Large Area TOPCon Technology Achieving 23.4% Efficiency

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***Abstract* — We report on the development of the TOPCon technology on large area focusing on the deposition technology for the a-SiC$_x$(n) layer and the rear side metallization. We demonstrate that kHz direct-plasma technology can be used to deposit the a-SiC$_x$(n) layers and that concerns about ion bombardment damaging the thin SiO$_x$ are not justified. Excellent surface passivation quality was achieved with lifetimes up to 13 ms (1 Ωcm *n*-type). The layers can be contacted using ITO reaching specific contact resistivities in the range of 5 mΩcm^2. Solar cells with a boron diffused emitter and TOPCon rear are presented resulting in an efficiency of 23.4 % with laser contact opening and NiCuAg plating.**

***Index Terms* — passivating contacts, NiCu plating, n-type, silicon.**

I. Introduction

Passivating and carrier-selective contacts which consist of an ultrathin SiO$_x$ layer and a heavily doped silicon film like TOPCon or poly-Si [1-5] are an appealing technology to further push the efficiency of silicon solar cells. The replacement of a partial rear contact (PRC) scheme by TOPCon as a full-area rear contact has so far resulted in efficiencies up to 25.8 % [6], but so far the full potential of this technology was only demonstrated on small area (4 cm^2). While first steps towards solar cells of practical size (≥ 100 cm^2) featuring a TOPCon rear and a diffused front side were presented recently [7], the actual goal is the transfer of all processes to industrial-size (156×156 mm^2) and solar-grade material. One of the missing links in the processing chain is the deposition of the doped TOPCon Si layer using industrial technology, the other one is a module-compatible rear side metallization. Here, we focus on these components. As an alternative deposition technology for the doped Si layer, we investigate tube furnace direct plasma-enhanced chemical vapor deposition (PECVD). Due to the operating frequency in the kHz range, it has to be investigated if ion bombardment causes damage to the ultrathin tunnel oxide layer [8,9]. Regarding the rear side metallization, one option is to use a low-temperature approach similar to a-Si hetero-junction solar cells using transparent conductive oxide (TCO), but in contrast to a-Si with higher flexibility in the process temperatures. At the device level, the focus is on *n*-type silicon solar cells with the TOPCon rear side and a boron-diffused front side as shown in Fig. 1, with the front side being contacted by laser contact opening (LCO) and a plated stack of nickel, copper and silver (NiCuAg).

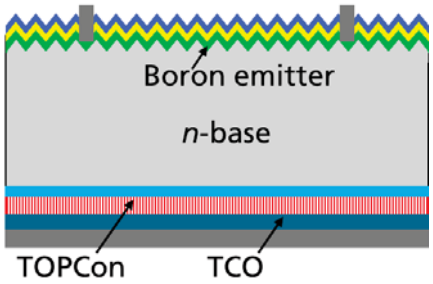

Fig. 1. Layout sketch of the investigated solar cell structure. Note that for the cells presented in Table I, the TCO was omitted as the process was not available at the time.

II. Industrial-Scale TOPCon Deposition Technology

So far, for the deposition of doped amorphous silicon or silicon-rich silicon carbide (SiC$_x$) thin films as used in the TOPCon scheme small laboratory reactors, usually operating in the MHz range were used. Recently, it was demonstrated that it is possible to use industrial scale tube furnace PECVD reactors operating in the kHz range [10]. Initially, there were concerns due to the low operating frequency in the kHz range, resulting in possible surface damage by ion bombardment [8,9]. However, it was shown that these concerns are not justified and excellent surface passivation can be achieved using this approach.

A. Experimental Details

To evaluate the surface passivation quality, we used 1 Ωcm *n*-type FZ c-Si wafers of 100 mm wafer diameter with 200 µm thickness. The wafers received an RCA cleaning, after which they received a thermal oxidation at 1050 °C to reduce the number of bulk defects [11]. The oxide was then removed in buffered HF and the tunnel oxide layer was grown in nitric acid (HNO_3) or—for samples marked as "TO"— thermally in a tube furnace at 600 °C for 10 min in O_2/N_2 ambient. On top of the tunnel oxide a-SiC$_x$(n) layers were deposited

symmetrically in a centrotherm cPLASMA tube furnace PECVD tool operating at 40 kHz. After the deposition, the samples were annealed in a tube furnace in inert ambient at 850 °C and 900 °C in case of HNO_3 and TO, respectively. Finally, the samples received a thermal treatment in atomic hydrogen atmosphere [12] at 400 °C. To determine the contact resistivity, a stack of titanium, palladium and silver was thermally evaporated on the samples using a linear TLM pattern measured by four-terminal sensing. To evaluate the passivation on solar-grade material, we used 156×156 mm^2 pseudo-square 2 Ωcm Cz *n*-type c-Si wafers of approx. 180 µm thickness. The Cz wafers were processed similarly to the FZ wafers with two changes. (i) Prior to the initial cleaning, the wafers received a saw damage etch in KOH. (ii) At the end, the atomic hydrogen treatment was omitted as the technology was not yet available at this wafer size.

