19.9 % EFFICIENT BIFACIAL N-TYPE SOLAR CELL PRODUCED BY CO-DIFFUSION-COBIN

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ABSTRACT: We present co-diffused bifacial n-type solar cells (CoBiN) with peak efficiencies of 19.9 %. The co-diffusion process is based on a high temperature step in an atmosphere containing $POCl_3$ and a BSG/SiO_x layer stack deposited by atmospheric pressure chemical vapor deposition. Secondary ion mass spectroscopy measurements show that the reaction of $POCl_3$ with the SiO_x layer results in the formation of a PSG layer converting a fraction of the SiO_x layer. Electrochemical capacitance voltage measurements do not detect an influence of $POCl_3$ on the boron emitter.
Keywords: n-type, bifacial, co-diffusion

1 INTRODUCTION

Bifacial n-type solar cells allow for conversion efficiencies beyond 20.6 % [1], while featuring a relatively simple, one dimensional cell geometry. In order to reach high efficiencies this cell concept exploits the high bulk lifetime of n-type silicon, which is due to a high tolerance to common metallic impurities and the absence of B-O complexes and thus light induced degradation [2]. Additionally the bifaciality allows for increasing the energy yield or a broadening of the energy output over the day, depending the physical surrounding and module placement [3]. Currently there are 4 main issues complicating industrial application: the high wafer price of n-type material, metallization induced losses in the open circuit voltage [4], high currents under reverse bias [5], and complex production processes. One possibility to decrease complexity of the production process is the use of co-diffusion, meaning the formation of emitter and back surface field (BSF) in one high temperature step using different combinations of gaseous and solid sources [6-9]. This paper presents a co-diffusion process based on an atmosphere containing $POCl_3$ and a BSG layer deposited by atmospheric pressure chemical vapor deposition (APCVD). The main advantage of this approach is its industrial feasibility. Diffusion furnaces for $POCl_3$ diffusion already exist in current production lines for standard p-type solar cells. The only upgrade needed for the diffusion process is an APCVD machine which is known to be suitable for large scale industrial production e.g. from experience in the microchip industry and represent a cost effective deposition method without the need of vacuum technology.

This paper first discusses details of the co-diffusion process and then presents solar cell results.

2 EXPERIMENT

Bifacial n-type solar cells (Fig 1) are fabricated according to the process sequence presented in Fig. 2.

Exclusively industrial type production equipment at the pilot line PV-TEC at Fraunhofer ISE and at SCHMID Group is used for fabrication. We use 156 mm x 156 mm pseudosquare n-type Cz Si wafers with a base resistivity of ~3 Ωcm. After alkaline texturing and cleaning, a BSG layer covered by a SiO_x capping layer is deposited by APCVD on one side of the wafers in one deposition process using an inline tool by SCHMID Group. Then

wafers are subjected to a $POCl_3$ based co-diffusion process [10, 11]. A hydrofluoric acid (HF) based solution then removes the resulting PSG layer as well as the BSG and SiO_x capping layer.
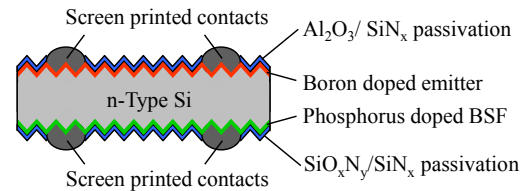
Figure 1: Cross section of bifacial n-type solar cell (CoBiN).

Now the boron emitter is passivated by a stack consisting of a 4 nm thick Al_2O_3 layer covered by a 70 nm thick layer of SiN_x and the phosphorus BSF by a SiO_xN_y/SiN_x stack[12, 13]. The Al_2O_3 layer is deposited by atomic layer deposition using an inline tool, the additional layers by plasma enhanced chemical vapor deposition (PECVD). For the metallization we use advanced printing processes. The paste on the phosphorus doped BSF is applied using double printing

