HIGH RESOLUTION INLINE DETECTION OF CHANGES IN THE CONDUCTION TYPE OF MULTICRYSTALLINE SILICON BY CONTACT LESS PHOTOCONDUCTIVITY MEASUREMENTS

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ABSTRACT

Changes in the conduction type of a multicrystalline brick can occur, since a high phosphorus concentration is typical for the low quality feedstock that is usually used in PV industry. The inline detection of these changes is made possible via photoconductivity measurements. The measured photoconductivity depends strongly on the resistivity of the sample. With a developed computer algorithm the sharp raises of the photoconductivity at pn-changes can be detected in bricks. With these measurements it is possible to detect pn-changes with a one mm resolution as early as possible in the production process.

INTRODUCTION

The PV industry currently strives to use more and more low quality material for low cost production of solar cells. Usually this low cost material as umg-Si contains a high phosphorus concentration. Phosphor has an equilibrium segregation coefficient of 0.35 and is therefore segregating at the top of the brick (last part that solidifies). The concentration can be so high, that even changes in the conduction type from p to n can occur. Of course the n-type material cannot be used anymore for the solar cell production. Hence it is very important to detect such pn-changes with a high resolution and as early as possible in the production process. Since the actual segregation coefficients depend e.g. on the growth rate, the furnace properties can be optimized to shift the pn-junctions to the topmost part of the brick that has a very low material quality due to the segregation and back diffusion of metal impurities. In that way a minimal loss of material can be achieved.

EXPERIMENTAL TECHNIQUE

The photoconductivity is measured by the method MDP (microwave detected photoconductivity). MDP is a novel technique, which is used for inline applications as well as defect investigations [1-3].
The sample is excited with a rectangular laser pulse and the photoconductivity is measured via microwave absorption. The effective minority carrier lifetime is extracted from the transient decay of the photoconductivity signal after the light has been switched off. The high detection sensitivity of MDP enables the application also of weak laser pulses with unlimited duration, facilitating experiments with steady or non steady state photogeneration.
The measurements are performed with a MDP inline system at as-grown bricks. This inline tool enables the simultaneous mapping of the photoconductivity and minority carrier lifetime with a resolution of one mm, along with a linescan of the resistivity. With the wafer system a whole wafer map can be measured with a resolution of 2.5 mm in less than one second. The novel ingot tool has the capability of determining the spatially resolved photoconductivity and the minority carrier lifetime of two surfaces of a whole brick with a resolution of one mm within less than two minutes.

The used measurement parameters are summarized in table 1.

Table1 Measurement conditions

	MDP
excited area [mm^2]	0.79
pulse width [µs]	200
photons/pulse	4.9x10^{14}
laser power [mW]	500
photons/(pulse cm^2)	6.3x10^{16}

THEORY

As mentioned above phosphorus has an equilibrium segregation coefficient of 0.35, whereas boron has a coefficient of 0.8 and therefore is not segregating at the top of the brick so strongly [4]. This leads to pn-changes at the top of the brick, if the phosphorus concentration is sufficiently high.
Before the conduction type changes completely to n-conductivity, there is a narrow part of the brick that is compensated and has a very high resistivity. Figure 1 shows an exemplary resistivity curve, that result of a typical distribution of boron and phosphorus.

A highly resolved resistivity measurement by eddy current measurements is very difficult to achieve, so that in MDP inline tools only a linescan in the middle of the brick is measured. The detection of a pn-junction with only one resistivity linescan is can be inaccurate, because the junctions often proceed diagonal or with a strong bow through the brick (see Fig. 4). With the highly resolved photoconductivity map, these problems can be overcome.

There are several effects on the photoconductivity and lifetime, which have to be considered, if a pn-junction occurs.

