Temperature-dependent performance of silicon heterojunction solar cells with transition-metal-oxide-based selective contacts

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Abstract

The temperature coefficient (TC) is an essential figure of merit to accurately evaluate solar cell performance at various operating temperatures, and hence, enabling the comparison between different cell technologies. Recently, solar cells that use passivating contacts based on transition metal oxide (TMO) layers have attracted much attention due to their excellent performance. Therefore, knowledge of their TCs and insights into their performance at various operating temperatures are of significant interest.

In this study, we investigate the temperature-dependent performance of solar cells with TMO-based passivating contacts at various illumination intensities. We then compare their performance to that of standard silicon heterojunction (SHJ) solar cells. The efficiency TC (TC_\eta) of solar cells that use passivating contacts based on molybdenum oxide (MoO_x) and titanium oxide (TiO_x) films are found to be almost identical. Both outperform the TC_\eta of the standard SHJ cells and are greatly superior to those of cell structures without passivating contacts. The superior TC_\eta of the MoO_x-based cells is mainly due to their favourable TCs of the short-circuit current density (TC_{Jsc}) and fill factor (TC_{FF}), whereas the superiority of TC_\eta of the TiO_x-based cells is solely resulting from the superior TC_{FF}. The favourable TC_{Jsc} of the MoO_x-based cells is explained by an enhanced spectral response at short wavelengths with increasing temperature, due to the improvement of the passivation quality of the MoO_x-based passivating contacts. The beneficial TC_{FF} of both solar cells are partly resulting from the improvement of the contact resistivity of the TMO-based passivating contacts which counterbalances some of the fill factor losses at elevated temperatures. Although an improvement of the passivation quality of the TMO-based passivating contacts is observed at elevated temperature, it does not have a strong impact on the TC of the open-circuit voltage of the investigated solar cells. Furthermore, we also found that the studied cells are less sensitive to temperature variation at higher illumination intensities.

Keywords: SHJ, MoO_x, TiO_x, TMO, passivating contacts, temperature coefficient, temperature dependence, silicon solar cells.
1. Introduction

Photovoltaic (PV) devices operate under a wide range of temperatures,\(^1\) however, they are often characterized and optimized only at standard testing conditions (STC; at 25 °C with an irradiance of 1000 W/m\(^2\) under the AM1.5G solar spectrum). Since the temperature sensitivity of various cell technologies is different,\(^2\) the temperature coefficient (TC) is an essential figure of merit to evaluate the cell performance at different operating temperatures and to allow a more in-depth comparison between various cell technologies.\(^2-^4\) More importantly, in combination with the typical meteorological data, this parameter enables to accurately evaluate the energy yield of PV installations. Hence, it plays a crucial role in the selection of suitable cell technologies for a PV field at a specific site to maximize the annual energy yield. The performance of silicon (Si) solar cells is typically reduced with increasing temperature, which is mainly attributed to the reduction of the cell’s open-circuit voltage (\(V_{oc}\)).\(^5\) In general, the higher the cell’s \(V_{oc}\), the better the open-circuit voltage TC (TC\(_{Voc}\)), and hence the efficiency TC (TC\(_{\eta}\)).\(^5\) To achieve a favourable TC\(_{\eta}\), cell structures enabling a high \(V_{oc}\) are therefore desired.\(^5\)

Recent studies have demonstrated the capability of solar cells that integrate passivating contacts to achieve high efficiencies.\(^6-^{11}\) Such contacts are typically composed of three layers: (1) films that provide surface passivation, (2) films that ensure carrier selectivity, and (3) metal (or degenerately doped transparent conductive oxide) electrodes that ensure electrical connection to the external circuit. Only in rare cases, one layer is sufficient for all three tasks,\(^12\) whereas, in most of the cases, layers (2) and (3) both play a role in selectivity and can also contribute to passivation.\(^13-^{17}\) Efficient passivating contacts minimize the recombination losses at the Si interfaces and ensure an effective collection of only one type of charge carrier.\(^13-^{15}\) Cell structures that integrate these contacts usually exhibit a high \(V_{oc}\),\(^9,^{18-21}\) and hence, they are expected to have a favourable TC\(_{\eta}\). This was confirmed by our recent study demonstrating that the TC\(_{\eta}\) of solar cells with polysilicon passivating contacts is superior to those of cell structures without passivating contacts [such as passivated emitter and rear contact (PERC), passivated emitter rear totally diffused (PERT), and more].\(^22,23\) It highlights the advantage of using solar cells that integrate passivating contacts in the field.

