Fabrication of high-power CIGS modules by two-stage processing, and analysis of the manufacturing cost

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ABSTRACT

Of the various copper indium gallium diselenide (CIGS)-formation processes, a so-called 'two-stage process', consisting of sputtering and selenization, has been successfully applied in large-scale production thanks to its stable process scheme and high-fidelity production equipment. A CIGS module with a power of 231W, corresponding to a total area-based efficiency of 16% for 902mm × 1,602mm, was demonstrated when this two-stage process was employed in a pilot production line at Samsung (although all the technology concerning CIGS production has now been transferred to Wonik IPS, whose main business is to provide production equipment for the semiconductor and display industry). The high-power module suggests significant potential for CIGS modules to compete with multicrystalline Si modules in terms of both cost and performance. This paper addresses the important process technologies for achieving high efficiency on large-area substrates, and presents a cost analysis using the data obtained from the operation of the pilot production line. As a result of the synergistic effect of low material cost and high efficiency of the two-stage process, the CIGS manufacturing cost is expected to be reduced to US$0.34/W.

Introduction

Owing to the rapid cost reduction in the production of crystalline silicon (c-Si) PV modules, the thin-film PV industry has unexpectedly been adversely affected. At the moment, US$1/W is the target system cost for c-Si PV systems. Copper indium gallium diselenide (CIGS) is the only thin-film module technology that is expected to supersede c-Si in the near future.

In recent years there has been considerable progress in the performance of CIGS thin-film solar cells: cells of this type with power conversion efficiencies of almost 14% have been commercialized in the PV market [1]. Moreover, CIGS systems are among the most promising absorber materials for the fabrication of low-cost solar cells. The highest efficiencies reported thus far have already exceeded those of polycrystalline Si-based solar cells, while pioneering research groups and industries are striving to further increase the efficiencies by employing various alternative substrates [2–4].

There are two conventional methods for creating CIGS absorber layers:

1. The simultaneous evaporation of metallic elements in the presence of vaporized selenium (co-evaporation).

2. Heat treatment of metal precursors in H_2Se gas (two-step process) [5–7].

A large number of studies have focused on the formation of CIGS absorber layers by the co-evaporation process; the best efficiencies have always been reported for cells fabricated that way. On the other hand, several studies on CIGS absorber layers fabricated via the two-step approach have been carried out by various industries, in particular the Institute of Energy Conversion (IEC) at the University of Delaware, with the aim of commercializing this method.

"With the two-step process, total area efficiencies of 17.9% and 16% for modules of 300mm × 300mm and 902mm × 1,602mm respectively have been achieved at Samsung's pilot line."

The two-step process has been under development for seven years at Korea University and Samsung/Wonik IPS for application to large-area modules. The large-area equipment for the production processes was designed and manufactured in collaboration with equipment providers. With the two-step process, total area efficiencies of 17.9% and 16% for modules of 300mm × 300mm and 902mm × 1,602mm respectively have been achieved at Samsung's pilot line; this excellent module performance is due to the synergistic effect of the high-efficiency process technology and the capability of large-area processing [8].

Despite the rapid progress in the performance of the two-stage process, no detailed cost analysis has been reported so far. The authors therefore

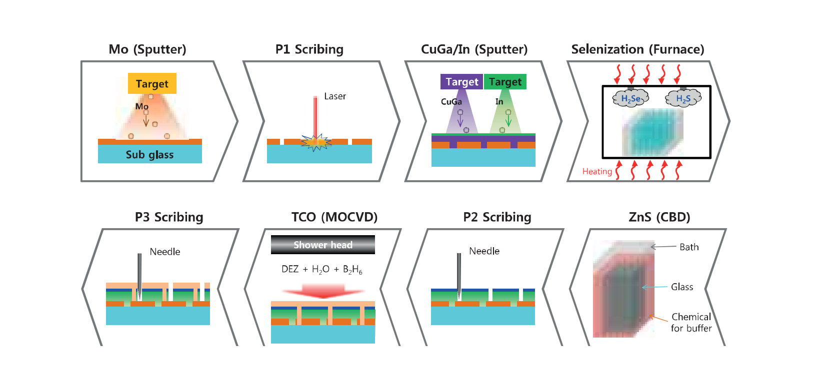

Figure 1. Process flow for CIGS module production using the two-stage process.

recently conducted an analysis of the CIGS manufacturing cost using the accumulated data from the pilot line at Samsung; the results are presented in this paper. Besides the evaluation of the cost-effectiveness of CIGS modules, the various cost elements of CIGS PV modules are broken down in detail, and the possibility of utilizing technological improvements for further cost reduction in the manufacturing process are highlighted.

