A silicon carbide-based highly transparent passivating contact for crystalline silicon solar cells approaching efficiencies of 24%

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A highly transparent passivating contact (TPC) as front contact for crystalline silicon (c-Si) solar cells could in principle combine high conductivity, excellent surface passivation and high optical transparency. However, the simultaneous optimization of these features remains challenging. Here, we present a TPC consisting of a silicon-oxide tunnel layer followed by two layers of hydrogenated nanocrystalline silicon carbide (nc-SiC:H(n)) deposited at different temperatures and a sputtered indium tin oxide (ITO) layer (c-Si(n)/SiO2/nc-SiC:H(n)/ITO). While the wide band gap of nc-SiC:H(n) ensures high optical transparency, the double layer design enables good passivation and high conductivity translating into an improved short-circuit current density (40.87 mA cm⁻²), fill factor (80.9%) and efficiency of 23.99 ± 0.29% (certified). Additionally, this contact avoids the need for additional hydrogenation or high-temperature postdeposition annealing steps. We investigate the passivation mechanism and working principle of the TPC and provide a loss analysis based on numerical simulations outlining pathways towards conversion efficiencies of 26%.

At present, the efficiency of most crystalline silicon (c-Si) solar cells is limited by recombination in the diffused emitter regions and at the contact between metal electrodes and the silicon absorber. Device designs that avoid diffused emitter regions and direct metal-absorber contacts, commonly denoted as passivated contacts, are key enablers for a further increase of efficiency. So far, three concepts have been developed that enable junction formation in crystalline silicon solar cells without diffused emitters. These concepts are: the silicon heterojunction (SHJ) based on intrinsic and doped amorphous silicon; the so-called TOPCon or POLO concepts using a combination of silicon oxide and polycrystalline silicon (SiO2/poly-Si); and the use of metal oxides/nitrides/intrinsic and doped amorphous silicon; the so-called TOPCon or POLO concepts using a combination of silicon oxide and polycrystalline silicon (SiO2/poly-Si). While nc-SiC:H(n) is an obvious candidate to achieve highly transparent front contacts, so far efficiencies have lagged behind due to difficulties in obtaining nc-SiC:H(n) that features high transparency, good conductivity and at the same time provides sufficient hydrogenation for passivation. These three properties are the challenges to be overcome for high efficiency c-Si solar cells, as depicted in Supplementary Note 1 in the Supplementary Information.

The present paper demonstrates how to overcome this drawback by using exclusively low-temperature processes and by the implementation of a highly transparent passivating contact (TPC) scheme consisting of a thin, wet-chemically grown SiO2, tunnel oxide and a hot-wire chemical vapour deposition (HWCVD) fabricated wide band gap nc-SiC:H(n) (Eg of approximately 2.7–3 eV) contact layer, as depicted in Fig. 1b. Here, we demonstrate an independently confirmed efficiency of 23.99 ± 0.29%. This efficiency was achieved by introducing a double layer stack of nc-SiC:H(n) deposited first with low and subsequently with high filament temperatures to tackle the trade-off between passivation and conductivity.
Furthermore, a systematic investigation and optimization of the ITO sputtering conditions combined with a low-temperature curing contributed to the efficiency improvement.

Development of a nc-Si:C:H(n) double layer stack

For nc-Si:C:H(n) deposited at low filament temperatures ($T_f < 1,750^\circ$C), the electrical conductivity is usually below $10^{-10} \Omega^{-1} \text{cm}^{-1}$ compared to filament temperatures between 1,900 and 2,100$^\circ$C where the electrical conductivity drastically increases to 0.07–0.9 $\Omega^{-1} \text{cm}^{-1}$ (see Supplementary Note 2 for more information about the electrical properties of nc-Si:C:H(n)). Given that the higher band gap of nc-Si:C:H(n) is a natural advantage in terms of optical transparency, the optimization of the nc-Si:C:H(n) layer still has to tackle the trade-off between passivation and conductivity that hampered earlier attempts to make efficient silicon solar cells with SiC-based contacts.

