Light Trapping in Silicon Based Tandem Solar Cell: A Brief Review

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ABSTRACT: Among the various types of solar cells, silicon based two terminal tandem solar cell is one of the most popular one. It is designed to split the absorption of incident AM1.5 solar radiation among two of its component cells, thereby widening the wavelength range of external quantum efficiency (EQE) spectra of the device, in comparison to that of a single junction solar cell. In order to improve the EQE spectra further and raise short circuit current density (Jsc) an optimization of the tradeoff between the top and bottom cell is needed. In an optimized cell structure, the Jsc and hence efficiency of the device can further be enhanced with the help of light trapping scheme. This can be achieved by texturing front and back surface as well as a back reflector of the device. In this brief review we highlight the development of light trapping in the silicon based tandem solar cell.

Key words: Amorphous silicon tandem solar cell, Light trapping, Surface texture, Back reflector, External quantum efficiency, Current density

Nomenclature

Voc : open circuit voltage, Volts
Jsc : short circuit current density, mA/cm²

Subscript

EQE : external quantum efficiency
EQE₁ : EQE without light trapping
EQE₂ : EQE with light trapping
Jsc₁ : Jsc without light trapping
Jsc₂ : Jsc with light trapping
q : electronic charge
h : PlANKS constant
c : speed of light
φ : AM1.5 spectra
λ : wavelength
BR : back reflector
TCO : transparent conducting oxide
LPCVD : Low pressure chemical vapor deposition
CVD : chemical vapor deposition

AZO : aluminum doped zinc oxide
ITO : indium tin oxide

1. Introduction

Light trapping in a solar cell is a technique used to confine light within the device to enhance optical absorption in the photosensitive active layer. Commercial advantage of using light trapping is that, material cost for the device fabrication can be reduced, as cells can be made thinner with light trapping scheme¹. Usefulness of the light trapping within a thin film was described by Yablonovitch and Cody in 1982 in a statistical mechanical approach and ray optical analysis². As an example, investigation with a hydrogenated amorphous silicon solar cell shows that 80% of incident light can be trapped within the cell³. Soon this scheme is found to be useful for solar cell⁴. Interestingly, the analysis³ shows that the intensity of this confined light inside a non-absorbing textured film can be larger than the incident light intensity, implying that light absorption in such a film morphology can be enhanced. Since then a large number of investigations have been made on various types of solar cells, like single junction⁵,⁶, tandem⁷-⁹ and triple junction solar cells¹⁰ and considered as a state of the art technique to improve device performance.

Achievable photovoltaic conversion efficiency of a tandem
solar cell can be more than that of a single junction solar cell under the broad band AM1.5G insolation. The primary advantage of a tandem solar cell is that light absorption is divided among two component cells, where top cell is made of a relatively wider band gap material so that high energy photons are absorbed in the top cell while relatively low energy photons are transmitted through it. This unabsorbed light then enters a relatively thicker second cell made up of lower band gap material. This technique of spectrum splitting is more popular in practical sense than other techniques where mirror or gratings-like optical elements are used to split the solar spectra that are then incident into separate cells.

2. Techniques adapted for light trapping

To the best of our knowledge, literature on effect of optical confinement in a tandem solar cell can be found as early as 1988, in which textured tin oxide front electrode and indium tin oxide/Ag back reflector (BR) was reported to provide light trapping in a silicon carbide (top cell active layer), silicon germanium (bottom cell active layer) tandem cell structure, leading to improved device performance. In 1997 fabrication of micro-morph solar cells were reported while a similar investigation was reported four years later in 2001 by Schropp et al. The difference in these two investigations are that the former investigations were based on back reflector coated glass superstrate, while the later one was of deposited tandem cell on stainless steel substrate. In these cells, light confinement was enhanced due to surface morphology of polycrystalline silicon layer. Later micro-morph cells were fabricated with textured BR. Fig. 1 schematically demonstrates the ideal or expected ray diagram of trapped light in the bottom cell and Fig. 2 indicates that actual ray diagram in this configuration is different from the expected one. It is straight forward to be able to enhance current density of a tandem cell by light trapping.

It appears that the investigation of light trapping in tandem cell started with surface morphology of polycrystalline silicon layer. In principle, if the technique is designed and implemented properly whereby the light is confined within surface of the active layer (as demonstrated in Fig. 1), it can become one of the most effective methods in enhancing device performance. However, this does not happen in practice because trapped light travels to doped layers as well and also not all types of solar cells are made of polycrystalline silicon. Therefore, alternative methods are necessary to achieving surface texture and improvement in light trapping.

