Published in Journal of Non-Crystalline Solids 266-269, 1099-1103, 2000
which should be used for any reference to this work

Hydrogenated microcrystalline silicon: how to correlate layer properties and solar cell performance

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Abstract

Undoped hydrogenated microcrystalline silicon (μc-Si:H) layers and cells have been deposited by plasma chemical vapour deposition at low temperature at different powers and silane dilutions. Electronic transport properties and defect density of the layers have been compared to the cell performances to identify the important material properties for solar cell applications. A correlation is found between the defect density, $\mu^0\tau^0$ quality parameter, and cell efficiency. Anisotropy of the transport properties in some μc-Si:H is also demonstrated.

1. Introduction

Microcrystalline hydrogenated silicon (μc-Si:H) deposited at low temperatures (<300°) has gained world-wide interest for applications as a photovoltaically active material. Despite studies (by various groups), it is still unknown in which respect the material (used in the i-layers of n–i–p or p–i–n solar cells) must be optimised to obtain the largest solar cell efficiency. Following a strategy already successful for a-Si:H, Goerlitzer et al. [1] showed that (at least in some cases) solar cell efficiency correlates with the $\mu^0\tau^0$ product (deduced from ambipolar diffusion length, L_{amb}, and steady-state photoconductivity, σ_{ph}, measurements). However, due to the crystallographic texture, as well as to the columnar growth of most device-grade μc-Si:H layers, we expect anisotropy of the transport properties.

The objective of this paper is to study transport properties such as dark conductivity, σ_{dark}, L_{amb}, L_D (measured from surface photovoltage (SPV)), $\mu^0\tau^0$ products, and defect densities in four series of μc-Si:H layers, to investigate the transport properties and their anisotropies. Performance of solar cells incorporating the same layers will also be compared with layer properties to identify the most important material properties for application as a photovoltaically active layer.

2. Experimental

All μc-Si:H cells were grown by the very high frequency glow discharge (VHF-GD) deposition technique at frequencies between 70 and 130 MHz at a temperature around 200°C. Two series of layers were deposited at a fixed VHF power (6 and

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30 W) at various silane concentrations in hydrogen (1.25% to 7.5% and 5% to 8%, respectively), and two series were deposited at fixed silane concentration (5% and 7.5%) but at various powers (9 to 25 W and 30 to 70 W, respectively). A gas purifier was used to limit the incorporation into the material of oxygen contaminants coming from the gas source. Layers were either deposited on glass (Schott AF45) for conductivity and SSPG (steady-state photocarrier grating) measurements, or on glass Asahi type U or ZnO coated glass for SPV measurements. Measurements of σ_{ph} and L_{amb} were performed at a generation rate of $\approx 1.7 \times 10^{20}$ cm^{-3} s^{-1} using a Kr laser at a wavelength of 647 nm. Defect densities were deduced from the true material optical absorption at 0.8 eV; true absorptions were obtained by taking into account the light scattering effect in A-CPM (absolute constant photocurrent measurement) [2,3]. An overview of the sample deposition conditions and resulting deposition rates is shown in Fig. 1. In this figure, we note that some of the samples deposited at larger silane concentration and/or smaller power are amorphous or may have a larger amorphous fraction. Surface roughness of the layers was obtained from atomic microscope analysis.

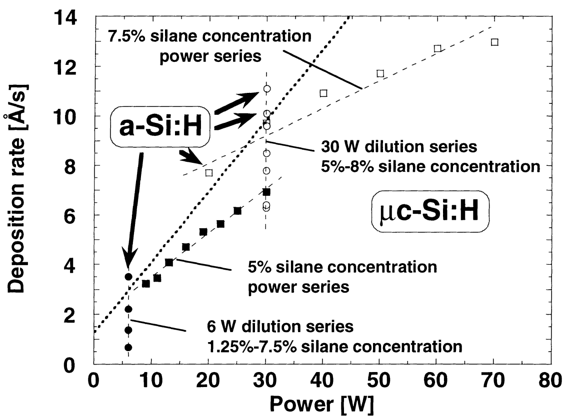

Fig. 1. Deposition rates as a function of VHF power obtained for the two dilution series (at 6 and 30 W VHF power) as well as for the two power series (5% and 7.5% silane concentration). The transition between amorphous and microcrystalline growth (as seen in optical absorption data) is schematically indicated. Lines are drawn as guides for the eye.