Figure 2 shows the implied open-circuit voltage ($iV_{oc}$) of the c-Si(n) wafer symmetrically passivated by the TPC (Fig. 2a) and the contact resistivity of the TPC stack (Fig. 2b) as a function of the filament temperature. For a single nc-Si:C:H(n) layer (thickness of 30 nm) deposited at increased filament temperatures the passivation quality of the TPC is reduced, while high $T_f$ is needed for low contact resistivities (Fig. 2b). Thus, a single nc-Si:C:H(n) layer deposited by HWCVD cannot maximize passivation quality and minimize resistive losses at the same time. To overcome this trade-off, the filament temperature during the deposition was changed, hence a double layer stack of nc-Si:C:H(n) was implemented (9 nm for the first layer and 25–30 nm for the second layer). The modified process starts with a lower $T_f$ of 1,775$^\circ$C for the layer in direct contact with the tunnel oxide. This is followed by a layer deposited using a higher $T_f$ which was initially varied as shown in Fig. 2a. This double layer nc-Si:C:H(n) stack allows to keep the passivation quality nearly independent of $T_f$ in the second stage resulting in a maximum $iV_{oc}$ of 740 mV. At the same time, the contact resistivity is kept at a low value of 38 m$\Omega$cm$^2$, as shown in Fig. 2b. Achieving the same low contact resistivity in a single layer would cause a substantial loss in passivation quality ($iV_{oc} < 720$ mV).

Three mechanisms presumably contribute to the reduced $iV_{oc}$ at higher $T_f$. First, the nc-Si:C:H(n) deposited at higher $T_f$ contains less hydrogen than at lower $T_f$. However, hydrogen is necessary to passivate remaining dangling bonds at the c-Si/SiO$_2$ interface. Second, the substrate temperature is increased due to increased thermal radiation of the filaments at increased $T_f$. An increased substrate temperature is known to reduce the TPC passivation quality, which might be caused by an out-diffusion of hydrogen from the interface. Third, higher $T_f$ leads to an increased hydrogen radical density during the HWCVD deposition. The hydrogen radicals can be a source of damage for the crystalline silicon interfaces, thus increase the density of dangling bonds and deteriorate the passivation quality.

In addition to the filament temperatures, the thicknesses of both nc-Si:C:H(n) layers and the doping gas flow might also be factors influencing passivation quality and conductivity. To be able to judge which deposition parameters have the strongest influence on the overall solar cell performance, we conducted a design of experiment (DoE). In this DoE we found that the thickness of the first nc-Si:C:H(n) layer for passivation with low electrical conductivity has the strongest influence on the fill factor. By decreasing the thickness from 13 to 3 nm to decrease the bulk resistance, the series resistance was reduced from 2.5 to 0.65 $\Omega$cm$^2$ resulting in a fill factor increase from 63 to 77% while maintaining the high passivation quality (see Methods and Supplementary Discussion 1 for more details about the DoE).

Passivation mechanism and working principle of TPC

In contrast to SiO$_2$/poly-Si passivating contacts, the passivation of SiO$_2$/nc-Si:C:H(n) works without any high-temperature recrystallization, hydrogenation or firing steps. The as-deposited low-temperature (heater set temperature of 250$^\circ$C) nc-Si:C:H(n) deposited by HWCVD was found in literature to allow for an effective interface hydrogenation for c-Si(n)/SiO$_2$/poly-Si contacts without additional steps. Since no high-temperature steps are involved in the TPC fabrication process, the hydrogen supplied during HWCVD deposition is also found to accumulate at the c-Si(n)/SiO$_2$ interface. This effect can be seen in Fig. 3a displaying the secondary-ion mass spectrometry (SIMS) profiles. This hydrogen avoids the demand of any further hydrogenation steps. For the single layer stack shown in the upper graph of Fig. 3a, the hydrogen concentration in the nc-Si:C:H(n) bulk is decreased for increased $T_f$ while the hydrogen concentration at the interface is increased. The reason for the accumulation of hydrogen at the interface is most probably the increased sample temperature as higher thermal radiation of the hot wires enables a higher diffusivity of the hydrogen. Another potential reason for the accumulation is that the higher...
One sample was used for each data point in the $\text{I-V}$ behaviour of the measured data in the case of single nc-SiC:H(n) layers. The vertical error bars represent the standard error for each measurement also reported for SiO$_2$/poly-Si contacts$^{21}$. The grey box marks the area of 9–25 nm stack, where $\rho$ of the passivation layer is fixed up to 740 mV. The stronger band bending and thereby stronger field-effect passivation explains the lower hydrogen content at the interface but similar passivation quality that is found in the double layer stack with the conductive nc-SiC:H(n) deposited at higher $T_f$ visualized in the lower graph of Fig. 3a. The accumulation of electrons at the c-Si(n) interface promotes the tunnelling through the thin SiO$_2$ layer to the conductive nc-SiC:H(n) layers. In this respect, the measured activation energy of the dark conductivity is 50 to 100 mV (refs. $^{13,26}$), which represents the energy difference between the conduction band edge and the Fermi level. Such a low value reveals the negligible contribution of nc-SiC:H(n) to the potential barrier for collecting electrons. Hence, TPCs based on nc-SiC:H(n) enable excellent energy alignment for an efficient field-effect passivation and for electron extraction.