Several methods were proposed for surface texturing of the transparent electrodes, glass superstrate etc so that cells that do not have polycrystalline material can also have benefits of the light trapping. Low pressure chemical vapor deposition (LPCVD) is found to be promising in that respect. ZnO films deposited by this LPCVD method shows highly textured surface useful for the light trapping. Advantage of the technique is that the film becomes self textured, and no chemical or physical method is necessary for surface texturing. However it may be possible that
due to high level of surface texturing some localized surface defects can also be created that may degrade cell performance\(^6\). Few other methods of texturing TCO are high deposition rate in a reactive mid-frequency sputter deposition of AZO\(^{37}\), LP CVD deposited AZO may have better performance\(^{38}\), excimer laser annealing and chemical etching of AZO\(^{39}\) etc.

### 2.1 Textured front surface

Intrinsic hydrogenated amorphous silicon (a-Si:H), amorphous silicon germanium (a-SiGe:H) have reasonable optoelectronic properties to be used in tandem solar cell. The intrinsic a-Si:H have wider optical gap (1.7~1.8 eV) and hence good component for the top cell. Although a-Si/ a-Si tandem cell\(^{19,40}\) can be fabricated but performance of the bottom cell will remain low, as a result lower tandem cell efficiency can be obtained (8.1\%\(^{79}\)). A similar a-Si/a-Si tandem cell with textured SnO\(_2\) front (transparent conducting oxide or TCO) electrode was reported in 1989 having a relatively higher efficiency (9.3\%\(^{40}\)). It was observed that front surface texturing can reduce reflection loss of incident light\(^{38}\); this is effective in a broader wavelength range as compared to anti reflection coating\(^{31,42}\) where the later is wavelength dependant.

In order to enhance effect of front surface texturing, texturing of glass superstrate can be advantageous\(^{33-40}\) over which ZnO can be deposited\(^{37}\). Another approach is texturing the TCO front electrode. Several attempts in this direction showed its benefit, eg. a double layer of indium tin oxide (ITO) and aluminum doped zinc oxide (AZO) multi textured front electrode\(^{29}\), transparent nano textured front electrode, low pressure chemical vapor deposition (LPCVD) grown boron doped zinc oxide (BZO)\(^{48,49}\) to mention the few.

Depending on the surface texture, the front surface reflectivity can simply be expressed as\(^{50}\)

\[
R = (R_{\text{flat}})^n
\]

where \(R_{\text{flat}}\) is flat surface reflectivity and \(n\) is a number dependant on type of surface texture.

### 2.2 Back Reflector (BR)

The back reflector (is a special kind of mirror that) reflects the light back to the solar cell for further absorption. Depending on the type of mirror, that is flat or textured, the light trapping can be retro reflective or diffused reflective. Textured back reflector are preferable than a simple smooth BR\(^{5,8,10}\). In a textured BR, the reflected light remains diffused, thereby increasing average optical path length of reflected light within the cell and also raising a possibility of keeping more light outside the escape cone and thereby enhanced light trapping\(^{10}\). A typical expected signature of light trapping is enhanced red response of external quantum efficiency (EQE) spectra. Various types of textured BR have been used so far, like the following: randomly textured glass\(^{40}\) or any other substrate\(^{15,51,52}\), Si substrates\(^{5,51,53-54}\), plastic substrate\(^{52}\), photonic plasmonic crystal BR\(^{59}\), varying surface texture of Ag/AZO BR\(^{56}\), Ag nano particle used in the BR\(^{57}\) for strong scattering of long wavelength light\(^{58}\), surface textured electrically conductive photonic crystal back reflector\(^{59}\), nano textured Ag BR\(^{40}\), patterned BR\(^{59}\), 3D photonic crystal intermediate reflector\(^{61}\) etc. At the front side of the solar cell, transparency and diffused transmission of the front electrode is another important necessity for light trapping\(^{62}\).

