INTERDIGITATED BACK CONTACT SILICON SOLAR CELLS WITH TUNNEL OXIDE PASSIVATED CONTACTS FORMED BY ION IMPLANTATION

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ABSTRACT: In this work interdigitated back contact (IBC) silicon solar cells featuring tunnel oxide passivated contacts (TOPCon) formed by ion implantation into amorphous silicon (a-Si) layers are proposed. Ion implantation is applied to locally overcompensate an in-situ boron-doped TOPCon layer with phosphorus which opens a promising route to a simplified fabrication process for IBC solar cells featuring passivated contacts. The impact of ion implantation doses and annealing conditions on the passivation quality of the phosphorus-doped TOPCon layers was studied. It was found that excellent surface passivation with implied open-circuit voltages (iV_{oc}) of 710 mV can be achieved for phosphorus implantations overcompensating the in-situ boron-doped TOPCon layers which exhibit iV_{oc} values of 680 mV. The TOPCon layers were implemented into small area IBC silicon solar cells leading to open-circuit voltages (V_{oc}) of 681 mV and pseudo fill factors (pFF) of 82.2% showing the potential of this concept. However, further investigations are required to reduce the contact resistance which at the current status of the development limits the extraction of charge carriers and thus the conversion efficiency.

Keywords: amorphous silicon, annealing, back contact, deposition, heterojunction, lifetime, passivation, polycrystalline, recombination, solar cells

1 INTRODUCTION

The technology of passivated contacts in interdigitated back contact (IBC) silicon solar cells gained a lot of interest since its first introduction by SunPower [1] and proved its excellent carrier selectivity properties by allowing excellent conversion efficiencies of 25.0% [2]. Another approach for a passivated contact, the HIT (heterojunction with intrinsic thin layer) technology, was pioneered by Sanyo/Panasonic. It is based on the application of doped and intrinsic amorphous silicon /crystalline silicon (a-Si)/(c-Si) heterojunctions as passivated contacts which effectively suppress the recombination of minority carriers while posing little resistance to majority carriers [4]. Their implementation into an IBC solar cell design led to a new world record of 25.6% [3]. However, applied to IBC solar cells, both passivated contact technologies require patterning of the layers on one side, resulting in complex processes and an increase in the number of fabrication steps.

The tunnel oxide passivated contact (TOPCon) consisting of an ultra-thin tunnel oxide and an amorphous or semi-crystalline silicon layer was recently introduced [5,6]. Owing to its unique electronic properties, solar cells with open-circuit-voltages (V_{oc}) of close to 700 mV and fill factors (FF) of above 81% were achieved for a both-sided contact solar cell with in-situ doped TOPCon layers implemented as emitters and back surface fields (BSF) [7]. Apart from the in-situ doping of the TOPCon layers in a plasma-enhanced chemical vapor deposition (PECVD) process, doping of the TOPCon layers by ion implantation of boron (B) and phosphorus (P) dopants into the a-Si layer was proposed [8]. The combination of ion implantation with in-situ masking facilitates the formation of locally P and B-doped regions and, therefore, opens a promising route to a simplified fabrication process for IBC solar cell featuring passivated contacts. The concept of ion implantation into polysilicon layers for creating alternating ex-situ doped regions in IBC solar cells was also recently presented with excellent passivation results [9].

In this work interdigitated back contact (IBC) silicon solar cells featuring tunnel oxide passivated contacts (TOPCon) formed by ion implantation into a-Si layers are proposed. Ion implantation is applied to locally overcompensate an in-situ boron-doped TOPCon layer with phosphorus. Thus, the boron-doped TOPCon emitter is locally inverted to obtain a phosphorus-doped TOPCon BSF, see Fig. 1.

