INTRODUCTION

To increase the light absorption of solar cells, the reflectance of Si wafers should be reduced. The light absorption can be decreased by texturing and anti-reflection coating (ARC) techniques. Anti-reflection coating technique uses the interference of lights to reduce the reflectance and is designed to maximize destructive interference at a specific wavelength, which is controlled by the ARC material and the coating thickness. Typically, ARC materials are insulators. Si$_3$N$_4$ is a commercial material that is frequently applied as an ARC layer since it is easy to deposit at low temperatures ($\leq$400)$^\circ$C using plasma-enhanced chemical vapor deposition (PECVD) and is compatible with other conventional fabrication processes, such as metal screen printing.$^2$ A further decrease in the reflectance can be achieved by depositing a double-layer ARC (DLARC). Various types of DLARCs, such as SiO$_2$/SiN, SiO$_2$/TiO$_2$, ZnS/MgF$_2$, and Al$_2$O$_3$/SiON, and the like for reducing the reflectance have been reported in many areas of research.$^6$ Even though some of the DLARC materials require further study, the DLARC technology can better enhance the generation current density by minimizing the reflectance than single-layer ARCs. Therefore, DLARCs are normally used to reduce the reflectance in conventional...
solar cell structures that do not use a transparent conductive oxide (TCO) layer. Passivated emitter solar cells (PESCs), passivated emitter and rear cells (PERCs), interdigitated back contact cells (IBCs), passivated emitter rear locally diffused cells (PERLs), and buried contact solar cells (BCSCs).\textsuperscript{13-20}

However, as shown in Figure 1, heterojunction with intrinsic thin-layer (HIT) solar cells do not have an insulation material for ARC layer since the TCO layer acts as an ARC layer.\textsuperscript{21-23} To maximize the destructive interference at a specific wavelength, the materials and thickness of the TCO layer must be chosen carefully. Moreover, the TCO layer must have sufficiently high transmittance and electrical conductivity for application in a solar cell.

In this manuscript, the DLARC theory was applied to a HIT solar cell by depositing a thin insulator or an additional TCO layer on an initial TCO layer. We first used OPAL 2\textsuperscript{24,25} to simulate the reflectance in various insulator/ITO/Si wafer structures and a TCO/ITO/Si wafer structure. Second, in this paper, we also reported the experimental results for a HfO\textsubscript{2}/HIT solar cell based on the simulations.

## EXPERIMENTS

### Simulation by OPAL 2

We applied OPAL 2\textsuperscript{24,25} to simulate the reflectance of insulator/TCO and TCO/TCO structures. Figure 1 shows a schematic of the structure employed in the simulation. The purpose of the simulation was to optimize the layer thickness and maximize the light absorption by the substrate. We set the substrate as 180-μm-thick Si (Crystalline, 300K, Gre08). ITO, a conventional TCO material, was selected as the TCO layer. A random upright pyramid structure with a 54.74° angle was applied to the surface morphology. AM 1.5G illumination (Gue95) with a 0° zenith angle was selected as the incident radiation. The light trapping model was given by the equation $Z = 4 + \{\ln [n^2 + (1 - n^2)e^{-4\pi W}]/\lambda W\}$. The simulation was adjusted to maximize the generation current density in the Si substrate. The total current density from the light source was fixed at 44 mA/cm\textsuperscript{2}. The reflected current density, the current density absorbed by the film, and the current density absorbed by the Si (generation current density) were analyzed. Moreover, the reflectance as a function of the wavelength was also analyzed. The air/ITO/Si structure without an insulator was first simulated to optimize the ITO thickness. The doping concentration of the ITO was also varied in the simulation. Second, based on the optimized ITO thickness determined from the ITO simulation, the air/insulator or TCO/ITO/Si substrate structures (Figure 1) were simulated. ZnS (evaporated, Siq88), HfO\textsubscript{2} (cubic hafnia, Woo90), Al\textsubscript{2}O\textsubscript{3} (atomic layer deposition (ALD) on glass, Kum09), SiO\textsubscript{x} (PECVD, Mc114), SiO\textsubscript{x}N\textsubscript{y} (80% Sopra), MoO\textsubscript{x} (ALD, Mac15), and TiO\textsubscript{2} (ALD 75°C, Cui16) were applied in the air/insulator/ITO/Si substrate structures as insulators. ITO, ZnO (sputtered, EIA15), B-doped ZnO (Fan15), and ZnO:Al (EIA15) were applied to the air/TCO/ITO/Si substrate structure as TCO materials. In the case of the ITO/ITO/Si substrate structure, the doping concentration of the top ITO layer was varied from 1.7 × 10\textsuperscript{19} to 4.9 × 10\textsuperscript{20} cm\textsuperscript{-3}, and the doping concentration of the bottom ITO was fixed at 6.1 × 10\textsuperscript{20} cm\textsuperscript{-3}. The insulator and TCO thickness were optimized to maximize the generation current density in the Si substrate.