Materials and methods

The key steps for CIGS module production by the two-stage process are shown in Fig. 1. For a monolithically integrated module, the Mo layer is scribed with a high-power laser (P1) after deposition of the Mo back electrode by the sputtering method. The width of the P1 scribing is optimized according to the desired current density and the thickness and quality of the transparent conducting oxide (TCO) layer.

After the Cu–Ga/In precursors are deposited on the P1-scribed Mo layers, CIGS absorber layers with a thickness of ~1.6μm are formed via the reaction of the precursors with H_2Se and H_2S gases. The element sodium (Na) is essential for high-performance CIGS solar cells and its quantity should be carefully controlled. The amount of Na from the glass substrates can be controlled by employing SiO_2 as the barrier layer before sputtering the Mo back contact, or by the sodium-containing Cu–Ga (Cu–Ga:Na) layer deposited on the Mo back contact.

The thickness and deposition conditions of the precursor layers are freely modified by the glass transfer speed, plasma power and pressure of the Ar gas. The reaction process is optimized with respect to temperature and time range. To induce the reaction process, the chamber is heated to 480–500°C and filled with H_2Se/N_2 gas. The first selenization step is then carried out for 25–35min. In the second step, the selenized film is exposed to H_2S/N_2 gas at 550–600°C for 60–90min. The chamber is cooled down to 300–350°C under a H_2S/N_2 atmosphere, and then purged with N_2 gas. The reaction takes place in a specially designed reaction chamber that can endure the highly corrosive H_2Se gas environment.

The buffer layer, used to reduce the number of shunt paths and to increase the interface quality, is grown on the absorber layer by a chemical bath deposition (CBD) process. The Zn(OH,O,S)-based buffer layer is deposited onto the CIGS absorber layer using $ZnSO_4$, NH_4OH and thiourea (CH_4N_2S) as sources in deionized (DI) water. Pre-rinsing is done using DI water at room temperature. The buffer layer is grown at the deposition-bath temperature of 60°C; its thickness is about 3–5nm.

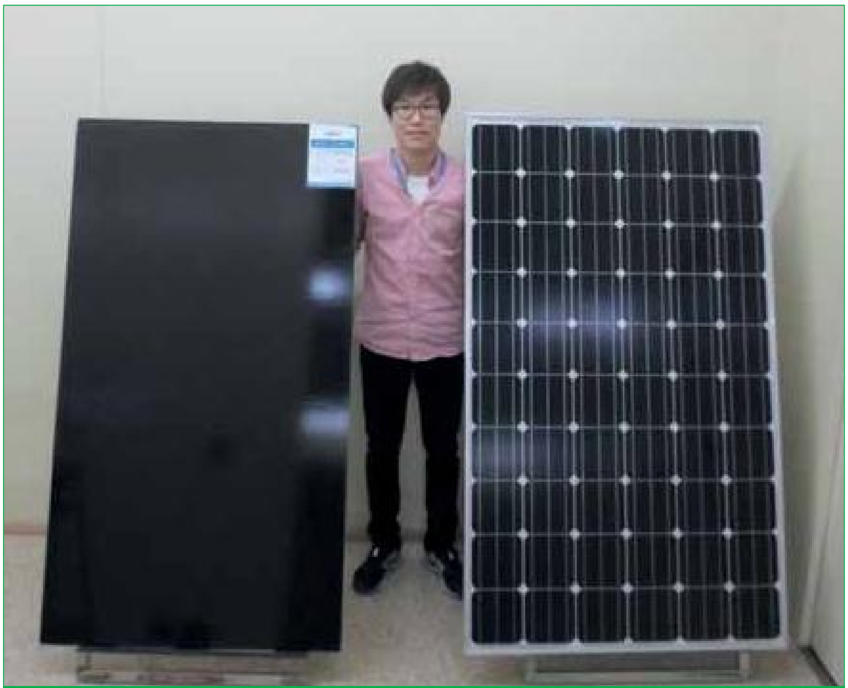

Figure 2. The CIGS module (left) fabricated at Samsung SDI in collaboration with Wonik IPS, and the c-Si module (right).

The openings for the series connections between the unit cells separated by P1 are formed by mechanical scribing (P2). The gap between P1 and P2 is minimized to reduce the percentage of dead area within the total module area.

