

## 비정질/마이크로 탠덤 구조형 실리콘 박막 태양전지

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### a-Si:H/ $\mu$ c-Si:H thin-film tandem solar cells

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**Key words** : solar cell(태양전지), thin-film(박막), 비정질 실리콘(a-Si:H), 마이크로 실리콘( $\mu$ c-Si:H), tandem(적층)

**Abstract** : This paper briefly introduces silicon based thin film solar cells: amorphous (a-Si:H), microcrystalline ( $\mu$ c-Si:H) single junction and a-Si:H/ $\mu$ c-Si:H tandem solar cells. The major difference of a-Si:H and  $\mu$ c-Si:H cells comes from electro-optical properties of intrinsic Si-films (active layer) that absorb incident photon and generate electron-hole pairs. The a-Si:H film has energy band-gap ( $E_g$ ) of 1.7-1.8eV and solar cells incorporating this wide  $E_g$  a-Si:H material as active layer commonly give high voltage and low current, when illuminated, compared to  $\mu$ c-Si:H solar cells that employ low  $E_g$  (1.1eV) material. This  $E_g$  difference of two materials make possible tandem configuration in order to effectively use incident photon energy. The a-Si:H/ $\mu$ c-Si:H tandem solar cells, therefore, have a great potential for low cost photovoltaic device by its various advantages such as low material cost by thin-film structure on low cost substrate instead of expensive c-Si wafer and high conversion efficiency by tandem structure. In this paper, the structure, process and operation properties of Si-based thin-film solar cells are discussed.

### I. INTRODUCTION

Silicon based thin-film solar cells (Si-TFSC) have been promising candidate for low cost and high efficiency photovoltaic devices. Although wafer-based crystalline silicon (c-Si) solar cells have possessed more than 90% of world PV market over the fast few decades<sup>[1]</sup>, high material cost and feedstock shortage of c-Si substrates have been still obstacles for wide spread use of c-Si solar cells. On the contrary to c-Si cells, Si-TFSC has a great potential for reducing material cost since it use very thin-films on low cost substrate such as glass, stainless steel sheet, plastic, etc, instead of using expensive thick (250-350  $\mu$ m) c-Si wafer. Regardless of this low cost potential of Si-TFSC, the market possession is still low. The amorphous silicon (a-Si:H) thin-film solar cells has been introduced early in the 1970s and market share has been more than 25% in 1990 but drastically decreased to about 6% in 2003<sup>[1]</sup>. The main reason for this reduced market possession of a-Si:H solar cells might be resulted from low module efficiency and stability problem (*Staebler-Wronski Effect*)<sup>[2]</sup>, by

which the production cost (\$/Wp) of a-Si:H solar cells has not been competitive with c-Si solar cells. Although a-Si:H thin-film modules have similar or slightly less production cost over the c-Si cells, the installation area should be more than double in order to generate the same electricity because of its low efficiency. During the 1990s, microcrystalline silicon ( $\mu$ c-Si:H) thin-film and solar cell have a great attention since they have no stability problem and high potentials for improving efficiency<sup>[3-5]</sup>. The  $\mu$ c-Si:H layer is known to be a complex material consisting of crystalline and amorphous silicon phases plus grain boundaries<sup>[6]</sup>. The band-gap energy ( $E_g$ ) is the same with single c-Si (1.1eV). However, the  $\mu$ c-Si:H thin-film solar cells have shown some drawbacks and the efficiency has stayed near 10%. This low efficiency of  $\mu$ c-Si:H cells is related to material properties of  $\mu$ c-Si:H layer; its low light absorption coefficient and imperfect material quality. The world record  $\mu$ c-Si:H solar cells give current density(jsc) of 26mA/cm<sup>2</sup> and voltage (Voc) of 0.55V which is

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quite low compared to commercially available c-Si solar cells<sup>[7]</sup>. The low  $j_{sc}$  of  $\mu c$ -Si:H cells mainly results from incident photon loss since thickness of intrinsic  $\mu c$ -Si:H layer is just a few  $\mu m$  that is not enough to fully absorb incident photon; at least 50 $\mu m$  silicon needed to absorb 90% of photon. In order to effectively utilize incident photon, tandem concepts are introduced<sup>[8]</sup>. The a-Si:H/ $\mu c$ -Si:H tandem solar cells consist of wide  $E_g$  (1.7eV) a-Si:H top-cell and narrow  $E_g$  (1.1eV)  $\mu c$ -Si:H bottom-cell. The high photon energy is absorbed at a-Si:H top-cell and low energy at  $\mu c$ -Si:H bottom-cell. The series interconnection of two cells produces high voltage of solar cells, which is beneficial to reduce series resistance loss by transparent conducting oxide (TCO) in a large area module. The Kaneka corp. has already achieved 14.7% efficiency in a lab-scale small area tandem cells and about 10% in mass-produced meter-scale modules<sup>[9]</sup>. However, the module efficiency more than 15% and production cost of 50 $\$/m^2$  should be realized for photovoltaics with Si-TFSC to have competitiveness with conventional power source.