Besides polysilicon passivating contacts, passivating contacts based on transition metal oxide (TMO) films have also attracted much attention due to their excellent performance.\(^10,11\) Depending on the electrical properties (such as work function, conductivity, and band alignment), these contacts can be used as hole- or electron-selective collectors.\(^15\) For example, for hole-selective contacts, molybdenum oxide (MoO\(_x\)),\(^11,24\) vanadium oxide (V\(_2\)O\(_x\)),\(^25,26\) and tungsten oxide (WO\(_x\))\(^25,27\) are often used due to their high work functions. Meanwhile, titanium oxide (TiO\(_x\))\(^10,28\) and tantalum oxide (Ta\(_2\)O\(_x\))\(^29,30\) have been integrated into Si solar cells as electron-selective contacts due to their suitable electronic properties for band alignment.\(^14,31\) It is noteworthy that many of the high-efficiency TMO-based solar cells utilize MoO\(_x\) and TiO\(_x\) films as hole- and electron-selective contacts, respectively.\(^10,11,28,32,33\) Although a few studies presented the temperature dependence of \(V_{oc}\) and fill factor (FF) of MoO\(_x\)-based solar cells,\(^34,35\) the TC\(_{\eta}\) of these cells has not been reported. For TiO\(_x\)-based solar cells, to our knowledge, neither the temperature dependence of cell parameters nor the TCs of these cells has been reported.
In this study, we investigate the temperature-dependent performance of MoO\textsubscript{x}- and TiO\textsubscript{x}-based solar cells and compare them to that of SHJ cells. We also examine the temperature-dependent behaviour of the surface saturation current density ($J_{0s}$) and the contact resistivity ($\rho_c$) of those contacts to gain a deeper understanding regarding their impact on $TC_{V_{oc}}$ and the TC of the $FF$ ($TC_{FF}$), respectively.
2. Experimental details

2.1 Sample preparation

Textured float zone (FZ) n-type wafers (resistivity: 1.7-2.3 $\Omega \cdot \text{cm}$, thickness: 190±10 µm) were used to fabricate the solar cells. All the wafers were first cleaned using the Radio Corporation of America (RCA) procedures followed by immersion in 5% diluted hydrofluoric (HF) acid. The wafers were then divided into three groups:

1) For the **SHJ cells** (control cells), a stack of 6-nm hydrogenated intrinsic and 7.5-nm hydrogenated p-doped amorphous Si [a-Si:H(i) and a-Si:H(p), respectively] layers was deposited on the front side using a plasma-enhanced chemical vapor deposition system. A stack of 6-nm a-Si:H(i) and 9.5-nm hydrogenated n-doped amorphous Si [a-Si:H(n)] films was formed on the rear side using the same system.

2) For the **MoO$_x$-based cells**, a 6-nm a-Si:H(i) layer was deposited on the front, followed by a 4-nm thermally evaporated MoO$_x$ film. Their rear structure is identical to that of the SHJ cells.

3) For the **TiO$_x$-based cells**, the rear side composes a stack of 6-nm a-Si:H(i) film and 1.5-nm TiO$_x$ layer formed by atomic layer deposition (done at 230 °C) while their front structure is identical to that of the SHJ cells.

Additional information regarding the conditions used during the depositions can be found in Ref. [11]. The metallization process of the front contact was similar for the three cell structures. 70-nm indium tin oxide (ITO) film was deposited by a sputtering system through a mask to form active areas of $2 \times 2 \text{ cm}^2$. A silver (Ag) grid was then screen-printed on top of the front ITO film, followed by a curing process at 210 °C for the SHJ cells, 130 °C for the MoO$_x$-base cells, and 160 °C for the TiO$_x$-based cells for 30 min in air ambient. The rear contacts of the SHJ and MoO$_x$-based cells were formed by 150-nm sputtered ITO and 100-nm sputtered Ag layers, whereas that of the TiO$_x$-based cells composes 1-nm thermally evaporated lithium fluoride (LiF) and 200-nm aluminium (Al) films. The LiF film enables an ohmic contact between the TiO$_x$ layer and the Al electrode. Sketches of the investigated devices are shown in Figs. 1(a)-(c).

![Figure 1: Sketches of (a) standard SHJ, (b) MoO$_x$-based, and (c) TiO$_x$-based solar cells used in this study.](image-url)
To investigate the temperature-dependent behaviour of the MoOx- and TiOx-based passivating contacts, symmetrical lifetime structures for effective lifetime ($\tau_{\text{eff}}$) measurements and $J_0$ extraction were prepared using the same wafers, cleaning, and deposition processes as the solar cells. The lifetime test wafers were passivated with either a-Si:H(i)/MoOx or a-Si:H(i)/TiOx stack on both sides.

To extract $\rho_c$, Cox and Strack test structures were fabricated using both n-type and p-type FZ textured wafers (1.7-2.3 Ω·cm, 190±10 µm). We use p-type wafers for measurements of the MoOx-based contacts to avoid back-to-back diodes. The same layer stacks as for the lifetime test structures were applied to the front side of the Cox and Strack structures, followed by the formation of circular ITO/Ag and LiF/Al contacts with different diameters (from 0.02 to 0.8 cm) on top of the MoOx and TiOx layer, respectively. Sputtered Ag (MoOx-based structures) and thermally evaporated Al (TiOx-based structures) contacts were applied to the rear side.

The symmetrical lifetime and the Cox and Strack test structures were annealed at 130 °C (for the MoOx-based contacts) and 160 °C (for the TiOx-based contacts) for 30 min in air ambient to mimic the thermal budget of the Ag paste curing process.

A similar set (symmetrical lifetime and Cox and Strack test structures) was also prepared for the a-Si:H(i/p)- and a-Si:H(i/n)-based passivating contacts as references. Sputtered Ag contacts were applied to the rear side of the Cox and Strack structures. The test structures were annealed at 210 °C for 30 min in air ambient.

