CHARACTERIZATION OF INTERFACES IN AMORPHOUS/CRYSTALLINE SILICON HETEROJUNCTION SOLAR CELLS BY SURFACE PHOTOVOLTAGE SPECTROSCOPY

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ABSTRACT: We use wavelength and intensity dependent surface photovoltage spectroscopy (SPV) in order to characterize the interfaces in amorphous/crystalline silicon heterojunction solar cells. A series of solar cell structures, TCO/a-Si:H(n)/c-Si(p), with a-Si:H(n) emitter layers of different thickness in the range of 5 – 480 nm, has been investigated by means of SPV in order to probe the two interfaces, TCO/a-Si:H(n) and a-Si:H(n)/c-Si(p). The maximum value of the surface photovoltage, which is reached right after the excitation laser pulse, is monitored as a function of the excitation intensity (intensity dependent SPV). Using this technique with an excitation wavelength ensuring dominant emitter absorption (i.e. 505 nm) and analyzing thick emitter layers (480 nm), it is shown that the TCO/a-Si:H(n) front contact is depleted. Analyzing ultrathin emitter layers (5 nm), it can be proofed that the depleted front contact will reduce the band bending in the crystalline c-Si(p) absorber. Applying an excitation wavelength which ensures that emitter absorption can be neglected (i.e. 910 nm), the influence of the effective a-Si:H(n)/c-Si(p) interface state density, D_{it}, which contributes to the total solar cell recombination, can be measured. This is demonstrated by comparing the onset of the intensity dependent SPV for a-Si:H(n)/c-Si(p) solar cell structures with a different c-Si(p) surface pre-treatment but otherwise identical deposition conditions. Under the assumption that the system reached steady-state conditions when the laser pulse is switched off, numerical simulations have been performed using the simulation program AFORS-HET [1]. However, analyzing the currently used measurement-setup (room temperature measurements with a laser pulse width varying from of 10 – 160 ns), it is shown that even a 160 ns laser pulse will not generate steady-state conditions in the case of a-Si:H(n)/c-Si(p) heterostructures (contrary to a plain c-Si(p) wafer surface). In order to get quantitative information, either the measurements have to be repeated using longer laser pulses or the simulations have to be extended to non-steady state conditions.

Keywords: c-Si, Interfaces, Experimental Methods

1 INTRODUCTION

Solar cell devices based on amorphous/crystalline silicon heterojunctions, a-Si:H/c-Si, have raised considerable interest, offering a low temperature processing alternative to conventional diffused p/n homojunction silicon solar cells, while maintaining high solar cell efficiency [2], [3]. Thin film a-Si:H layers are deposited on both sides of a high quality c-Si wafer, thus realizing a low temperature emitter and back surface field layer of the solar cell. Due to the comparatively low conductivity of doped a-Si:H, at least one additional layer of a transparent conductive oxide (TCO) at the top of the solar cell is required. The resulting solar cell performance not only depends on the bulk properties of the deposited a-Si:H layers, but also on the quality of the two interfaces, a-Si:H/c-Si and TCO/a-Si:H.

We investigated simple a-Si:H(n)/c-Si(p) and TCO/a-Si:H(n)/c-Si(p) solar cell structures by means of spectral and intensity dependent surface photovoltage spectroscopy, in order to study interface properties. It is demonstrated that intensity dependent SPV gives valuable information on the TCO/a-Si:H(n) front contact as well as on the enhanced solar cell recombination due to an a-Si:H(n)/c-Si(p) interface state density.

2 INTENSITY DEPENDENT SPV

In order to measure SPV, the heterostructure under investigation, which is electrically contacted at the back side, is illuminated with a laser pulse through an insulating transparent metal/insulator front contact (TCO/mica), see Fig. 1. Ideally, the system is under a steady-state condition 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, that is the change of the surface potential $qV_{dynamic}(t)$, relaxing from its state under illumination to its state in the dark, can be measured. The maximum value of the SPV, right after the laser pulse, V_{SPV}, is then given by the difference of the surface potentials (or equivalently the difference of the surface conduction band energies) in the dark and under illumination (see Fig.1)

$$V_{SPV} = \varphi_{dark}(0) - \varphi_{illum}(0) = (E_{Cdark}(0) - E_{Cillum}(0))/q$$

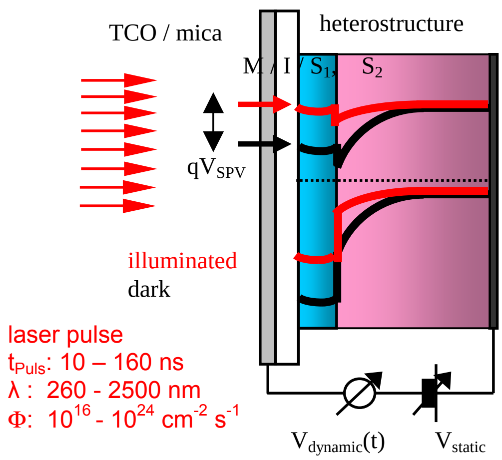


Figure 1: sketch of the measurement principle of SPV

Typical SPV relaxation times for a-Si:H(n)/c-Si(p) heterostructures are in the µs range with the measured dynamic relaxation $V_{dynamic}(t)$ shown in Fig. 2.