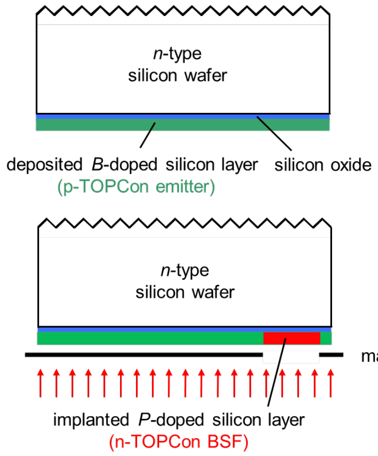

Figure 1: Schematic illustration of the interdigitated back contact (IBC) silicon solar cell with a tunnel oxide passivated contact (TOPCon) where the in-situ boron-doped TOPCon emitter (top) is locally overcompensated by ion implanted phosphorus using a mask to obtain a phosphorus-doped TOPCon BSF (bottom).

2 EXPERIMENTAL

2.1 Lifetime and suns-V_{oc} samples

Symmetrical lifetime samples were fabricated on shiny-etched <100>-oriented phosphorus-doped n-type float-zone silicon wafers with a specific resistivity of 1 Ωcm and a thickness of 200 µm. After a standard RCA cleaning was applied, an ultra-thin approximately 1.5 nm silicon oxide (SiO_x) layer was grown on both sides by exposure to an ultraviolet (UV) excimer source, creating O_3 molecules which oxidize the silicon surface [15]. Subsequently, a 15 nm thin boron-doped amorphous silicon (a-Si) layer was deposited by plasma-enhanced chemical vapor deposition (PECVD) on both sides of the wafers. Phosphorus dopants were then introduced into the a-Si layers by ion implantation at different ion doses between $1x10^{15}$ cm^{-2} and $1x10^{16}$ cm^{-2} at ion energies of 2 keV to overcompensate the boron doping on both sides for the lifetime samples and only on the front side for the asymmetric suns-V_{oc} samples, see Fig 2. The ion implantations were performed in a Varian VIISta HC tool. Following the ion implantation, the a-Si layers were subjected to a high-temperature furnace anneal at 800°C or 900°C to activate the dopants. Finally, a hydrogen passivation of the samples was applied at 400°C to activate the passivation [16]. On the front side a 70 nm indium tin oxide (ITO) layer was sputtered for the suns-V_{oc} samples and on the rear side a thermal evaporation of a 200 nm thin silver (Ag) layer was performed.

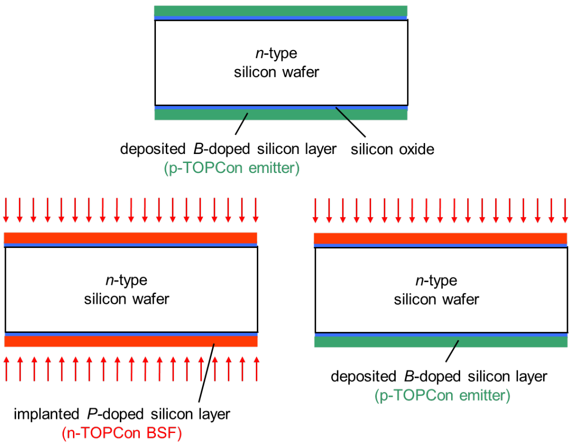

Figure 2: Schematic illustration of the lifetime (bottom, left) and Suns-V_{oc} samples (bottom, right) that were fabricated by ion implanting a phosphorus doping into an in-situ boron-doped TOPCon emitter (top) to overcompensate the emitter and obtain a phosphorus-doped TOPCon BSF (bottom).

The influences of the ion implantation dose and the annealing temperature on the passivation were investigated by quasi-steady state photoconductance measurements (QSSPC) [17] and suns-Voc measurements [18] to determine the implied open-circuit voltage (iV_{oc}) of the symmetric samples and the V_{oc} of the asymmetric samples. These measurements were performed by a WCT-120 lifetime and suns-V_{oc} tool from Sinton Instruments . The doping profiles in the a-Si and crystalline silicon (c-Si), formed during the high-temperature furnace anneal, were determined by electrochemical capacitance voltage (ECV) measurements with a CVP21 tool from WEP.