### HfO\textsubscript{2} deposition experiment

The HIT solar cell structure for the experiment is shown in Figure 2. A 180-μm-thick n-type Czochralski Si wafer with a resistivity of 3.8 ohm-cm was used for the experiment. Both surfaces of the Si wafer were randomly textured. Amorphous i/n and i/p Si layers were deposited on front and back surfaces, respectively, of the Si wafer. Afterward, an 80-nm-thick ITO layer was deposited on both sides. Front and back contacts were then formed by evaporation and plating after a photolithography process. Based on the simulation results, HfO\textsubscript{2} was chosen as one of the insulators and was deposited using ALD on the HIT solar cell after metallization. The thickness of the HfO\textsubscript{2} layer was controlled by varying the number of cycles. To analyze

![FIGURE 1](image1.png)

**FIGURE 1** OPAL 2 simulation structure with an insulator

![FIGURE 2](image2.png)

**FIGURE 2** Heterojunction with intrinsic thin-layer solar cell structure for the insulator experiment
the solar cell characteristics, the solar cell parameters were measured before and after HfO₂ deposition using a solar simulator. The external quantum efficiency (EQE) was also measured to compare the efficacy of the ARC. Separately, the HfO₂ was deposited on a silicon substrate to analyze the HfO₂ characteristic.

3 | RESULTS AND DISCUSSION

3.1 | OPAL 2 simulation results with an insulator/ITO/Si wafer structure

Figure 3 shows the results of the ITO simulation performed without an insulator to maximize the generation current density in the Si substrate. The absorbed current density changed as a function of the ITO doping concentration and ITO film thickness. The actual ITO doping concentration should be applied in an insulator/ITO/Si structure to simulate it more precisely. In general, doping concentrations above $1 \times 10^{20}$ cm$^{-3}$ have been reported to give conductive and transparent ITO layers. Therefore, ITO doping concentrations of 2.0, 4.0, and $6.1 \times 10^{20}$ were chosen in the insulator/ITO/Si structure. In the simulations of the insulator/ITO/Si structure, the optimized ITO thickness and the various ITO doping concentrations were used.

Figure 4 shows the simulation results for the insulator/ITO/Si structure with an ITO doping concentration of $6.1 \times 10^{20}$ cm$^{-3}$: (A) HfO₂, (B) Al₂O₃, (C) SiOₓNₓ, (D) MoOₓ, (E) SiOₓ, (F) ZnS, and (G) TiO₂.
for all the insulators. As a representative example, in the
results for HfO₂, the reflected current density gradually de-
creased as the thickness of the HfO₂ layer increased, thereby
increasing the generation current density. The cause of the
reduction in the reflected current density was a decrease in
the reflectance from approximately 200 to 300 nm and from
500 to 1400 nm, although the reflectance increased from
approximately 300 to 500 nm (Figure 5A). However, the
generation current density decreased when the thickness of
some of the insulators increased beyond the optimum value
(Figure 4B-F). For example, in the case of ZnS (Figure 4F),
the best generation current density of 41.18 mA/cm² was
achieved when the thickness of the ZnS layer was 13 nm.
However, as the thickness increased beyond 13 nm, the

FIGURE 5 Reflectance simulation results for (A) HfO₂ and (B) ZnS

FIGURE 6 Optimized simulation results before and after insulator deposition on the ITO/Si wafer as a function of the ITO doping
concentration
generation current density decreased, while the current density absorbed by the film and the reflected current density increased. This increase in the reflected current density resulted from the fact that the increase in reflectance from approximately 200 to 550 nm was larger than the decrease in the reflectance from approximately 550 to 1400 nm (Figure 5B).

Figure 6 shows the simulation results for the insulator/ITO/Si substrate structures that maximized the generation current density. Regardless of the doping concentration of ITO, the deposition of an insulator with an appropriate thickness on the ITO layer improved the absorbed current density of the Si substrate because the total reflection was reduced by the ARC effect. Based on the above simulations, we proposed that the insulator/ITO structure could increase the current density of the HIT solar cell.