## II. Solar Cells Structure and Process

### 2-1. Device structure

Figure 1 shows a cross sectional structure and operation mechanism of *superstrate pin* a-Si:H/ $\mu c$ -Si:H tandem cells. All single junction and tandem solar cells are prepared on glass substrate. As a front transparent conducting oxide(TCO), SnO<sub>2</sub>:F (Asahi-U glass) or ZnO:Al with rough surface are used. The ZnO:Al films with textured surface are prepared by chemical etching(1% HCl) of rf-sputtered ZnO:Al that has originally flat surface morphology. The front TCOs with textured surface has been reported to give improved solar cell performances by their advanced optical properties such as low reflectance and high scattering of incident light. As a p-type window materials, a-SiC:H,  $\mu c$ -Si:H single layer and c-Si:H/ $\mu a$ -SiC:H by-layer are employed. The effect of different p-type window layers on a-Si:H solar cells will be discussed in the following section. The tandem solar cells composes of series connection of *pin* a-Si:H top-cell and  $\mu c$ -Si:H bottom-cell. The ZnO buffer between top and bottom cells reportedly gives higher current to top-cell by internal reflection of incident light at ZnO buffer, by which degradation (SW-effect) of a-Si:H top cell can be reduced by making a-Si:H intrinsic layer thin. The Ag and ZnO/Ag are used as a back contact.

### 2-2. Solar cell process

The a-Si:H,  $\mu c$ -Si:H and a-Si:H/ $\mu c$ -Si:H thin-film solar cells were fabricated with multi-chamber cluster tool system. The system consists of five process, two central and load/unload chambers.

The process chambers contain 2 PECVDs, VHFCVD, HWCVD and rf sputtering systems. Robot arm is located inside the central chamber in order to transfer substrate into each process chamber without breaking vacuum. With this system, the solar cells can be produced without any impurity contaminations during deposition of *pin* thin-films and sample transfer. The intrinsic a-Si:H and  $\mu c$ -Si:H thin-films were deposited by 60MHz VHFCVD with SiH<sub>4</sub> and H<sub>2</sub> gas mixture. The p c-Si:H and n a-Si:H layers were prepared by conventional PECVD method. The ZnO intermediate buffer in a tandem cell was deposited by rf sputtering method with ZnO:Al<sub>2</sub>O<sub>3</sub> target at room temperature. The low rf power was employed to prevent surface damage by ion collisions during sputtering of intermediate ZnO film. The solar cell area was defined to be 0.25cm<sup>2</sup> by shadow mask during deposition of ZnO:Al and Ag back contact.

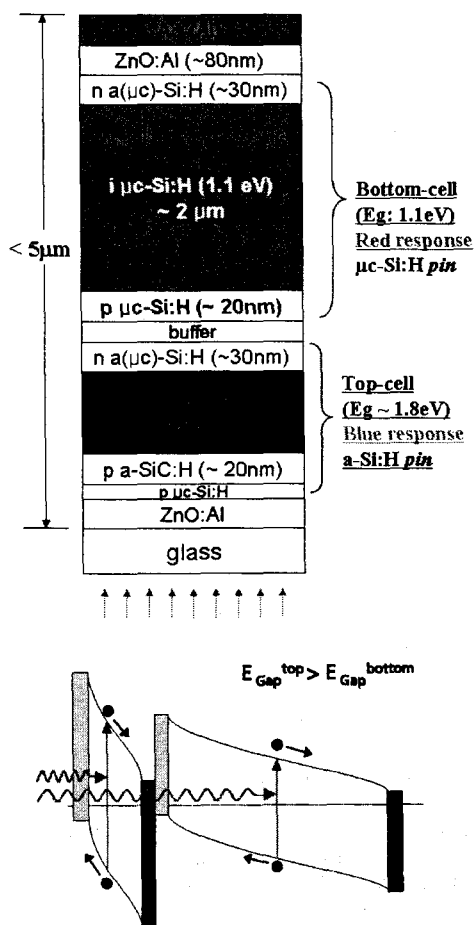


Figure 1. Structure and operation mechanism of a-Si:H/ $\mu c$ -Si:H tandem solar cells.