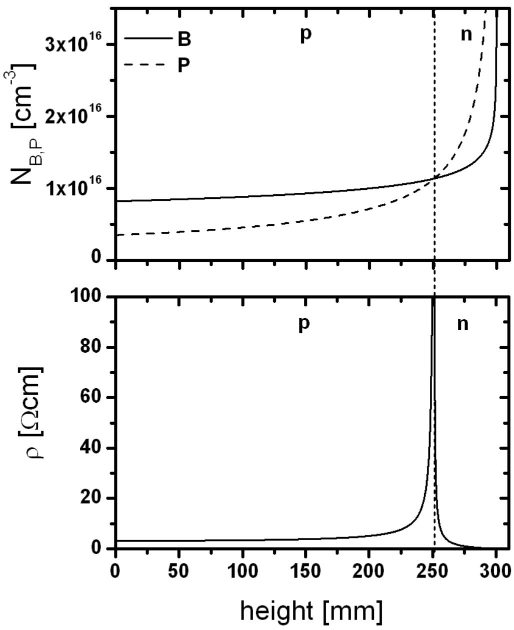

Figure 1 Typical concentrations of boron and phosphor versus the brick and the resulting resistivity versus brick height determined by the Scheil equation with $C_{0,B} = 10^{16}$ cm^{-3}, k_B = 0.82 and $C_{0,P} = 10^{16}$ cm^{-3}, k_P = 0.35

The skin depth of the used microwave increases strongly with an increasing resistivity. This has a strong influence on the measured lifetime at bricks, since more carriers in the bulk are measured, which not reach the surface. Hence the surface influence decreases with increasing skin depth. In an earlier publication the influence of different measurement regimes along with different laser wavelength or doping concentrations on the measured lifetime was studied extensively by simulating the carrier profiles, that develop during a measurement [5]. Since MDP uses a steady state photo generation only this measurement regime is considered here.

Figure 2 displays the effect of the changing skin depth on the measured lifetime for different sample thickness, which was simulated as described in [5]. It is obvious that the measured lifetime is limited by the sample thickness and the skin depth of the microwave. For bricks with a thickness of 156 mm the skin depth and therefore the resistivity is crucial for the measured lifetime and the deviation from the bulk lifetime. To summarize, if the resistivity increases also the measured lifetime increases.

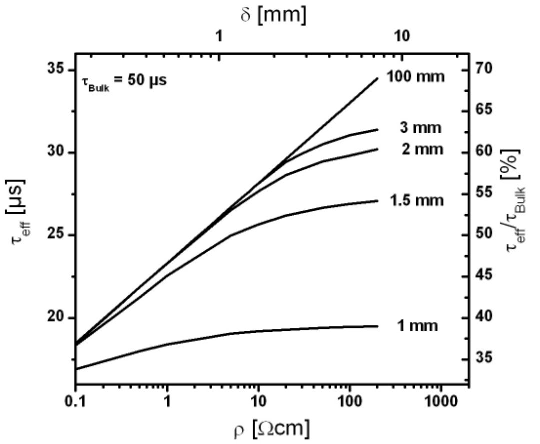

Figure 2 Effective lifetime and relative deviation from bulk lifetime versus resistivity and skin depth for different sample thickness

Another effect is caused by the shift of the Fermi level with resistivity. This has an influence on the efficiency of the recombination centre in the sample. This effect also leads to an increasing lifetime for an increasing resistivity. Furthermore the minority carrier lifetime is usually higher in n-type silicon.

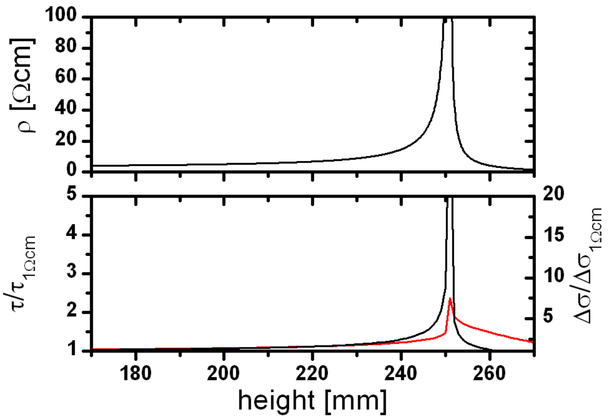

Figure 3 simulated resistivity linescan for a pn junction and resulting changes in the measured lifetime (red) and photoconductivity (black) compared to the values at 1 Ωcm

