

Research Article

Study of an Amorphous Silicon Oxide Buffer Layer for p-Type Microcrystalline Silicon Oxide/n-Type Crystalline Silicon Heterojunction Solar Cells and Their Temperature Dependence

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Intrinsic hydrogenated amorphous silicon oxide (i-a-SiO:H) films were used as front and rear buffer layers in crystalline silicon heterojunction (c-Si-HJ) solar cells. The surface passivity and effective lifetime of these i-a-SiO:H films on an n-type silicon wafer were improved by increasing the CO₂/SiH₄ ratios in the films. Using i-a-SiO:H as the front and rear buffer layers in c-Si-HJ solar cells was investigated. The front i-a-SiO:H buffer layer thickness and the CO₂/SiH₄ ratio influenced the open-circuit voltage (V_{oc}), fill factor (FF), and temperature coefficient (TC) of the c-Si-HJ solar cells. The highest total area efficiency obtained was 18.5% ($V_{oc} = 700$ mV, $J_{sc} = 33.5$ mA/cm², and FF = 0.79). The TC normalized for this c-Si-HJ solar cell efficiency was $-0.301\text{%/}^{\circ}\text{C}$.

1. Introduction

High-efficiency solar cells with low production costs are still needed for manufacturers. Generally, operating a solar cell in a high-temperature environment degrades its conversion efficiency [1–4]. Therefore, developing solar cells for use in tropical regions is important. Crystalline silicon heterojunction (c-Si-HJ) solar cells with ultrathin intrinsic hydrogenated amorphous silicon (i-a-Si:H) passivation layers are an attractive crystalline silicon solar cell technology because they have low temperature coefficients (TCs) and high efficiencies [5–7]. However, light absorption lost to the hydrogenated amorphous silicon (a-Si:H) window layer lowers the short circuit current (J_{sc}) and solar cell performance. Using wide bandgap materials is a potential solution to this problem. Hydrogenated silicon oxide is a good candidate for the window layer material because hydrogenated amorphous silicon oxide (a-SiO:H) exhibited excellent passivation [8–10].

Furthermore, hydrogenated microcrystalline silicon oxide (μ c-SiO:H) exhibited better electrical properties and lower optical absorption coefficients than a-Si:H [11–14]. Thus, combining a-SiO:H and μ c-SiO:H for the heterojunction solar cell window layer is promising. In this paper, we investigated the effect that using intrinsic hydrogenated amorphous silicon oxide (i-a-SiO:H) films with wide optical bandgaps as the buffer layers had on p-type hydrogenated microcrystalline silicon oxide (p- μ c-SiO:H)/c-Si-HJ solar cell performance at high operating temperatures.

2. Experimental Details

2.1. Deposition of i-a-SiO:H Films. The i-a-SiO:H films were prepared on soda-lime glass substrates and float-zone (FZ) silicon wafers (100) using n-type 1–5 Ωcm double side polished wafers 260–300 μm thick. Prior to the deposition, the

TABLE 1: Deposition conditions for the i-a-SiO:H films.

Parameters	Values
H_2/SiH_4	3.3
CO_2/SiH_4	0–0.5
Plasma frequency	60 MHz
Deposition temperature	180°C
Deposition pressure	300 mTorr
Power density	20 mW/cm ²
Thickness	50 nm

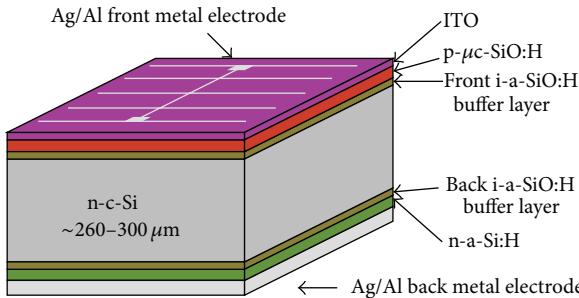


FIGURE 1: Schematic diagram of c-Si-HJ solar cells.