The SiC-based tunnel-junction front contact has some comparable properties to the common low-temperature approach of the a-Si SHJ double stack (doped/intrinsic). These similarities include the supply of H$_2$ to the interface by the intrinsic/passivation layer, field-effect passivation and carrier selectivity provided by the doped/conductive layer. The key difference lies in the absence of the smaller band gap and the low transparency of the doped a-Si or even poly-Si layers relative to the nc-SiC:H(n). Additionally, using the tunnel oxide rather than intrinsic a-Si:H as the interface passivation layer on top of the c-Si, the TPC further facilitate the advantage in terms of transparency.

**Investigation and mitigation of sputter degradation**

On completion of the devices we observed a substantial difference between the implied $V_{oc}$ after nc-SiC:H(n) deposition and the actual $V_{oc}$ of the finished devices. This difference of up to 32 mV indicates that during ITO sputtering the passivation quality is substantially deteriorated, which is similar to that reported for solar cells passivated by a-Si:H$^{27}$ and SiO$_2$/poly-Si$^{28,29}$. Degradation of the passivation due to ITO sputtering can originate either from ion bombardment or from ultraviolet (UV) light emitted for example by oxygen in the plasma ($\lambda = 130.5$ nm) during sputtering$^{30,31}$.

To identify the main source of the sputter degradation, we conducted model experiments measuring the minority charge carrier lifetime of wafers that were symmetrically passivated by TPC. The wafers were partially covered with different optical filters and exposed either to a pure oxygen plasma without sputtering or a complete ITO deposition process (see details in Supplementary...
During the pure plasma treatment, only those areas that were covered with filters blocking wavelengths down to 130 nm radiation preserved a high lifetime. In contrast, during ITO deposition all areas that were covered by any filter, blocking or partly transparent to the 130 nm radiation were damaged to a certain extent. Furthermore, the uncovered areas showed only a moderate degradation compared to the results from the pure plasma experiment. We therefore conclude that during the deposition process the damage by radiation is increasingly limited by the optical transparency of the growing ITO film and the sputter flux not only reduces the initial damage but also allows some of the damage to be cured, for example by the reduction of dangling bonds via a photo lithography based metallization.

This finding indicates that an optimization of the ITO deposition process by adjusting the ion flux density by the sputter power ($P_{\text{sputter}}$) and the secondary-ion energy by the deposition pressure ($p_{\text{dep}}$) is required. For the latter, a higher pressure reduces the free path and therefore reduces the kinetic energy of the ions. The best solar cell performance of the four best solar cells after the curing experiment (Supplementary Fig. 16) leading to a certified efficiency $\eta = 23.99 \pm 0.29\%$ and $J_{\text{sc}} = 40.87 \pm 0.57 \text{mA cm}^{-2}$ (Supplementary Fig. 19). The evolution of the solar cell parameters due to the optimization of the SiC double layer, transparent conductive oxide (TCO) and ARC is summarized in Fig. 4. For comparison, nc-SiO$_2$/nc-SiC:H(n) stack (vertical grey dashed lines). $E_c$ (black solid line) is the conduction band energy; $E_f$ (blue solid line) is the valence band energy and $E_f$ (red dashed line) is the Fermi level.
reported by Kaneka. Here, Kaneka used the copper plating technology for metallization and a finger width of approximately 30–40 µm (refs. 35,36). However, due to the lack of information concerning the metallization fraction and ARC of this solar cell, we cannot provide an in-depth comparison. For our cells, we used a finger width of approximately 60 µm and a circumferential busbar outside of the active area (Supplementary Fig. 20).

The optimized front contact stack includes 70 nm of ITO, 30 nm of conductive nc-SiC:H(n) and 3 nm of passivating nc-SiC:H(n). A shading loss due to front contact metal fingers and the ARC of 125 nm of MgF2 are taken into consideration in the simulation. The legend indicates each optical part, with the integration current density shown in brackets. The EQE and optical losses (reflection R and absorbance A) are simulated using GenPro4. The real EQE is calculated from the spectral response data certified at CalTec ISFH.

**Fig. 5 | Optical loss analysis of the optimized TPC solar cell.** The optimized front contact stack includes 70 nm of ITO, 30 nm of conductive nc-SiC:H(n) and 3 nm of passivating nc-SiC:H(n). A shading loss due to front contact metal fingers and the ARC of 125 nm of MgF2 are taken into consideration in the simulation. The legend indicates each optical part, with the integration current density shown in brackets. The EQE and optical losses (reflection R and absorbance A) are simulated using GenPro4. The real EQE is calculated from the spectral response data certified at CalTec ISFH.

