RECOMBINATION ANALYSIS AT THE N-DOPED A-SI:H(N)/C-SI(P) HETEROJUNCTION BY MEANS OF TIME AND INTENSITY DEPENDENT SURFACE PHOTOVOLTAGE

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ABSTRACT: Interface recombination is investigated at amorphous/crystalline silicon heterojunctions by means of time and intensity dependent surface photovoltage and photoluminescence. Two series of samples have been prepared in order to distinguish between the mechanisms which suppress the interface recombination: (1) a variation of the interface defect state density D_{it} and (2) a variation of the c-Si band bending $q\varphi_{s0}$. The sensitivity of the used measurement methods to the a-Si/c-Si interface recombination is demonstrated. Additionally, numerical computer simulations have been performed. Comparing experimental results and simulation interface defect state density of the samples can be estimated to be in the range of $10^{11} < D_{it} < 10^{12}$ cm^{-2}.
Keywords: heterojunction, defect density, recombination

1 INTRODUCTION

Amorphous/crystalline silicon heterojunctions, a-Si:H/c-Si, produced by plasma enhanced chemical vapour deposition (PECVD) of ultrathin (5-10 nm) hydrogenated amorphous silicon layers, a-Si:H, on crystalline silicon substrates, c-Si, attract an increasing interest in order to realize low cost, low process temperature and high efficiency solar cells. For the realization of high efficiency solar cells it is necessary to suppress the interface recombination at the a-Si:H/c-Si interface. This can be achieved by decreasing the interface defect state density $D_{it}(E)$ of the a-Si:H/c-Si interface or by increasing the c-Si band bending $q\varphi_{s0}$. To characterize the interface recombination we investigated the a-Si:H/c-Si heterojunction by means of time dependent and intensity dependent surface photovoltage, TD-SPV and ID-SPV. These measurements are supported by additional photoluminescence (PL) measurements and numerical computer simulations.

To be able to distinguish between the influence of the interface defect state density and of the c-Si(p) band bending on the interface recombination we prepared two series of a-Si:H(n)/c-Si(p) heterojunctions: series 1 with different wafer pre-treatment and series 2 with different wafer resistivities. While series1 samples reflect a variation of defect state density D_{it}, series 2 samples cover the variation of the c-Si band bending $q\varphi_{s0}$.

2 SAMPLE PREPARATION

Various 12 nm thin identical emitter layers of n-doped, hydrogenated amorphous silicon, a-Si:H(n) have been deposited by PECVD on p-doped crystalline silicon wafers, c-Si(p) [1]. Two series have been realized, one dependent on the wafer pre-treatment (series 1) and the other are dependent on the wafer resistivity (series 2).

The way of wafer pre-treatment changes the surface defect state density D_{it} of the c-Si(p) before the a-Si:H(n) emitter is deposited. Differences in the electronic behaviour remain even after the same a-Si:H emitter is deposited. Thus, we are able to change the a-Si/c-Si interface defect state density D_{it}, (series 1). Various wafer pre-treatment procedures such as NH$_4$F-dip or HF-dip can be used [2]. For the samples of series 1 we applied prior to the deposition of a-Si:H(n) a simple HF-

dip and an NH$_4$F-dip on the <100> oriented surface of the c-Si(p) wafer. An NH$_4$F-dip on an <100> oriented c-Si surface is known to degrade the surface passivation [2 and references therein].

A change of the c-Si(p) band bending $q\varphi_{s0}$ (series 2) can be achieved by the use of c-Si wafers with a different resistivity. Thus, the doping level of the substrates is varied. This variation has no effect on the Fermi level in a-Si:H(n), but a higher c-Si doping shifts the Fermi level in c-Si towards the band edge. Therefore, low doped c-Si wafers have a high wafer resistivity and a high c-Si band bending, and vice versa for highly doped c-Si wafers. For sample series 2 we used samples with a wafer resistivity from 0.02 Ωcm to 16.0 Ωcm. This corresponds to a relative change of the c-Si band bending of 160 mV. However, one has to keep in mind, that not only the c-Si(p) band bending, but also the c-Si(p) bulk recombination is varied by using differently doped c-Si(p) wafers. A higher doping naturally leads to a higher c-Si(p) bulk recombination. Prior to the a-Si:H deposition of series 2 we used a simple HF-dip as a wafer pre-treatment.

