ANALYSIS OF SINGLE JUNCTION A-Si:H SOLAR CELLS GROWN ON DIFFERENT TCO’S

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ABSTRACT
A study was carried out on hydrogenated amorphous silicon (a-Si:H) solar cells with diluted intrinsic a-Si:H absorber layers deposited on glass plate covered with different transparent conductive oxide (TCO) films. The TCO layer forms the front contact of the superstrate solar cell and has to exhibit good electrical (high conductivity) and optical (high transmittance) properties.

KEYWORDS
Thin film Solar Cell, Hydrogenated Amorphous Silicon, Transparent Conductive Oxide

1. INTRODUCTION
Hydrogenated amorphous silicon (a-Si:H) is a promising semiconductor material for low-cost solar cells. Solar applications of a-Si:H are limited due to the metastable defect creation, the so-called Staebler-Wronski effect [1]. It has been demonstrated that solar cells with a-Si:H absorber layers prepared from silane source gas diluted with hydrogen in plasma enhanced chemical vapour deposition (PECVD) showed less degradation during light exposure than their conventional undiluted counterparts [2]. At present, the most important research area in the field of a-Si:H based solar cells is considered to be further development and implementation of efficient light trapping. Light trapping techniques help to capture light in the desired parts of a solar cell, which are the absorber layers, and prevent it from escaping. Efficient light trapping in a-Si:H silicon solar cells is based on scattering of light at rough interfaces and the employment of highly reflective back contacts and refractive index matching layers in order to manipulate reflection in the cell. Scattering of light at rough interfaces results in a longer average optical path through the absorber layer. Repeated reflection at the back and front contacts causes multiple passes of light through the absorber layer. These processes ensure efficient light confinement that substantially enhances light absorption in the absorber layer and increases the photocurrent of the solar cell. Transparent conductive oxide layers play a central role in light trapping approaches and, at present, determine the efficiency of the state-of-the-art solar cells. The development of TCO materials with required optical and electrical properties and optimal surface texture is today the most important issue in the field of thin film silicon solar cells.

2. EXPERIMENTAL DETAILS
The a-Si:H films under study (Tab. 1) were prepared by the 13,56 MHz rf excited parallel plate PECVD SAMCO 220N deposition system onto a clean Corning glass and silicon substrates. A change in the amount of H₂ incorporated in the films was obtained by varying the deposition conditions, especially by using the different flow rate ratios (FRR) of hydrogen and the mixture of silane in argon gas (10% SiH₄/Ar). The dilution ratio R = (H₂) / (SiH₄/Ar) was kept at the values of 0, 20, 40, 50. Summary of the deposition conditions is listed in Table 1. Several samples for each hydrogen dilution were deposited and investigated to obtain more accurate information about the microstructure properties in dependence on the deposition conditions and on the other hand also to obtain the information about reproducibility of the deposition processes. The thickness of the films varied from 140 to 570 nm.

ZnO thin films were prepared in a planar RF sputtering system, using ceramic targets in Ar working gas at a constant pressure of 1.3 Pa. Thin films with thicknesses of 800nm were deposited on Corning 7059 glass substrates at room temperature.

A series of a-Si:H p-i-n solar cells have been deposited using an rf-PECVD four chamber system equipped by load lock. Pressure during the deposition of intrinsic layer was kept at the value of 2 mbar. The plasma-enhanced chemical vapour
deposition (PECVD) method is widely used compared to other methods to deposit a-Si:H because of high quality material uniformity on a large area substrate at low temperature.

In this paper we focused our attention on influence of different TCO’s used as a front contact in solar cells with structure as follows: TCO (800, 950nm)/p-type μc-Si:H (~5nm)/p-type a-Si:H (10nm)/a-SiC:H buffer layer (~5nm)/intrinsic a-Si:H absorber layer with dilution R=[H₂]/[SiH₄]=20 (300nm)/n-type a-Si:H layer (20nm)/Ag + Al back contact (40 + 300nm). Diode sputtered ZnO:Ga, textured and non-textured ZnO:Al and commercially fabricated ASAHI U-type TCO’s have been used.