B. *Results and Discussion*

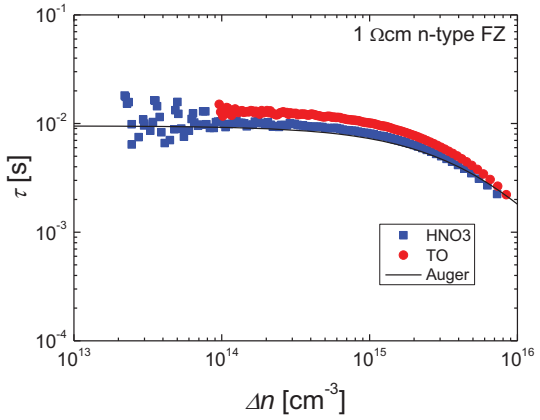

Fig. 2. Injection-dependent effective minority carrier lifetime for the cPLASMA TOPCon layers with HNO_3 and thermal (TO) tunnel oxide. The solid line gives the intrinsic bulk lifetime (according to Richter *et al.* [13]) for the used substrate.

Fig. 2 shows the measured injection-dependent minority carrier lifetime τ for the planar FZ Si samples. Already using the HNO_3 tunnel oxide, we achieved an excellent lifetime of around 9-10 ms at $\Delta n < 5\times10^{14}$ cm^{-3}, which is at the same level as the intrinsic bulk lifetime according to Richter *et al.* [13]. Using the thermal oxide, the measured lifetimes were even higher, with up to 12-13 ms. This is an extraordinary result for such a new process, especially considering the original concerns regarding the ion bombardment the tunnel oxide has to withstand, concerns which were thus successfully disproved. The excellent minority carrier lifetimes resulted in an implied V_{OC} of approx. 735 mV for both oxides. The good injection-dependency resulted in an implied *FF* above 87 %.

To prove that the new layers not only result in excellent surface passivation quality, but can also be contacted, we determined the contact resistivity using TLM structures. Here, all measured values were in the range of 3-6 mΩ cm^2 with only very low variation, meaning that all of the layers exhibit good contact ability and no impact on the series resistance is expected by either combination.

On Cz material, we observed (by photoluminescence imaging) a homogeneous surface passivation. The remaining inhomogeneities were attributed to wafer handling. Over the whole carrier, we determined an implied V_{OC} of 719 ± 2 mV averaged over 22 wafers. The gap to the samples discussed above can mainly be explained by the absence of the hydrogen passivation, which so far on this wafer size remains to be done. However, even at 719 mV implied V_{OC}, it is highly unlikely that the rear side will induce a limitation in the V_{OC} of the final cell structure.

III. Transparent Conductive Oxide on TOPCon

For module integration it is important to have a rear side metallization compatible with module technology. One possibility here is to use a TCO.

A. *Experimental Details*

To investigate the properties of the TOPCon/ITO system, we used TOPCon lifetime samples with layers from the cPLASMA tool fabricated as described in the previous section. Tin-doped indium oxide (ITO) was then deposited symmetrically on both sides using DC-magnetron sputtering. The contact resistivity was determined by measuring the resistance between the surfaces. The doping level of the TOPCon poly-Si was varied since this might influence the contact ability of the ITO to this layer.

B. *Results and Discussion*

Fig. 3. gives the implied V_{OC} determined before and after depositing ITO in dependence of the doping level of the TOPCon poly-Si. Only for the lowest investigated poly-Si doping a degradation was observed in the range of 10 mV. For the higher doping levels, the implied V_{OC} remained approx. the same. However, even though degradation due to sputter damage was observed for the best samples, the implied V_{OC} after TCO deposition at 720 mV was still high enough to not induce a significant limit for the solar cells, for which the estimated V_{OC} would be in the range of 700-710 mV (on 156×156 mm^2 Cz). As an alternative, the sputter damage could also be cured by thermal treatment [14]. In the experiment, we also observed a trend towards lower PH_3, which is caused by too much in-diffusion of dopants from the poly-Si into the c-Si resulting in a significant increase in the recombination. The results from the resistance measurements showed that the ITO to poly-Si contact had specific contact resistivities of approx. 5 mΩcm^2 for all poly-Si doping levels. Hence an increase in the doping level is not necessary for a low series resistance.