2.2 Characterization

The current-voltage (I-V) parameters of the solar cells are measured from 25 to 70 °C while Suns-$V_{oc}$ measurements are performed by a customized Sinton Suns-$V_{oc}$ system from 80 to 30 °C. The cell’s series resistance ($R_s$) is calculated by comparing the one-sun current density-voltage ($J-V$) curve to the $R_s$-free $J-V$ curve obtained from the Suns-$V_{oc}$ measurements. TCs are extracted from the slopes of linear fits of the cell parameters as a function of temperature and are normalized to their values at 25 °C (relative TCs).

The external quantum efficiency (EQE) of the studied solar cells is measured by a solar cell spectral response system (QEX7, PV Measurements Inc.).

To extract $\rho_c$ of the passivating contacts, dark I-V measurements are performed on the Cox and Strack structures in the temperature range from 25 to 80 °C. The I-V curves of all the test structures have been found to be linear in the voltage range from −0.1 V to +0.1 V and the total resistances ($R_{\text{tot}}$) are obtained from the slopes of the linear fits within this range. Note that the rear ohmic contact of these test structures is assumed to have a negligible contribution to the total resistance ($R_{\text{tot}}$). Hence, the obtained $\rho_c$ represents its upper limit.

Sinton lifetime tester (WCT-120TS) is used to measure $\tau_{\text{eff}}$ as a function of temperature (25 to 80 °C). $J_0$ is extracted from the $\tau_{\text{eff}}$ curves using the curve fitting features of Quokka 2 and the approach of Dumbrell et al. The uncertainty in the extracted $J_0$ is calculated from the uncertainty of
photoconductance measurements using the approach of McIntosh et al. The models of Schenk, Richter et al., and Klaassen are used to determine the effective intrinsic carrier concentration ($n_{\text{eff}}$), the intrinsic lifetime, and the mobility, respectively.

3. Results and discussion

3.1 Temperature-dependent performance of solar cells

The cell parameters of the standard SHJ, MoO$_x$-, and TiO$_x$-based solar cells as a function of temperature are presented in Figs. 2(a)-(d). As expected, for all the investigated solar cells, the $V_{oc}$, $FF$, pseudo fill factor ($pFF$), and efficiency ($\eta$) decrease, whereas the short-circuit current density ($J_{sc}$) increases at elevated temperatures. The reduction of $V_{oc}$, $FF$, and $pFF$ is explained by the increase of $n_{\text{eff}}$ at elevated temperatures caused by bandgap narrowing. The same effect can also explain the improvement of $J_{sc}$. Compared to the performance of state-of-the-art devices using MoO$_x$-based passivating contacts at STC, our MoO$_x$-based cell shows comparable $V_{oc}$ and $J_{sc}$. Although our $FF$ is lower than that of the champion cell reported in Ref. [11], it is comparable to the average $FF$ stated in the same reference. For the TiO$_x$-based cell, our cell parameters are slightly lower (by 1.0%abs in efficiency) than those of the state-of-the-art devices reported in Ref. [30].

The $V_{oc}$ of the MoO$_x$-based cell is comparable to that of the standard SHJ cell at any given temperature. It seems that the surface passivation in these cells is dominated by the integrated a-Si:H(i) layers. Meanwhile, the lower $V_{oc}$ of the TiO$_x$-based cell can be explained by a slight degradation of the rear surface passivation either before the TiO$_x$ deposition (since the deposition was done in a different facility after a long transportation time of a few weeks) or during the TiO$_x$ deposition that was done at 230 °C.

It is noteworthy that at any given temperature, the $J_{sc}$ of the MoO$_x$-based cell is higher than that of the standard SHJ cell. This is due to the higher optical bandgap of the MoO$_x$ layer compared to that of a-Si:H(p) film, resulting in a better spectral response at the short wavelength region (see Fig. 1S). Meanwhile, the $J_{sc}$ of the TiO$_x$-based cell is lower than that of the standard SHJ cell despite their identical structure at the front side. This can be attributed to (i) the lower reflectivity of Al compared to that of Ag, and (ii) the absence of the rear ITO layer. Without the ITO layer, the parasitic absorption within the rear metal layer can be increased. They both result in a low spectral response at the long wavelength region (see Fig. 9 and Supplementary Information Fig. 1S).
Figure 2: Cell parameters of the standard SHJ, MoO$_x$-, and TiO$_x$-based solar cells including (a) $V_{oc}$, (b) $J_{sc}$, (c) $FF$ and $pFF$ (open symbols), and (d) $\eta$ under one-sun illumination as a function of temperature.

Compared to the $FF$ of the SHJ solar cell at 25 °C, the TiO$_x$-based cell’s $FF$ is lower. It can be explained by the lower $V_{oc}$ of the TiO$_x$-based cell caused by the slight degradation of the rear surface passivation as mentioned above and the high $\rho_c$ of the TiO$_x$-based passivating contact (see Fig. 7). Non-linear behaviour of the temperature-dependent $FF$ in the temperature range from 25 to 40 °C is observed for all the investigated solar cells. The occurrence of this phenomenon has been reported for standard SHJ$^{2,57-59}$ and MoO$_x$-based passivating contact solar cells$^{35}$ however, it has not been reported for TiO$_x$-based passivating contact solar cells yet. This trend is often attributed to thermionic barriers at the heterojunctions of these cells.$^{2,59}$ The decrease of $FF$ of the MoO$_x$- and TiO$_x$-based solar cells in the temperature range from 40 to 70 °C is less pronounced compared to that of the SHJ solar cell. Note that for all the cells, the decreasing trend of the $FF$ is different from that of the $pFF$ as a function of temperature. This difference can be used to assess the contribution of $R_s$ to the temperature-dependent behaviour of $FF$, as will be discussed in Section 3.3.