2.2 Solar cells

The 2 cm × 2 cm IBC solar cells were fabricated on <100>-oriented phosphorus-doped n-type float-zone silicon wafers with a specific resistivity of 1 Ωcm and a thickness of 200 µm. The front side was textured with random pyramids in a potassium hydroxide (KOH) and isopropyl alcohol (IPA) solution. After cleaning, the ultra-thin silicon oxide (SiO_x) layer was grown and the thin boron-doped a-Si layer was deposited as described above. Via a photoresist mask phosphorus dopants were then introduced by ion implantation using an ion dose of $7.5x10^{15}$ cm^{-2} at an ion energy of 2 keV. Following the ion implantation, the a-Si layers were annealed during a high-temperature furnace step at 800°C or 900°C to activate the dopants. After another cleaning, a stack of a 10 nm aluminum oxide (AlO_x) and a 60 nm silicon nitride (SiN_x) was deposited on the front side by atomic layer deposition (ALD) and PECVD, respectively. Then also a hydrogen passivation of the samples was applied at 400°C to activate the passivation. Prior to a thermal evaporation of a 5 µm thick aluminum (Al) layer, a 70 nm indium tin oxide (ITO) layer was sputtered on the rear side, followed by a hotplate anneal. The Al layer was etched in a mixture of phosphorus acid (H_3PO_4) and HNO_3 whereas a hydrochloric acid (HCl) was applied to etch the ITO layer before, in both cases using a photoresist as an etch mask.

The influences of the two different anneals on the diode behavior of the IBC solar cells were investigated by suns-V_{oc} measurements and by current-voltage (IV) measurements on a sun simulator under standard testing conditions (STC).

3 RESULTS

3.1 Lifetime and suns-V_{oc} samples

The in-situ boron-doped TOPCon layers allowed iV_{oc} values measured by QSSPC of 680 mV when annealed at 800°C and 900°C, see Fig. 3. Ion implantation of phosphorus into the in-situ boron-doped TOPCon layers at doses of $1x10^{15}$ cm^{-2} to $4x10^{15}$ cm^{-2} lead to poor passivation qualities after annealing at 800°C or 900°C and hydrogen passivation. This poor passivation quality is expressed by iV_{oc} values between 550 mV and 640 mV. At an ion implantation dose of $5x10^{15}$ cm^{-2} iV_{oc} values of almost 680 mV were obtained for both annealing temperatures after hydrogen passivation. For these ion implantations the V_{oc} values measured by suns-V_{oc} were 670 mV and 665 mV when annealed at 800°C and 900°C, respectively. This indicates that a sufficiently high doping is obtained to maintain the internal quasi-Fermi level spitting expressed by iV_{oc} at the external contacts [19].

For ion implantation doses of $7.5x10^{15}$ cm^{-2} and $1x10^{16}$ cm^{-2} iV_{oc} values above 700 mV were observed after annealing at 800°C and hydrogen passivation. The very good passivation quality when applying an ion implantation dose of $7.5x10^{15}$ cm^{-2} shown by an iV_{oc} value of 710 mV is only slightly lower compared to the passivation quality of the in-situ phosphorus-doped TOPCon layers with iV_{oc} values of 720 mV. In contrast to the passivation quality of the TOPCon layers that were annealed at 800°C, the passivation quality of the TOPCon layers that were annealed at 900°C is decreasing with ion implantation doses of $7.5x10^{15}$ cm^{-2} and $1x10^{16}$ cm^{-2} and iV_{oc} values of only 660 mV and 640 mV were reached, respectively.

The influence of the ion implantation dose on the passivation quality of the TOPCon layers annealed at 900°C can be explained by taking a closer look at the doping profiles. It is worth to mention that no doping profiles could be measured for TOPCon layers annealed at 800°C, assuming that no significant diffusion into the c-Si occurred during the high temperature furnace anneal.