Layers of the 7.5% silane concentration power series and 30 W dilution series (the most interesting samples given their deposition rates) were also incorporated as the i-layer of n–i–p cells deposited on TCO-(transparent conductive oxide) coated glass substrates (Asahi type U for the power series and ZnO coated AF45 for the dilution series). The cells were terminated either with a ZnO or ITO (Indium tin oxide) top contacts. Transparent contacts on both sides were thus provided for charge collection experiments. All cells of the 7.5% silane concentration series were approximately 3.5 μm thick while sample of the 30 W series were all between 2.0 and 2.45 μm. Current vs. voltage measurements, $C(V)$, were made under air mass 1.5 conditions at 100 mW/cm^{-2} using a two-source solar simulator.

3. Results

σ_{dark}, σ_{ph} as well as L_{amb} of all samples analysed here are plotted in Fig. 2. Effect of the deposition rate is apparent on the two dilution series. Samples deposited at larger silane concentration and with a resulting increased deposition rate have smaller σ_{dark} due to fewer impurities incorporated into the material [4,5]. Materials with smaller σ_{dark} are therefore more intrinsic and thus have smaller σ_{ph}. The same trend is also observed in the 5% dilution series. The case of the 7.5% dilution series differs. This material deposited at the larger rates has the largest oxygen contamination, as observed by SIMS (secondary ion mass spectroscopy) measurements. Evidence of post-deposition oxidation is indicated by the change of σ_{dark} with time; this oxidation could be attributed to a different morphology of these μc-Si:H layers. Note that such an effect does not take place in solar cell because the doped and contact layers act as effective sealing layers. The variations of L_{amb} are approximately opposite to those of σ_{ph}, as expected.

One of the properties of μc-Si:H intrinsic layers which affects solar cells performance is the defect density. Recently, our group showed that the quality parameter, $\mu^0\tau^0$, was correlated with solar cell efficiencies [1]. Furthermore, μc-Si:H surface roughness may also affect efficiencies by increasing

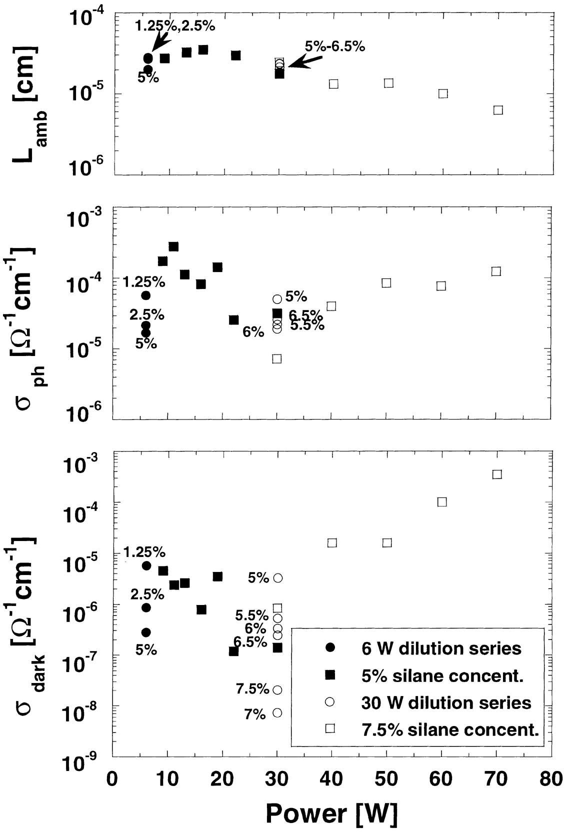

Fig. 2. Dark conductivity σ_{dark}, photoconductivity σ_{ph} and ambipolar diffusion length as a function of VHF power for the two dilution series (at 6 and 30 W) and the two power series (at 5% and 7.5% silane concentration). For the two power series, silane concentration is also indicated next to the data points. a-Si:H samples are omitted in this plot.

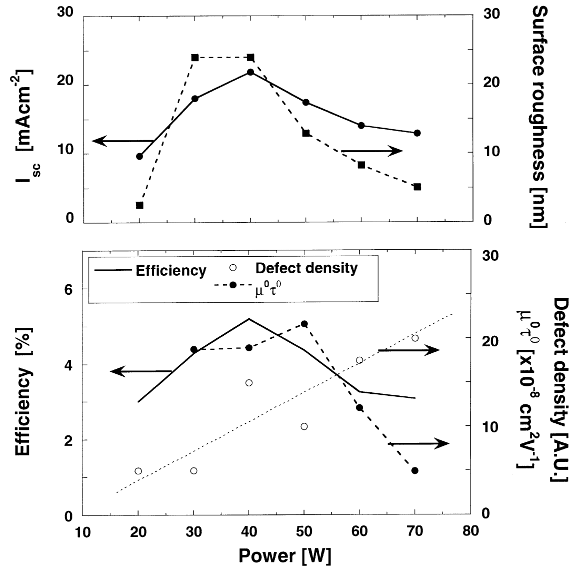

Fig. 3. Short circuit current I_{sc} and cell efficiency as a function of VHF power for the 7.5% silane concentration power series, compared with the surface roughness (evaluated from atomic force microscope scans), defect density and $\mu^0\tau^0$ product of intrinsic layers deposited under the same conditions. Sample deposited at 20 W is amorphous. Lines are drawn as guides for the eye. The errors of the measurement for I_{sc} are ±5%, for roughness ±3 nm, for $\mu^0\tau^0$ ±2%, for efficiency ±10% (relative), for defect density ±5 a.u.