Boron-doped ZnO (BZO) is used as the TCO layer, deposited by low-pressure metal–organic chemical vapour deposition (MOCVD). The thickness and sheet resistance of the TCO layer are 950nm and 11–13Ω/sq. respectively.

The next step, for separating the unit cells, is done by the mechanical scribing process P3. After the P3 step, the Mo/CIGS/buffer/TCO multilayer films are removed along the glass edges to electrically isolate the active cell regions from the outside and to ensure hermetic sealing of the module. This process is called *edge deletion* or *edge trimming*; typically, the width of the deleted border is 8–9mm.

Electrical contacts are created by charge-collection tape (CCT) between the first and the last cell. The specific contact resistance between CCT and $MoSe_2$/Mo was calculated from transmission line measurements (TLM) to be much lower than 10mΩ·cm^2.

Hot, molten butyl sealant is dispensed around the glass edge for sealing, before the lamination process is carried out at 155°C for 18–20min. The EVA (film using evaporated a-Si) used in this process is a commercially available standard fast-cure EVA film. The gel-content test is the most appropriate method for measuring the percentage of cured EVA; the value of the gel percentage was in the range of 85–92%.

Finally, the junction box and rails are attached to the back side of the substrates using adhesive. The junction box enables a module to be electrically connected to other modules.

Fig. 2 shows a completed CIGS module (left) using this process, along with a conventional c-Si module (right). It is noted that the frameless modules passed the standards IEC 61646 ('Design qualification and type approval') and IEC 61730 ('Photovoltaic (PV) module safety qualification').

Development history

Fig. 3 shows the performance history of CIGS modules developed at Samsung, along with the *I–V* characteristics measured at TÜV Rheinland, Germany, in the case of a 902mm × 1,602mm module. All processing steps have been optimized to maximize the module output power, as well as to satisfy reliability requirements. After the development of small cells of 5mm × 5mm in 2008, the module size was gradually increased to 300mm × 300mm in the first pilot line.

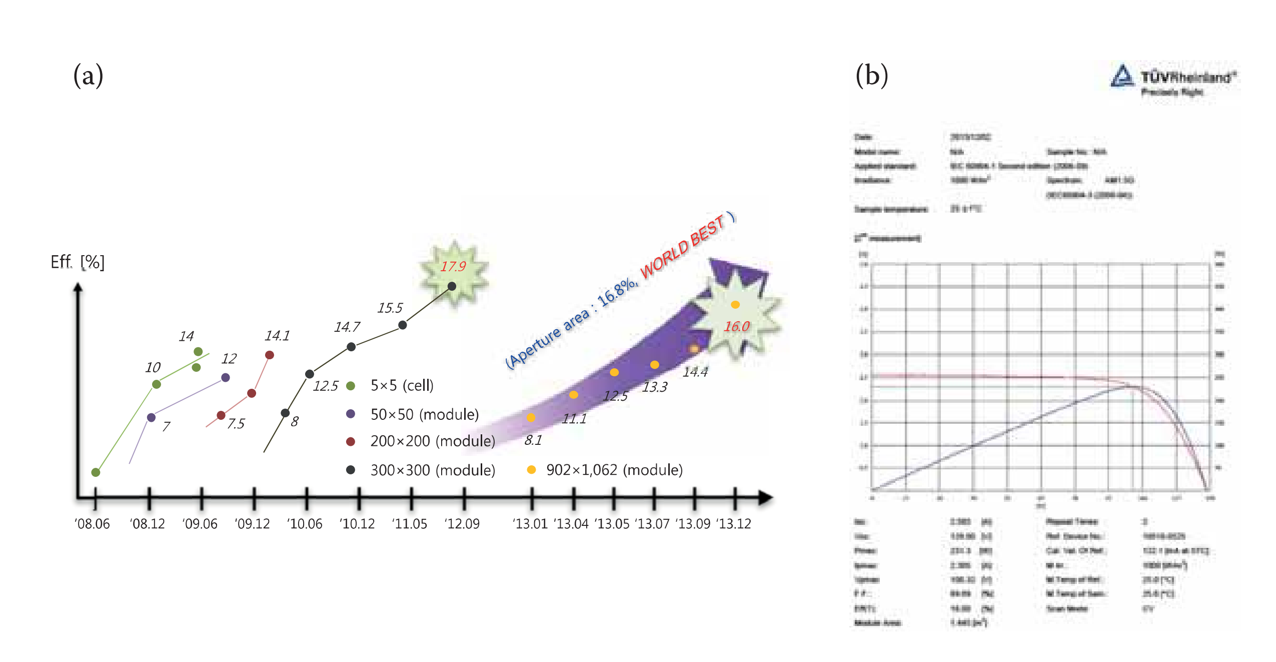

Figure 3. (a) History of efficiency improvements – small cells (5×5) to large-area modules (902×1,602). (b) The performance certification from TÜV Rheinland, Germany (902×1,602).