### 3.2 | OPAL 2 simulation results with a TCO/ITO/Si wafer structure

Figure 7 shows the simulation results for the ITO/ITO/Si wafer structure. Even though the absorbed current density in the film increased from 1.55 to 1.7 mA/cm², the generation current density increased with the deposition of an additional ITO layer since the decrease in the reflected current density was greater than the increase in the absorbed current density in the film (Figure 7A,C). As the doping concentration of the additional ITO layer increased to $4.9 \times 10^{20}$, the reflected current density increased gradually because although the reflectance decreased in the wavelength range of 300-500 nm, the reflectance increased to a larger degree in the other ranges at the $4.9 \times 10^{20}$ doping concentration (Figure 7B).
Figure 8 shows the simulation results for the various ZnO/ITO/Si wafer structures with different ZnO materials. After the deposition of ZnO, B-doped ZnO, and ZnO:Al, the current density improved concomitantly with a decrease in the reflected current density. A similar trend was observed for the ITO/ITO/Si wafer structure. Even though the reflectance increased in the wavelength range of 300-500 nm, the reflectance decreased to a larger degree in the other ranges when ZnO was deposited on ITO.

As the results for the TCO or insulator/ITO/Si wafer simulations show, not only insulator deposition but also TCO deposition on ITO with proper thickness and doping concentration reduced the total reflection through the ARC effect.

### 3.3 HfO₂ experimental results

As a result of the ellipsometry, the refractive index of the deposited HfO₂ is shown in Figure 9. The refractive index at 600 nm of deposited HfO₂ by ALD was 2.02. The HfO₂ was applied to the insulator/HIT solar cell structure. As we observed in the simulations with HfO₂, the generation current density was experimentally shown to be improved by the deposition of HfO₂ (Figure 11B). When the thickness of the
HfO₂ layer was 3 nm, the highest generated current density of 38.75 mA/cm² was achieved, and this value was 1.5 mA/cm² higher than the original value (Figure 13). However, when the thickness of the HfO₂ layer was 5 nm or more, the current density was only 0.25-0.5 mA/cm² higher than the original value. When comparing the simulation result (Figure 5A) and the experiment result (Figure 10), even though there were small differences at the level of the reflectance and the wavelength range, the reflectance decreases and increases showed the similar trend according to HfO₂ thicknesses. These changes in the reflectance were due to shifted maximum destructive interference wavelength and changed the reflectance of the wavelength region by HfO₂. Table 1 shows average solar cell parameters before and after HfO₂ deposition. Figure 11 shows the difference of each parameter before and after HfO₂. The reflectivity changed by HfO₂ deposition appeared to give increased current density (Jsc) in simulations and in experimental results because it had a lower reflectivity at higher intensities of sunlight. This effect caused changes in the EQE (Figure 12). Even though the EQE decreased in the wavelength region from 380 to 600 nm, the generation current density appeared to increase as a result of the increase in the EQE in the wavelength regions from 600 to 1100 nm and from 300 nm to 380 nm. Therefore, the current density of the solar cell was increased by the formation of an HfO₂/ITO double layer rather than a single layer of ITO.

Figure 11B shows that not only the current density but also the open-circuit voltage increased as HfO₂ was deposited. The reason for this increase was that the damage caused by sonication was repaired by HfO₂ deposition. The solar cell used in this paper required a photolithography process for the selective plating on ITO, which was necessary for the metalization process. In the photolithography process, a sonicator was used to remove the photoresist efficiently. The use of a sonicator decreased the lifetime and the open-circuit voltage of the solar cell according to the Suns-Voc plot (not shown in this paper). The initial open-circuit voltage of the HIT solar cell was restored when HfO₂ was deposited. As shown in Figure 11B, as the thickness of the HfO₂ layer increased, the open-circuit voltage gradually increased, eventually recovering and saturating at the original value. The initial open-circuit voltage was recovered because the sonicator damage was repaired by HfO₂ deposition. Therefore, the average solar cell efficiency was observed to increase from 18.21% to 20.75% after HfO₂ deposition, which was mainly due to increases in the open-circuit voltage and the current density (Figure 11A).

Another cause of the increase in the efficiency of the solar cell was an increase in the fill factor. The series resistance before the HfO₂ deposition was 1.9-2.9 Ohm-cm², and that after HfO₂ deposition was 1.2-1.3 Ohm-cm². The high series resistance of the HIT solar cell before HfO₂ deposition was due to the lack of tips in the solar simulator measurements. However, since the change in the series resistances did not give rise to a significant change in the current density (approximately 0.01 mA/cm²), the increase in the current density was attributed to HfO₂ deposition.