3 EXPERIMENTAL METHODS

3.1 Time dependent surface photovoltage (TD-SPV)

In order to measure SPV, the a-Si:H(n)/c-Si(p) sample under investigation, which is electrically contacted at its back side, is illuminated with a laser pulse through an insulating transparent metal/insulator front contact (TCO/mica). The pulse length is 6 ns and the wavelength is 910 nm. Ideally, the system is in steady state when the laser pulse is switched off. The dynamic rearrangement and recombination of the generated excess carriers due to the sudden offset of the laser pulse can be capacitively measured by monitoring the change of the surface potential. Thus, the time dependent SPV signal, SPV$_{dynamic}$(t), indicates the change of the surface potential relaxing from its excited state under illumination to its equilibrium state in the dark. Then, the maximum value of the SPV signal right after the laser pulse, SPV(0), is given by the difference of the surface potential in the dark and under illumination.

Typical SPV relaxation times for a-Si:H(n)/c-Si(p) heterostructures are in the µs range. An overview of typical time dependent characteristics of the SPV

transient at different excitation intensities is shown in Fig. 1. The maximum of the SPV signal at t = 0, SPV(0); is the difference of the surface potential under illumination and in the dark. At a low intensity no SPV signal can be observed. The beginning of the SPV signal at a specific excitation intensity is the so-called onset. At higher excitation intensities SPV(0) increases. Furthermore, there is a pronounced change in the initial decay behaviour: The fast initial decay at low excitation energies changes to a slow one at high excitation energies.

SPV(0) is higher at a higher excitation, because the change of the band bending increases with an increased excitation. The slow initial decay indicates an additional recombination path which is dominant in the initial part of the transient. This path can be assigned to the recombination at the a-Si:H/c-Si interface but also to a charge transfer and recombination in the a-Si:H(n) emitter.
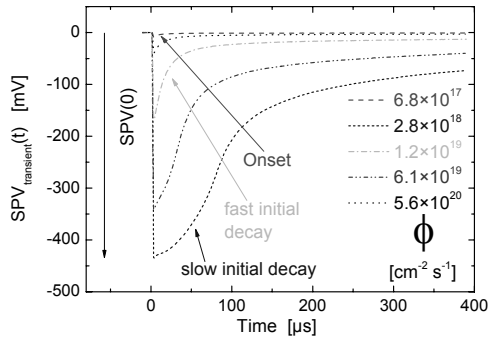

Figure 1: Typical time dependent surface photovoltage signal, TD-SPV, of an a-Si:H(n)/c-Si(p) heterostructure at different laser excitation intensities.

3.2 Intensity dependent surface photovoltage (ID-SPV)

In ID-SPV experiments only the maximum SPV(0), right after the laser pulse, is recorded as a function of the photon flux (excitation intensity).

If the excess carriers are generated in the c-Si(p) absorber (excitation at 910 nm), the absorption in the a-Si:H(n) emitter is negligible and the recombination of the excess carriers via the a-Si:H(n)/c-Si(p) interface is independent from the emitter thickness. Therefore also the resulting intensity dependent SPV signals are almost independent from the emitter thickness [3]. At pure absorber excitation, the front surface of the heterostructure (the free a-Si:H(n) surface or the TCO/a-Si:H contact) has no influence on the SPV signal [3]. Contrary, the intensity dependent SPV signal is very sensitive to the a-Si:H(n)/c-Si(p) interface defect state density, D_{it}, and the c-Si(p) band bending $q\varphi_{s0}$.

3.3 Photoluminescence

Photoluminescence (PL) measurements are performed at an excitation wavelength of 750 nm using a 1 ns laser pulse. The value of the PL measurement depends on the interface defect state density of the a-Si:H/c-Si heterostructure as well as on the c-Si(p) band bending $q\varphi_{s0}$, because interface recombination quenches the radiative recombination and thus, the PL signal.

3.4 Computer simulation

The computer simulations have been performed with the computer program AFORS-HET [4], which allows to simulate the output of different measurement techniques for an arbitrary sequence of semiconducting layers and interfaces with an arbitrary number of defects.

The simulation is able to reproduce the SPV measurements qualitatively. However, in the simulation steady-state conditions are assumed in order to calculate the light induced change of the surface potential. These conditions cannot be reached experimentally using a laser pulse length of 6 ns. Thus, it is not possible to fit the measurement to the simulation quantitatively.