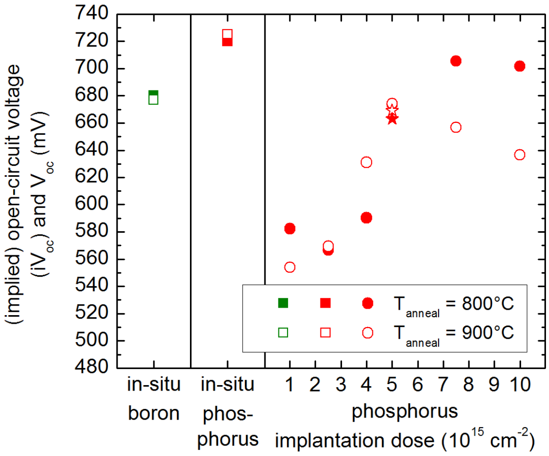

Figure 3: (Implied) open-circuit voltage (iV_{oc}) and (V_{oc}) vs. ion implantation dose of samples with in-situ doped TOPCon layers and of samples where phosphorus implantations are used to overcompensate the in-situ boron-doped TOPCon layer after annealing at 800°C (closed circles) or 900°C (open circles) and subsequent hydrogen passivation. For an ion implantation dose of 5x10^{15} cm^{-2} also V_{oc} values were determined for anneals at 800°C (closed asterisk) or 900°C (open asterisk).

The surface concentration and the depth of the boron doping profile of the in-situ boron-doped TOPCon layers in crystalline silicon (c-Si) is 1.5x10^{19} cm^{-3} and 140 nm, respectively, when annealed at 900°C, see B1 in Fig. 4. The boron doping concentration in the B-doped silicon layer is much higher than the surface concentration in c-Si. After ion implantation of phosphorus into the in-situ boron-doped TOPCon layers at a dose of 1x10^{15} cm^{-2} a still boron doping profile in c-Si but with a lower surface concentration of 1x10^{19} cm^{-3} and a smaller depth of 120 nm was determined, see P1. Furthermore, it seems that the boron doping concentration in the B-doped silicon layer is lower than the surface concentration in the c-Si. In this case, no complete overcompensation took place and thus the boron-doped TOPCon emitter was not inverted to obtain a phosphorus-doped TOPCon BSF. The reduced boron doping concentration in the B-doped silicon layer, the lower surface concentration and smaller depth in c-Si might be an indication for the poor passivation quality and the observed iV_{oc} values of only 550 mV.

The complete overcompensation of the in-situ boron-doped TOPCon layers is, however, achieved when using higher ion implantation doses. The ion implantation of phosphorus into the in-situ boron-doped TOPCon layers at a dose of 2.5x10^{15} cm^{-2} leads to a phosphorus doping profile in c-Si with a surface concentration and depth in c-Si of 2x10^{19} cm^{-3} and 200 nm, respectively, see P2. Nevertheless, the phosphorus doping concentration in the P-doped silicon layer is lower compared to the surface concentration in the c-Si. This might be an indication for the poor passivation quality and the obtained iV_{oc} values of only 570 mV. At ion implantation doses of 5x10^{15} cm^{-2} a high phosphorus doping concentration in the P-doped silicon layer and in c-Si was obtained, see P3. The increased phosphorus doping concentration in the P-doped silicon layer, the high surface concentration and larger depth in c-Si might be an indication for the very good passivation quality and observed iV_{oc} values of only 680 mV.

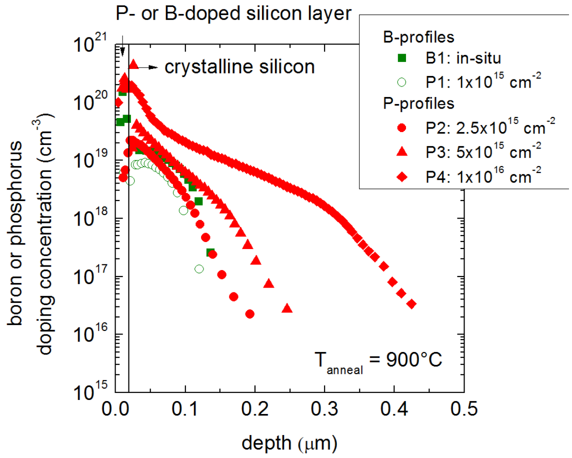

Figure 4: Boron (B) and phosphorus (P) doping profiles in the silicon layer and in crystalline silicon obtained by ion implantation at different doses and after annealing at 900°C. The first data points correspond to measurements of the B- and P-doped silicon layer which are prone to errors. The vertical line represents the approximate position of the interface.