"It is encouraging that it was possible to enhance module efficiency from 8.1% to 16.0% within one year."

Following the achievement of a maximum module efficiency of 17.9% with 300mm × 300mm modules, a second pilot line was established to develop large-area modules of size 902mm × 1,602mm. The width and length of the modules were decided by taking into account factors such as the balance of system (BOS) cost, mechanical strength, weight and compatibility with c-Si modules.

All the tools for the second pilot line were designed to handle 1.8-mm thick, 902mm × 1,602mm glass substrates and to conduct uniform and reproducible processes. The specifications of the process tools were decided with the aim of achieving processing conditions similar to those developed for the first pilot line. Most of the key process tools – including the sputter system for the Cu/Ga and In precursors, the selenization furnace, the MOCVD system and the CBD system – were constructed in order to evaluate their suitability for a 200MW production capacity.

Fig. 4 shows the set-up of the four main process tools in the pilot production line for large-area CIGS modules. It is encouraging that it was possible to enhance module efficiency from 8.1% to 16.0% (Fig. 3(a)) within one year for a glass size comparable to that of a crystalline module. The rapid progress in efficiency enhancement of the large-area modules indicates that the two-stage process is favourable for increasing the substrate size and matching the parameters of different process tools.

Results and discussion

Analysis of the CIGS production cost

For the manufacturing-cost analysis of the CIGS modules, every input item of the cost-analysis template used previously for determining the manufacturing cost of crystalline silicon cells at Samsung was upgraded. A detailed analysis was conducted of the manufacturing costs on the basis of the data acquired from the operation of the CIGS pilot line for a period of more than a year. Material costs and capital expenditure for the equipment were aggregated using the data provided by the material and equipment suppliers. Cost calculations were performed for a three-year period and based on forecast technology improvements.

The basic assumptions for the manufacturing cost calculations were as follows:

- Module efficiencies are 15.2%, 15.9% and 16.3% in 2015, 2016 and 2017 respectively.
- The thickness of the absorber layer is 1.6μm until 2016 and then reduces to 1.3μm in 2017.
- The yields in module manufacturing remain constant at 97%.
- Plant utilization is 90%.
- The location of the production site is in China.
- The 1GW plants produce 5.5, 5.6 and 5.7 million modules a year in 2015, 2016 and 2017 respectively.
- The module structure is glass-to-glass without a frame. Four aluminium rails are attached onto the back side of the modules for installation.
- The depreciation period is assumed to be seven years for the cell-production equipment, and ten years for the module-production equipment and the entire plant, corresponding to the assumptions used for the Greentech Media report [9].

"The production of CIGS seems to be feasible below $0.4/W from Q4 2016 onwards, while mc-Si might still stay above $0.40/W."

Comparison with the production cost of multicrystalline Si modules

Table 1 shows the CIGS cell-to-module manufacturing cost per watt for the next three years (Q4 2015–Q4 2017). It is assumed that multicrystalline Si modules are produced through the procurement of wafers and the manufacturing process of cells and modules. The *CIGS cell process* is defined as all the process steps starting from substrate cleaning and finishing with P3 scribing, so that