Obviously these two effects also influence the photoconductivity. Additionally the mobility rises with increasing resistivity and the transfer function of the microwave system depends on the resistivity. At high resistivities the measurement system is much more sensitive to changes in the photoconductivity. All in all the photoconductivity or more precisely the height of the signal is very sensitive to changes in the resistivity. Figure 3 displays ones more a typical resistivity curve for a pn change and the resulting change in the lifetime and photoconductivity compared to the values for 1 Ωcm. Whereas the measured lifetime only increases by the factor 2, the photoconductivity rises by the factor 20. Hence the photoconductivity was chosen to detect changes in the conduction type.

With a clever computer algorithm, it is possible to detect the sharp rise in photoconductivity, so that a pn-change can be detected with a resolution of 1 mm. This algorithm can be implemented into the software of the MDPingot tool, so that a detection of pn-changes is already possible at bricks.

DETECTION ALGORITHM

The detection algorithm was designed to be relatively simple and not very resource consuming.

The last half of every line of the photoconductivity map is used for the algorithm. First the line scan is smoothed and the first derivative is computed. From this derivative minimum and maximum are determined.
Afterwards the slope of the vector between the minimum and maximum is determined and add up for all lines and every point of the x-axes (brick height).
Figure 4 shows an example of such a photoconductivity linescan (a), the derivative (b) and the computed values for the algorithm (c).

If the photoconductivity rises sharply the algorithm computes a high value. To avoid an influence of noise, which can also lead to an apparent sharp rise of the photoconductivity, only signals with a certain signal to noise ratio are included into the algorithm.
The last step is to integrate all values in the x-direction and to set a limit from which value a pn-change is detected. This value was determined by analysing a vast amount of bricks with a pn-junction.

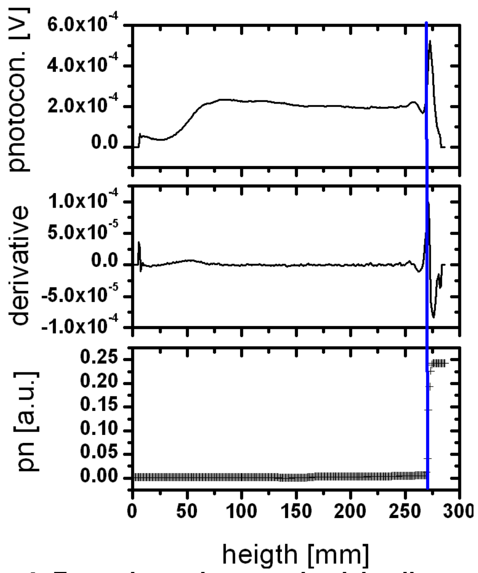

Figure 4 Exemplary photoconductivity linescan, its derivative and the resulting output of the detection algorithm

RESULTS

Figure 5 displays two photoconductivity maps with an obvious pn change. The pn-junction can be easily recognized by the very high photoconductivity at a height of approximately 200 mm and 250 mm respectively. The height at which the algorithm has detected the pn-change is indicated with a vertical line. Figure 6 shows the average linescan of the photoconductivity and the linescan of the determination algorithm. It is obvious, that the algorithm is responding to the pn change correctly. As a comparison the resistivity linescan of the middle of the bricks is displayed as well. If only this linescan would be used to detected pn changes, e.g. by using the height at which the resistivity rises above 3 Ωcm, for brick (a) an error of approximately 20 mm would occur. Brick (b) exhibits a very straight pn-junction and in this case the result of the pn-Algorithm and the resistivity linescan are in good agreement, proving ones more that the algorithm is working correctly.