and is the same paste that is commonly used to contact the emitter of a p-type solar cell. For the metallization of the boron emitter a paste containing silver and aluminum is double printed in order to form the fingers grid. The busbars on the boron emitter are printed using a non-contacting Ag-paste. After contact formation in a belt furnace a laser edge isolation is
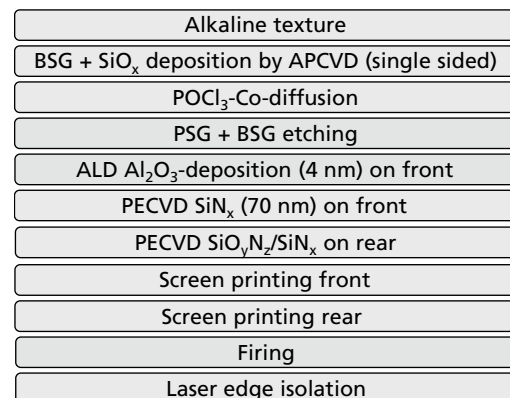
Figure 2: Solar cell process for co-diffused bifacial solar cell based on n-type Cz-Si substrates (CoBiN).

performed. The presented cell efficiency is determined at

Fraunhofer ISE Callab PV Cells using two different measurement chucks, while the parallel resistance and the current under reverse bias is determined using an industrial cell tester.

In order to characterize the co-diffusion process shiney etched p-type float zone (FZ) wafers with an edge length of 125 mm are used. After deposition of the BSG/SiO_x layer stack by APCVD, half of these wafers are subjected to the same $POCl_3$ based high temperature step that is used for solar cell fabrication. The other half is subjected to a similar high temperature step, however without any $POCl_3$ in the process atmosphere. After diffusion the atomic concentrations of boron, phosphorus, oxygen and silicon in the BSG/SiO_x layer stack are determined by secondary ion mass spectroscopy (SIMS). After wet chemical removal of the doped glasses in an HF based solution, the doping profiles are determined using electrochemical capacitance voltage measurements.

3 RESULTS

The function of the BSG/SiO_x layer stack in a co-diffusion processes is twofold. On the one hand it needs to allow for the formation of a suitable boron doping profile for the boron emitter. Additionally it is important to prevent phosphorus diffusion from the gaseous atmosphere into the boron emitter, thus avoiding (over-) compensation of the boron emitter.

3.1 Barrier properties of BSG/SiO_x layer stack

Fig. 3 presents a SIMS measurement of the BSG/SiO_x layer stack after the $POCl_3$ based co-diffusion process on a shiney etched surface. The concentrations of boron (B) and phosphorus (P) are calibrated using boron and phosphorus reference implantations in thermally grown SiO_2. The concentrations of silicon (Si) and oxygen (O) are given in relative units of counts per second.
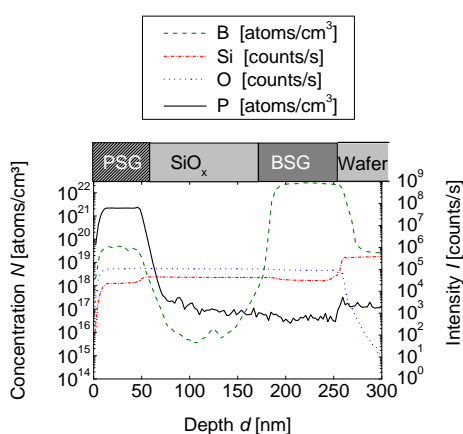
Figure 3: SIMS measurement of BSG/SiO_x layer stack after $POCl_3$ based co-diffusion process

The silicon wafer with the boron emitter is located at the right side for depths larger than 260 nm, followed by the BSG layer for 180 nm$<d<$260 nm, with a boron concentration above 10^{22} cm^{-3}. The SiO_x layer for 65 nm$<d<$180 nm features a lower concentration of boron but similar concentrations concerning silicon and oxygen. For $d<$65 nm a significant concentration of phosphorus

larger than 10^{21} cm^{-3} is detected. This phosphorus stems from the $POCl_3$ based atmosphere of the high temperature process. Due to the high phosphorus concentration the layer for $d<$65 nm is denoted as a phosphosilicateglass (PSG) layer. Since the phosphorus only partly penetrates the SiO_x layer, concerning planar surfaces, no significant effect of $POCl_3$ on the boron doping profile is expected. Interestingly also an increased boron concentration is detected in the PSG layer. We attribute this to outdiffusion of boron from the BSG layer, through the SiO_x layer into the PSG layer due to a higher solubility of boron in PSG compared to SiO_x.