4 RESULTS AND DISCUSSION

4.1 Variation of the defect state density

The influence of the variation of the interface defect state density D_{it} (series 1) of the a-Si:H(n)/c-Si(p) heterojunctions has been investigated by means of ID-SPV and PL measurements. In Fig. 2 the SPV signal at t = 0, SPV(0), of series 1 is plotted versus the photon flux during the excitation laser pulse. The inset shows the complete ID-SPV measurement in the photon flux range of $10^{16} - 10^{21}$ cm^{-2} s^{-1}. No big difference of the ID-SPV signals independence on the wafer pre-treatment can be observed. However, a small shift of the ID-SPV onset can be detected when enlarging the intensity range of the onset $(5 \times 10^{17} - 4 \times 10^{19}$ cm^{-2} s$^{-1})$, see Fig. 2. The onset shifts towards higher excitation intensities for the sample with used a NH$_4$F-dip as a wafer pre-treatment.
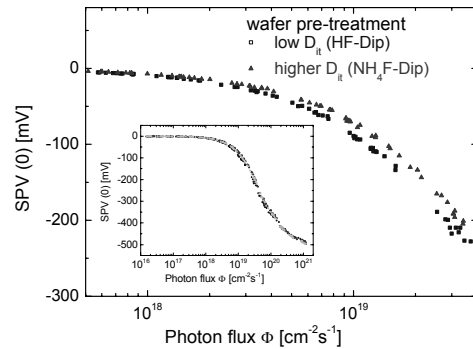

Figure 2: Enlargement of a small part of an intensity dependent (ID)-SPV measurement for a-Si:H(n)/c-Si(p) heterostructures (series 1) with a different c-Si(p) surface pre-treatment. The inset shows the entire measurement.

The shift of the ID-SPV onset is the result of a different interface recombination due to a different defect state densities D_{it}. In case of a higher D_{it} more excess carriers are needed in order to achieve a splitting of the quasi Fermi energies. However, as a certain splitting of the quasi Fermi energies is needed in order to change the c-Si(p) band bending, the onset of SPV(0) shifts towards higher intensities for a larger interface defect state density.

Fig. 3 shows the corresponding PL measurements. The highest PL signal is observed for the sample with the simple HF-dip used for the wafer pre-treatment. A higher PL signal represents a lower a-Si/c-Si interface

recombination. As the c-Si(p) band bending can be assumed to be constant in series 1, (using the same a-Si:H(n) emitter and the same c-Si(p) absorber), a lower interface recombination denotes a lower interface defect state density D_{it}. Thus, the lowest interface defect state density is obtained if a simple HF-dip is used as wafer pre-treatment. These results are in total agreement to the analysis of the ID-SPV onset discussed above.
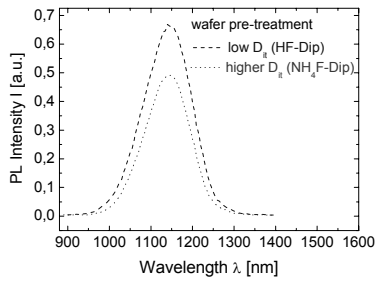

Figure 3: Photoluminescence (PL) intensity as a function of the wavelength for a-Si:H(n)/c-Si(p) heterostructures (series 1) using a different c-Si(p) surface pre-treatment before the a-Si:H deposition.

The simulation of ID-SPV measurements at different interface defect state densities, D_{it}, is shown in Fig. 4. A marginal shift of the ID-SPV onset can be observed if D_{it} is in the range of $0 \leq D_{it} \leq 10^{11}$ cm^{-2}, while it shifts significantly for $D_{it} = 10^{12}$ cm^{-2}. If one qualitatively compares these results with the measurement (see Fig. 2), where only a small shift of the ID-SPV onset can be observed, one might conclude $D_{it} < 10^{12}$ cm^{-2}.
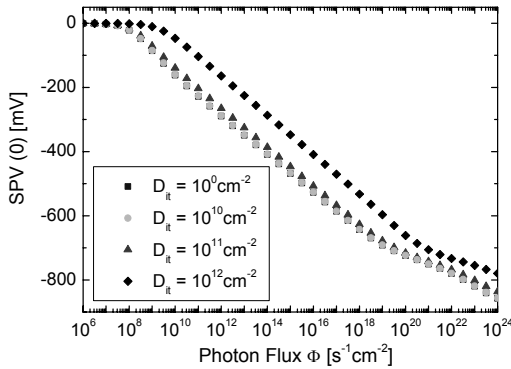

Figure 4: Simulation of ID-SPV for a-Si:H(n)/c-Si(p) heterostructures (series 1) with different interface defect state density.