3. RESULTS AND DISCUSSION

Cell performance is often determined by the transport properties of minority carriers, which are holes in a-Si:H. Commonly the steady state photocarrier grating (SSPG) technique is used to determine the ambipolar diffusion length in amorphous silicon, from which the mobility lifetime product of the holes is calculated. Doping of hydrogenated amorphous silicon plays an important role. The purpose of doping is to manipulate the type of electrical conductivity and its magnitude by adding a controlled amount of special impurity atoms. The principal doping elements used in a-Si:H are the same as in crystalline silicon: boron for p type and phosphorus for n type material. In 1975 Spear and LeComber from Dundee University first reported that amorphous silicon could be doped by addition of boron and phosphorus. They achieved a change in conductivity of a-Si:H by mixing the silicon source gas, silane (SiH₄), with phospine (PH₃) or diborane (B₂H₆) during deposition using the glow discharge method. In a-Si:H, most of the phosphorus atoms are incorporated according to the 8–N rule. They adopt the optima threefold coordination that represents the nondoping state and is thus electrically inactive. The doping efficiency in a-Si:H, which is defined as the fraction of dopant atoms with foufold coordination, is rather low. In comparison to single crystal silicon, where the doping efficiency at room temperature is almost unity, it is in the range of 10⁻² – 10⁻¹ in a-Si:H. This means that relatively high concentrations of phosphorus atoms must be introduced in order to obtain material with high conductivity. A phosphorous atom can also be incorporated in the network as the neutral donor P⁺⁺, as illustrated in Fig. 1.c, but this configuration is characterized by a much higher energy than the optima P⁺⁺ configuration and is therefore unstable in the continuous random network. Most of the phosphorous atoms which contribute to doping are not P⁺⁺ neutral donors but charged phosphorus atoms P⁺⁺. The formation of the P⁺⁺ charged state is accompanied by formation of negatively charged dangling bond Si⁺, as illustrated in Fig. 1.b. The P⁺⁺ and Si⁺ configuration is energetically more favourable than the P⁺⁺ donor and is called the defect compensated donor.

The formation of defect compensated donors in the case of phosphorus atoms and defect compensated acceptors in the case of boron atoms is the major doping mechanism in a-Si:H. This mechanism was explained by Streed and is known as the autocompensation model. The most important result of this model is that doping of a-Si:H inelitely leads to the creation of dangling bonds. Doped a-Si:H has a defect density two or three orders of magnitude larger than intrinsic a-Si:H. The diffusion length of charge carriers in doped a-Si:H is very small compared to single crystal silicon. For this reason, a-Si:H solar cells cannot function successfully as a p-n junction, a relatively defect free intrinsic layer has to be inserted between the p type and n type layers.

Fig. 1: Possible configuration of a phosphorous atom in an a-Si:H network: (a) the nondoping state P⁺⁺, (b) the defect compensated donor state P⁺⁺ + Si⁺, (c) the neutral donor P⁺⁺.

An additional important difference between a-Si:H and single crystal silicon is that when the concentration of boron and phosphorous atoms in a-Si:H increases, the Fermi level does not move closer to the valence and conduction band mobility edges than 0,30 eV and to 0,15eV, respectively. The presence of tail and defect states in the bandgap does not allow a full shift of the Fermi level towards the band edges. A shift towards the band edges is accompanied by the building up of a large space charge in the exponentially increasing tail states that compensates the charge created by ionized doping atoms. This shift also decreases the probability that the doping state configurations of incorporated
dopant atoms are formed. The limited shift of the Fermi level in doped layers restricts the built-in potential in the junction of an a-Si:H solar cell, resulting in a lower value of the open circuit voltage, $V_{oc}$, than expected from the value of the bandgap energy.

In a-Si:H, the diffusion length of the charge carriers is much shorter than in crystalline silicon. In device quality intrinsic a-Si:H the ambipolar diffusion length ranges from 0.1 to 0.3 μm. In doped a-Si:H layers, in which the defect density due to doping is two or three orders of magnitude higher than in intrinsic a-Si:H, the diffusion length of the minority carriers is even lower. A solar cell structure based on the transport of the minority carriers in the quasi-neutral regions of the p-n junction as in the case of crystalline silicon does not work for a-Si:H. Due to the very short diffusion length the photogenerated carriers would virtually all recombine in the doped a-Si:H layers before reaching the depletion region of the p-n junction. Therefore, an a-Si:H solar cell is designed differently compared to the standard p-n junction of a crystalline silicon cell.