The extracted TCs are summarized in Table 1. The $TC_{FF}$ and $TC_\eta$ of all the investigated cells are extracted from linear fits in the temperature range from 40 to 70 °C. Using this temperature range minimises the non-linear effects at low temperatures while still providing information regarding the expected temperature range in the field.$^1$ The $FF$ and $\eta$ at 25 °C are then obtained by extrapolation to determine relative TCs. The TCs obtained in this study are compared to those of other cell structures reported in Refs. $[2,22]$ and presented in Figs. 3(a)-(d).

<p>| Table 1: Extracted TCs and the gamma factor ($\gamma$), as well as their statistical errors determined from the standard deviation of the linear regression, for the standard SHJ, MoO$_x$- and TiO$_x$-based solar cells. |</p>
<table>
<thead>
<tr>
<th></th>
<th>TC_{Voc} (%/°C)</th>
<th>TC_{Jsc} (%/°C)</th>
<th>TC_{FF} (%/°C)</th>
<th>TC_{pFF} (%/°C)</th>
<th>TC_{η} (%/°C)</th>
<th>γ</th>
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<tbody>
<tr>
<td>SHJ cell</td>
<td>−0.254±0.001</td>
<td>+0.039±0.002</td>
<td>−0.088±0.004</td>
<td>−0.077±0.001</td>
<td>−0.301±0.007</td>
<td>3</td>
</tr>
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<td>MoO_x-based cell</td>
<td>−0.248±0.001</td>
<td>+0.046±0.001</td>
<td>−0.059±0.003</td>
<td>−0.067±0.002</td>
<td>−0.264±0.003</td>
<td>2.4</td>
</tr>
<tr>
<td>TiO_x-based cell</td>
<td>−0.264±0.001</td>
<td>+0.037±0.001</td>
<td>−0.036±0.006</td>
<td>−0.107±0.001</td>
<td>−0.265±0.008</td>
<td>1.4</td>
</tr>
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</table>

Focusing on TC_{Voc}, it is well known that the temperature sensitivity of V_{oc} of a Si solar cell is defined by the following equation:

\[
TC_{Voc} = \frac{dV_{oc}}{dT} = -\frac{E_{g0}}{q} - \frac{V_{oc} + \gamma k_B T}{q} \frac{dV_{oc}}{dT} \tag{1}
\]

where \( E_{g0} \) is the semiconductor bandgap linearly extrapolated to 0 K, \( V_{oc} \) is reported at the initial temperature (25 °C in this study), \( q \) is the elementary charge, \( k_B \) is the Boltzmann constant, and \( T \) is the temperature. The gamma factor (\( \gamma \)) represents the temperature dependence of the diode saturation current density in the solar cells, and hence, it contains information about the dominant recombination mechanism.\(^1\),\(^6\) The extracted values for \( \gamma \) using Eq. 1 are summarised in Table 1. Here we use \( E_{g0} \) of 1.206 eV for all the calculations of the studied cells due to their similar wafer resistivity.\(^\)\(^5\)\(^1\) The TC_{Voc} of the MoO_x-based cell is slightly superior to that of the standard SHJ cell, despite a negligible difference between the initial \( V_{oc} \) of the two cell structures [731.2 mV (standard SHJ) and 728.9 mV (MoO_x-based) at 25 °C]. The different TC_{Voc} can be explained by different \( \gamma \) (see Table. 1), suggesting that \( V_{oc} \) of these cells is limited by different mechanisms. The inferior TC_{Voc} of the TiO_x-based cell is expected as its initial \( V_{oc} \) is lower than those of the standard SHJ and MoO_x-based cells. For this cell structure, the impact of \( V_{oc} \) on TC_{Voc} is being dominant over that of \( \gamma \).

Compared to the TC_{Voc} of other cell structures as shown in Fig. 3(a), the obtained TC_{Voc} of the MoO_x-based solar cell is comparable to that of the SHJ cells while the TiO_x-based cell’s TC_{Voc} is almost identical to the tunnel oxide passivated contact (TOPCon) cells’ TC_{Voc}. The TC_{Voc} of both MoO_x- and TiO_x-based cells are superior to those of the cells without passivating contacts [PERC, PERT, Al back surface field (Al-BSF), etc]. Battaglia et al.\(^3\) and Sacchetto et al.\(^3\)\(^5\) reported that the decreasing trend of \( V_{oc} \) of the MoO_x-based cells is less pronounced compared to that of the SHJ cells as a function of temperature. This implies a superior TC_{Voc} of the MoO_x-based cells, agreeing with our findings.