### III. RESULTS AND DISCUSSION

#### 3-1. Front TCO

As a front TCO in a superstrate *pin* solar cells, ZnO:Al should give high conductivity, transmittance and scattering properties. Besides these properties, good interface formation with p-layer is important since the grain growth of silicon films is strongly dependent on the underlying substrate geometry (textured ZnO:Al in our case). Figure 2 presents the effect of surface morphology of front textured ZnO:Al on  $\mu\text{c-Si:H}$  single *pin* solar cells. The front ZnO:Al films are prepared at different Ar pressure (1.0 and 2.0 mTorr) and hence give different surface morphology after short chemical etching. The feature size of etched ZnO:Al films decreases with elevated Ar pressure during sputtering. Due to smaller feature size, the ZnO:Al films prepared at high pressure (2 mTorr) has less light scattering (small haze ratio) compared to the 1 mTorr films. Two important things are observed in QE measurements: (1)  $J_{sc}$  not proportional with haze ratio and (2) occurrence of light voltage bias dependence,  $QE(-1V)/QE(0V)$ , in the solar cells on ZnO:Al with small feature size. The high wavelength dependence of the QE ratio means the presence of higher density of recombination centers inside the intrinsic layer. As reported by Kondo et al.<sup>[10]</sup>, collisions of grain growth in  $\mu\text{c-Si:H}$  film are enhanced when deposited on ZnO:Al with small feature size, giving rise to high defect density within the films. As shown in Table 1, the low  $V_{oc}$  and fill factor (FF) of solar cells prepared on 2.0 mTorr ZnO:Al TCO may be caused by high recombination and shunt leakage.

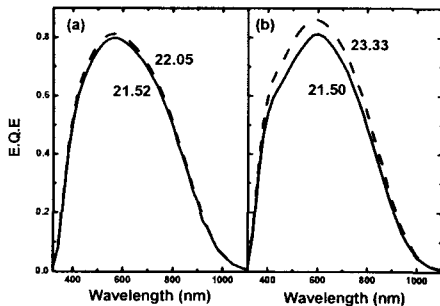


Figure 2. Voltage bias dependence of EQE of *pin*  $\mu\text{c-Si:H}$  solar cells on textured front ZnO:Al sputtered at (a) 1.0 mTorr and (b) 2.0 mTorr: solid line QE under the short circuit and dashed line at -1V applied voltage. Estimated values of  $J_{sc}$  are also indicated.

Table 1. The Photovoltaic parameters of  $\mu\text{c-Si:H}$  solar cells on different ZnO:Al

	0.5 mTorr	1.0 mTorr	2.0 mTorr
$V_{oc}$ (mV)	520	511	490
$J_{sc}$ ( $\text{mA}/\text{cm}^2$ )	20.8	21.5	21.5
FF (%)	68.6	69.5	60.0
Eff (%)	7.4	7.6	6.3

Figure 3 shows the QE of top and bottom cells separately for a-Si:H/ $\mu\text{c-Si:H}$  tandem solar cells deposited on different front TCOs. ZnO:Al films give higher spectral response of top and bottom cells than  $\text{SnO}_2\text{:F}$  (Asahi-U glass) because of their higher haze and transmittance. Similar to  $\mu\text{c-Si:H}$  single *pin* solar cells, highest  $J_{sc}$  of top and bottom cells are obtained using 2 mTorr ZnO:Al films.

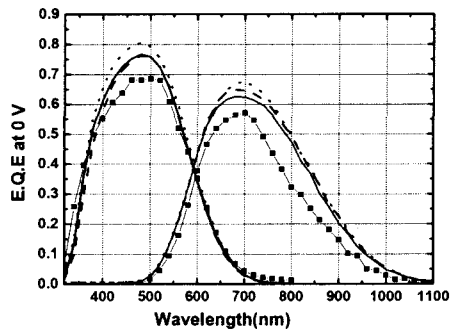


Figure 3. External quantum efficiency of top and bottom cells on different TCOs: solid line (0.5 mTorr ZnO:Al), dashed line (1.0 mTorr), dotted line (2.0 mTorr) and filled square ( $\text{SnO}_2\text{:F}$ ).