wafers were cleaned (ethanol/acetone/ethanol: 15/15/15 min) and dipped into diluted 5% hydrofluoric acid (HF) to remove any native oxide before depositing the i-a-SiO:H films. The i-a-SiO:H films were deposited via a 60 MHz very high frequency plasma enhanced chemical vapor deposition (VHF-PECVD) in a multichamber with a parallel plate configuration. We used silane (SiH_4), hydrogen (H_2), and carbon dioxide (CO_2) as the reactant gases. The substrate temperature, plasma power density, and deposition pressure were held at 180°C, 20 mW/cm² and 300 mTorr, respectively. The deposition conditions are summarized in Table 1. Afterwards, the effects of the CO_2/SiH_4 ratio on the film properties were investigated. The i-a-SiO:H film passivation quality was characterized using the quasi-steady-state photoconductance (QSSPC) lifetime [15, 16]. The lifetime samples were deposited as i-a-SiO:H films on both sides of the n-c-Si wafer, and their passivation quality was measured in terms of the effective lifetime (τ_{eff}). The optical properties and thickness of these i-a-SiO:H films coated on soda-lime glass substrates were evaluated via spectroscopic ellipsometry (SE).

2.2. Fabrication of Heterojunction Solar Cells. Crystalline silicon heterojunction solar cells were fabricated with i-a-SiO:H buffer layers. To investigate the effect the front i-a-SiO:H buffer layer had on the solar cell performance, c-Si-HJ solar cells were fabricated with Al/Ag/ITO/p- μ c-SiO:H/i-a-SiO:H/n-c-Si/i-a-SiO:H/n-a-Si:H/Ag/Al structure. The schematic diagram of the c-Si-HJ solar cells is shown in Figure 1. The p- μ c-SiO:H window layer was doped with 3%-hydrogen-diluted trimethylboron (TMB: $B(CH_3)_3$) and deposited via 40 MHz VHF-PECVD. Additionally, the a-Si:H n-layer was doped with 3%-hydrogen-diluted phosphine (PH_3) and prepared via 60 MHz VHF-PECVD. An indium tin oxide (ITO) was used as the transparent conducting

oxide (TCO) and as the antireflection coating layer and was deposited via radio frequency magnetron sputtering. The front and back metal electrodes were evaporated using thermal boat sources with silver and aluminum pallet sources. The τ_{eff} of the solar cells was evaluated from the photoconductance decay before depositing the ITO and metal electrodes. The photovoltaic parameters (PV) of the solar cells were investigated under standard conditions (AM 1.5,100 mW/cm², and 25°C) using a double light source solar simulator. The total solar cell area was 1 cm². The quantum efficiency (QE) of the solar cells was characterized using the spectral response measurements. To determine the temperature dependence of the solar cell performance, we measured the solar cell parameters using a solar simulator on a probe station at ambient temperatures (T) ranging from 25°C to 65°C with a step increment of 10°C under 1-sun irradiation. The TC value can be expressed as follows:

$$TC \left(part/^\circ C \right) = \frac{1}{Z} \times \left(\frac{\delta Z}{\delta T} \right) \Big|_{T_n=25^\circ C}, \quad (1)$$

where Z means the solar cell parameters of efficiency (η), open-circuit voltage (V_{oc}), J_{sc} , and fill factor (FF). A normalized temperature (T_n) of 25°C was chosen because it corresponds to the standard test solar cell measurement conditions.