Practical efficiency potential for TPC solar cells

The theoretical efficiency ($\eta_{th}$) limit for a c-Si solar cell according to Richter et al., which considers the intrinsic limitation and relies on the assumption of a perfect Lambertian light trapping scheme, is predicted to be $\eta_{th}=28.66\%$. In the calculation, a 170-µm-thick c-Si wafer with a resistivity of 1 Ω·cm as also used in this work is assumed, leading to a theoretical $V_{oc}^{th}=746.9$ mV, theoretical $J_{sc}^{th}=43.72$ mA·cm$^{-2}$ and theoretical FF, $FF_{th}=87.75\%$. The difference between the theoretical limit of $\eta_{th}=28.66\%$ and the actual achieved efficiency in this work of $\eta_{act}=23.99\%$ is 16.3% relative. Among the IV parameters, the FF shows the strongest potential for improvement with 7.8%, while for $J_{sc}$ the potential is 6.5% and for $V_{oc}$, it is 2.9%.

To investigate the reason for the FF difference, we conducted a FF loss analysis using a two-diode equivalent circuit to model the solar cell. For this analysis, the losses in FF are parameterized by the losses due to the saturation current density of the first and second diode ($J_{sh}$ and $J_{02}$), as well as by the shunt resistance ($R_{sh}$) and the series resistance ($R$). The saturation current density $J_{02}$ describes recombination currents in the quasi-neutral bulk and the solar cell surfaces, while $J_{sh}$ mostly describes the recombination attributed to Shockley–Read–Hall defects in the space charge region. The results are presented in Fig. 6. The maximum FF for our optimized solar cells by avoiding all $J_{02}$, $R_{sh}$ and $R_{02}$ related losses is the FF, and it is calculated to be approximately 85%. From the FF loss analysis, it becomes clear that the shunt resistance does not contribute any notable loss to the FF. The loss due to the series resistance is the largest loss (2.96%) followed by the loss of 1.11% due to recombination in the space charge region ($J_{sh}$). The transmission line method (TLM) measurement for the front TPC (ITO/nc-SiC:H(n)/SiO$_2$/c-Si(n)) and the rear SHJ contact (ITO/a-Si:H(p/i)/c-Si(n)) delivers contact resistivities of 38 and 350 mΩ·cm$^2$, respectively, indicating that the rear SHJ contact contributes most strongly to the series resistance and is the bottleneck for FF improvement, which is consistent with the TCAD simulation results.
From the Suns-$V_{oc}$ measurement for the optimized solar cells, an $R_s$ of 0.58$\Omega$cm$^2$ can be determined. Using an anticipated value of 0.45$\Omega$cm$^2$ by optimizing the contact resistivity at the rear SHJ contact, a FF of 81.5% can be calculated. Concerning the $J_{sc}$ loss, it is shown in the last section, that the shading loss and parasitic absorption in the ITO are the two biggest losses that need further optimization. By reducing the finger width from 60 to 40$\mu$m (shading ratio from 3.1 to 2.1%), a $J_{sc}$ gain of 0.46 mA cm$^{-2}$ can be calculated. Combining this gain with the optimization of the transparency of TCO and reflection minimization, a $J_{sc}$ of 42 mA cm$^{-2}$ is practically achievable. Considering that there is still an $V_{oc}$ to $V_{oc}$ drop of 12 mV, further optimization on improving the $V_{oc}$ and decreasing the $V_{oc}$ to $V_{oc}$ drop are important for a higher $V_{oc}$. The optimization of the SiO$_2$ preparation process is ongoing. First results show that a 7 mV gain in $V_{oc}$ is possible, which indicates that a $V_{oc}$ of 730 mV is in reach. An efficiency of 25% can finally be predicted assuming the practical IV parameters of $V_{oc}$ of 730 mV, $J_{sc}$ of 42 mA cm$^{-2}$ and FF of 81.5%

Numerical simulations are performed using the TCAD Sentaurus to identify directions and potentials for further improving the power conversion efficiency of solar cells using the TPC. The results reveal that optimizing the rear SHJ contact stack the $V_{oc}$ and FF could be improved up to 739 mV and 84.2%, respectively. Such an improvement would be due to the field-effect passivation in case of $V_{oc}$ and interface transport in case of FF enhancement. Furthermore, considering advanced metalization techniques, for example copper plating, we have the flexibility to have smaller pitch sizes and front metallization fraction. Addressing these two aspects could potentially lead to FF improvements up to 85% due to the decreased lateral transport in the smaller finger pitch (500$\mu$m pitch size and 10$\mu$m front contact width), and $J_{sc}$ above 42 mA cm$^{-2}$ due to the smaller metallization fraction (<2% front metallization). In fact, front and back contacted solar cells using TPC technology will be promising candidates to break the 26% threshold for c-Si single junction solar cells.