The TC_{Jsc} of the TiO_x-based solar cell is comparable to that of the standard SHJ cell, whereas the TC_{Jsc} of the MoO_x-based cell is more favourable than those of the former two cells. The spectral response of the studied cells at different temperatures will be presented and discussed in Section 3.5 to clarify this trend. The TC_{Jsc} of the MoO_x-based cell is comparable to that of the TOPCon cell and better than those of all the others, except for the Al-BSF cell (the superior TC_{Jsc} of the Al-BSF cell is discussed in Ref. [22]). Meanwhile, the TC_{Jsc} of the SHJ and TiO_x-based cells are comparable to those of the advanced PERT, PERT, and PERC cells.
Figure 3: (a) TC_{Voc}, (b) TC_{Jsc}, (c) TC_{FF} and TC_{pFF}, and (d) TC_{η} of the standard SHJ, MoO_x- and TiO_x-based solar cells extracted from the slopes of linear fits of the cell parameters as a function of temperature as shown in Fig. 2. Error bars are obtained from the linear fits. TCs of solar cell structures reported in the literature^{2,22} (axis labels with star mark) are also shown for comparison.

The TC_{FF} of the MoO_x- and TiO_x-based solar cells are superior to those of any other cell (in the range above 40 °C), including the SHJ. Furthermore, their TC_{FF} are better than their TC_{pFF}, whereas the standard SHJ cell shows an opposite trend. This indicates that R_s of the two former cells reduces at elevated temperatures while the latter cell’s R_s increases. The temperature-dependent behaviour of R_s of the investigated cells will be discussed in Section 3.3. To quantify the contribution of V_{oc} and R_s to TC_{FF} of the studied cells, the following equations are used^{62,63}:

\[
\frac{dFF}{dT} = (1 - 1.02FF_0) \left( \frac{1}{V_{oc}} \frac{dV_{oc}}{dT} - \frac{1}{T} \right) \frac{R_s}{V_{oc}/I_{sc} - R_s} \left( \frac{1}{R_s} \frac{dR_s}{dT} \right) 
\]

(2)

where

\[
FF_0 = \frac{V_{oc} - \ln(V_{oc} + 0.72)}{V_{oc} + 1}
\]

(3)

where FF_0 is the FF in the absence of R_s and shunt resistance (R_{sh}) effects, and V_{oc} is the normalized V_{oc} to the thermal voltage (nKT/q). The first term in Eq. (2) represents the contribution of V_{oc} to TC_{FF} while the second term indicates the contribution of R_s to TC_{FF}. For the cell structures studied here, the contribution of V_{oc} to TC_{FF} is dominant and accounts for more than 60%; indicating that the
temperature-dependent behaviour of $FF$ strongly depends on the increase of $n_{\text{eff}}$ at elevated temperatures caused by bandgap narrowing.\textsuperscript{47} It is noteworthy that the contribution of $R_s$ to $TC_{FF}$ is considerably more significant for the TiO$_x$-based cell (nearly 36\%) than for the other studied cells. It offsets the decrease of the TiO$_x$-based cell’s $V_{oc}$ at elevated temperature, resulting in a greatly superior $TC_{FF}$ of this cell.

The $TC_{\eta}$ of the MoO$_x$- and TiO$_x$-based solar cells are almost identical. They are better than that of the standard SHJ cell and greatly superior to those of other cell structures reported in the literature. The obtained $TC_{\eta}$ highlight the advantage of using TMO-integrated cells in the field. As expected, the contribution of $TC_{V_{oc}}$ to $TC_{\eta}$ is larger than the contributions of $TC_{FF}$ and $TC_{J_{sc}}$ and accounts for more than 60\% for all the cell structures shown in Fig. 3. Battaglia \textit{et al.}\textsuperscript{34} and Sacchetto \textit{et al.}\textsuperscript{35} also reported that the decreasing trend of the MoO$_x$-based cells’ efficiency is less pronounced compared to that of the SHJ cells’ efficiency as a function of temperature. This implies a favourable $TC_{\eta}$ of the MoO$_x$-based cells in agreement with our findings.

Since the $TC_{\eta}$ of the TiO$_x$-based cells is superior to that of the SHJ cells, it is expected that the performance difference between the structures will reduce at higher temperatures. As the efficiency of the TiO$_x$ cell is relatively low at 25 °C, its better $TC_{\eta}$ is not expected to compensate for the entire difference in the typical operating temperature range. Nevertheless, avoiding the slight degradation of the rear surface passivation and maintaining a similar $TC_{\eta}$, will ensure comparable efficiencies of the TiO$_x$-based and the SHJ cells at 70 °C.

### 3.2 Temperature and illumination intensity dependence of solar cells

In Section 3.1, we discussed the temperature sensitivity of the cell parameters at one-sun. However, in the field, solar cells do not only operate at different temperatures, but they are also exposed to a large range of illumination intensities. Since $TC_{V_{oc}}$ dominates $TC_{\eta}$ for all the studied cells, it can indicate the temperature sensitivity of the cells at different intensities. Owing to our customized Suns-$V_{oc}$ tool, measurements can be done in a wide range of illumination intensities (from 0.001 suns to >100 suns), which enable deeper insights into the temperature-dependent performance of Si solar cells for different applications. Although, the illumination intensity range from 0.1 suns to 1 sun is the most relevant for terrestrial PV applications, the information at higher illumination intensities can be used for concentrator cells\textsuperscript{64} while the performance at lower intensities may be valuable for the Internet of Things applications.