3. Results and Discussion

3.1. Properties of the i-a-SiO:H Films. The effects the CO_2/SiH_4 ratio had on the surface passivation quality and optical properties of the i-a-SiO:H films were investigated. CO_2 was used as O source gas during the i-a-SiO:H film deposition. The samples were prepared by increasing the CO_2/SiH_4 ratios from 0.0 to 0.50 with a thickness of approximately 50 nm. The samples exhibited an i-a-SiO:H (CO_2/SiH_4 : 0.0–0.50)/n-c-Si/i-a-SiO:H (CO_2/SiH_4 : 0.17) structure. The CO_2/SiH_4 ratio affected the τ_{eff} of n-c-Si wafers passivated with i-a-SiO:H films as shown in Figure 2. The τ_{eff} increased with increasing CO_2/SiH_4 ratios. For a CO_2/SiH_4 ratio of 0.0, the sample showed a low τ_{eff} of 51 μ s because the i-a-Si:H layer grew epitaxial silicon on the crystalline substrate. The epitaxial interface is a defect and deteriorates the passivation quality. However, the τ_{eff} increased rapidly from 232 μ s to 2500 μ s upon increasing the CO_2/SiH_4 ratio from 0.17 to 0.50. Therefore, increasing the CO_2/SiH_4 ratio can suppress the epitaxial silicon growth. Meanwhile, the implied V_{oc} increased from 583 mV to 708 mV with increasing CO_2/SiH_4 ratio. In addition, the optical bandgap of the i-a-SiO:H films increased gradually with increasing CO_2/SiH_4 ratio. The optical bandgap of a conventional i-a-Si:H film with a CO_2/SiH_4 ratio of 0.0 was 1.72 eV. Increasing the CO_2/SiH_4 ratio from 0.17 to 0.50 increased the optical bandgap of the i-a-SiO:H films from 1.81 eV to 1.95 eV.

3.2. Fabrication of Heterojunction Solar Cells. The effect of the CO_2/SiH_4 ratio for the front i-a-SiO:H buffer layer on the c-Si-HJ solar cell performance was investigated for

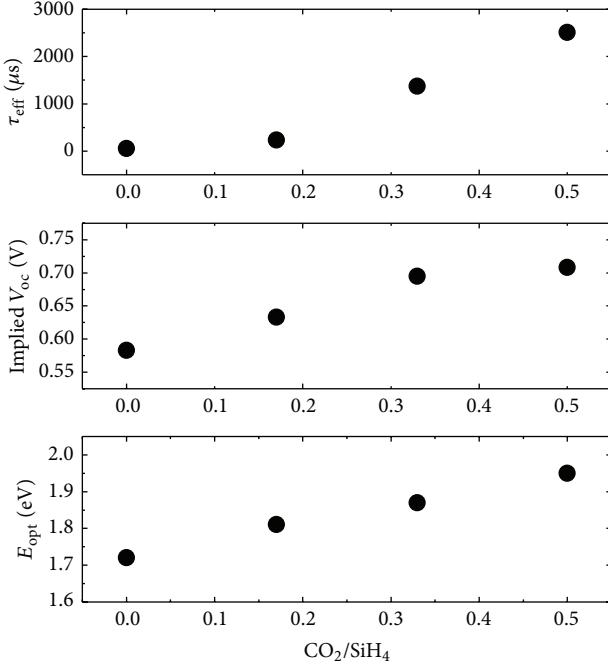


FIGURE 2: Effective lifetime (τ_{eff}) of n-c-Si passivated by the i-a-SiO:H films, which implied that V_{oc} of the i-a-SiO:H films and optical bandgap (E_{opt}) of the i-a-SiO:H films are a function of the CO_2/SiH_4 ratio.

various CO_2/SiH_4 ratios. First, the front i-a-SiO:H buffer layer thickness in the c-Si-HJ solar cell was optimized. The front i-a-SiO:H buffer layer thickness was varied from 2 nm to 8 nm. Figure 3 shows the PV parameters and τ_{eff} as a function of the i-a-SiO:H layer thickness. Increasing the front i-a-SiO:H buffer layer thickness increased the V_{oc} from 655 mV to 691 mV due to the improved surface passivation. The τ_{eff} increased from 586 μs to 1125 μs with increasing front buffer thicknesses. A high V_{oc} of 692 mV and solar cell efficiency of 18.4% were obtained using the optimized thickness of 6 nm. A front buffer layer thickness below 6 nm decreased the V_{oc} of the solar cell. A thicker front buffer layer improved the passivation quality but reduced the FF of the solar cell due to the increased series resistance.