For even higher ion implantation doses of 1x10^{16} cm^{-2}, higher phosphorus doping concentrations in the P-doped silicon layer and in c-Si were observed with surface concentrations above 1x10^{20} cm^{-3} and a depth of 450 nm, see P4. The increased phosphorus doping concentration in the P-doped silicon layer, the very high surface concentration and larger depth in c-Si might be an indication for the decrease in passivation quality and the reduction of iV_{oc} to 640 mV due to an increased recombination in the silicon layer and in c-Si as well as a possible degradation of the silicon oxide.

The passivation quality of the TOPCon layers that were ion implanted with phosphorus at doses of 7.5x10^{15} cm^{-2} and 1x10^{16} cm^{-2} and that were annealed at 800°C was very good compared to the TOPCon layers that were annealed at 900°C. Since no doping profiles could be measured, it is believed that no significant diffusion into c-Si occurred during the high temperature furnace anneal, leading to a decreased recombination and a silicon oxide that was not degraded. Therefore, iV_{oc} values above 700 mV were reached for higher ion implantation doses.

3.2 Solar cells

The TOPCon layers investigated in this work were implemented into small area IBC silicon solar cells leading to relatively high V_{oc} and pseudo fill factors (*pFF*), see Tab. 1, indicating that no significant additional recombination especially in the space charge region is caused by the sharp transition between the TOPCon emitter and TOPCon BSF region (high-high pn-junction) where ion implantation of phosphorus is applied to locally overcompensate an in-situ boron-doped TOPCon emitter. The V_{oc} of 682 mV for the IBC solar cells with TOPCon layers annealed at 800°C is quite close to the maximum V_{oc} of 690 mV determined by area weighting the corresponding saturation current densities which were obtained from the iV_{oc} values of each region, see Fig. 3.

Table I: Open-circuit voltage (V_{oc}) and pseudo fill factor (*pFF*) of interdigitated back contact (IBC) silicon solar cells fabricated in this work.

T_{anneal} (°C)	V_{oc} (mV)	*pFF* (%)
800	682	82.2
900	631	82.1

The high V_{oc} and *pFF* values for the IBC solar cells show the potential of the presented concept, but further investigations are required to reduce the contact resistance which at the current status of the development limits the extraction of charge carriers. These contact problems can occur at the interface between the TOPCon layer and c-Si, between the ITO and TOPCon layer or between the Al and the ITO layer. The authors are confident that by overcoming these contact problems high conversion efficiencies can be achieved.

4 CONCLUSIONS

In this work interdigitated back contact (IBC) silicon solar cells featuring tunnel oxide passivated contacts (TOPCon) formed by ion implantation into amorphous silicon (a-Si) layers is proposed. Ion implantation is applied to locally overcompensate an in-situ boron-doped TOPCon layer with a phosphorus doping and, thus, opens a promising route to a simplified fabrication process for IBC solar cells featuring passivated contacts. The impact of ion implantation doses, ranging from $1x10^{15}$ cm^{-2} and $1x10^{16}$ cm^{-2} at ion energies of 2 keV, and anneals at 800°C or 900°C on the passivation quality of the phosphorus-doped TOPCon layers was studied. It was found that excellent surface passivation with implied open-circuit voltages (iV_{oc}) of 710 mV can be achieved for phosphorus implantations overcompensating the in-situ boron-doped TOPCon layers which exhibit iV_{oc} values of 680 mV when annealed at 800°C. The TOPCon layers were successfully implemented into small area IBC silicon solar cells leading to open-circuit voltages (V_{oc}) of 681 mV and pseudo fill factors (*pFF*) of 82.2% when annealed at 800°C and V_{oc} values of 631 mV and *pFF* values of 82.2% when annealed at 900°C. These relative high V_{oc} and *pFF* values at an anneal of 800°C show the potential of this concept, but further investigations are required to reduce the contact resistance which at the current status of the development limits the extraction of charge carriers significantly and thus the conversion efficiency.

5 ACKNOWLEDGEMENTS

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