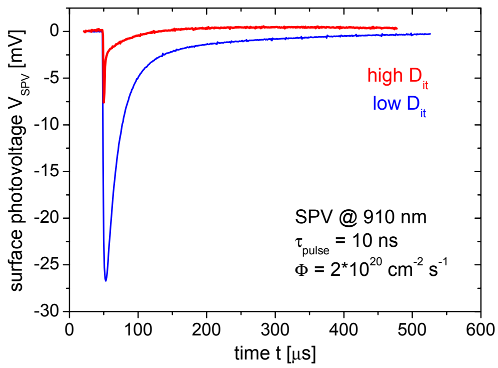


Figure 2: SPV transients for two a-Si:H(n)/c-Si(p) heterostructures with a different c-Si(p) surface pre-treatment but otherwise identical deposition conditions.

Using the different measurement setups available at the HMI, the wavelength of the laser pulse can be varied between 400 nm and 2500 nm, and the intensity (photon flux) during the laser pulse can be varied for eight orders of magnitude, from 10^{24} down to 10^{16} photons cm^{-2} s^{-1}. If not stated otherwise, the duration of the laser pulse was 10 ns and there was no external voltage applied across the heterostructure (V_{static}=0).

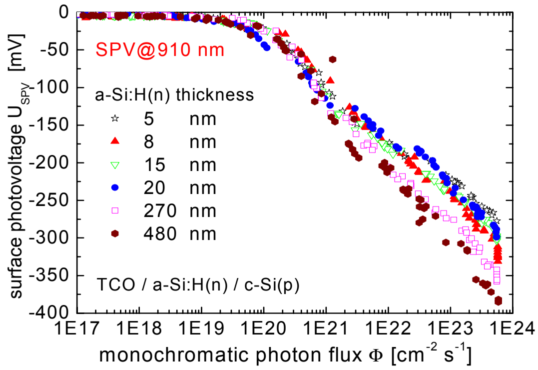
A variation of the wavelength of the excitation laser pulse leads to a variation of the depth of excess carrier generation within the TCO/a-Si:H(n)/c-Si(p) or the a-Si:H(n)/c-Si(p) structure under investigation. There is thus the possibility to select an interface: Exciting at short wavelengths (i.e. 505 nm) and studying thick emitter layers (i.e. 480 nm) means that excess carrier generation and recombination takes place in the a-Si:H(n) emitter only. The emitter band bending due to the TCO/a-Si:H(n) contact or due to the free emitter surface can then be studied, as the SPV signal then monitors the change of the a-Si:H(n) band bending. Contrary, exciting at long wavelengths (i.e. 910 nm) means that excess carrier generation takes place in the c-Si(p) absorber only. The recombination via the a-Si:H(n)/c-Si(p) interface states can then be studied, as the SPV signal then monitors the change of the c-Si(p) band bending.

If there is an excess carrier generation in the high quality c-Si absorber, the excess carriers will recombine not only in the c-Si(p) bulk, but also significantly at the c-Si(p) interfaces. The larger the a-Si:H(n)/c-Si(p) interface recombination, the more excess carriers will be needed in order to change the c-Si(p) band bending. A large interface recombination can thus be monitored by a late onset of the surface photovoltage, if the maximum value of the SPV is recorded as a function of the excitation intensity (intensity dependent SPV). Assuming that an increase of the a-Si:H(n)/c-Si(p) interface state density will not alter the c-Si(p) band bending (which is true for interface state densities $\leq 10^{12}$ cm^{-2}), the onset of intensity dependent SPV is thus a sensitive measure of the a-Si:H(n)/c-Si(p) interface state density.

