

6th International Conference on Silicon Photovoltaics, SiliconPV 2016

In-situ doping and local overcompensation of high performance LPCVD polysilicon passivated contacts as approach to industrial IBC cells

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Abstract

In this work, we investigate polysilicon passivation contacts, to be used for high performance IBC cells. We demonstrate an LPCVD process for in-situ p-type doped polysilicon. The p-type polysilicon can be locally overcompensated to n-type polysilicon using phosphorous implantation or POCl_3 diffusion. Both contacts show excellent surface passivation, with recombination current (J_0) of 12 fA/cm^2 for p-poly on a polished Si surface, and less than 10 fA/cm^2 for compensated n-poly both on textured and polished surfaces. These polysilicon layers are implemented in the fabrication of n-PERT cells with front and rear polysilicon contacts. The resulting textured half-fabricated cells have an implied V_{oc} of 701 mV after hydrogenation via PECVD deposition of $\text{SiN}_x\text{:H}$. Different metallization processes, relevant for IBC cells, are applied. A V_{oc} of 685 mV is obtained for the best cell metallized with low-temperature metallization (ITO/low-temperature Ag paste), and 678 mV is obtained for the best cell with industrial screen-printed firing-through contacts. In these n-PERT cells the same thin oxide layer is used for p-type and n-type polysilicon contacts.

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Peer review by the scientific conference committee of SiliconPV 2016 under responsibility of PSE AG.

Keywords: polysilicon; passivating contacts; surface passivation

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1. Introduction

Passivated contacts enable decoupling of the metal surface and base region, greatly reducing minority carrier recombination. Thin interfacial “tunnel”-oxides and doped polysilicon have been shown to be excellent candidates for both n and p doping types allowing passivated contacts for both electron and hole extraction. The light absorption of the polysilicon means thicker layers can be best applied on only the rear surface of a cell. Hence, a back-junction back-contact (IBC) cell is the ideal architecture for a fully (both emitter and BSF) contact-passivated solar cell. For cost-effective processing of IBC cells, recent progress on overcompensated polysilicon is interesting [1, 2, 3]. Here a full layer of p-doped polysilicon is used, which is locally converted into n-type, creating passivated emitter and BSF regions. In this way only one thin oxide and polysilicon deposition step is needed, and self-alignment is inherent. In order to be successful, this needs to result in excellent passivation and transport characteristics for both dopant types, and the thin oxide needs to facilitate both electron and hole tunnelling.

In this paper the polysilicon is grown by LPCVD, a well-established low-cost industrial process. However, p-type doping of LPCVD polysilicon is so far a challenge. Post-deposition doping by diffusion or implantation adds significant costs and can damage the tunnel oxide. In-situ p-type doping can be subject to interference of boron with polysilicon growth, and damage to tunnel oxide can occur in a post-anneal. In this work we aim to show that in-situ boron doped polysilicon deposited by LPCVD is an excellent candidate for a p-type polysilicon (p-poly) passivated contact layer. This includes the suitability of the overcompensation approach to be used on this p-type layer.

We study the surface passivation by p-poly and overcompensated n-poly layers on symmetric test samples. n-PERT cells with n-poly FSF and p-poly rear emitter are fabricated and used to study the metallization as well as degradation of surface passivation due to the metallization processes. In a companion paper [4] the properties, optimization, and use of n-poly in n-PERT cells with diffused boron emitters is described, resulting in a BSF recombination current of 2.4 fA/cm^2 and cell efficiency of 20.7%.

2. Experiments

Symmetric samples with p-poly layers were made in the ECN cleanroom, on $\sim 5 \text{ Ohm}\cdot\text{cm}$ 156 mm Cz n-type Si wafers, and J_0 and implied V_{oc} (iV_{oc}) measured using the Sinton WCT-120 tool. Substrates with random pyramid textured and polished Si surface were both used, and simple and short cleaning processes were applied prior to deposition. Stack layers of a few nanometer SiO_x and $\sim 150\text{--}200 \text{ nm}$ in-situ boron-doped p-poly layers were deposited by a Tempress LPCVD system [5]. Doped boron was activated by annealing in a tube furnace. Post-anneal hydrogenation to enhance the surface passivation was executed by PECVD $\text{SiN}_x\text{:H}$ deposition followed by a firing process. In the tests of overcompensation of p-poly, different phosphorous implant doses of 2.5, 5 and $10 \times 10^{15}/\text{cm}^2$ were applied, followed by activation anneal. Additionally compensation by POCl_3 diffusion was tested, with similarly good results, but those results are not described in this paper. Overcompensated n-poly on p-type wafers were analyzed for sheet resistance by Sherescan and dopant concentration profile by the electrochemical capacitance-voltage (ECV) profiling method.