Conclusion

The present paper has demonstrated that a promising front passivating contact system (SiO$_2$/nc-SiC:H(n)/ITO) provides a possibility to solve the triple challenge of conductivity, passivation, and transparency. The evolution of TPC solar cells and simulations demonstrate that the SiC-based TPC has an inherent, not yet fully exploited, advantage over other heterojunction contacts in terms of transparency ($J_{sc}$) with the potential to achieve $J_{sc}$ in the range of 42 mA cm$^{-2}$ likes diffused junctions\textsuperscript{11}. At the same time, the high $V_{oc}$ of the heterojunctions can be maintained. Thus, innovations such as the double layer nc-SiC:H(n) stack allow to optimize all three photovoltaic parameters without the need of compromising between them. In addition, we demonstrate that the process flow for the TPC is very lean, the extra hydrogenation or high-temperature postdeposition annealing steps, which add cost and energy to the process flow of other passivated contact schemes\textsuperscript{11,44}, are not needed. Finally, in view of the short research history, we see scope for further improvements beyond the present efficiency of 24% to a practical efficiency of 25%. Numerical simulations predict an efficiency of 26% by improving FF and $V_{oc}$ via optimizing the SHJ contact at the rear side and introducing a frontier metallization approach such as copper plating.

Methods

Fabrication of symmetric samples and solar cells with TPC. The symmetric samples and solar cells were fabricated with Czochralski grown n-type double-side textured, 170-µm-thick, 12.4 cm silicon <100> wafers provided by LONGi. The wafers were cleaned in a cleanroom according to standard RCA cleaning\textsuperscript{45}. The native oxide was afterwards removed in 1% diluted hydrofluoric acid for 5 min. Afterwards, the wet-chemical oxide was produced in a mixture of H$_2$O$_2$:H$_2$SO$_4$ at 2:1 at a temperature of around 60 °C for 10 min. This results in a SiO$_2$ thickness of roughly deposited by HWCV 10 nm (ref. \textsuperscript{46}). The nc-SiC:H(n) layers were deposited partly in an in-house built system and partly in a commercial system built by MRG. As precursors 5% monomethylsilane diluted in H$_2$ (MMS, 6 standard cubic centimeters per minute (sccm)), hydrogen (H$_2$, 94 sccm) and nitrogen (N$_2$, 30 sccm) were used if not stated otherwise. As a catalyst, three 15 cm curled tungsten wires were used. The substrate is heated by a sublimation lamp set to 250 °C. The deposition pressure was 0.75 mbar. The filament temperature was tuned by adjusting the electrical current through the wires. For double layer stacks, the temperature of the hot-wire filaments was ramped up during the deposition. For symmetric samples, the first layer of nc-SiC:H(n) was deposited at $T_f=1,775$ °C with a thickness of 9 nm. The filament temperature for producing the conductive second layer was varied between $T_f=1,805$ and 2,055 °C depending on the thicknesses of 25–30 nm. The solar cells for the ITO development were deposited with nc-SiC:H(n) layers deposited at $T_f=1,775$ °C with a thickness of 3 nm, followed by $T_f=1,950$ °C with a thickness of 30 nm.

For solar cells, the back side SiO$_2$ was removed in a hydrofluoric acid dip for 5 min following SiC deposition. Afterwards, the a-Si:H(7) nm and a-Si:H(p) 7.4 nm layers were deposited at 200 °C in an AK1000 PECVD system provided by Meyer Burger. The intrinsic layer was deposited at 50 W with an H$_2$ flow of 650 sccm and a SiH$_4$ flow of 145 sccm. The p-type layer was deposited at 90 W with an H$_2$ flow of 500 sccm, a SiH$_4$ flow of 30 sccm and 1% trimethylboron in H$_2$. The doping of the conducting layer was performed at 100 W with an H$_2$ flow of 100 sccm. In this system, all back contacts for each solar cell experiment were deposited at once. The ITO was sputtered from a 3% ITO target rotating at 10 rpm. At a sample heater temperature of 250 °C and through a mask to create four 2 x 2 cm$^2$ solar cells on each wafer. The ITO on the a-Si:H(p) was sputtered, using a deposition pressure of 6 mbar, deposition power of 5 kW, an Ar flow of 90 sccm and an O$_2$ flow of 5 sccm. The ITO deposition of the back side was kept the same throughout this study. For sputtering on the nc-SiC:H(n) the reference ITO was deposited at a deposition pressure of 6 mbar, deposition power of 5 kW, an Ar flow of 197 sccm and an O$_2$ flow of 3 sccm. In the ITO optimization experiment for the n-side, deposition pressures of 10, 15 and 20 mbar and deposition powers of 0.5, 3.35 and 6.2 kW are tested. The metal contacts have been screen printed by an MT-605TVC screen printer from Micro-tec using a low-temperature silver paste H9481 provided by NAMICS. The silver paste was afterwards annealed at 190 °C in an oven for 40 min. The curing of the solar cells was performed on a hot plate at 220°C for 10 + 10 min. A MgF$_2$, ARC (125 nm) was thermally evaporated by an electron beam as an ARC on the front side of the best solar cell. The cell was subsequently annealed for 10 min on a hot plate at 200 °C. The oxygen plasma treatment of the sample covered with UV filters was done in an Oxford Instruments OpAL ALD reactor for 15 min. The O$_2$ flow was 100 sccm at 0.12 mbar and 300 W at 50 °C. The respective ITO deposition was performed at 3.35 kW and 15 mbar.