Suns-$V_{oc}$ measurements of the investigated cells in the temperature range from 30 to 80 °C are presented in Figs. 4(a)-(c). For all three cell structures, a significant reduction of $V_{oc}$ with increasing temperature can be seen at low illumination intensities. This reduction is less pronounced at higher illumination intensities. $TC_{V_{oc}}$ of the studied cells extracted from Suns-$V_{oc}$ measurements (open symbols) as a function of illumination intensity is presented in Fig. 4(d). $TC_{V_{oc}}$ obtained from $I-V$ measurements (solid symbols) at one sun illumination are also shown for comparison. We find that the $TC_{V_{oc}}$ at one sun illumination extracted from both measurement methods match well (in the range of 1.2\%). For all the cells, the absolute value of $TC_{V_{oc}}$ decreases with increasing illumination intensity (less negative); indicating that the studied cells are less sensitive to temperature variation at higher
illumination intensities. It is noteworthy that the TC\textsubscript{Voc} of the MoO\textsubscript{x}-based and SHJ cells behave similarly as a function of illumination intensity while the illumination intensity dependence of TC\textsubscript{Voc} is more pronounced for the TiO\textsubscript{x}-based cell. For most of the intensity range, this observation can be attributed to the lower initial \textit{V}\textsubscript{oc} of the TiO\textsubscript{x}-based cell compared to the initial \textit{V}\textsubscript{oc} of the other cells (see Supplementary Information Fig. 2S). However, at high illumination intensities (> 3 suns), it seems that the impact of \( \gamma \) on the TC\textsubscript{Voc} of the TiO\textsubscript{x}-based cell becomes significant.

![Figure 4: Suns-\textit{V}\textsubscript{oc} measurements of (a) the standard SHJ, (b) MoO\textsubscript{x}-, and (c) TiO\textsubscript{x}-based solar cells at different temperatures. (d) TC\textsubscript{Voc} extracted from Suns-\textit{V}\textsubscript{oc} (open symbols) and \textit{I-V} (solid symbols) measurements as a function of illumination intensity.](image)

### 3.3 Temperature dependence of \( R_s \)

Figure 3(c) highlights the superiority of TMO-based solar cells regarding TC\textsubscript{FF}. As mentioned, we expect that \( R_s \) of the MoO\textsubscript{x}- and TiO\textsubscript{x}-based solar cells reduce at elevated temperatures, whereas the standard SHJ cell’s \( R_s \) increases. This section investigates the temperate dependence of the studied cells’ \( R_s \), and several components that contribute to \( R_s \) to explain the findings.

\( R_s \) of the studied cells as a function of temperature are shown in Fig. 5. Indeed, \( R_s \) of the MoO\textsubscript{x}- and TiO\textsubscript{x}-based solar cells reduce with increasing temperature while the standard SHJ cell’s \( R_s \) increases. As expected from the difference between TC\textsubscript{FF} and TC\textsubscript{pFF} of these cells [see Fig. 3(c)], the reduction of the TiO\textsubscript{x}-based cell’s \( R_s \) at elevated temperatures is more pronounced compared to that of the MoO\textsubscript{x}-based cell’s \( R_s \). The extracted TC\textsubscript{R\textsubscript{s}} of the studied solar cells are summarized in Table 2. Note that the \( R_{sh} \) of these cells, as determined from the linear fit of the \textit{I-V} measurement around \( V = 0 \) V

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(not shown here), are extremely large (in the range of 10k-30k $\Omega \cdot \text{cm}^2$). $R_{sh}$ is therefore assumed not to impact the temperature dependence of $FF$.

Table 2: Extracted $TC_{R_s}$ and their statistical errors of the linear regression determined from the standard deviation for the standard SHJ, MoO$_x$- and TiO$_x$-based solar cells.

<table>
<thead>
<tr>
<th></th>
<th>Standard SHJ cell</th>
<th>MoO$_x$-based cell</th>
<th>TiO$_x$-based cell</th>
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<tbody>
<tr>
<td>$TC_{R_s}$ (%/°C)</td>
<td>+0.281±0.082</td>
<td>−0.414±0.057</td>
<td>−1.314±0.149</td>
</tr>
</tbody>
</table>

$R_s$ of the studied cells consists of the contributions of the rear metal contact, the electron-collector ($R_{e-col(r)}$), the Si wafer, the hole-collector ($R_{h-col(f)}$), the lateral transport within the front ITO layer, the interfacial contact between the front ITO layer and the front metal contacts, and the front metal contacts including fingers and busbars. $R_{e-col(r)}$ and $R_{h-col(f)}$ can be obtained from the $\rho_c$ test structures. Since the temperature of the curing process after metallization is different for the investigated solar cells (see Section 2.1), the possibility that this process varies the contribution of the other components to the cells’ $R_s$ might not be excluded. Note that $R_{e-col(r)}$ and $R_{h-col(f)}$ obtained from the $\rho_c$ test structures represent their upper limit. They will be presented in the next sections.