The fabrication of n-PERT solar cells was initiated with symmetric p-poly on n-type Cz wafers, followed by overcompensation into n-poly by implanting phosphorous on one side, and activation anneal. PECVD $\text{SiN}_x\text{:H}$ was deposited on both sides for hydrogenation. These half-fabricated cells were then split into two groups, to be finalized with different metallization processes. Firing-through contacts were directly screen printed on the cells capped with SiN_x , using standard n+ contacting Ag paste on n-poly and p+ contacting Ag/Al paste on p-poly, followed by firing. To form low-temperature (low-T) contacts, the $\text{SiN}_x\text{:H}$ layers were stripped off in HF. An ITO contact was sputtered onto the front side and ITO/pure Ag on the back side. The front side was finalized by screen printed low-T Ag paste grid followed by a low-T post anneal. Cell performance was characterized by I-V measurement (Wacom AAA steady state solar simulator).

3. Results and discussion

3.1. In-situ doped p-type polysilicon

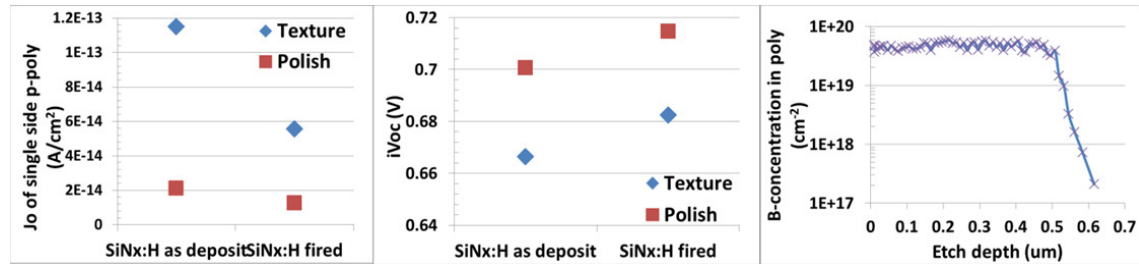


Fig. 1. J_0 (left) and iV_{oc} (middle) of lifetime samples on 156 mm n-Cz wafers; ECV measurement (right) shows the B-concentration profile in the p-poly of $3\text{--}4 \times 10^{19}/\text{cm}^3$ (determined on a thicker p-poly layer than the samples used for lifetime measurements or cells, but deposited with similar process conditions).

In order to properly ex-situ dope polysilicon with boron, one needs a considerably higher thermal budget than for n-type doping, whether the doping is done by ion implantation or a deposited dopant source. Combined with the fact that silicon oxide is a much worse diffusion barrier for boron this makes the fabrication of a p-doped polysilicon passivated contact much more difficult. Tempress has developed in-situ boron doped polysilicon growth in an industrial LPCVD furnace [4]. Optimization of hardware and growth process results in a uniform doped polysilicon. A mild anneal temperature can be used to activate the dopant, avoiding damage to the underlying interfacial oxide.

Symmetric $\text{SiO}_x/\text{p-poly}$ stack layers were deposited on polished as well as textured n-type 156 mm Cz wafers. The samples on textured surface show iV_{oc} of 667 mV with a J_0 of 115 fA/cm² after hydrogenation, where hydrogenation was accomplished by depositing $\text{SiN}_x\text{:H}$ on both sides. However, on a polished surface, a much lower J_0 of 21 fA/cm² and higher iV_{oc} of 700 mV are obtained. This indicates that the quality of the passivation by the p-poly stack is highly sensitive to the condition of the substrate surface. A flat and smooth surface is beneficial, possibly due to better thickness uniformity and denser layer formation. Surface passivation shows further enhancement upon firing: iV_{oc} of 715 mV and J_0 of 12 fA/cm² on polished, and iV_{oc} of 682 mV and J_0 of 55 fA/cm² on textured sample are then achieved. Although better passivation on polished than on textured surface remains, the J_0 decrease (from 20 to 12 fA/cm²) on a polished surface upon firing is less pronounced than that on a textured surface (from 115 to 55 fA/cm²). This may imply that already a large fraction of dangling bonds on the polished interface is passivated after initial hydrogenation during $\text{SiN}_x\text{:H}$ deposition.