Next, the effect the CO_2/SiH_4 ratio of the front i-a-SiO:H buffer layer had on the solar cell performance was studied. The front i-a-SiO:H buffer layer CO_2/SiH_4 ratio was varied from 0.0 to 0.50 while holding the thickness at 6 nm. Figure 4 shows the PV parameters and τ_{eff} as a function of the CO_2/SiH_4 ratio for the front i-a-SiO:H buffer layer. The solar cells exhibited a low V_{oc} of 626 mV at a CO_2/SiH_4 ratio of 0.00 due to epitaxial silicon growth [17, 18]. The V_{oc} then increased to 699 mV at a CO_2/SiH_4 ratio of 0.17 and reduced to 683 mV at a CO_2/SiH_4 ratio of 0.50. The τ_{eff} was 1610 μs for a CO_2/SiH_4 ratio of 0.17 and then decreased to 357 μs for a CO_2/SiH_4 ratio of 0.50. However, the τ_{eff} tended to increase with increasing CO_2/SiH_4 ratio as shown in Figure 2. For the solar cell, increasing the CO_2/SiH_4 ratio in the front i-a-SiO:H buffer layer decreased the V_{oc} and FF because of the increased series resistance. Figure 5 shows the I-V characteristics of c-Si-HJ solar cells with CO_2/SiH_4

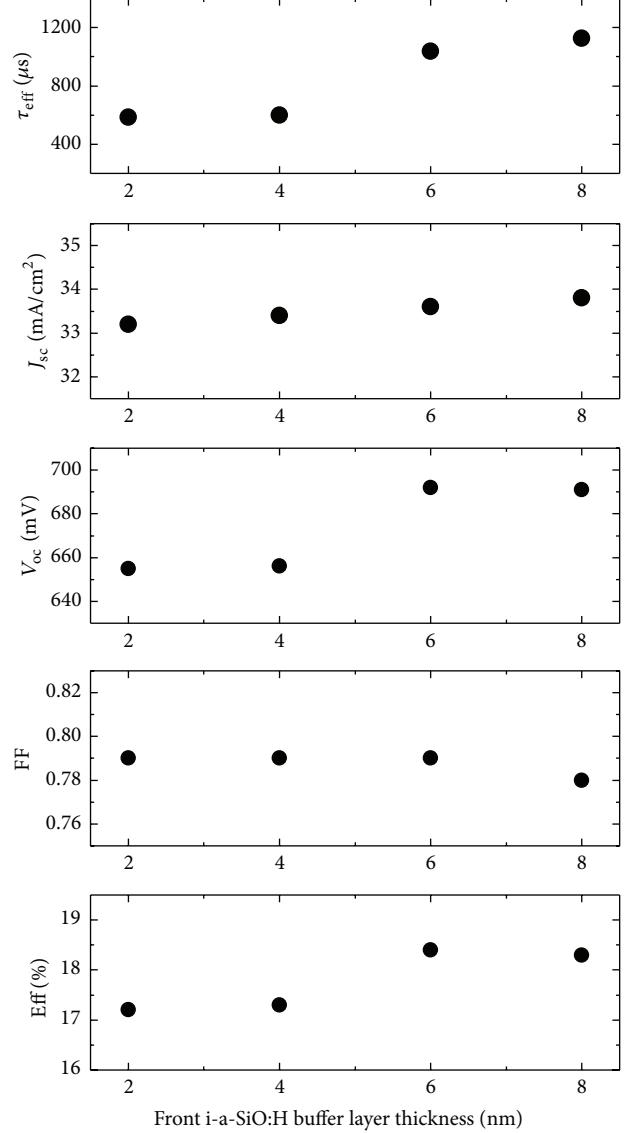


FIGURE 3: PV parameters and τ_{eff} as a function of front i-a-SiO:H buffer layer thickness.