TABLE I
I-V MEASUREMENT RESULTS FOR THE 100×100 MM^2 TOPCON SOLAR CELLS. ALL RESULTS EXCEPT PFF ARE CALIBRATED MEASUREMENTS BY FRAUNHOFER ISE CALLAB.

Front Contact Opening	Front Metal	Area [cm^2]	V_{OC} [mV]	J_{SC} [mA/cm^2]	*FF* [%]	*pFF* [%]	η [%]
Lithography	TiPdAg / PVD	100	713	41.4	83.1	84.8	**24.5**
Laser	NiCuAg / Plated	100	697	41.4	81.2	84.3	**23.4**

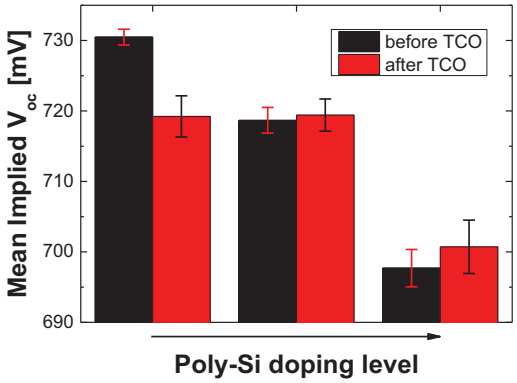

Fig. 3. Implied V_{OC} of TOPCon lifetime samples before and after sputtering of ITO for a variation of the poly-Si doping level.

IV. LARGE-AREA TOPCON SOLAR CELLS

Solar cells of significant area (100×100 mm^2) were fabricated similarly as described in [7]. The cells featured a homogeneous 140 Ω/sq boron emitter and *n*-TOPCon as passivating rear contact.

The results of the I-V measurements are given in Table I. For lithographically structured contacts, a high V_{OC} of 713 mV was achieved, underlining the excellent performance of the front and rear passivation. A high J_{SC} of 41.4 mA/cm^2 and an excellent *FF* of 83.1 % prove that a very good balance between shading and resistance losses was found. Overall, this proves that the cell structure is capable of 24.5 % cell efficiency. With laser contact opening, we observed a lower V_{OC} of 697 mV, which can be attributed to the laser-induced damage [7] as well as a higher contact fraction (increase from 0.5 % to 1.5 %), since in this case contacting bus bars were applied. While the J_{SC} at 41.4 % was similar, the *FF* was slightly lower at 81.2 %, but still at a high level. The difference to the lithography cell can be partially attributed to an increased front recombination leading to a loss in FF_0/pFF of 0.5 %$_{abs}$. The remaining ~1 %$_{abs}$ loss in the *FF* can be attributed to a higher grid resistance compared to the evaporated fingers. Overall, a good cell efficiency of 23.4 % was achieved underlining the potential of the laser contact opening and NiCuAg plating.

In regard to the future development of the solar cell concept, it was shown in [7] that the main limitation in the cell performance currently are the optical losses and recombination losses due to the front contacts and grid, mainly due to the metal/silicon contact area and shading area of the front bus bars. If the metal/silicon contact area underneath the bus bars are omitted (e.g. by using a bus bar-less cell and the smart wire cell interconnection) , the contact fraction can be reduced to 0.4 % and thus the J_0 contribution due to the front contacted area can be reduced and a V_{OC} of approx. 708 mV can be achieved. Further improvement in the LCO process should allow for reduced laser damage and thus even lower J_0 contribution. Combined with the advantages in plating homogeneity and reduced optical losses, it should be a goal to fabricate bus bar-less solar cells focusing on wire-interconnection, since this should allow the cell concept to close the gap to the 24.5 % lithography cell and possibly even exceed its performance without requiring a selective emitter.

V. CONCLUSION

We demonstrated that kHz direct-plasma PECVD can be used to deposit TOPCon layers. Concerns about ion bombardment degrading the tunnel oxide layer were disproved. Instead we determined excellent surface passivation quality, in conjunction with a thermally grown tunnel oxide with up to 13 ms on 1 Ωcm n-type. In addition, we demonstrated that the passivation on large solar-grade material is very good achieving a mean implied V_{OC} of 719 mV and that the layers can be contacted using ITO. At the device level, we fabricated cells on 100×100 mm^2 achieving efficiencies of 24.5 % with lithographic contact opening on the front and 23.4 % with laser contact opening.

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