3 SAMPLE PREPARATION

Thin film (5 – 480 nm) layers of phosphorous-doped hydrogenated amorphous Silicon, a-Si:H(n), have been deposited on top of a boron-doped, crystalline wafer (FZ, <100>, 1 Ohm cm) by means of plasma enhanced chemical vapor deposition. Standard RCA cleaning and an HF-dip immediately before the a-Si:H(n) deposition was used as c-Si(p) pre-treatment in order to achieve low a-Si:H(n)/c-Si(p) interface state densities. However, for some samples a natural surface oxide was allowed to form (by just waiting some hours after the HF dip) in order to deterioite the interface. Furthermore, for most samples an additional TCO layer (80 nm ZnO) was deposited on top of the a-Si:H(n) by means of dc magnetron sputtering.

4 RESULTS



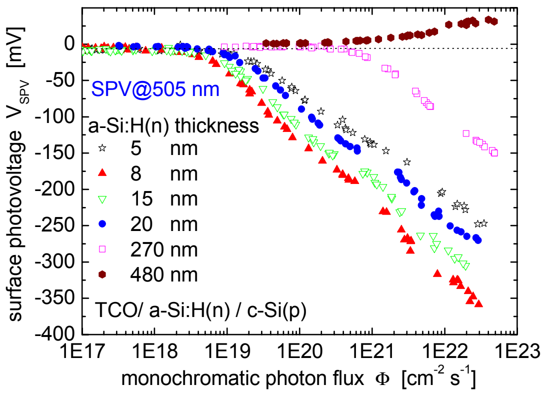


Figure 3: intensity dependent SPV for TCO/a-Si:H(n)/c-Si(p) structures with varying a-Si:H(n) emitter thickness. Excitation (a) at 910 nm and (b) at 505 nm respectively.

A typical example for an intensiy dependent SPV measurement is shown in Fig. 3. TCO/a-Si:H(n)/c-Si(p) heterostructures of different emitter thickness (varying from 5 – 480 nm) have been excited at 910 and at 505 nm respectively. The maximum SPV, V_{SPV}, right after the laser pulse, is recorded as a function of the photon flux during the laser pulse (excitation intensity).

If the excess carriers are generated in the c-Si(p) absorber (excitation at 910 nm), the resulting intensity dependent SPV signal is nearly independent from the emitter thickness (see Fig. 3.a): There is a negligible absorption in the a-Si:H(n) emitter and the recombination of the excess carriers via the a-Si:H(n)/c-Si(p) interface is independent of the emitter thickness.

If the excess carriers are predominantly generated in the a-Si:H(n) emitter (excitation at 505 nm), the intensity dependent SPV signal varies significantly with the emitter thickness (see Fig. 3.b).

5 EMITTER EXCITATION (SPV@505 NM)

If the emitter is sufficiently thick (i.e. 480 nm), all excess carriers are generated in the a-Si:H(n) emitter for all excitation intensities used. As the a-Si:H(n) recombination is quite large, all excess carriers will also recombine within the emitter. The SPV signal thus probes the change of the emitter band bending due to the TCO/a-Si:H(n) interface under illumination. The measured positive V_{SPV} (see Fig. 3.b) means that the bands are upward bend, that is, the a-Si:H(n) emitter is depleted due to the TCO/a-Si:H(n) contact and the illumination will reduce this depletion. This is illustrated by simulating the corresponding band diagram in the dark and under illumination, using the simulation program AFORS-HET [1], see Fig. 4.

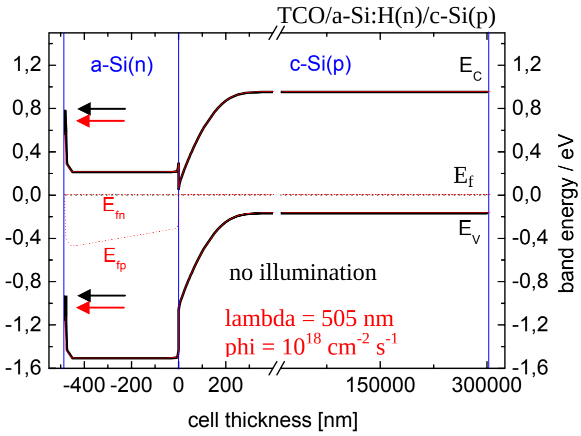


Figure 4: simulated band diagram (in the dark and under steady-state illumination of 10^{18} photons cm^{-2} s^{-1}) for a TCO/a-Si:H(n)[480 nm]/c-Si(p) heterostructure, using an excitation wavelength of 505 nm.

If the emitter gets thinner, there will be an intensity which is large enough, that excess carriers are also generated in the c-Si(p) absorber. Furthermore, there will be carrier injection from the emitter to the absorber. The SPV signal then monitors the difference of the change of emitter and absorber band bending. Due to the low recombination within the c-Si(p) absorber, the change of c-Si(p) bend bending will dominate, that is V_{SPV} gets negative with increasing intensity (see Fig. 3.b and Fig. 5).