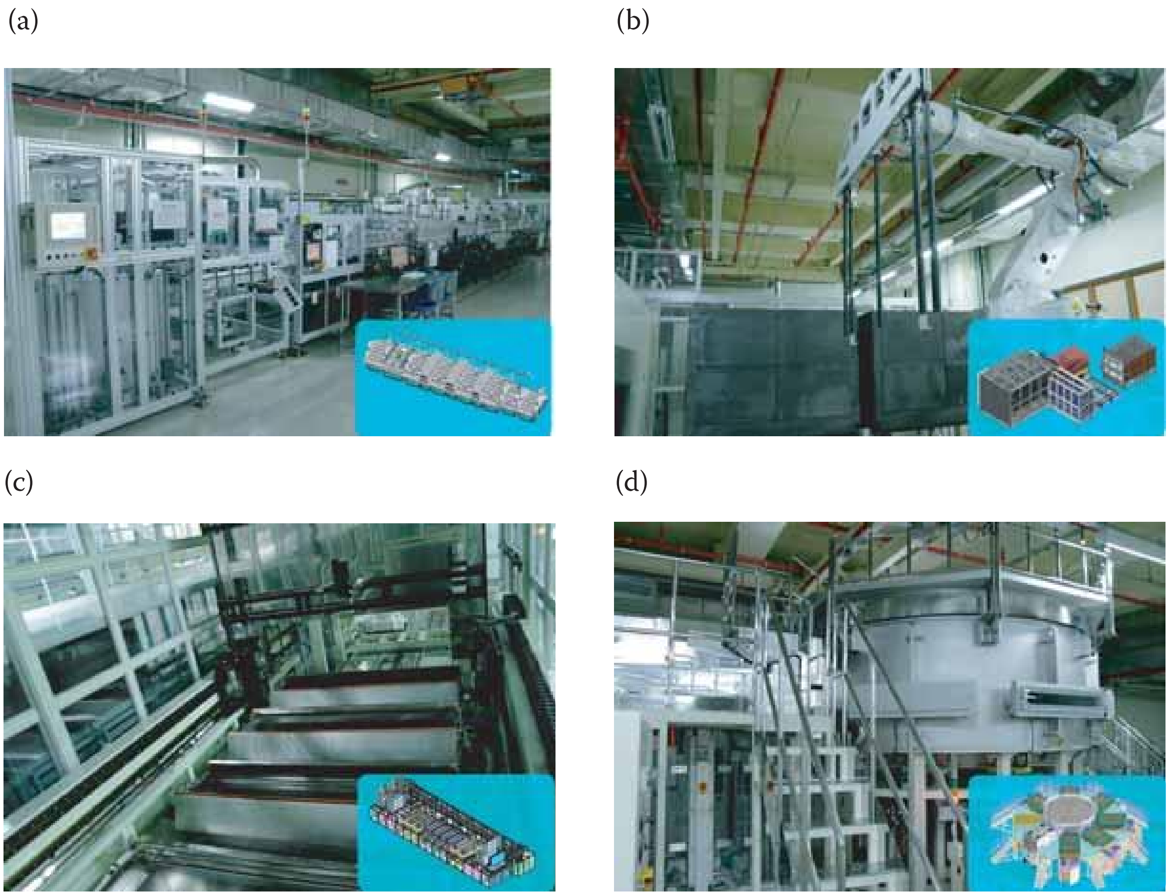

Figure 4. Set-up of the main process tools in the pilot production line for large-area CIGS modules: (a) sputter system for Mo deposition; (b) selenization furnace; (c) CBD system; and (d) MOCVD system.

comparisons with the silicon-cell process can be made; however, there is no clear separation between cell and module in the case of CIGS.

The cost is broken down into six components: material cost in the cell process (such as substrate glass, target and H_2Se for the CIGS production), material cost in the module process (such as cover glass, junction box and EVA), capital (depreciation), labour, utilities and yield loss. As a result, the unit cost of CIGS in Q4 2015 is $0.404/W, which is about 13% less than in the case of mc-Si ($0.465/W). The cost gap between CIGS and mc-Si will increase over one year: the cost ratio of CIGS to mc-Si is expected to be 83% in Q4 2016 and 79% in Q4 2017. The production of CIGS seems to be feasible below $0.4/W from Q4 2016 onwards, while mc-Si might still stay above $0.40/W.

The material costs account for 58–60% in CIGS (see Table 2), whereas they are forecast to be well above 80% in mc-Si for the next three years. A significant portion of the materials cost is substrate glass, cover glass, target, junction box and H_2Se gas. It appears that the operating rate of the glass-production capacity could have a significant impact on the substrate-glass price. Current worldwide CIGS production is not sufficient to consume all the substrate glass from a single glass-production line of 70,000 tons/year. Even though mc-Si owes its high ratio of material cost to the assumption of procuring wafers, it is obvious that mc-Si has a much higher share of material cost than CIGS.

CIGS requires much more intensive capital and slightly less intensive labour than crystalline Si. The CIGS production line has precursor deposition and

Cost element	Q4 2015E [$/W]	Q4 2016E [$/W]	Q4 2017E [$/W]
Materials (cell)	0.133	0.119	0.104
Materials (ex-cell)	0.109	0.101	0.095
Depreciation	0.088	0.072	0.063
Labour	0.010	0.010	0.010
Utilities	0.045	0.052	0.051
Yield loss	0.019	0.018	0.017
Total cost	**0.404**	**0.372**	**0.340**

Table 1. Estimated cell-to-module manufacturing cost ($/W) of CIGS, broken down according to the individual cost elements.