ratio in front i-a-SiO:H buffer layer. Increasing the CO_2/SiH_4 ratio decreased the V_{oc} and FF of I-V curves and showed S-shape influenced from the increased series resistance with the CO_2/SiH_4 ratio of 0.50. These results indicate controlling the CO_2/SiH_4 ratio can improve the surface passivation quality and solar cell performance. The spectral response of the solar cells improved with increasing CO_2/SiH_4 ratios as shown in Figure 6 because of the increased optical bandgap of the i-a-SiO:H layer.

The effects the CO_2/SiH_4 ratio of the i-a-SiO:H front buffer layer had on the photovoltaic parameters at various operating temperatures were investigated. Figure 7 presents the normalized solar cell parameters for c-Si-HJ solar cells containing i-a-SiO:H layers with various CO_2/SiH_4 ratios measured in the initial state as a function of the operating temperature. The J_{sc} gradually increased with increasing operating temperature due to the increase in the diffusion

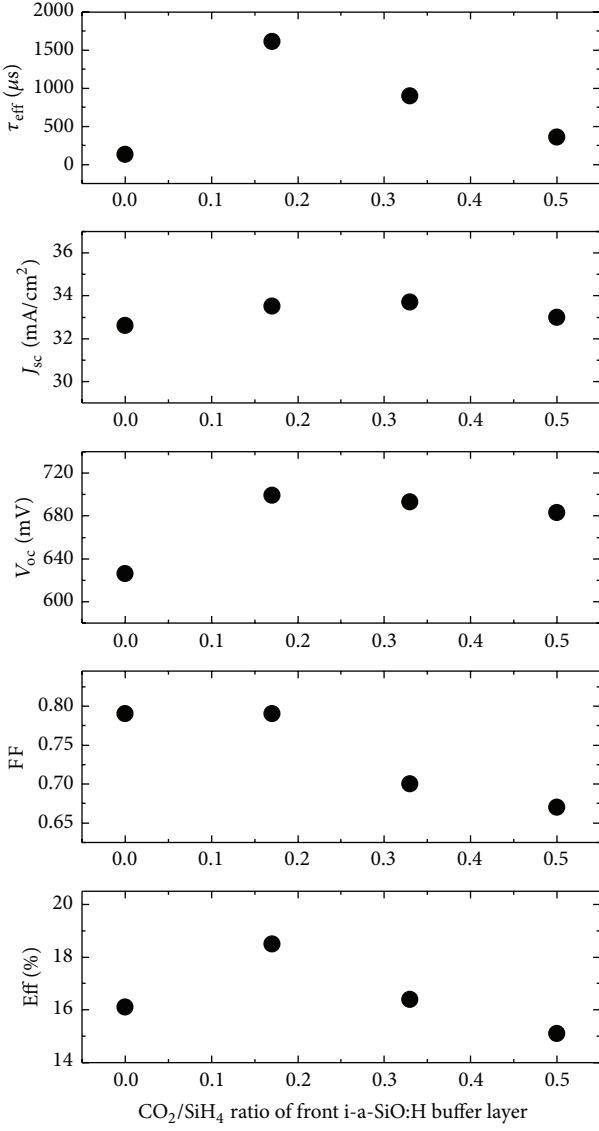


FIGURE 4: PV parameters and τ_{eff} as a function of the CO_2/SiH_4 ratio for the front i-a-SiO:H buffer layer.

length of the minority carriers. The FF and solar cell efficiency decreased with increasing operating temperature due to the significantly reduced V_{oc} . The V_{oc} decreased with increasing operating temperature because of an increase in the reverse saturation current. The normalized TC for the V_{oc} of a solar cell with a CO_2/SiH_4 ratio of 0, 0.08, and 0.17 in i-a-SiO:H were $-0.318^\circ/\text{C}$, $-0.314^\circ/\text{C}$, and $-0.290^\circ/\text{C}$, respectively. Therefore, the normalized TC for η of the solar cell with CO_2/SiH_4 ratios of 0, 0.08, and 0.17 in i-a-SiO:H were $-0.312^\circ/\text{C}$, $-0.306^\circ/\text{C}$, and $-0.301^\circ/\text{C}$, respectively. The experimental results indicate that the i-a-SiO:H film is a promising buffer layer material for c-Si-HJ solar cells operating at high temperatures.