Correspondingly, the onset of V_{SPV} (the first intensity at which there is a measurable negative V_{SPV}) will decrease with decreasing emitter thickness, as more and more excess carriers are generated in the absorber. E.g., according to Fig. 3.b the onset decreases from 9 10^{18} cm^{-2} s^{-1} for a 20 nm thick emitter to 3 10^{18} cm^{-2} s^{-1} for a 8 nm thick emitter.

However, for a ultrathin emitter (5 nm) the onset suddenly increases again up to 1 10^{19} cm^{-2} s^{-1}. This is due to a reduction of the c-Si(p) band bending in the dark due to the depleted TCO/a-Si:H(n) front contact, if the a-Si:H(n) emitter gets too thin. A reduced c-Si(p) band bending in the dark will increase the onset of V_{SPV}, as under illumination a higher splitting of the quasi fermi energies (that is more excess carriers) is needed in order to change the c-Si(p) band bending.

In order to shield the electric field imposed by the TCO/a-Si(n) contact, the depletion width within the a-Si:H(n) emitter is in the range of several nm. If the emitter gets thinner than its natural depletion width, additional carriers from the c-Si(p) absorber and recharged defects of the emitter have to be used in order to shield the field. This considerably alters the band bending of the crystalline absorber. This has already been predicted by means of numerical simulation [4] and is thus experimentally proofed. For efficient a-Si:H/c-Si solar cell structures, the emitter thickness should be chosen close to this critical emitter thickness [4].

6 ABSORBER EXCITATION (SPV@910 NM)

If the excitation is performed at 910 nm, all excess carriers are generated in the c-Si(p) absorber. Assuming an ohmic back contact, the SPV signal thus probes the change of the c-Si(p) band bending due to the a-Si:H(n)/c-Si(p) contact under illumination.

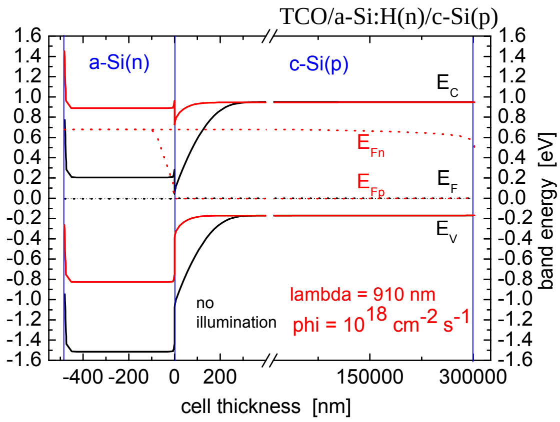


Figure 5: simulated band diagram (in the dark and under steady-state illumination of 10^{18} photons cm^{-2} s^{-1}) using an excitation wavelength of 910 nm.

The measured negative V_{SPV} means that the bands are bend downward, the c-Si(p) absorber is accumulated or even depleted due to the a-Si:H(n)/c-Si(p) contact and the illumination will reduce this accumulation/depletion, see Fig.5.

Under absorber excitation, the front surface of the heterostructure (the TCO/a-Si:H(n) interface or the free a-Si:H(n) surface respectively) has no influence on the SPV signal. Contrary, the intensity dependent SPV signal is very sensitive to the a-Si:H(n)/c-Si(p) interface state density, D_{it}. This is proofed experimentally (see Fig. 6) as well as by numerical simulation (see Fig. 7). Experimentally, a higher D_{it} shifts the onset of V_{SPV} one order of magnitude, from 1 10^{20} cm^{-2} s^{-1} to 1 10^{18} cm^{-2} s^{-1}. The different interface quality of the two sample is also proofed by potoluminescence. Within the simulation, the onset of V_{SPV} can shift over 8 orders of magnitude, if one varies the a-Si:H(n)/c-Si(p) interface D_{it} !

Due to the high diffusion length of the c-Si(p) wafer, recombination at the wafer interfaces will contribute significantly to the total cell recombination. In case of a higher D_{it} more excess carriers are needed in order to achieve a splitting of the quasi fermi energies. But a certain splitting of the quasi fermi energies is needed in order to change the c-Si(p) band bending. Therefore, the onset of V_{SPV} shifts towards higher intensities.