the light-scattering and, as a consequence, by increasing the apparent cell thickness. Therefore, these three layer properties were monitored together with the corresponding cell properties such as short-circuit current, I_{sc}, open-circuit voltage, V_{oc}, fill-factor, FF, and efficiency, η.

In Fig. 3, layer and cell data of the 7.5% dilution series are plotted. We note that a correlation is found between surface roughness and I_{sc}, $\mu^0\tau^0$, and the cell efficiency. Decrease of the efficiency and of $\mu^0\tau^0$ at greater deposition powers is attributed to the increase of the defect density. For the 30 W power series, efficiency and $\mu^0\tau^0$ are relatively invariant (see Fig. 4). Compared to the 7.5% series, the smaller density of defects results in larger $\mu^0\tau^0$s, and greater cell efficiency, which do not change much with silane dilution. At 7% silane concentration the material is a mixed phase of a-Si:H and μc-Si:H (as seen in the optical absorption spectra) and an increase of surface roughness is observed. At larger silane concentration the material becomes more and more amorphous, the surface roughness decreases and cell performances degrade dramatically. We observed also that the V_{oc} increases close to the transition a-Si:H to μc-Si:H. Note that this transition is relatively sharp under VHF deposition conditions [6]. Further optical and structural properties of the μc-Si:H layers can be found in Ref. [7].

4. Discussion

From conductivity and defect density data, all μc-Si:H layers presented here (with the exception

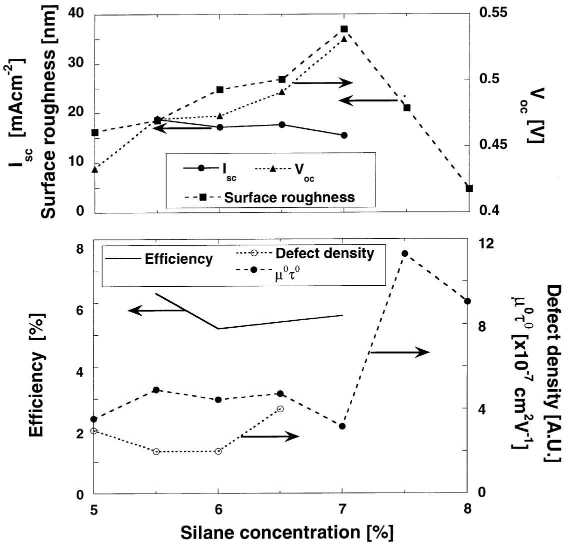

Fig. 4. Short circuit current I_{sc}, open circuit voltage V_{oc} and cell efficiency as a function of silane concentration for the 30 W dilution series, compared with the surface roughness (evaluated from atomic force microscope scans), defect density (same arbitrary units as Fig. 3) and $\mu^0\tau^0$ product of intrinsic layers deposited under the same conditions. Sample deposited at 7% is in the transition regime between amorphous and microcrystalline growth. Lines are drawn through data symbols of each type. The errors of measurement are the same as for Fig. 3 (±1% for V_{oc}).

of those deposited in the transition regime) can be considered as 'device-grade' material. For the best cell operation, a smaller σ_{dark} is required to have a more intrinsic material and therefore obtain an optimal field distribution within the i-layer of the device. However, as observed in the 30 W dilution series (cf. Fig. 2 and Fig. 3), σ_{dark} does not affect the cell performance (for the σ_{dark} measured here). More important, a decrease of I_{sc} and cell efficiency is observed, in the 7.5% dilution series, with the increase of the defect density due to the increase of the VHF power (cf. Fig. 3). Furthermore, 30 W dilution series samples (Fig. 4) have greater efficiencies which is correlated with their smaller defect densities.

When developing μc-Si:H cells, we aim at reducing as much as possible the thickness of the i-layer (which has to be relatively thick due to the indirect bandgap of c-Si) to keep the deposition time short. In this context, a material with a larger surface roughness increases the light scattering and increases the apparent cell thickness and the cell current. This suggestion seems to be confirmed by the observation of the correlation between I_{sc} and surface roughness in Fig. 3. However, on these relatively thick cells ($\geqslant$ 3.5 μm) the effect should be masked by the increase of both σ_{dark} and the defect density.