A schematic structure of a single junction a-Si:H solar cell is shown in Fig. 2. The active device consists of three principal layers: a p type a-SiC:H layer, an intrinsic a-Si:H layer, and an n type a-Si:H layer, which form a p-i-n junction. This structure is called the single junction a-Si:H solar cell. The doped layers are usually very thin: a p type a-SiC:H layer is ~10nm thick, and an n type a-Si:H is ~20nm thick. The doped layers have two functions in an a-Si:H solar cell. First, they set up an internal electric field across the intrinsic a-Si:H layer. The electric field should be high enough to ensure that the photogenerated carriers in the intrinsic a-Si:H layer are collected. The strength of the electric field depends on the doping level in the doped layers and the thickness of the intrinsic layer. Second, the doped layers establish low loss ohmic electrical contacts between the a-Si:H part of the solar cell and the external electrodes. Therefore, a sufficiently high electrical conductivity is required for both p and n type layers in order to form a high built-in voltage across the p-i-n junction and low resistance contacts with the electrodes.

The intrinsic layer with an optical bandgap of about 1.75eV serves as an ‘absorber’ layer. The electron-hole pairs that are generated in the absorber layer experience the internal electric field, which facilitates separation of electrons and holes. The material quality of the intrinsic layer and the strength and profile of the internal electric field determine the collection of the photogenerated charge carriers and thus the solar cell performance. The electric field profile in the absorber layer strongly depends on the defect density and its distribution in the bulk of the intrinsic layer and at the interfaces with the doped layers. The photogenerated carriers move towards the doped layers (electrons towards the n type layer and holes towards the p type layer) and are collected by the electrodes. The dominant transport mechanism of the photogenerated carriers is drift in the internal electric field, and therefore, an a-Si:H solar cell is often denoted in the literature as a drift device.

Determining the optimal thickness of the intrinsic a-Si:H layer in the solar cell is the crucial part of the solar cell structure design. The thickness of the intrinsic layer is a delicate trade-off between the absorption, which is higher in a thicker layer, and the collection, which improves when the layer gets thinner. Since the collection depends on the drift of the photogenerated carriers in the internal electric field, it is the magnitude of the electric field across the intrinsic layer and the mobility and lifetime of the carriers that determine the collection. The positions of the Fermi levels in the doped layers determine to a large extent the built-in potential across the device. The built-in potential together with the thickness of the intrinsic layer determine the magnitude of the electric field. However, the electric field is not uniform across the intrinsic layer but strongly depends on the distribution of the space charge in this layer. The space charge in
this intrinsic a-Si:H layer, resulting from trapped carriers in the gap states, cannot be neglected as is often possible in crystalline silicon solar cells. Due to the large density of the localized states in the bandgap, the charge trapped in these states substantially contributes to the overall charge in the device and determines the electric field profile. The presence of large defect densities at the interfaces with the doped layers can lead to a strong electric field in these interface region, while in the bulk of the intrinsic layer, the electric field is relatively low.

Fig.

The external parameters of the solar cells (efficiency $\mu$, fill factor FF, short-circuit current density $J_{SC}$, and open-circuit voltage $V_{OC}$) were determined from I-V measurements, which have been carried out under standard illumination conditions using an Oriel Corporation solar simulator. The experimental results were supported by the numerical simulation using ASA software developed at Delft University of Technology [3], which is designed for the simulation of multilayered device structures based on amorphous and microcrystalline solar cells. In our simulation we have focused on optical as well as electrical characterization of prepared structures.

4. CONCLUSIONS
As the result, a remarkable improvement of the $V_{OC}$ has been obtained possibly due to the use of higher ratio of hydrogen-to-silane flow during intrinsic a-Si:H absorber layer generation. Efficiency of the solar cells prepared with textured ZnO:Al front contacts in average is comparable with those prepared with commercial ASAHI U-type TCO.

5. ACKNOWLEDGEMENTS
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6. REFERENCES