### 3. Modeling, simulation, theory

Theoretical investigation shows that efficiency of a tandem cell can be improved by light trapping\(^{5,10}\). There exists a tradeoff of light trapping among the two components of tandem cell\(^{63}\). It is simple to understand that for a constant incident light (AM1.5G insolation) the light trapping and management can cause change in light absorption in the component cells. In other words, if more light is absorbed in the top cell then available light for the bottom cell becomes lower. This may result in a top cell short circuit current density (\(J_{sc1}\)) becoming larger than that of the bottom cell (\(J_{sc2}\)), or \(J_{sc1} > J_{sc2}\). Then the output short circuit current density (\(J_{sc}\)) of a two terminal tandem cell becomes bottom cell limited, or \(J_{sc} = J_{sc2}\). A reverse situation can arise when the bottom cell absorbs more light. In either of the cases, a light equivalent to the difference between the top and bottom cell current density (\(\Delta J_{sc2} = J_{sc1} - J_{sc2}\)) will be lost. Such a cell will perform poorer than its capability, primarily because of poorer light management. One simple rule that is followed in fabricating a tandem cell by all is, top cell is made thinner than the bottom cell. Although light trapping can raise the current density of all the tandem cells (irrespective of whether the cell structure is optimized or not), however, in order to fully utilize the capability of light trapping, an improved method of optimization becomes necessary.

Several attempts have been made in that direction. Simulation of light trapping using PC-1D\(^{64}\), analysis of light trapping by ray tracing\(^{5,51,65,66}\), are few of them.

The optically enhanced EQE (or EQE\(_2\)) can be expressed in
terms of EQE without light trapping, EQE; as follows:

$$\text{EQE}_2 = \text{EQE}_1 (1+x)$$

(2)

Here x is wavelength dependant EQE enhancement factor.

Similarly, the optically enhanced short circuit current density ($J_{sc2}$) can be expressed in terms of $J_{sc1}$ without light trapping ($J_{sc1}$) as

$$J_{sc2} = J_{sc1}(1+y)$$

(3)

$$y = \frac{q}{(hc)} \int (\text{EQE}_2 - \text{EQE}_1) \phi(\lambda) d\lambda,$$

where q charge of electron, h Planck’s constant, c speed of light, $\phi$ is AM1.5 spectra, $\lambda$ is wavelength.

Using a simple logic and ideal sharp band structure of materials, one can say that the usable part of solar spectra should be divided into two halves, where the shorter wavelength half should be allocated for the top cell and the bottom cell should be exposed by the second half of the spectra. Based on this, it can be suggested that the allocated spectral range for the top cell should be below 650 nm (Fig. 3) while that of the bottom cell should be 650 to 1200 nm, assuming 1200 nm is the usable long wavelength limit.

In summary, the effect of light trapping in a tandem solar cell can be described by EQE spectra, as given in Fig. 4. At the beginning, the quantum efficiency spectra of the cell will enhance due to successful light trapping, this will lead to enhanced current density and hence efficiency of the device.

Additional key components for improved device performances are, improved optoelectronic properties of the cell layers. Various works have been reported and also going on to improve material and hence further enhancement of device performance. As this topic outside the scope of this article, so we prefer not to discuss it any further.

### Table 1. Effect of light trapping on performance of a photo voltaic device

| Element of light trapping | Effect on parameter | Ref |
|---------------------------|---------------------|-----|
| Front texture             | Reflectance         | Decrease |
| Tex-ZnO, front            | $J_{sc}$            | Increase by 20 to 25% |
| Tex BZO, front            | $J_{sc}$            | Increase by 4.8% |
| Flat BR                   | Efficiency EQE      | Increase by 0.95 mA/cm², 0.74%, 12% |

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### 4. Conclusions

State of the art design of a two terminal tandem solar cell should include opto-electronic aspects of the device in such a way that high $V_{oc}$ and $J_{sc}$ are achievable. High $J_{sc}$ can only be achieved when current generated by the top and bottom cells are equal. In order to achieve high $J_{sc}$ an optimization is needed with of thickness of all the layers of the device, texture of front and back surfaces, and back reflector. Optimization of design of a tandem solar cell is a complicated process, as it involves optoelectronic properties of top and bottom cells. Under a constant illumination a tradeoff in absorption among top and
bottom cell exists that depend on material and structural design of the layers of the component cells. In a tandem solar cell a higher open circuit voltage is achievable but $J_{sc}$ or current density decreases in comparison to that of a single junction solar cell. Effective light trapping can improve the current density of both the top and bottom cells and hence the overall device efficiency can be improved. Several different optimized cell structure is possible that may be unique to material and design of the cells, yet the fundamentals of all these is to incorporate textured front surface and back reflector for a state of the art tandem solar cell.

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