As an alternative to defect density measurements of μc-Si:H with A-CPM (which implies inclusion of light-scattering effects), we can measure σ_{ph} and L_{amb} and deduce the $\mu^0\tau^0$ quality factor. This factor has the advantage of taking into account both the band mobility and the defect density (through the recombination time) while being insensitive to the Fermi level, E_F [8]; this latter property is an advantage in the case of μc-Si:H where E_F may vary considerably with impurity incorporation. The $\mu^0\tau^0$ 'tool', developed for a-Si:H, seems also to work in the case of μc-Si:H [1], as also observed in Fig. 5. The validity of the $\mu^0\tau^0$ concept for μc-Si:H is not very surprising, to us, given the similarities in the transport properties of a-Si:H and of μc-Si:H [9]. One further advantage of $\mu^0\tau^0$ (with respect to other layer 'quality monitors') is the fact that it can be measured at illumination levels close to those of working solar cells.

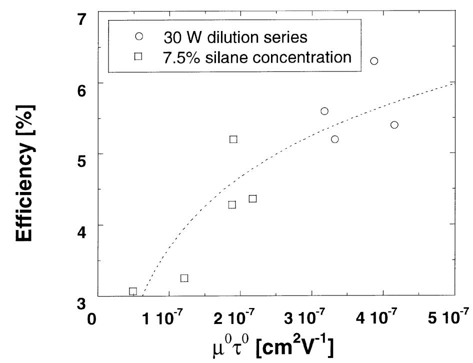

Fig. 5. Cell efficiencies as a function of the i-layer $\mu^0\tau^0$ product for the 7.5% silane concentration power series and for the 30 W dilution series. The dashed curve indicates the observed correlation for μc-Si:H samples. The errors of measurement are the same as for Fig. 3. The dashed line is drawn as a guide for the eye.

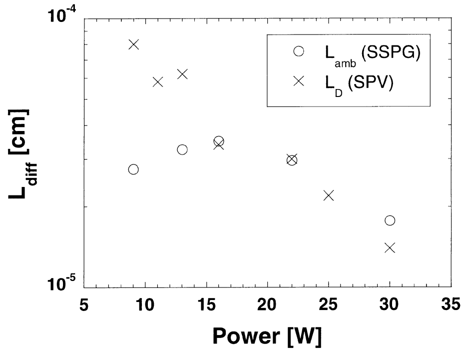

Fig. 6. Comparison between the diffusion length L_D measured by SPV and the ambipolar diffusion length L_{amb} measured by SSPG) on the power series of μc-Si:H deposited at 5% silane concentration. The errors of measurement for L_{diff} are $\pm 10^{-5}$ cm.

As far as the problems of $\mu^0\tau^0$ in μc-Si:H are concerned, this quality parameter depends on the transport in coplanar configuration, which can differ from the transport relevant for solar cells; note that this problem concerns also the CPM technique. On some device quality μc-Si:H samples, deposited usually at smaller deposition rates, such an anisotropy of the transport properties can be identified when comparing L_{amb} with L_D measured by the SPV technique (cf. Fig. 6). This anisotropy has also been observed by comparing dc and ac conductivity on the same samples [10]. However, evaluation of L_D on samples deposited close to the a-Si:H/μc-Si:H transition regime is problematic, due to yet unknown reasons.

A key parameter for greater efficiency μc-Si:H cell is V_{oc}. Improvements in V_{oc} can be made by deposition close to the transition regime (as seen in Fig. 4). However, due to the sharpness of the latter (in VHF-GD deposition), it is difficult to achieve larger V_{oc} without decreasing in FF and I_{sc}.

5. Conclusions

On high efficiency μc-Si:H cells (controlled by the bulk properties of the i-layer rather than by the interface or doped layer properties), a correlation can be observed between the defect density of the i-layer, or its $\mu^0\tau^0$, and the cell efficiency. In this context, the defect density or the $\mu^0\tau^0$ are inputs for judging the potential of μc-Si:H layers for solar cell applications. For most samples, $\mu^0\tau^0$ seems a reliable tool which has the advantage of being insensitive to E_F and affected by material properties in conditions close to those of a working solar cell. An anisotropy of the transport properties is observed in some μc-Si:H layers. This anisotropy may distort the evaluation of the layer quality factor, $\mu^0\tau^0$. The same problem could also affect the use of CPM technique.

Acknowledgements

This work is supported by the Swiss National Science Foundation under grant FN-52337 and by the Swiss Federal Office of Energy under grant 19431.

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