Temperature-dependent performance of polysilicon passivating contacts and their solar cells

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The temperature coefficient (TC) is an essential figure of merit to accurately evaluate the cell performance at different operating conditions. Recently, tunnel oxide passivated contact (TOPCon) cells [1] have shown outstanding cell performance with an efficiency exceeding 26% [2]. Moreover, they exhibit a high potential to be integrated into existing photovoltaic production lines [3]. So far, their performance has mainly measured at standard testing conditions (STC). Therefore, the knowledge of the cell performance of TOPCon cells at realistic operating temperatures, as well as insights into their TCs, are of significant interest.

In this study, we investigate the temperature-dependent performance of TOPCon solar cells and quantify their TCs. We also study the temperature dependence of the contact resistivity (ρ_c) to gain a better understanding regarding its impact on TC of fill factor (TC_{FF}). The TCs are then compared to the values reported in the literature for different cell technologies. Furthermore, the cell performance of TOPCon cells under different illumination intensities is also investigated.

Compensated Czochralski-grown upgraded metallurgical-grade (UMG-Cz) n-type silicon (Si) wafers (1.2 Ω·cm, 150±10 µm) were used to fabricate TOPCon cells. All the fabricating procedures of these cells can be found in Ref [4]. To study the temperature-dependent ρ_c of the poly-Si passivating contacts, Cox and Strack test structures [5] using n-type Cz Si wafers (290±10 µm, 2 Ω·cm) with a poly-Si passivating contact applied only to one side were employed. State-of-the-art monoPoly^{TM} [3] busbar-less solar cells are used to validate our results. These cells were employed using n-type Cz Si wafers (1.1 Ω·cm, 160±10 µm). The fabricating procedures of these cells can be found in Ref [3].

Current-voltage (I-V) measurements are performed from 25 to 70 °C using I-V testers. TCs are normalized to the value at 25 °C and presented as relative TCs in this study. Suns-V_{oc} measurements from 80 to 30 °C are done using a customized tool from Sinton Instruments [6]. Determination of the cell's series resistance (R_s) is done by comparing the R_s-free current density-voltage (J-V) curve to the one-sun J-V curve [7]. Dark I-V characteristics of the Cox and Strack test structures are measured from 25 to 80 °C to determine ρ_c.

The cell parameters of the TOPCon and monoPoly^{TM} cells as a function of temperature are shown in Fig. 1(a)-(d). As expected, we observed that the open-circuit voltage (V_{oc}), fill factor (FF), and cell efficiency (η) decrease at elevated temperatures while the short-circuit current (J_{sc}) increases. The temperature-dependent behavior of V_{oc}, J_{sc}, and FF can be explained by band gap narrowing of Si material with increasing temperature [8]. The pseudo fill factor (pFF) of TOPCon cells is also presented in Fig. 1(c). Note that the reduction of FF with temperature is less pronounced than that of pFF, indicating a contribution of R_s to the temperature-dependent FF.

The obtained TCs of the studied cells are shown in Fig. 1(e)-(h). TCs of other cell technologies reported in Ref [9] are also presented for comparison. Interestingly, the TOPCon and monoPoly^{TM} cells exhibit a similar TC of the open-circuit voltage (TC_{Voc}), although their V_{oc} at STC are different [see Fig. 1(a)]. As reported by Green [10], TC_{Voc} of well-performed Si-based cells depends not only on the initial V_{oc} at STC, but also on their gamma factor (γ) which is related to the dominant recombination mechanism in the cell. Therefore, we attribute their similar TC_{Voc} to different gamma factors. Using Equation 15 in Ref [10], the calculated γ for TOPCon and monoPoly^{TM} cells are 1.24

and 3.71, respectively. TC_{Voc} of the studied cells are superior to those of the cells without passivating contacts, such as passivated emitter rear totally diffused (PERT), advanced PERT, passivated emitter and rear contact (PERC), and aluminum back surface field (Al-BSF) cells. Compared to Si heterojunction (SHJ) cells, they show slightly smaller values, which can partly explained by a higher V_{oc} of SHJ cells at STC (733 mV) [9].

TC of the short-circuit current density (TC_{Jsc}) of the TOPCon cells is superior to most of the other cell structures and comparable to that of the Al-BSF cells. It is well known that J_{sc} of Si-based solar cells mainly depends on the minority carrier diffusion length which is calculated by the product of the minority carrier mobility and carrier lifetime [11]. In compensated wafers that were used to fabricate the studied TOPCon cells, the minority carrier mobility has a weak temperature dependence due to the counterbalance between the mobility reduction caused by the lattice scattering and the mobility improvement associated with the ionized impurity scattering at elevated temperatures [12]. Therefore, we attribute the favorable TC_{Jsc} of TOPCon cells to the weak temperature dependence of the carrier mobility in compensated wafers.

We also observed a superior TC_{FF} of the TOPCon cells compared to those of other cell structures reported in Ref [9]. As expected from Fig. 1(c), TC_{FF} shows a smaller absolute value compared to TC_{pFF}. This indicates an improvement of the TOPCon cells' R_s with increasing temperature, which can be correlated to ρ_c of poly-Si passivating contact.