4.2 Variation of the c-Si(p) band bending

Also the influence of the variation of the c-Si band bending $q\varphi_{s0}$ (series 2) on the a-Si:H(n)/c-Si(p) heterojunction has been investigated by means of ID-SPV and PL experiments. The ID-SPV measurements of the variation of the c-Si(p) band bending of series 2 are shown in Fig. 5. Now, when varying gradually the wafer resistivity from 16 Ωcm to 0.02 Ωcm, a strong shift of the ID-SPV onset towards higher excitation intensity is observed. This behaviour is contrary to series 1 (variation of D_{it}, Fig.2), where only a small onset shift has been observed. Additionally, at high excitation

intensities the ID-SPV signal for samples with a high wafer resistivity crosses the ID-SPV signal for those with a smaller wafer resistivity.
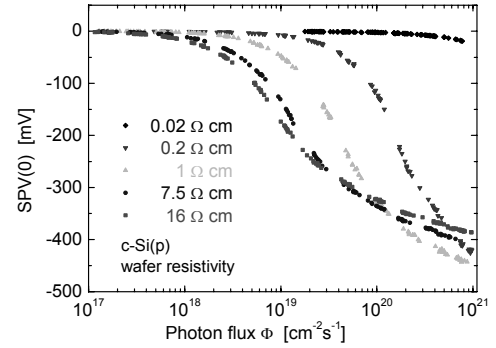

Figure 5: Intensity dependent (ID)-SPV for a-Si:H(n)/c-Si(p) heterostructures with a varying c-Si(p) wafer resistivity from 0.02 Ωcm to 16 Ωcm (series 2).

For a lower wafer doping (high wafer resistivity) the c-Si(p) band bending is high. This results in very efficient suppression of the interface recombination. A suppressed interface recombination will shift the ID-SPV onset towards lower excitation intensities as discussed before.

In Fig. 6 the corresponding PL measurements are presented. The sample with the lowest wafer doping (highest wafer resistivity) exhibits the highest PL signal. For a lower wafer doping (higher wafer resistivity) the c-Si(p) bulk recombination is lower. Furthermore, the c-Si(p) band bending $q\varphi_{s0}$ is higher and the interface recombination is more suppressed. Therefore the radiative recombination, measured via PL, is quenched less, and the PL signal increases. This is in agreement with the shift of the ID-SPV onset discussed above, too.
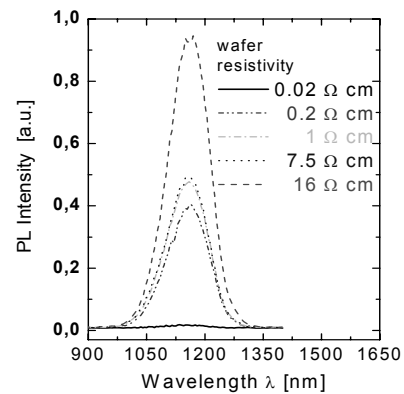

Figure 6: Photoluminescence (PL) measurements for a-Si:H(n)/c-Si(p) heterostructures with a varying c-Si(p) wafer resistivity from 0.02 Ωcm to 16 Ωcm (series 2).

A numerical computer simulation, see Fig.7, allows to separate the influence of the change of the c-Si(p) bulk recombination and the change of the c-Si(p) band bending of series 2. In comparison with the measurement (Fig. 5), the same qualitative behaviour (significant onset shift and signal crossing for a high wafer resistivity) can

be reproduced. However, in order to model the signal crossing stated before, an interface defect state density larger then $D_{it} > 10^{11}$ cm^{-2} has to be assumed. If one neglects the a-Si/c-Si interface state density within the simulation, the signal crossing cannot be modelled.