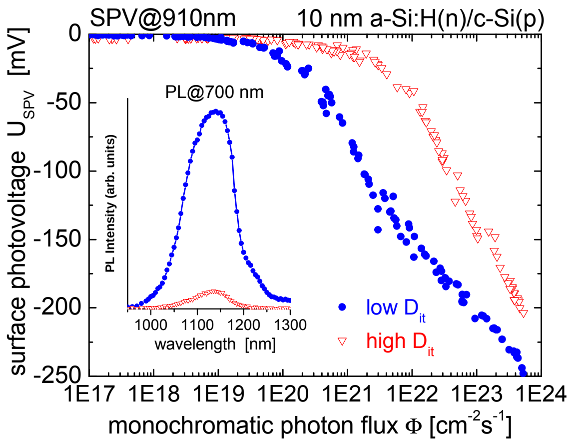


Figure 6: photoluminescence, PL, (inset) and intensity dependent SPV for two a-Si:H(n)/c-Si(p) heterostructures with a different c-Si(p) surface pre-treatment but otherwise identical deposition conditions.

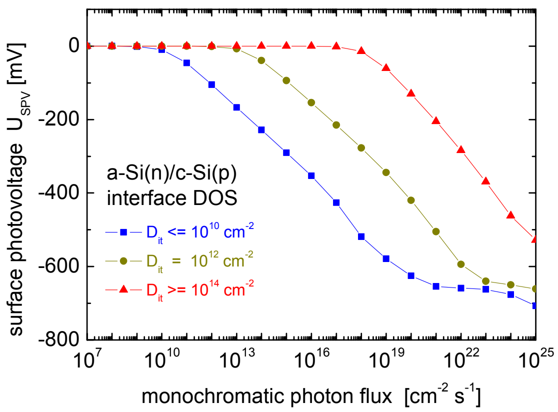


Figure 7: simulated intensity dependent SPV for a-Si(n)/c-Si(p) heterostructures with varying interface state density D_{it},. Excitation at 910 nm.

5 EXPERIMENT/SIMULATION CONSTRAINTS

However, if one compares measurement to simulation, it is obvious, that the simulation cannot describe the measurement. In the simulation the maximum obtainable onset for bad interfaces ($D_{it} \geq 10^{14}$ cm^{-2}) is at 10^{18} cm^{-2} s^{-1}, so the measured onsets of 10^{19} cm^{-2} s^{-1} and higher cannot be described.

This discrepancy can be explained by the fact that a steady-state condition is not reached experimentally, when the laser pulse is switched off, see Fig. 8. However, the simulation assumes steady-state conditions. Indeed, measuring the same samples with a larger laser pulse width (160 ns instead of 10 ns), the onset of V_{SPV} is already shifted by 5 orders of magnitude towards lower intensities, see Fig. 9. Thus, in order to get quantitative information, either the measurements have to be repeated using even longer laser pulses or the simulations have to be extended to non-steady state conditions.

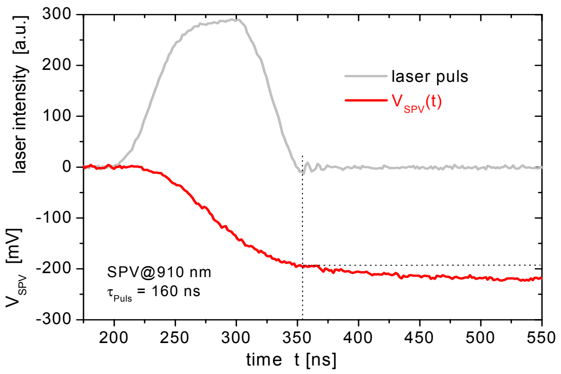


Figure 8: SPV transients, measured on a ns time scale for an a-Si:H(n)/c-Si(p) heterostructure.

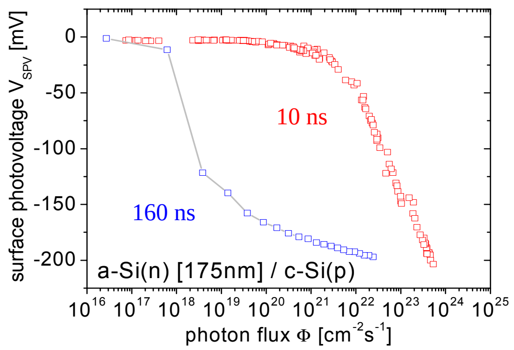


Figure 9: measured intensity dependent SPV for a a-Si(n)/c-Si(p) heterostructure using different laser excitation pulse width.

7 SUMMARY

Studying TCO/a-Si:H(n)/c-Si(p) heterostructures with intensity dependent SPV it could be proofed that (1) the TCO/a-Si:H(n) contact leads to a depletion of a-Si:H(n), (2) this contact depletion reduces the absorber band bending for ultrathin emitters (3) intensity dependent SPV is a very sensitive measure for the a-Si:H(n)/c-Si(p) interface state density.

8 REFERENCES

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