DoE for double layer stack development of nc-SiC:H(n). To be able to judge which HWCV deposition parameters has a significant influence on the device performance, we varied five parameters on two levels (high and low). We varied the filament temperature (and thereby the conductivity) of the nc-SiC:H(n) deposition as well as the layer thickness for the passivation and the conductive layer separately. The filament temperature was changed from 1,775 to 1,875 °C and the layer thickness from 1,950 to 2,060 °C for the passivation and the conductive layer, respectively. The layer thickness was changed from 3 to 13 nm and from 11 to 27 nm for the passivation and conductive layer, respectively. The wire temperature was measured using a Raytek Marathon pyrometer with an accuracy

\[ \text{FF} = \frac{P_{	ext{max}}}{P_{	ext{in}}} \]

\[ \text{FF} = \frac{V_{	ext{oc}} J_{	ext{sc}}}{P_{	ext{in}}} \]

\[ \text{FF} = \frac{V_{	ext{max}}}{} \]

\[ \text{FF} = \frac{J_{	ext{sc}}}{\text{FF}} \]

\[ \text{FF} = \frac{\Delta J_{	ext{sc}}}{\Delta V_{	ext{oc}}} \]
of approximately ±20°C. The layer thickness is estimated from thickness measurements of nc-SiC:H(n) on polished silicon substrates. The doping gas flow rate of nitrogen was kept the same for both layers but was varied between 30 and 100 sccm. If all parameter combinations were to be investigated this would result in a total number of 32 experiments. Therefore, we decided to use the advantage of a fractional factorial plan that allowed us to reduce the experiments to 16. Additionally, we did three centre-point experiments (experiments 17–19 in Supplementary Table 1) where all five parameters had the centre value between high and low levels to judge the significance of the parameters. Nevertheless, by this reduction in number of experiments we sacrificed complete information about all interactions of the deposition parameters. To be able to see the influences of the five parameters we calculated the effect E of each parameter: $E_i = E_{high} - E_{low}$, where $E_{low}$ is the mean value of the results y when the parameter was set to the low level and $E_{high}$ is the mean value of the results y when the parameter was set to the high level. The result hereby means the measured value by current–voltage (IV) or photoconductance measurements (for example, efficiency, fill factor or $V_{oc}$). The stronger the absolute effect is, the stronger is the influence of the investigated parameter on the final result. When the effect is positive, changing the level of the parameter from low to high results in an increase of $y$.

In the case of the effect of the passivation layer thickness on the fill factor as shown in Supplementary Fig. 2, the effect is negative meaning that the fill factor can be increased by decreasing the layer thickness. If the output parameter should be decreased to increase the efficiency of the final device as is the case for the series resistance (Supplementary Fig. 3), a parameter with a positive effect should be set to its low value to decrease the series resistance.

To evaluate the significance of each effect, we computed the pure error, PE, from the variance, $V_{cp}$, of the results for the three centre-point experiments.

$$PE = \sqrt{\frac{\mu \cdot f \cdot (f+1)}{n}}$$

where n is the number of experiments excluding the centre points (for this DoE, n = 16). PE is then multiplied with the t value of Student’s distribution with the confidence level α and the degrees of freedom, d.f. (for this DoE, 2)

Threshold $= PE \times t (\frac{1}{2},d.f.)$

The threshold is marked by a dashed line in the Supplementary Figs. 2–5 to visualize whether an effect is significant or not. If an effect lays within the grey area not exceeding the threshold, the effect has no significant influence on the result of the experiment.

Characterization of passivation quality. The passivation quality of the layer was tested on symmetric samples and solar cells before ITO deposition by measuring the photo-conductance of the wafer using a Sinton WCT-120 lifetime tester.