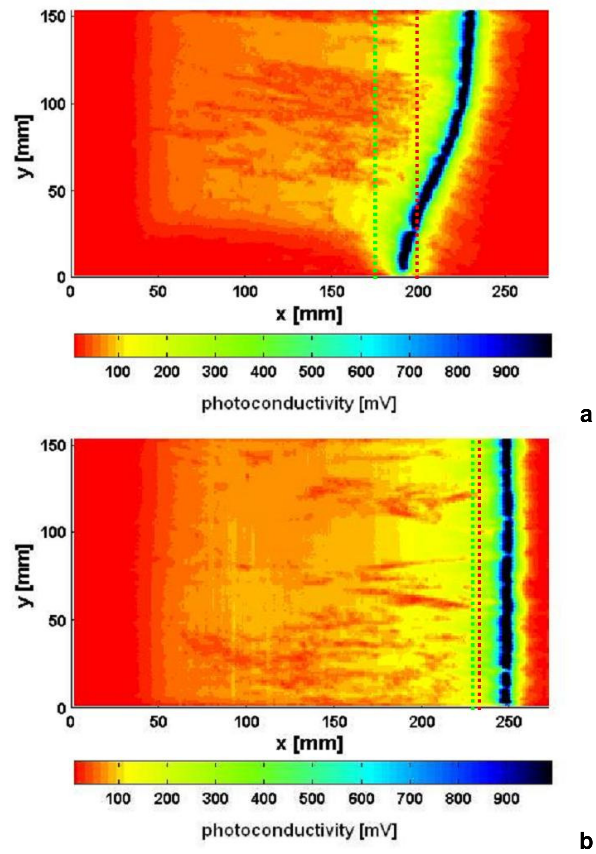

Figure 5 Exemplary photoconductivity maps of two mc-Si bricks with indicated detection height of the algorithm (green line) and height at which the resistivity linescan rises above 3 Ωcm (red line)

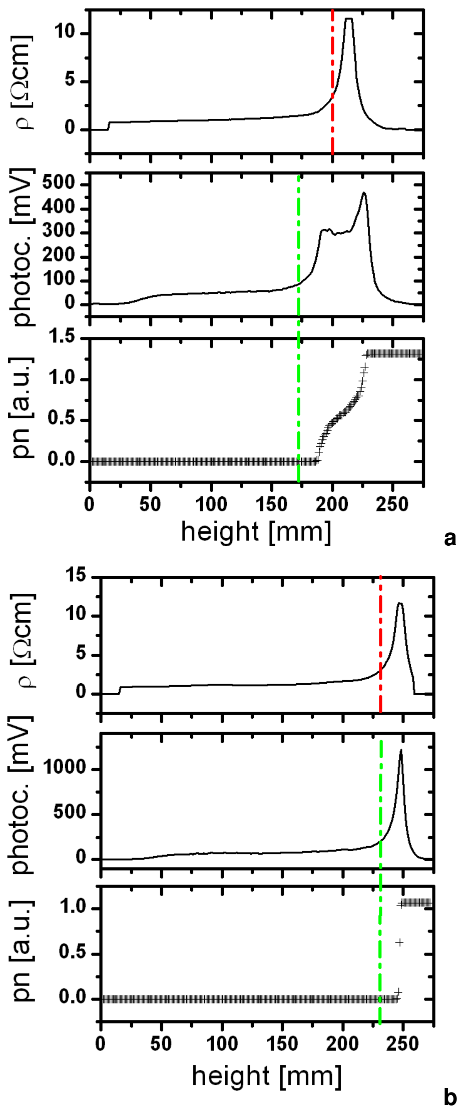

Figure 6 Average photoconductivity linescan of the bricks shown in figure 4 along with the corresponding output of the pn detection algorithm and the resistivity linescan measured in the middle of the brick

CONCLUSIONS

In this paper, it was proven by simulations and measurements, that the highly spatial resolved detection of changes in the conduction type is possible via photoconductivity measurements. With a clever computer algorithm the sharp rise of the photoconductivity at a pn junction can be detected. This algorithm can be easily implemented in the software of the MDPingot tool. The detection of pn changes enables the optimization of furnace and growth parameters directly after growing and sawing the bricks. Hence the areas with n-type regions can be sorted out and the yield of solar cells can be improved.

ACKNOWLEDGEMENT

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