![Figure 5: $R_s$ of the standard SHJ, MoO$_x$-, and TiO$_x$-based solar cells as a function of temperature.](image)

3.3.1 Temperature dependence of the contact resistivity of the hole-collector

To gain a deeper understanding regarding the difference between the standard SHJ and MoO$_x$-based cells, the a-Si:H(i/p)- and MoO$_x$-based test structures are studied. Figure 6 presents $\rho_c$ obtained from these structures as a function of temperature. Interestingly, the temperature dependence of $\rho_c$ shows opposite trends. When the temperature increases from 25 to 80 °C, the $\rho_c$ of the a-Si:H(i/p)-based structures increases from 0.17 to 0.23 $\Omega \cdot \text{cm}^2$, whereas the $\rho_c$ of the MoO$_x$-based structures decreases from 0.32 to 0.17 $\Omega \cdot \text{cm}^2$. The carrier transport via thermionic barrier is usually improved at elevated temperatures. Therefore, the significant decrease of $\rho_c$ of the MoO$_x$-based structures may indicate a large thermionic component in the carrier transport across the contact. Meanwhile, the $\rho_c$...
increase of the a-Si:H(i/p)-based structures may imply that the carrier transport via thermionic barrier in this contact becomes less pronounced. It is noteworthy that the rate of change of the $\rho_c$ against temperature for the two test structures is lower than that of the $R_s$ for the corresponding cells, indicating that other components also contribute to the temperature-dependent behaviour of their $R_s$. It seems that the improvement of $\rho_c$ of the MoOx-based structures at elevated temperatures counterbalances some of the FF losses, resulting in a less temperature-sensitive FF.

Figure 6: $\rho_c$ of the a-Si:H(i/p)- and MoOx-based test structures as a function of temperature. Sketches of the Cox and Strack test structures are shown next to the figure.

### 3.3.2 Temperature dependence of the contact resistivity of the electron-collector

To compare between the standard SHJ and TiOx-based cells, the a-Si:H(i/n)- and TiOx-based test structures are investigated. Figure 7 presents $\rho_c$ obtained from these structures as a function of temperature. The extracted $\rho_c$ at STC of both structures are comparable to those previously reported.\(^5\)\(^2\),\(^5\)\(^8\) Again, an opposite trend is observed. When the temperature increases from 25 to 80 °C, the $\rho_c$ of the a-Si:H(i/n)-based structures increases from 0.10 to 0.15 $\Omega\cdot\text{cm}^2$, whereas the $\rho_c$ of the TiOx-based structures decreases from 0.68 to 0.04 $\Omega\cdot\text{cm}^2$. As in the previous section, a large thermionic component in the carrier transport can explain the significant decrease of $\rho_c$ of the TiOx-based structures.\(^5\)\(^8\) We also find that the rate of change of the $\rho_c$ against temperature for the two test structures is lower than that of the two corresponding cells’ $R_s$. Similar to the MoOx-based structures, the improvement of $\rho_c$ of the TiOx-based structures with increasing temperature counterbalances some of the FF losses of this cell, resulting in its favourable TCFF.

As shown in Figs. 6 and 7, the a-Si:H-based test structures’ $\rho_c$ increases at elevated temperatures and its rate of change against temperature is lower than that of the TMO-based structures’ $\rho_c$, indicating less temperature sensitivity of the former structures. This is probably due to the efficient temperature-independent tunneling transport in the a-Si:H-based passivating contacts.\(^5\)\(^8\) Compared to the a-Si:H(i/p)-based test structures, the $\rho_c$ of the a-Si:H(i/n)-based test structures is lower at any given temperature as shown in the inset of Fig. 7. This phenomenon was also reported in Ref. [58] and can be explained by the usually much smaller conduction band offset in the a-Si:H(i/n)-based structure compared to the valence band offset in the a-Si:H(i/p)-based structures.\(^6\)\(^5\) Thus, the hole transport is impeded by the a-Si:H(i) layer.\(^6\)\(^5\)

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3.4 Temperature dependence of surface passivation

In this section, we investigate the temperature-dependent behaviour of $J_{0s}$, one of the key parameters indicating the quality of a passivating contact. The extracted $J_{0s}$ values using lifetime measurements on the symmetrical test structures as a function of temperature are depicted Figs. 8(a)-(b). We observe a significant increase of $J_{0s}$, which is due to the increase of $n_{i,eff}$ caused by bandgap narrowing,\textsuperscript{47} since $J_{0s}$ is proportional to $n_{i,eff}^2$.\textsuperscript{66} More meaningful information is obtained from the $J_{0s}/n_{i,eff}^2$ ratio as a function of temperature. If the rise in $J_{0s}$ at elevated temperatures is solely determined by $n_{i,eff}$, the ratio needs to be temperature independent. As a reduction of the ratios with increasing temperature is observed regardless of the test structures, an improvement of the passivation quality at elevated temperature can be assumed. TCs of the $J_{0s}/n_{i,eff}^2$ ratio are extracted and summarized in Table 3. The improvement is more pronounced for the MoO$_x$-based lifetime test structures compared to the other structures. Nevertheless, it seems that the improvement of the passivation quality observed for all the lifetime test structures does not have a strong impact on TC$_{Voc}$ of the investigated solar cells. Note that in the real devices, the possibility that the metal contact impacts both the passivation quality and its temperature dependence might not be excluded.

Table 3: Extracted TCs of the $J_{0s}/n_{i,eff}^2$ ratio and their statistical errors determined from the standard deviation of the linear regression for the a-Si:H- and TMO-based lifetime test structures.