4. Conclusions

We investigated the surface passivation quality of i-a-SiO:H films for n-type silicon wafers. The τ_{eff} improved with

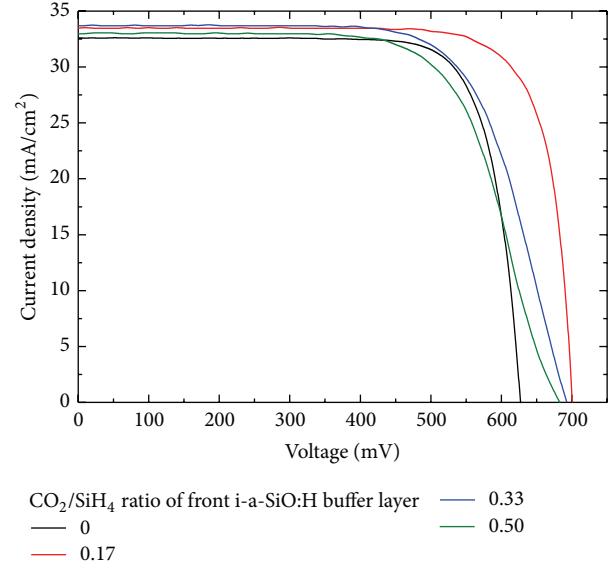


FIGURE 5: I - V characteristics of c-Si-HJ solar cells with CO_2/SiH_4 ratio in front i-a-SiO:H buffer layer.

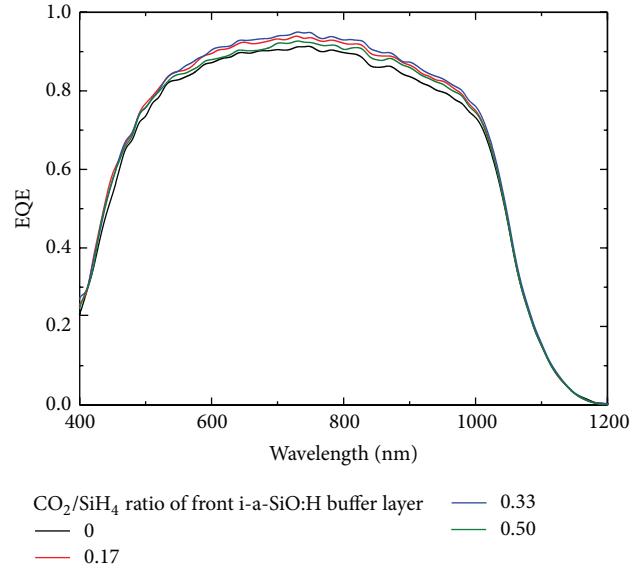


FIGURE 6: Spectral response as a function of the CO_2/SiH_4 ratio for the front i-a-SiO:H buffer layer.

increasing CO_2/SiH_4 ratio in the films. We also characterized c-Si-HJ solar cells containing front and rear i-a-SiO:H buffer layers. The thickness and CO_2/SiH_4 ratio for the front i-a-SiO:H buffer layer affected the V_{oc} and FF of c-Si-HJ solar cells. Optimized solar cells exhibited better efficiencies with the i-a-SiO:H front buffer layer than with the i-a-Si:H front buffer layer. The highest total area efficiency obtained was 18.5% ($V_{\text{oc}} = 700 \text{ mV}$, $J_{\text{sc}} = 33.5 \text{ mA}/\text{cm}^2$, and FF = 0.79). The normalized TC for this c-Si-HJ solar cell efficiency was $-0.301^\circ/\text{C}$. These experimental results indicate that the i-a-SiO:H film is a promising buffer layer material for c-Si-HJ solar cells operating at high temperatures.