Cost element	Q4 2015E [%]	Q4 2016E [%]	Q4 2017E [%]
Materials (cell)	32.80	31.95	30.64
Materials (ex-cell)	27.03	27.10	27.92
Depreciation	21.80	19.42	18.49
Labour	2.58	2.81	3.06
Utilities	11.13	13.98	14.97
Yield loss	4.66	4.74	4.92

Table 2. Estimated percentage cell-to-module manufacturing cost of CIGS, broken down according to the individual cost elements.

selenization equipment for the absorber layer, whereas silicon-based cell and module manufacturers purchase the silicon wafers that correspond to the CIGS absorber layer. The depreciation expense in CIGS is therefore higher than in mc-Si, making up to 18–22% of the total manufacturing cost. The depreciation ratio in CIGS is expected to gradually decrease to 19.42% in 2016 and to 18.49% in 2017 due to economies of scale.

The lower labour cost of CIGS is attributed to the large-area, automated production. For example, labour-intensive processes, such as interconnection and lay-up in the case of crystalline silicon modules, can be carried out by the fully automated system in the CIGS production line. The labour-portion cost in CIGS is therefore lower than in mc-Si, constituting 2–3% of the total manufacturing cost.

Electricity constitutes the biggest utility-cost portion because of the CIGS formation process, which includes precursor deposition and annealing. The second-largest factor is nitrogen gas, related to the operation of vacuum equipment.

Greentech Media [9] states that the decrease in silicon price and the increase in module efficiency have significantly contributed to the fall in the manufacturing costs of silicon-based modules. It was found that efficiency improvement is also one of the biggest cost-reduction factors for CIGS. From the authors' internal model calculations regarding efficiency improvement, it seems that cell efficiency can be increased to 17% without major changes in cell architecture. It is interesting to note that the production cost structure of CIGS is quite similar to that of LCDs (liquid crystal displays). Considering that LCD TV prices have dropped to one-fifth in 10 years, it is expected that the CIGS module manufacturing cost could be reduced to half of the authors' estimated cost within five years, if the industry could enjoy the benefit of 'economy of scale', as experienced in the display industry.

Conclusions

Because CIGS development has been pushed forward to the manufacturing level, a few equipment players, such as Wonik IPS, will have turnkey business, leveraging the equipment and manufacturing technology from universities and institutes. The turnkey Si providers have contributed to reducing the module manufacturing cost by propagating and standardizing screen-printing manufacturing technology. In this way they could reduce the entrance barriers to cell- and module-manufacturing businesses, and induce technology improvements, by supplying a new technology to the manufacturers through linking the R&D accomplishments from institutes or universities to the manufacturing companies. Unlike in the crystalline Si industry, although many different CIGS production technologies have been tried, only Solar Frontier has successfully entered the GW production scale employing the two-stage process, by overcoming problematic issues, such as low yield, low power, low efficiency and high manufacturing cost.

"The manufacturing cost of CIGS has the potential to be reduced to far below that of multicrystalline Si."

As discussed in this paper, the performance of CIGS modules is approaching that of multicrystalline Si, and the manufacturing cost of CIGS has the potential to be reduced to far below that of multicrystalline Si. If a few more companies join the CIGS business and start production on a GW scale, the benefit from 'economy of scale' will contribute to cost reduction throughout the CIGS supply chain, resulting in a boom in the CIGS industry similar to that experienced in the crystalline Si industry during the last few decades.

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Mr. Jeong Min Lee received his master's in engineering in 2006 from Korea Aerospace University, majoring in MOSFET (metal gate and dielectrics) technology. In 2010 he joined Wonik IPS, where he has worked on R&D in PECVD, ion implantation for crystalline solar cells, and MOCVD for CIGS. He is currently involved with business planning and cost analysis for CIGS.

Dr. Dong Seop Kim received his Ph.D. on CdS/CdTe solar cells from KAIST in 1994, and has more than 26 years' experience in both academia and industry with regard to PV research, including Cu(InGa)Se_2, crystalline silicon and CdTe. He worked on CIGS and c-Si solar cell development as director of the PV R&D team at Samsung SDI for seven years, and recently joined Wonik IPS, where he leads the CIGS development and turnkey business.

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