Characterization of passivation quality. The passivation quality of the layer was tested on symmetric samples and solar cells before ITO deposition by measuring the photo-conductance of the wafer using a Sinton WCT-120 lifetime tester. From these measurements, the implied open-circuit voltage ($V_{oc}$) at one sun, the saturation current density ($J_0$) at an excess charge carrier density of 5 × 10^13 cm^-3 and the effective minority charge carrier lifetime ($\tau_{can}$) at a charge carrier density of 1 × 10^10 cm^-3 were extracted.

SIMS measurement. The SIMS (time-of-flight SIMS IV by IONTOF) measurement was conducted to analyse the interface properties of the nc-SiC:H(n)/SiOx/c-Si(n) stack, to investigate the correlation between passivation quality and filament temperature. An area of 300 × 300 μm² was sputtered (using a 1 kV Cs ion beam), and an area of approximately 80 × 80 μm² was measured (using a 30 kV B1 ion beam).

STEM and energy dispersive X-ray measurements. The high-resolution bright-field STEM images were obtained with a probe aberration corrected Hitachi HF/5000 microscope. EDX mapping of the O-L edge, Si-L edge and C-K edge were obtained at the aberration corrected FEI Titan G2 80-200 microscope equipped with a four-quadrant EDX detector. The sample for STEM measurement and EDX mapping was prepared from the same batch of double nc-SiC:H(n) layer stack as that for SIMS measurement.

UV photoluminescence spectroscopy (UPS) measurement. The UPS system is a MULTIPROBE MXPS system from Scienta Omicron with an ARGUS hemispherical electron spectrometer and part of the JOSEPH cluster system in the Research Center Jülich. The light source for UPS measurements is a HIS13 Hel gas discharge vacuum UV source from FOCUS (main line HeI 21.22 eV). Spectra are collected with a path length of 2 eV, a digital resolution of 0.01 eV and a sample bias of 6 V at a takeoff angle of 8°. Since we suspected the absolute positions of the spectral features were influenced by sample charging, we only determined the ionization energy E from the distance of the cutoff at low kinetic energies and the valence band edge at high kinetic energies by linear fits to the spectrum. The measurements were averaged over four positions on the sample.

Characterization of contact resistivity and IV characteristics. The contact resistivity ($\rho_c$) was measured on an in-house setup using the TLM. The contact resistivity was evaluated for the complete front side layer stack of c-Si(n)/TPC/ITO/Ag. The efficiency, the fill factor, the open-circuit voltage and the short-circuit current density were measured by IV measurements under standard test conditions using the LOANA system from pv-tools. The series resistance was derived from $J_{oc} - V_{oc}$ measurement.

UV degradation experiment. For the UV degradation experiment, different UV filters were used to find the energy range in which the light has the ability to degrade the surface passivation. Therefore, the three filters had different transmission properties for the light. The transmission properties are summarized in Supplementary Table 2. For the experiment with oxygen plasma (Supplementary Fig. 14c), a thicker filter (5 mm) was used as compared to the ITO sputter experiment (Supplementary Fig. 14d). Thus, the thinner filter has a higher typical transmission.

Photoluminescence measurement. The lifetime-corrected photoluminescence images were taken using a Xencelis Cheetah 640 CL. InGaAs camera cooled to 0°C. To obtain a lifetime-corrected photoluminescence image, four images have to be taken during one illumination cycle. The method to calculate the lifetime-photoluminescence image from the four photoluminescence images taken during one illumination cycle is described in literature. The lifetime-photoluminescence image is corrected afterwards for the effective minority charge carrier lifetime measured by photo-conductance. A general description of the underlying physical principles of photoluminescence is described elsewhere.

Simulations. Electrical simulations based on the optimized TPC solar cells were performed using TCAD Sentaurus with parameters of c-Si(n) and amorphous layers as reported in ref. The simulations used measured electronic parameters of our conductive and passivating nc-SiC:H(n) layers. More details of the parameters can be found in the Supplementary Information (Supplementary Discussion 2 and Supplementary Tables 3 and 4). Optical simulations based on the optimized TPC solar cells were performed using GenPro4 (Ref. ). The simulations were based on double-side textured interfaces with layers’ measured thicknesses and complex refractive indices. More details of the parameters can be found in the Supplementary Information (Supplementary Table 5 and Supplementary Fig. 21).

Data availability
All data generated or analysed during this study are included in the published article and its Supplementary Information. Source data are provided with this paper.