<table>
<thead>
<tr>
<th></th>
<th>a-Si:H(i/p)</th>
<th>MoO$_x$-based</th>
<th>a-Si:H(i/n)</th>
<th>TiO$_x$-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC$<em>{J0s/n</em>{i,eff}}$ (%)/°C</td>
<td>−0.56±0.02</td>
<td>−0.90±0.03</td>
<td>−0.46±0.05</td>
<td>−0.47±0.05</td>
</tr>
</tbody>
</table>
Figure 8: $J_0$ and $J_0/n_{eff}$ ratios of (a) the a-Si:H(i/p)- and MoO$_x$-based, (b) the a-Si:H(i/n)- and TiO$_x$-based lifetime test structures as a function of temperature. Sketches of the symmetrical lifetime test structures used in this study are shown next to the figures.

3.5 Temperature dependence of EQE

As discussed above, the TC$J_{sc}$ of the TiO$_x$-based solar cell is comparable to that of the standard SHJ cell, whereas the TC$J_{sc}$ of the MoO$_x$-based cell is superior to those of the former two cell structures. Furthermore, in the previous section, we noticed that the passivation quality obtained by MoO$_x$ shows stronger improvement with temperature compared to the other passivation schemes. In this section, we use temperature dependent EQE measurements to shine more light on these findings.

The EQE measurements of the studied solar cells at 25 °C and 45 °C in the wavelength ranges of 300-600 nm (short wavelengths) and 900-1200 nm (long wavelengths) are presented in Figs. 9(a)-(b), respectively. For the short wavelength region, the EQE at the two temperatures are almost identical for the standard SHJ and TiO$_x$-based cells, whereas a slight increase is observed for the MoO$_x$-based cell. For the long wavelength region, the spectral response is improved with increasing temperature, regardless of the cell structures. This improvement is attributed to bandgap narrowing of the Si at elevated temperatures\textsuperscript{1,38} that has a critical impact on this wavelength range.

The gain of $J_{sc}$ between 25 °C and 45 °C determined from the EQE, split into different wavelength ranges, is presented in Fig. 9(c). The $J_{sc}$ of the MoO$_x$-based cell gains 0.36 mA/cm$^2$, 0.05-0.06 mA/cm$^2$ higher than the $J_{sc}$ gain of the other two cells. The $J_{sc}$ gains in the wavelength ranges of 600-900 nm...
and 900-1200 nm are almost identical for all the cells, whereas the $J_{sc}$ gain in the wavelength range of 300-600 nm is different.

Since the optical properties of MoO$_x$ films are almost identical at 25 °C and 45 °C (see Supplementary Information Fig. 3S), the better spectral response at short wavelengths of the MoO$_x$-based cell can therefore be explained by the larger improvement of the passivation quality with increasing temperature of this structure (Section 3.4). To strengthen this point, we established a model using the AFORS-HET simulation tool and successfully reproduce the trend of the spectral response at the short wavelength region by modifying the ratio between the electron and hole capture cross sections ($\sigma_n/\sigma_p$). Hence, the favourable $TC_{J_{sc}}$ of the MoO$_x$-based cell can be attributed to the large improvement of the passivation quality of the MoO$_x$-based passivating contacts, resulting in the increase of the spectral response at elevated temperatures in the short wavelength range.

Figure 9: EQE measurements of the standard SHJ, MoO$_x$-, and TiO$_x$-based solar cells at 25 °C and 45 °C in the range of wavelength (a) from 300 to 600 nm, and (b) from 900 to 1200 nm. (c) $J_{sc}$ gain between 25 °C and 45 °C at different wavelength regions.
4. Conclusion

The temperature-dependent performance of TMO-based passivating contacts and their devices was investigated. The TC$_\eta$ of the MoO$_x$- and TiO$_x$-based solar cells are almost identical. They are better than that of the standard SHJ cell, and greatly superior to those of the cell structures without passivating contacts. In terms of the temperature sensitivity, the findings highlight the advantage of using solar cells that integrate TMO-based passivating contacts in the field. Moreover, knowledge of their TC$_\eta$ and insights into their performance at various operating temperatures enable an accurate estimate of the annual energy yield of PV systems using TMO-based technology, and hence a comparison to other technologies.

The superior TC$_\eta$ of the MoO$_x$-based cell is mainly due to the favourable TC$_{Jsc}$ and TC$_{FF}$ while the TC$_\eta$ superiority of the TiO$_x$-based cell is solely from a superior TC$_{FF}$. The favourable TC$_{Jsc}$ of the MoO$_x$-based cell compared to the other two cell structures can be explained by a better spectral response at the short wavelength region with increasing temperature, resulting from an improvement in the passivation quality of the MoO$_x$-based passivating contacts. The superior TC$_{FF}$ of the MoO$_x$- and TiO$_x$-based solar cells are partly contributed by the improvement of $\rho_c$ of their passivating contacts at elevated temperatures which counterbalances some of the FF losses, resulting in a less temperature-sensitive FF.

Furthermore, it was concluded that the studied cells are less sensitive to temperature variation at higher illumination intensities. The TC$_{Voc}$ of the MoO$_x$-based and SHJ cells behave the same as a function of illumination intensity while the illumination intensity dependence is more pronounced for the TiO$_x$-based cell.

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References


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