The problem of lattice mismatch is aggravated by the difference of thermal expansion coefficients between III−V semi-conductors and silicon. The epitaxial process is usually needed to heat up the substrate to a few hundred degrees Celsius and then cool down to room temperature. This results in bowing, bending or cracking in the III−V on silicon wafers. The ther- mal expansion coefficients of III−V semiconductors typically range from 4.7×10^{-6} K^{-1} to 5.7×10^{-6} K^{-1}, whereas the thermal expansion coefficients of silicon is 2.6×10^{-6} K^{-1}. As a result, even with lattice-matched growth, e.g. GaP on silicon, strain is introduced in the III−V layer during the cooling down of the sample.

Notable III−V/Si solar cell results are mainly achieved by on-silicon heterepitaxy, wafer bonding and mechanical stacking, which will be described in this section. We will also review some novel approaches that could potentially address the issue of lattice mismatch.
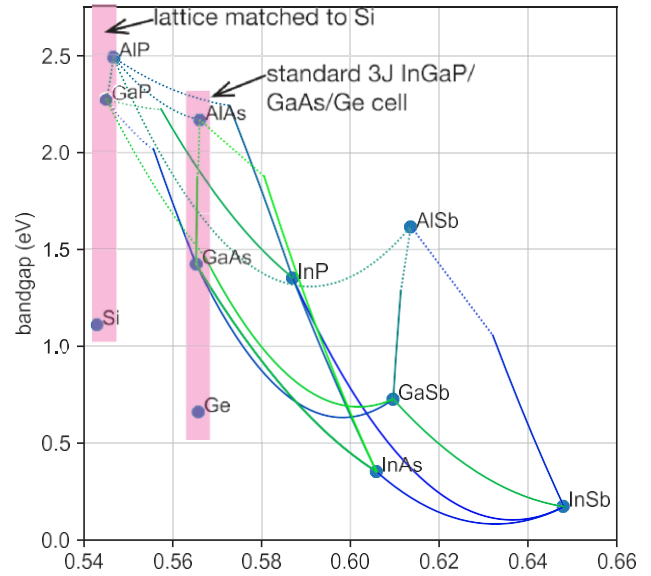
IV. POLYCRYSTALLINE THIN-FILM SOLAR CELLS ON SILICON

Unlike monocrystalline III–V or silicon, high defect tolerance of some polycrystalline or amorphous semiconductor solar cells [77] make them less demanding on the material quality and cheaper to make. Materials such as cadmium telluride (CdTe), copper indium gallium Di selenide and perovskites belong to this category. The main motivation of integrating these materials with silicon is to extend the absorption edge towards longer wavelengths. Since these materials have a higher tolerance on defects, lattice mismatch is not a major concern for them to deposit on silicon solar cells. However, not all of these materials can be deposited on silicon substrates with reasonable quality. At present, only a-Si, CdTe, perovskites integrated silicon are successfully demonstrated. Since the focus of this review paper is heterogeneous material integration with silicon, we will only review the recent prog- ress of chalcogenide and perovskite solar cells. Perovskite generally refers to crystals with a structure of ABX$_3$ formula, where X is oxygen or halogen. The larger A cation sits on a cub octahedral site surrounded by twelve X anions and the smaller B cation sits on an octahedral site surrounded by six X anions. Halide perovskite material such as CH$_3$NH$_3$PbX$_3$ emerges as a prominent candidate for next-generation solar cells because of its strong optical absorption, long diffusion length, tunable bandgap and low-cost processing. Also, like III–V semiconductors, the bandgap of perovskite can be tuned by changing the chemical elements and compositions [78]. Although reliability is still the main issue of perovskite solar cells, nearly 20%-efficiency has been achieved on a device stabilized by 1000 h exposure to one-sun at 50 °C [79]. The history and recent development of perovskite solar cells is reviewed in [80–82]. Replacing the conventional glass substrate by silicon brings the opportunity to further boost efficiencies. An SHJ cell is typically used as the bottom cell for this purpose, since the amorphous silicon not only passivates the crystalline silicon but also behaves as an interface layer for subsequent deposition of conductive oxides and perovskites. The bandgap of perovskite solar cells is tuned to match the current of silicon bottom cells. The top and bottom junctions are connected by a transparent conductive layer. Ideally, this layer should have

