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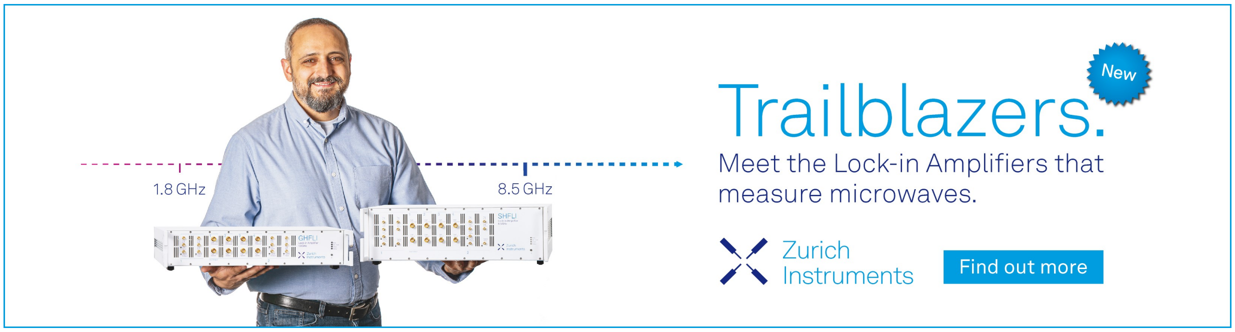

Effect of Implanted Phosphorus Profile on iV_{oc} Variations During Firing Process of n-type Silicon

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Abstract. Electrical activation of implanted phosphorus can be carried out simultaneously with boron dopants at high temperatures or separately at lower temperatures. In this study, we investigate the effect of high and low-temperature annealing processes for dopant activation following the phosphorous implantation process in n-type c-Si. Symmetrically implanted wafers are activated at 875 °C (low temperature) and 1050 °C (high temperature) and subsequently coated with PECVD SiN_x:H. iV_{oc} values of the samples activated at 1050 °C significantly decrease while those for the samples activated at 875 °C increase at a typical firing peak temperature which is generally applied for fire-through contact formation. We also show a strong dependence of iV_{oc} values of phosphorous implanted and unimplanted c-Si, which are activated at both high and low temperatures, on peak firing temperature.

INTRODUCTION

Recently, n-type silicon (Si) solar cells are of interest due to the lack of boron-oxygen (B-O) complexes and their resistance to metal impurities, which results in a higher minority carrier lifetime [1]. For p^{++} and n^{++} junction formation in n-type Si solar cells such as PERT and IBC, ion implantation allows local and single side doping in a simple way with a less number of process steps. Following ion implantation, an annealing process is required for electrical activation of the dopants introduced into Si. While implanted boron (B) atoms are usually activated above 1000 °C for dissolution of dislocation loops, phosphorus (P) atoms are activated below 900 °C [2][3][4]. Co-activation of P with B is convenient to reduce the number of process steps for solar cell fabrication; however, it has been shown that separate activation steps are necessary to reach higher cell efficiencies [4][5]. We present the possible root cause for the low performance of co-activated n-type Si solar cells and indicate the effect of firing peak temperature on iV_{oc} variations of P implanted n-type Si wafers which were activated at 875 °C and 1050 °C and subsequently passivated with SiN_x layer.

EXPERIMENTAL DESIGN

Alkaline textured and ozone (O_3) cleaned industrial 156.75x156.75 mm^2 n-type Cz wafers with bulk resistivity of 1-3 ohm.cm were used as substrates. They were initially P implanted with identical doses at an energy of 10 keV either at one side or at the double side. Following the implantation process, O_3 based surface cleaning was performed again to remove contaminants that can come from the sample holder, sample handling, or implantation process itself. Then, the samples were separated into two groups to be activated at either 875 °C or 1050 °C under nitrogen flow for 30 minutes. Similarly, a group of unimplanted textured wafers was also annealed at 875 °C and 1050 °C to investigate the effect of annealing condition on the bulk n-type Si. After all the implanted and unimplanted samples were dipped

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into HF to remove unintentionally grown thermal oxide during activation, double side implanted samples were coated with PECVD-SiN_x layers and exposed to a firing process in a conveyor belt furnace to release H atoms from SiN_x:H layer to the Si bulk. The temperature of the wafers was measured by a thermocouple attached to an identical wafer moving with the same conveyor speed. Symmetrical samples were used for iV_{oc} measurements after every process step with the photoconductance decay (PCD) method using a Sinton tool. Additionally, photoluminescence (PL) images of the fired samples were taken by the Semilab PLI-1001 tool. Sheet resistance (R_{sheet}) and doping profile measurements were performed on single side implanted samples by the four-point probe and electrochemical capacitance-voltage (ECV) methods, respectively.