The dopant profile in the p-poly shown in Fig. 1 was measured on a thicker p-poly layer, using ECV. The achieved boron concentration of $3\text{--}4 \times 10^{19}/\text{cm}^3$ is lower than that of a typical industrial BBr_3 -diffused emitter. Increase of this doping level may lead to an enhancement of the surface passivation due to increasing the field effect at the interface, while the contact resistance (R_{co}) of the metallization on the p-poly is expected to be reduced.

3.2. Overcompensated n-type polysilicon

Next, the in-situ doped polysilicon was overcompensated with phosphorous by ion implantation. Overcompensation by POCl_3 diffusion was similarly effective.

Optimization of overcompensation started with investigation of sheet resistance (R_{sheet}) and dopant concentration of n-poly for implant doses of 2.5 , 5 and $10 \times 10^{15}/\text{cm}^2$, aiming for similar values as previously resulted in good passivation after POCl_3 doping of intrinsic poly. Fig. 2 shows the highest R_{sheet} of ~ 770 Ohm which was obtained at the lowest implant dose of $2.5 \times 10^{15}/\text{cm}^2$, whereas the lowest R_{sheet} of ~ 53 Ohm was obtained for a dose of $10 \times 10^{15}/\text{cm}^2$. The excessively high R_{sheet} for the lower dose may be related to accumulation of phosphorous at grain boundaries, without much contribution to free carriers. Extra thermal processes, such as firing, seem to not further

reduce R_{sheet} . The ECV result in Fig.2 shows the phosphorous concentration profile. A highest phosphorous concentration of $3\text{--}4 \times 10^{20}/\text{cm}^3$ is achieved for the highest implant dose. It is observed for all ECV profiles that the phosphorous concentration significantly drops at an etching depth of ~ 150 nm, which is roughly equal to the poly layer thickness. This shows that the phosphorous diffusion into the wafer is strongly limited by the tunnel oxide, resulting in an insignificant amount of dopant concentration in the wafer even for the highest implant dose.

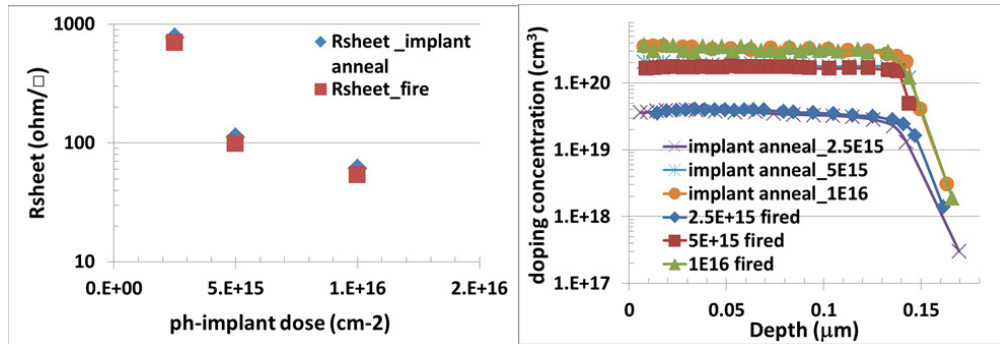


Fig. 2. sheet resistance (left) and ECV profiles (right) of overcompensated n-poly on textured p-Cz wafers.

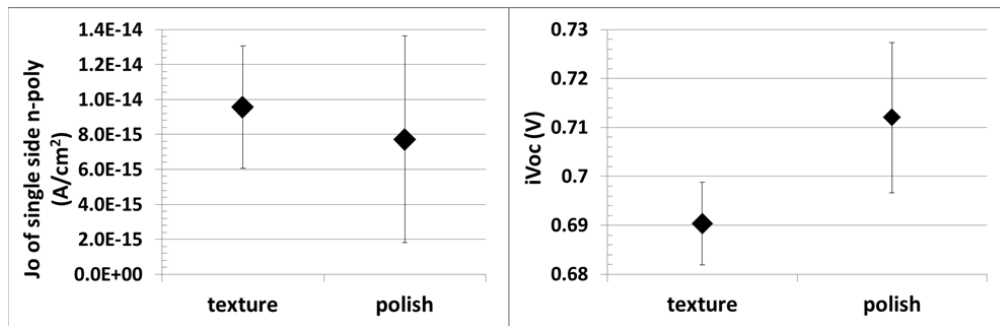


Fig. 3. J_0 (left) and iV_{oc} (right) of overcompensated n-poly after hydrogenation via $\text{SiN}_x\text{:H}$ deposition