Voltage bias dependence of a-Si:H/ $\mu\text{c-Si:H}$  tandem solar cells on 2 mTorr ZnO:Al is shown in figure 4. Contrary to single *pin*  $\mu\text{c-Si:H}$  solar cells (Fig. 1),  $QE(-1V)/QE(0V)$  ratio of top and bottom cells is close to unity. This small voltage bias dependence means that the carrier recombination is suppressed in a tandem structure even if the front ZnO:Al films have small feature size. Since a-Si:H top cells form first contact with ZnO:Al films in a tandem cell, the defects by collision of grains during  $\mu\text{c-Si:H}$  deposition are reduced by buffering of underlying a-Si:H top-cells. The smoothing of surface morphology by deposition of 200 nm a-Si:H top-cells could be one possible buffering effect. However, more precise analysis on this experimental phenomena should be done, for example, by investigating grain growth and defect formation on single *pin* and tandem cells.

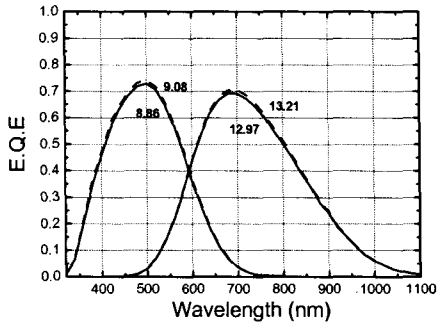


Figure 4. Voltage bias dependence of a-Si:H/c-Si:H tandem solar cells on 2.0mTorr front ZnO:Al. Solid and dashed lines under the short circuit and -1V, respectively

### 3-2. Current matching

As mentioned earlier, a-Si:H/ $\mu$ c-Si:H tandem solar cells are series inter-connected optically and electrically. Therefore, it is quite important to match current between top and bottom cells because total current of tandem cell is limited to the cell with lower current. The current matching usually can be done by changing thickness of light absorber of top and bottom cells. However, this method is no more effective when current mismatch occurs by a-Si:H top-cell because thickness increase of a-Si:H top-cell increases the light induced degradation by a-Si:H top-cell and lower stabilized efficiency of tandem cell. The alternative way, instead of increasing thickness, is to use intermediate reflector between top and bottom cells. Figure 5 shows illuminated I-V curves of tandem cells incorporating thin ZnO as an intermediate buffer. When the thickness of inter-ZnO is less than 5nm, the current of tandem cell is limited by top-cell. By increasing its thickness to 50nm, jsc of tandem cell improves from 11.0 to 12.28mA/cm<sup>2</sup>, which is resulted from enhanced reflection of light at inter-ZnO buffer. However, Jsc of tandem cell decrease with further increase of inter-ZnO layer due to the reduced transmission of light by thick buffer. At this point, the Jsc of tandem cell limited by  $\mu$ c-Si:H bottom cell.

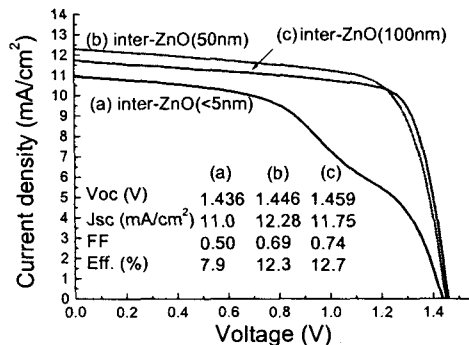


Figure 5. Illuminated I-V curves of a-Si:H/ZnO/ $\mu$ c-Si:H thin-film tandem solar cells with different inter-ZnO thickness.

## IV. CONCLUSION

In this paper, device structure, process and performance of Si-based thin-film solar cells (Si-TFSC) are briefly introduced. The a-Si:H/ $\mu$ c-Si:H tandem cells, composing of wide gap a-Si:H top cell and narrow gap  $\mu$ c-Si:H bottom cell, has a great potential to overcome the obstacles of present PV technology that uses high cost wafer-based c-Si solar cells. The outstanding merits of Si-TFSC over the conventional c-Si solar cells are reduced material cost by thin-film (less than 2% material usage compared to c-Si wafer), high throughput by in-line process, possible usage of a variety of substrates such as low cost glass, plastic, metal foil or sheet, etc by low temperature process. However, for these thin-film solar cells to be competitive with conventional technology, the following technical obstacles should be solved;

- low efficiency (currently, small area cells 14.7% and production modules 10%)
- light degradation of a-Si:H solar cells
- low deposition rate of silicon layers, especially  $\mu$ c-Si:H
- large efficiency gap between small area solar cells and large area modules
- low insight on material and device physics.

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