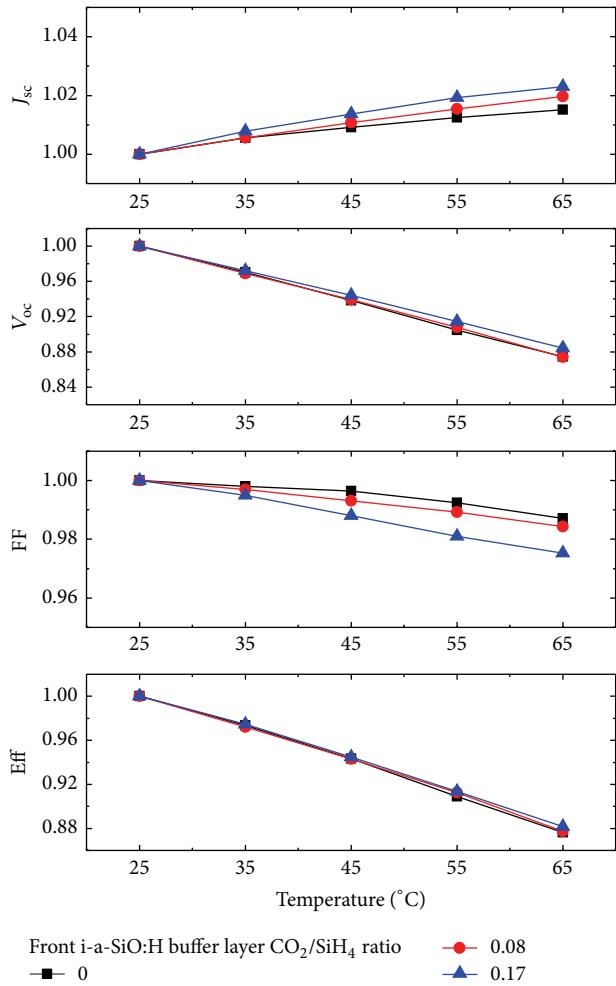


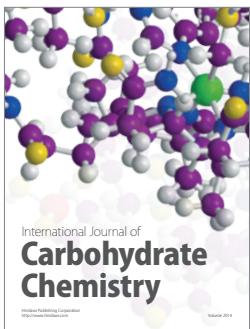
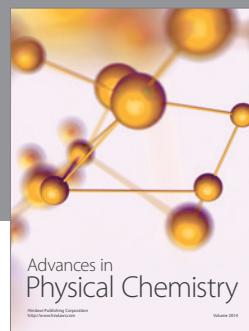
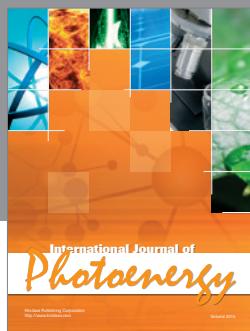
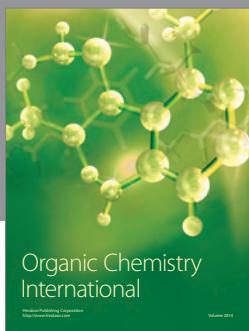
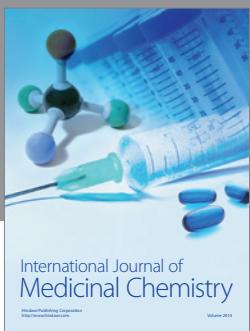
FIGURE 7: Normalized solar cell parameters measured in the initial state for the c-Si-HJ solar cells with a CO_2/SiH_4 ratio in the front i-a-SiO:H buffer layers as a function of the operating temperature.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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