small optical loss, high conductivity and reliability. ITO is ubiquitously used in thin-film solar cells as the transparent conductive layer in many types of thin-film solar cells, but the sputtering deposition of ITO raises the concern of damaging the layers underneath. Using a four-terminal configuration could increase the available selection of inter- connecting layers.

Successful demonstrations of perovskite/Si solar cells have been reported in a number of publications. We can see that despite the short history of perovskite/ Si solar cells, very rapid progress has been achieved in the last
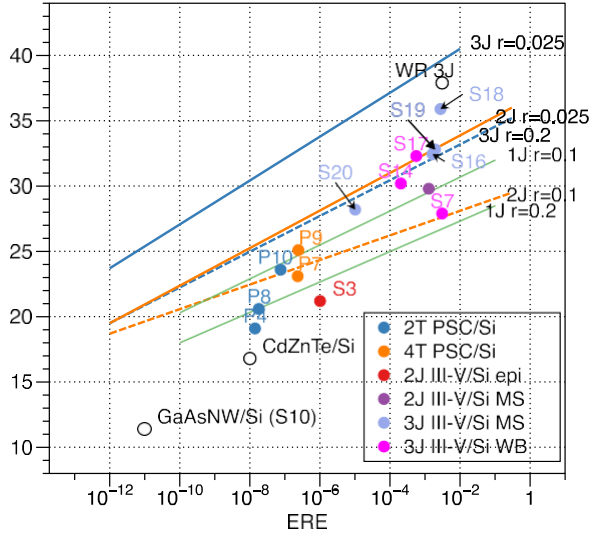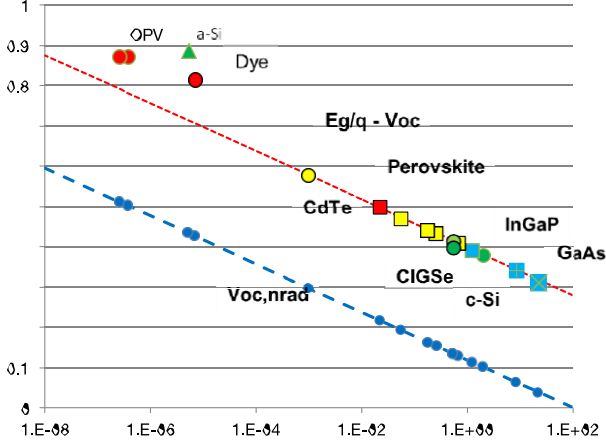
V. PROJECTING THE EFFICIENTS OF SILICON TANDEM SOLAR CELLS

Here, we introduce an analytical model for comparing the sources of efficiency loss of different types of silicon tandem solar cells. This model only attributes the efficiency loss to non-radiative recombination and resistance loss, which is a reasonable assumption because decent solar cells often have very small optical loss. The non-radiative recombination loss is quantified by external radiative efficiency (ERE), which is the ratio of radiatively recombined carriers against all recombined carriers. In other words, we have ERE = 1 at the

Shockley−Queisser limit. EREs of state-of-the-art solar cells can be found in a number of publications, such as [6, 96, 97],

or [98]. In this work, we estimate the EREs of silicon tandem solar cells by the following relation:

$$V_{oc} = V_{oc,rad} + \frac{kT}{q} \ln(\text{ERE}) \qquad (1)$$

where V_{oc} is the measured open-circuit voltage, k is Boltzmann constant, T is the temperature and q is the elementary charge. $V_{oc,rad}$ is the radiative open-circuit voltage. We use $V_{oc,rad}$ values reported in [97] in our analysis. The second term on the right-hand side of equation 1 is denoted as $V_{oc,nrad}$ because it associates to the voltage-loss due to non- radiative recombination. Bandgap-Voc-offset ($Eg/q − V_{oc}$) and $V_{oc,nrad}$ against EREs of state-of-the-art solar cells are plotted in figure 9. The resistance loss of a solar cell is esti- mated solely from the measured fill factor. The ideal fill fac- tor FF_0, defined as the fill factor without any resistance loss, is estimated by [99]

$$FF_0 = (v_{oc} - \ln(v_{oc} + 0.71))(v_{oc} + 1)^{-1} \qquad (2)$$

where v_{oc} is

$$v_{oc} = V_{oc} \left(nkT/q \right)^{-1}. \qquad (3)$$

The measured fill factors can then be related to the series resistance and shunt resistance by the following equation [99]:

$$\begin{aligned} FF &\simeq FF_0(1 - r_s)(1 - r_{sh}^{-1}) \\ &\simeq FF_0(1 - r_s - r_{sh}^{-1}) \\ &= FF_0(1 - r)^{-1} \end{aligned} \qquad (4)$$

where r_s is the series resistance and r_{sh} is the shunt resistance normalized to R_{CH}. R_{CH} is defined by [99]

$$R_{CH} = \frac{V_{oc}}{J_{sc}} \qquad (5)$$

where r is the total normalized resistance defined by $r = r_s + r_{sh}-1$.

By assuming no optical and resistance loss, we can project the efficiency of 2J and 3J silicon tandem solar cell at different EREs, which are listed in table 4. For III–V/Si solar cell, since state-of-the-art III–V top cells can achieve EREs of the order of 10-3, we can expect that the efficiency of III–V/ Si achieves 38% if the EREs can be improved by two orders of magnitudes. On the other hand, we expect chalcogenide/ Si or perovskite/Si can achieve an efficiency of 35.2%(2J) or 39.2%(3J), assuming that their EREs can be improved to 10-3.

The solid and dashed lines in figure 10 shows the calculated efficiencies against EREs of various values of r using equation 1 to equation 5. The efficiencies and EREs of notable silicon tandem solar cells are also plotted in the same figure for comparison. The values of r were selected so that these lines are close to the reported Si tandem results. We can see that the ERE of the most efficient mechanical stack III–V/Si solar cell(35.9%, [50]) is very close to the current best GaInP/GaAs/ InGaAs 3J device, indicating that the degradation of both the III–V and silicon cells due to this integration is manageable. The best wafer-bonded III–V/Si tandem cells [43] can also achieve very high EREs, but the efficiency is lower than the GaInP/GaAs/InGaAs 3J device because the top cell bandgaps in the silicon tandem device is not optimal. III–V/Si tandem solar cells fabricated by direct heteroepitaxy, GaAs-NW/Si and CdZnTe/Si have low efficiencies because their EREs are still far from ideal, and most of the EREs of these cells are already surpassed by those of perovskites/Si solar cells.

VI. Conclusion

We surveyed the progress of heterogeneous silicon tandem solar cells and analyzed the prospects of their conversion efficiencies. At present, III–V/Si and perovskites/Si lead the conversion efficiencies of silicon tandem solar cells.

Mechanically-stacked and wafer-bonded GaInP/GaAs/Si 3J solar cells can reach more than 30%-efficiency, but these approaches do not really reduce the cost of III–V multi-junction solar cells until low-cost wafer-reuse technology is established. Direct heteroepitaxy has the lowest potential cost to integrate III–V and silicon solar cells, but the best demonstrated efficiency struggles to compete with single-junction silicon solar cells. Two-terminal or four-terminal perovskite/Si solar cells have already achieved nearly 24% efficiency. Although this is still lower than the record efficiency of crystalline silicon, perovskite/Si shows great promise because of its rapid developments in the last few years. The development of chalcogenide solar cells on silicon is still preliminary, because fabricating good quality and high bandgap chalcogenide material is still challenging.