For study of the passivation, symmetric structures with overcompensated n-poly layers were formed on both textured and polished n-type Cz wafers by using the highest implantation dose. $\text{SiN}_x\text{:H}$ was deposited on both sides of the wafer for hydrogenation. As shown in Fig. 3, the average iV_{oc} is higher than 700 mV on textured and above 710 mV on polished wafers. A J_0 of less than $10 \text{ fA}/\text{cm}^2$ is obtained for polished as well as textured samples, showing less difference than for p-poly. This implies n-poly passivation is less sensitive to the condition of the substrate surface. The higher phosphorous concentration and resulting stronger field effect in the n-poly may (to some extent) compensate for the higher defect density of the random pyramid textured surface.

3.3. n-PERT cells with in-situ doped p-type polysilicon, and compensated n-type polysilicon

n-PERT cells were fabricated on 156mm textured n-type Cz wafers, with the layers described in the previous sections at the highest implantation dose. The cells are intended for checking the feasibility of integrating different passivating contacts in one cell, as well as for investigating the degradation of passivation after high or low temperature metallization processes.

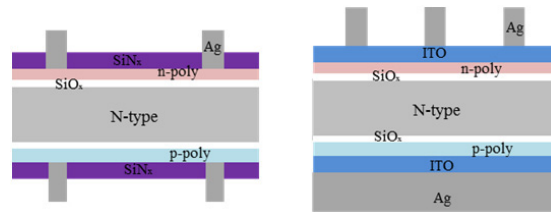


Fig. 4. n-PERT cell with n-poly at front and p-poly at rear with firing-through Ag contacts (left), and sputtered ITO contacts (right) with sputtered Ag rear and screen-printed low-T Ag paste front metallization

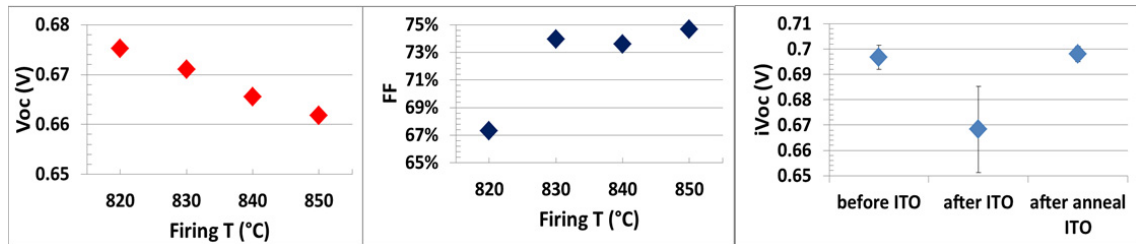


Fig. 5. left and middle: n-PERT cells with firing-through Ag contacts, V_{oc} and FF vs peak firing set temperature; Right: iV_{oc} of lifetime samples with n-poly, before and after one-sided ITO deposition, and after subsequent low temperature anneal.

We tested that the oxide thickness used (1.3 nm) is the minimum acceptable for phosphorous doping: thinner oxides result in too much phosphorous diffusion into the wafer and strongly increased J_0 . One question of interest is whether this minimum oxide thickness is compatible with sufficiently high hole transmission from wafer to p-type polysilicon. Measurements performed on n-PERT cells with diffused emitter and n-poly BSF contact do not indicate limitations due to the electron transmission [4], but in tunneling (if applicable), holes face a higher tunneling barrier [6].