Fig 4 presents ECV measurements on shiney etched surfaces of the boron emitter resulting from diffusion processes, which are identical with the exception that one features $POCl_3$ in the atmosphere ("with $POCl_3$") and the other one does not ("no $POCl_3$").
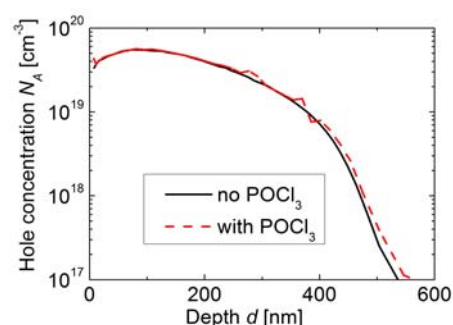
Figure 4: ECV measurements of boron emitter after high temperature step with and without $POCl_3$ in the process atmosphere.

Both doping profiles are identical within measurement accuracy, which confirms the hypothesis that $POCl_3$ in the process atmosphere does not significantly influence the boron doping profile. With respect to application as an emitter the maximum doping concentration as well as the depth are important. The maximum doping concentration of 6×10^{19} cm^{-3} is below the activation limit of boron in silicon which is around 9×10^{19} cm^{-3} for the maximum process temperature of 950°C used in the high temperature step [14]. Thus the presence of a boron rich layer is not expected, which is confirmed by high values of J_{sc} and V_{oc}.

3.3 Solar cell results

Co-diffused bifacial n-type solar cells (CoBiN) are fabricated according to the process sequence depicted in Fig. 2.

Table I: IV measurement of large are co-diffused bifacial n-type solar cells (CoBiN) at Fraunhofer ISE CalLab PVCells. The parallel resistance R_p is determined using an industrial cell tester.

Measurement chuck	V_{OC} [mV]	J_{SC} [mA/cm²]	FF [%]	**η** **[%]**	R_p [kΩcm²]
Black non conductive	647	38.3	78.7	**19.5**	19
Golden conductive	648	38.8	79.0	**19.9**	19
combined	648	38.8	78.7	**19.8**	19

The champion cell features an open circuit voltage V_{oc} of 648 mV, a short circuit current J_{sc} of 38.8 mA/cm², a fill factor of 79 % and an efficiency of 19.9 % determined on

a reflective conductive chuck. As pointed out by Böscke et al. [3], the use of a reflective and conductive chuck increases J_{sc} and FF compared to a non reflective and non conductive chuck. A "combined" efficiency, which corresponds to the monofacial efficiency in a module with a white non conductive back sheet, is calculated using V_{oc} and J_{sc} from the reflective chuck and FF from the non conductive chuck. This results in a combined efficiency of 19.8 %. A second point of interest is the behavior of the solar cell under reverse bias conditions. For a solar cell with a parallel resistance of 19 kΩcm², a current of 51 mA/cm² flows for a reverse bias of 12 V, while for a reverse bias of 1V a current of 0.07 mA/cm² is detected. The reason for the high currents under reverse bias is currently under investigation. The evolution of the current is comparable with results published by [5, 8].

5   CONCLUSION

We present co-diffused bifacial solar cells with peak efficiencies of 19.9% on 156mm n-type Cz-substrates. During the POCl$_3$ based co-diffusion process the BSG/SiO$_x$ layer stack deposited by APCVD acts as an effective diffusion barrier against phosphorus. The resulting boron doping profiles is not expected to feature a boron rich layer and thus does not require any post diffusion treatments. Further research will focus amongst others on the behavior of the solar cell under reverse bias conditions.

6   ACKNOWLEGEMENT

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