RESULTS AND DISCUSSION

Table 1. represents R_{sheet} values measured on single side implanted and activated n-type Si wafers. The results given in the table are an average of 25 points measured on the identical wafers for each parameter. For a similar implantation dose, activation at an annealing temperature of 875 °C and 1050 °C leads to R_{sheet} of 54.3 and 37.3 Ω/sq., respectively.

TABLE 1. R_{sheet} values of the samples measured by four-point-probe.

Sample Name	**Activation Temperature (°*C)***	***Sheet resistance (Ω/sq.)***
D1-875	875	54.3±1.7
D1-1050	1050	37.3±1.3

Figure 1. shows the measured ECV profiles of the samples named D1-875 and D1-1050, which were activated at 875 °C and 1050 °C for 30 minutes, respectively. An increase of annealing peak temperature from 875 °C to 1050 °C leads to a serious decrease in peak doping concentration from 2.32×10^{20} cm^{-3} to 5.06×10^{19} cm^{-3} and a deeper junction depth for P atoms in a n-type Si wafer.

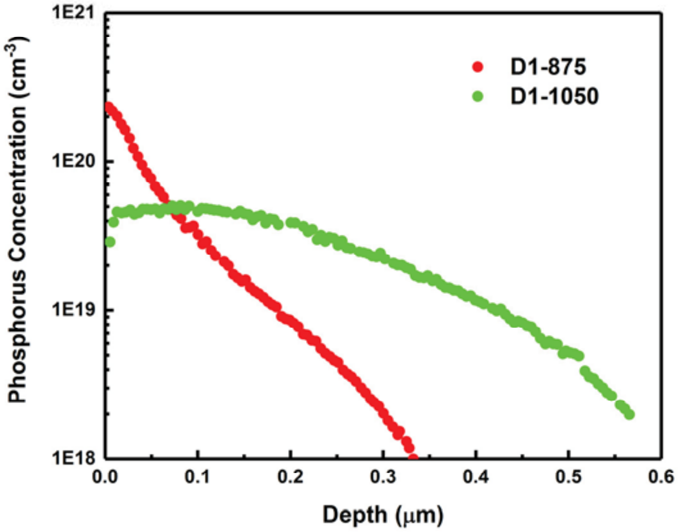

FIGURE 1. Doping profiles of P implanted n-Si, which were activated at 875 °C (red) and 1050 °C (green).

Figure 2. depicts the effect of doping profile obtained by two distinct activation temperatures as 875 °C and 1050 °C on iV_{oc} values of the P implanted n-Si symmetrical samples (n^+nn^+) measured after activation, SiN_x deposition, and firing processes. After the activation process (red boxes), the measured average iV_{oc} values of the samples annealed at 1050 °C are lower than those activated at 875 °C. This may be mainly due to the degradation of the bulk lifetime of the Si wafer after the high-temperature annealing process [6]. Following the deposition of SiN_x, the samples were exposed to the firing process at a peak temperature of 810 °C, leading to an increase of iV_{oc} values of D1-875 while

decreasing in those of D1-1050 compared to their initial values (green boxes). It has been discussed in the literature that H release from SiN_x:H increases significantly above 700 ºC [7][8]. Thus, degradation may be related to excessive H diffusion into Si, pronounced with the lower surface doping concentration [9].