Half-fabricated cells resulted in an implied V_{oc} of 701 mV after hydrogenation via deposited SiN_x on both sides (without firing). The bifacial cell structure with screen-printed firing-through contacts is shown in Fig. 4. Ag paste is printed on n-poly while Ag/Al paste is printed on p-poly followed by a co-firing process. Fig. 5 shows the V_{oc} and FF as a function of the setpoint of the peak firing temperature. By increasing this peak temperature from 820 to 850°C, the FF is significantly improved from 67% to 75%, however at the same time V_{oc} decreases from 678 to 662 mV. Furthermore, at the low peak temperature of 820°C, the V_{oc} is about 25 mV lower than the iV_{oc} indicating recombination, from the metal grid, is increased. In the studies of the n-PERT cell with n-poly BSF and diffused boron emitter [4] it was found that the high quality surface passivation of n-poly could be largely preserved even with firing-through metallization. Therefore, the enhanced recombination may be due to the p-poly side related to different paste behaviour, but also, as contact resistance scans (not shown) suggest, due to insufficient optimization of firing conditions. Polysilicon contacts with fire-through paste are sensitive to optimal firing conditions, and two-sided polysilicon layers metallized with two different pastes are more critical and sensitive than a one sided polysilicon layer. In addition, the p-poly was relatively low doped, resulting in high contact resistance and difficulty to optimize firing conditions.

The cell with low temperature contacts is also shown in Fig. 5. The $SiN_x:H$ layers used for hydrogenation are stripped off prior to ITO sputtering. It was checked that no degradation of passivation after stripping the $SiN_x:H$ took place. This type of metallization could remove the sensitivity of polysilicon passivation to fire-through contacts, in particular for thinner polysilicon layers. However, the surface passivation after ITO deposition, shown in Fig. 6, shows this is not quite the case. The V_{oc} drops from 697 to 668 mV after ITO sputtering, but it can be recovered after a low temperature anneal.

In table 1, the best cells from the two different approaches to metallization are compared. The V_{oc} of the cell with firing-through contacts is 13 mV lower than the cell with low-T contacting. Recombination at the interface is reduced but not completely avoided by the low-T metallization process. A higher FF and lower series resistance for low-T contacts are due to 1) the full area rear metallization layer; 2) lower R_{sheet} on front due to the ITO layer; 3) lower recombination resulting in higher PFF; and 4) sub-optimal firing optimization for the firing-through contacts. Although in these preliminary results cell performance with firing-through contacts is inferior, it is too early to rule out this approach to metallization. Screen-printed firing-through contacts are the dominant metallization method in the PV industry, using only few and simple process tools. Further improvement can be foreseen by applying proper pastes and/or optimizing the firing process.

The series resistance (R_{se}) of the cells with ITO depended sensitively on the post-ITO-deposition anneal (around 300°C), and limited optimization was done. The best R_{se} of about 3.4 mOhm is not much higher than for screen printed diffused n-PERT cells, but too high to be explained by grid losses alone. Therefore, it is relevant to investigate series resistances, in particular through the thin oxide and in particular for the p-poly side. This is subject of current experiments.

As mentioned, the low FF of the fire-through metallized cells is at least partly due to contact resistance from Ag paste to p-type polysilicon. We attribute this high R_{co} to the low p-type doping level ($2\text{-}3\text{E}19\text{ cm}^{-3}$, lower than in Fig. 2), which can be increased.

Table 1. best performance of n-PERT cells with different metallization approaches, J_{sc} is $\sim 31\text{ mA/cm}^2$ due to the thick front side polysilicon layer. Cell area is 239 cm^2 .

Cell metallization	V_{oc} (mV)	pFF (%)	FF (%)
Fire-through Ag paste	678	80.5	67.6
ITO and low-T Ag paste front, ITO and sputtered Ag rear	685	81.2	76.6

4. Conclusion

We demonstrate industrial processes enabling cost-effective production of p and n-type polysilicon from single depositions of tunnel oxide and polysilicon. Excellent passivation results are achieved on in-situ p-doped, overcompensated n-doped, and n-PERT half fabricates. This opens perspectives for simple fabrication of fully passivated-contact IBC cells.

High quality surface passivation was obtained with LPCVD-deposited in-situ doped p-poly, achieving a J_0 of 12 fA/cm^2 on a polished surface. The optimum P-implant dose to overcompensate p-poly to n-poly for 200 nm poly thickness was $1 \times 10^{16}/\text{cm}^2$. Overcompensated n-poly with a J_0 of less than 10 fA/cm^2 , both on textured and polished Si surface, was obtained. Limited degradation of passivation was realized on a fully polysilicon-contacted n-PERT cell by low-T metallization, with V_{oc} of 685 mV on the best performance n-PERT cell.

Acknowledgements

Part of this work was performed in the PV4facades project (TEMW140009) which receives funding from the Topsector Energie of the Dutch Ministry of Economic Affairs.

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