TC of the cell efficiency (TC_{η}) of the studied TOPCon cells is comparable to that of the SHJ cells and better than those of the cell structures without passivating contacts.

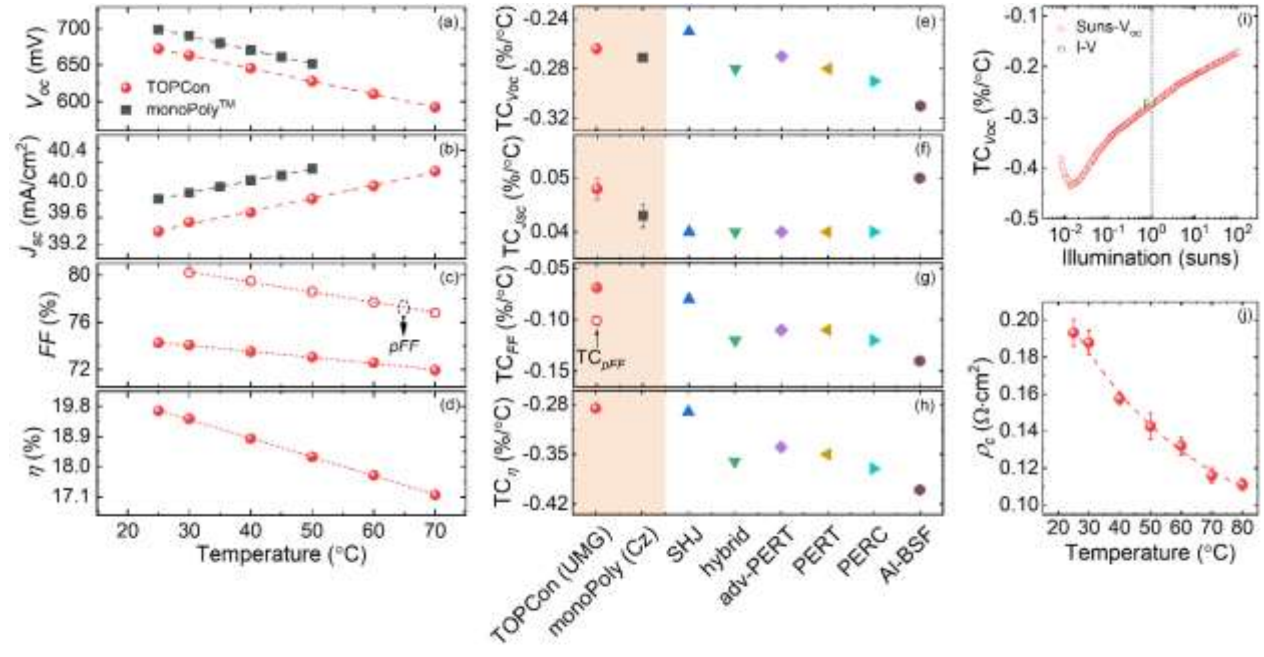

Figure 1: (a)-(d) Cell parameters of TOPCon and monoPoly™ solar cells under one-sun illumination as a function of temperature; (e)-(h) TCs of these cells and of other cell structures reported in Ref [9]. (i) The extracted TC_{Voc} of TOPCon cells from Suns-V_{oc} (red circles) and I-V (green squares) as a function of illumination intensity. (f) The extracted ρ_c using the Cox and Strack method.

The above discussion regards the cell performance at one-sun. It is interesting to gain more insights into their performance at different illumination intensities. TC_{Voc} is extracted from the Suns-V_{oc} measurements from 80 to 30 °C and presented as a function of illumination intensity in Fig. 1(i). The values obtained from I-V measurements are also shown for comparison. TC_{Voc} values extracted by the two above methods are nearly equal. It is clearly seen that the absolute values of TC_{Voc}

decrease when increasing illumination intensity in most of the illumination intensity range. This indicates that the studied TOPCon cells are less sensitive to temperature variation at high illumination intensities.

To gain a better understanding regarding the temperature-dependent behavior of the TOPCon cells' *FF*, the temperature-dependent ρ_c of the poly-Si passivating contacts is investigated and presented in Fig. 1(j). It decreases from 0.19 to 0.11 Ω·cm^2 when increasing temperature from 25 to 80 °C. We found that R_s reduces from 1.33 to 0.77 Ω·cm^2 when increasing temperature from 30 to 70 °C. This reduction is larger than that of ρ_c in the same temperature range. This indicates that the favorable TC_{FF} of the TOPCon cells can be partly explained by the ρ_c improvement which offsets some of the FF losses.

To summarise, in this study, the temperature-dependent performance of the TOPCon and monoPoly^{TM} cells were investigated. We found a favorable TC_{FF} of the TOPCon cells. This can be partly explained by the ρ_c improvement, which offsets some of the FF losses. A superior TC_{Jsc} of these cells can be attributed to the weak temperature dependence of the carrier mobility in compensated wafers. The extracted TC_{Voc} as a function of illumination intensity from Suns-V_{oc} measurements indicates that the studied TOPCon cells are less sensitive to temperature variation at high illumination intensities. TC_{η} of these cells is comparable to that of the SHJ cells and better than those of the cell structures without passivating contacts. This highlights the advantage of this cell structure in the field.

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