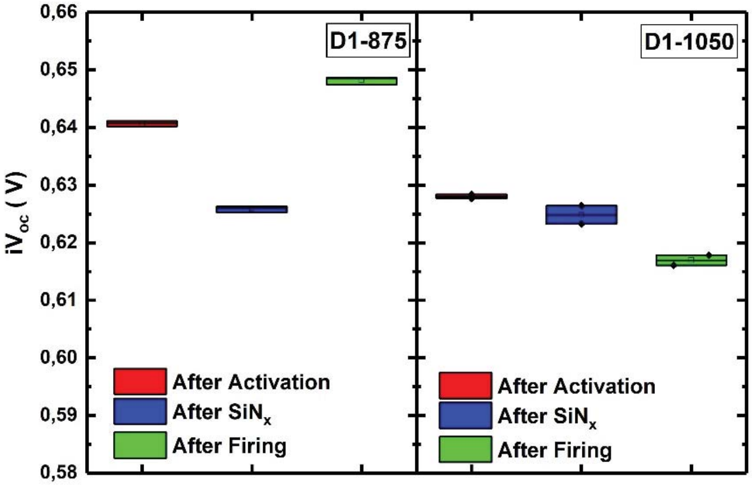

FIGURE 2. iV_{oc} values of the samples after activation, SiN_x deposition, and firing processes.

As illustrated in Fig 3., PL images of the fired samples also confirm the iV_{oc} results. The increase in defect density results in a lower PL density; that is, we can interpret that the sample annealed at a higher activation temperature has a higher recombination rate, thus a lower iV_{oc}.

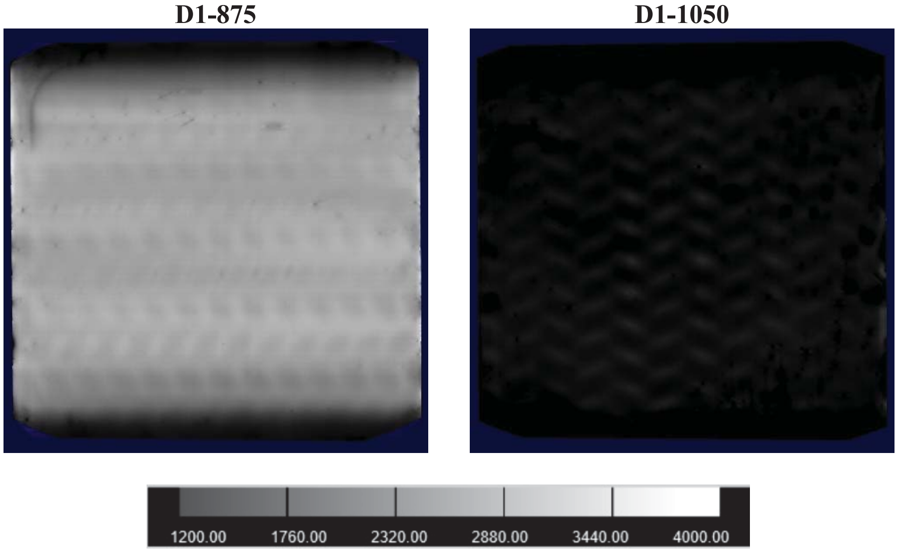

FIGURE 3. PL images of the samples named D1-875 and D1-1050 after firing process at a peak temperature of 810 ºC.

Moreover, we extensively studied the effect of firing peak temperatures on iV_{oc} of the implanted and unimplanted symmetrical samples. As can be seen in Fig 4., the trend of iV_{oc} variation according to the firing peak temperature is different for two doping profiles. This can be also attributed to change in the H diffusion mechanism due to different doping profiles [9]. iV_{oc} decreases with an increase in firing peak temperature for the deeper doping profile with lower surface doping concentration; while it initially increases and then decreases after a certain peak temperature around 735 ºC for the shallower doping profile with higher surface doping concentration. Nevertheless, the iV_{oc} value of P implanted n-Si is higher for activation temperature of 875 ºC for any firing temperature.