In conclusion, the ID-SPV onset seems to be less sensitive to the interface defect state density D_{it} than to the change of the c-Si(p) band bending $q\varphi_{s0}$. This has been observed experimentally as well as by means of numerical computer simulations.
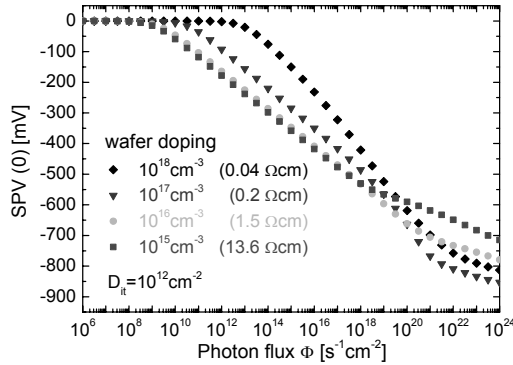

Figure 7: Simulation of ID-SPV for a-Si:H(n)/c-Si(p) heterostructures (series 2) with a varying c-Si(p) doping from 10^{15} cm^{-3} to 10^{18} cm^{-3}, assuming $D_{it} = 10^{12}$ cm^{-2}.

4.3 Time dependent surface photovoltage

In the following the interface recombination is investigated by means of TD-SPV. As shown in Fig. 1, the time dependent decay of the SPV signal (TD-SPV) at low excitation intensities is characterized by a fast initial decay. At higher excitation intensities a slow initial decay can be observed if the interface recombination dominates the bulk recombination. Otherwise the fast initial decay behaviour prevails (compare Fig 9).
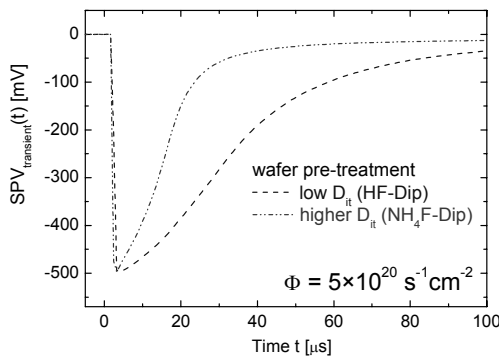

Figure 8: Time dependent (TD)-SPV signal at high excitation intensity for a-Si:H(n)/c-Si(p) heterostructures using a different c-Si(p) surface pre-treatment (series 1).

TD-SPV measurements at high excitation intensity ($\Phi = 5 \times 10^{20}$ s^{-1}cm^{-2}) for samples with a varying interface defect state density (series 1) are shown in Fig. 8. All measured curves exhibit a slow initial decay. The decay is slower for samples with a lower interface defect state density D_{it} (i.e. for the sample with a simple HF-dip used as a wafer pre-treatment).

The corresponding TD-SPV measurements at high excitation intensity with a different wafer resistivity

(series 2) are displayed in Fig. 9. For a low wafer resistivity the TD-SPV decay can be described by a slow initial decay while for a higher wafer resistivity the initial decay is fast, see Fig.9. If the c-Si(p) wafer doping is high (low wafer resistivity), the defect recombination in the bulk of c-Si(p) is high and therefore bulk recombination in the device is dominant. In this case only a fast initial decay of the TD-SPV transient can be observed. If the c-Si(p) wafer doping is low (high wafer resistivity), the corresponding bulk defect recombination is also low. Then the a-Si/c-Si interface recombination will significantly influence the entire recombination and a slow initial decay can be observed.
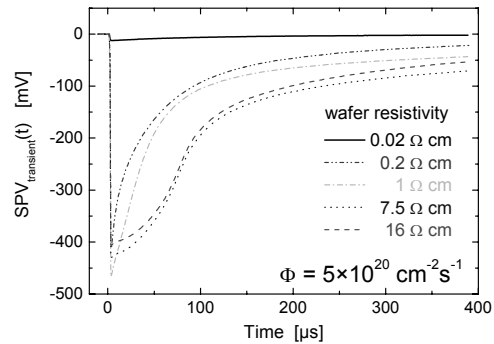

Figure 9: Time dependent (TD)-SPV signal for a-Si:H(n)/c-Si(p) heterostructures with a varying c-Si(p) wafer resistivity from 0.02 Ωcm to 16 Ωcm (series 2) at high excitation intensity.

5 CONCLUSIONS

ID-SPV, TD-SPV and PL are measurement methods, which are sensitive to the a-Si:H(n)/c-Si(p) interface recombination. A low interface recombination is indicated by an onset shift towards lower excitation intensities for ID-SPV, by a slow initial decay for TD-SPV measured at sufficiently high excitation intensities and by a high PL signal. Comparing qualitatively the experimental results to numerical computer simulations leads to the conclusion that for the samples under investigation the interface defect state density is in the range of $10^{11} < D_{it} < 10^{12}$ cm^{-2}.

7 REFERENCES

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