TABLE 1 Solar simulator results; (A) before HfO₂ deposition, (B) after HfO₂ deposition

(A) Before HfO₂ deposition

| Sample # | Jsc  (mA/sqcm) | Voc  (mV) | FF  | Eff. (%) |
|----------|----------------|----------|-----|----------|
| 1        | 37.25          | 700      | 72.9| 19       |
| 2        | 38             | 692      | 71.3| 18.75    |
| 3        | 38             | 672      | 70.5| 18       |
| 4        | 38             | 671      | 69.6| 17.75    |
| 5        | 38             | 674      | 70.3| 18       |
| 6        | 38             | 667      | 70  | 17.75    |

(B) After HfO₂ deposition

| Sample # | HfO₂ thickness (nm) | Jsc  (mA/sqcm) | Voc  (mV) | FF  | Eff. (%) |
|----------|---------------------|----------------|----------|-----|----------|
| 1        | 3                   | 38.75          | 724      | 74.9| 21       |
| 2        | 5                   | 38.5           | 723      | 75.4| 21       |
| 3        | 8                   | 38.5           | 723      | 74.5| 20.75    |
| 4        | 10                  | 38.5           | 723      | 73.6| 20.5     |
| 5        | 13                  | 38.25          | 724      | 74.9| 20.75    |
| 6        | 15                  | 38.5           | 720      | 74  | 20.5     |
Therefore, based on the above results, the recovery of the open-circuit voltage and the fill factor did not have a significant influence on the increase in the current density. As HfO₂, which is an insulator, was deposited, the total reflectance decreased and the current density increased. In conclusion, the solar cell’s best efficiency was 21% by the improvements of current density, open-circuit voltage, and fill factor (Figure 13). Moreover, based on the results of the simulations and HfO₂ experiments, we believe that not only HfO₂ but also other insulators could be the candidates for improving the efficiency of HIT solar cells. However, as shown in the simulations, the insulator must have an appropriate thickness.

4 | CONCLUSION

In this paper, OPAL 2 simulations were performed on insulator or TCO/ITO/Si wafer structures to increase the current density of HIT solar cells, and HfO₂ was experimentally deposited through ALD as an insulator. Based on the simulations, the generation current density increased due to ARC effect when not only an insulator but also when a TCO layer was deposited on the ITO/Si substrate. Based on the simulations, HfO₂ was
chosen as the insulator, and the average efficiency of the solar cell increased from 18.21% to 20.75% after HfO₂ deposition. This increase was mainly caused by the increase in the current density and in the open-circuit voltage. The increase in the current density by 0.5-1.5 mA/cm² over that in the HIT solar cell without HfO₂ was due to a decrease in the reflectance caused by the deposition of HfO₂ on ITO. The increase in the open-circuit voltage caused by HfO₂ deposition was due to the recovery of the open-circuit voltage, which had initially decreased due to the damage caused by the sonication process.

Based on the simulations and experiments, we believe that HfO₂ deposition on a HIT cell can increase the current density by decreasing the reflectance. Additionally, if sonication is performed during the fabrication of a solar cell, the initial open-circuit voltage can be regained by HfO₂ deposition. We are performing further experiments with other insulator/HIT solar cell and TCO/HIT solar cell structures. Other TCO materials besides ITO can also be applied. We believe that these other TCO materials will improve the efficiency of the insulator/HIT solar cells that use other insulators, such as Al₂O₃, SiO₂Nₓ, SiO₂, Si₃N₄, ZnS, MoOₓ, and TiO₂. Moreover, we believe that the efficiency of the TCO/HIT solar cell will also be improved. In particular, the ITO/HIT solar cell could effectively improve the efficiency since the additional ITO layer can be deposited after the original ITO deposition process by changing the deposition conditions. Furthermore, we also believe that the efficiency of the TCO/HIT solar cell can be improved based on the simulation results, and this improved efficiency is excellent for mass production because the simple addition of an insulator or TCO deposition process to the pre- or post-metallization process can improve the efficiency of the solar cell. Further experiments with new insulator/HIT solar cell and TCO/HIT solar cell structures will be conducted and reported.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20173010012940) and by the Ministry of Trade, Industry, and Energy, Korea Evaluation Institute of Industrial Technology (KEIT) (No. 10043793).

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