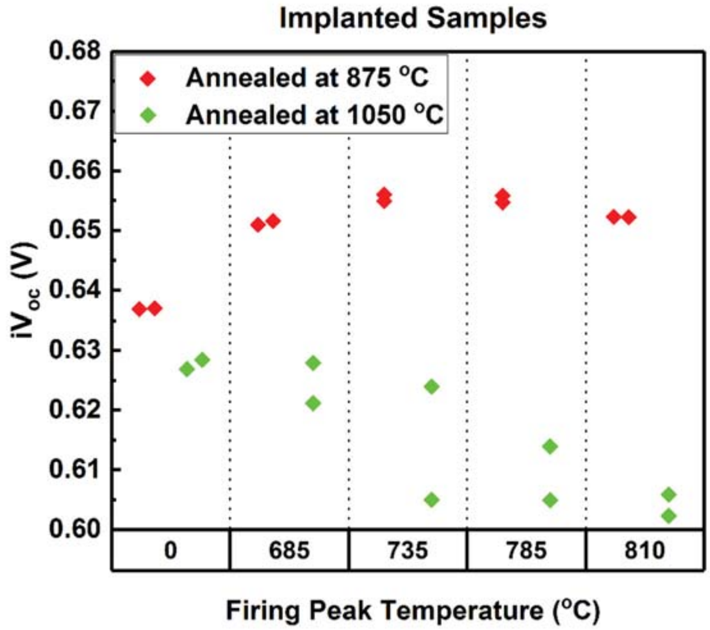

FIGURE 4. Effect of firing peak temperature on iV_{oc} values of P implanted n-type Si wafers, which were activated at 875 °C (red) and 1050 °C (green)

In the literature, it has been already discussed that the dissolution of oxygen precipitates in crystal Si at temperatures above 1000 °C results in the formation of metastable defects, thus a decrease in a bulk lifetime [10]. To investigate the effect of low and high-temperature annealing on the bulk quality of the wafers, we repeated the same experiment on unimplanted n-Si. Figure 5. illustrates the firing dependence of iV_{oc} of the n-type wafers annealed at high and low temperatures. Although the wafers annealed at 1050 °C become susceptible to high firing temperatures, the decrease in iV_{oc} values of the unimplanted wafers with increasing firing peak temperature is not as significant as that of implanted wafers.

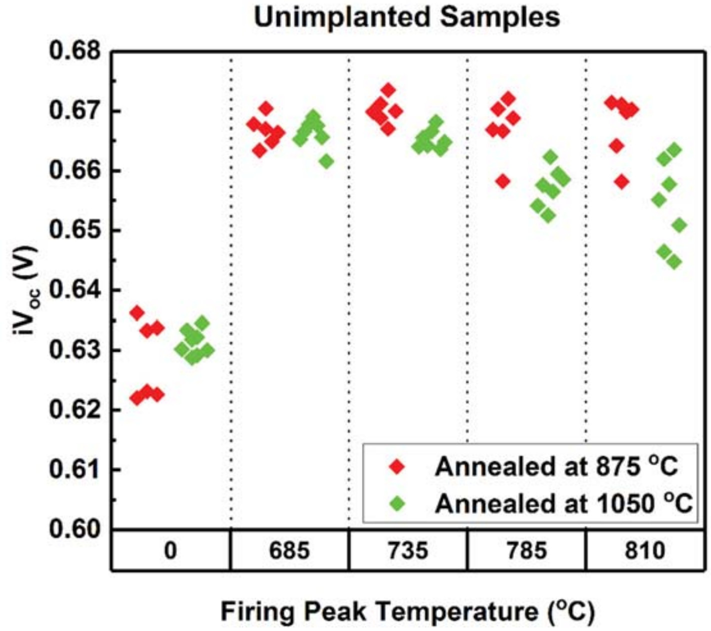

FIGURE 5. Effect of firing peak temperature on iV_{oc} values of unimplanted n-type Si wafers, which were annealed at 875 °C (red) and 1050 °C (green)

CONCLUSIONS

In this study, we showed the effect of implanted P profile on iV_{oc} variations during the firing process of n-type Si wafers. In this scope, unimplanted and symmetrically P implanted textured n-Si wafers were annealed at 875 ^oC and 1050 ^oC resulting in two distinct doping profiles. The results indicate that the trend of iV_{oc} variation during the firing process depends on the annealing temperature of the samples, especially the implanted ones. P implanted samples activated at 875 ^oC lead to higher iV_{oc} values for any firing peak temperature; therefore, the separate activation of P with B at a lower annealing temperature is necessary during the fabrication of an n-type Si solar cell.

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