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Author contributions
M.K. and M.P. designed the experiments. M.K. carried out the layer and device fabrication and characterization including use of the ellipsometer, quasi-steady-state photoconductance, transfer line method, photoluminescence, transmittance and reflectance, current-voltage and quantum efficiency. A.Z. contributed to the SiC deposition. A.L. and W.D. contributed to the Si:H, ITO and MgF2 deposition and optimization, and optical properties measurements. B.M. contributed to the TCO optimization. S.L., K.Q. and M.P. contributed to screen printing. A.Z. and A.E. developed the curing of MgF2. A.E. performed the IMS measurements. P.C. and M.L. performed HRSTEM measurements and EDX mapping. B.K. performed UPS measurements. P.P. and R.S. and O.I. executed the TCAD and GenPro simulation. M.K., M.P., K.Q., F.F., T.K., U.R. and K.D. contributed to the definition and presentation of the paper content. M.K., M.P., K.Q. and K.D. organized the research. M.P., F.F., U.R., K.D. and M.K. developed the concept of TPC by specific layer stack. M.K., K.Q., T.K. and U.R. wrote the paper, and all other authors discussed the results and proofread the paper.

Competing interests
The authors declare no competing interests.
Experimental design

Please check: are the following details reported in the manuscript?

1. Dimensions
   - Area of the tested solar cells
     - Yes
     - No
     - 20x20 mm²
     - A transparent conducting oxide was sputtered through a mask to define the cell area.

2. Current-voltage characterization
   - Current density-voltage (J-V) plots in both forward and backward direction
     - Yes
     - No
     - The same J-V results are obtained for our silicon solar cells when changing the scanning direction.
   - Voltage scan conditions
     - Yes
     - No
     - Scan direction: positive to negative, with 88 data points between -0.1 V and +0.744 V.
   - Test environment
     - Yes
     - No
     - The measurements are performed in air on a calibrated measurement system under standard test conditions.
   - Protocol for preconditioning of the device before its characterization
     - Yes
     - No
     - No protocol applies to the preconditioning of silicon solar cells.
   - Stability of the J-V characteristic
     - Yes
     - No
     - The J-V characteristic was stable over time also when measured again after several weeks.

3. Hysteresis or any other unusual behaviour
   - Description of the unusual behaviour observed during the characterization
     - Yes
     - No
     - Our cells did not show any unusual behavior or hysteresis.
   - Related experimental data
     - Yes
     - No
     - Our cells did not show any unusual behavior or hysteresis.

4. Efficiency
   - External quantum efficiency (EQE) or incident photons to current efficiency (IPCE)
     - Yes
     - No
     - Presented in the supporting information Supplementary Figure 18.
   - A comparison between the integrated response under the standard reference spectrum and the response measure under the simulator
     - Yes
     - No
     - Comparison was performed within the certification procedure.
   - For tandem solar cells, the bias illumination and bias voltage used for each subcell
     - Yes
     - No
     - We do not report on tandem cells.

5. Calibration
   - Light source and reference cell or sensor used for the characterization
     - Yes
     - No
     - AAA Loana Sun Simulator by pv-tools GmbH including a reference cell with a Sinus-220 LED light source by WAVELABS Solar Metrology Systems GmbH.
   - Confirmation that the reference cell was calibrated and certified
     - Yes
     - No
     - Reference cell was calibrated by pv-tools using a silicon solar cell calibrated at Physikalisch-Technische Bundesanstalt at Braunschweig Germany.
### Calculation of spectral mismatch between the reference cell and the devices under test

- **Yes**
- **No**

Spectral mismatch is calculated using a calibrated reference cell. For certified solar cells the spectral mismatch is calculated using IEC 60904-7.

### Mask/aperture

6. **Size of the mask/aperture used during testing**

- **Yes**
- **No**

3.61 cm² for in-house measurements, (3.487 ± 0.017) cm² for calibration.

7. **Variation of the measured short-circuit current density with the mask/aperture area**

- **Yes**
- **No**

No variation expected due to homogeneity of the solar cells.

### Performance certification

7. **Identity of the independent certification laboratory that confirmed the photovoltaic performance**

- **Yes**
- **No**

ISFH CalTeC D-K-18657-01-00

A copy of any certificate(s)

Provide in Supplementary Information

8. **Results are presented in supplementary information Supplementary Figure 17 and 19.**

### Statistics

8. **Number of solar cells tested**

- **Yes**
- **No**

Each wafer contains 4 nominally identical solar cells.

9. **Statistical analysis of the device performance**

- **Yes**
- **No**

Boxplots are used to show the statistics.

### Long-term stability analysis

9. **Type of analysis, bias conditions and environmental conditions**

- **Yes**
- **No**

For instance: illumination type, temperature, atmosphere humidity, encapsulation method, preconditioning temperature

Remeasuring the cells after several weeks in air lead to the same results.