LIGHT SCATTERING IN MICROCRYSTALLINE SILICON THIN FILM CELLS

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ABSTRACT: Different optical characterization methods were applied to a series of microcrystalline silicon thin films, either as grown, textured, or subsequently polished, mirror-like. They reveal contributions of bulk and surface light scattering effects to the phenomenon of optical absorption enhancement. The enhanced light absorption in textured layers is mainly due to a longer optical path as a result of an efficient diffuse light scattering at the textured film surface. Root mean square surface roughness of about 40nm is sufficient for completely diffusive scattering of silicon/metal back reflector.
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1. INTRODUCTION

Hydrogenated microcrystalline silicon (µc-Si:H) has been introduced as a new photovoltaic material and leads to thin-film single-junction cells with over 7% efficiency and over 25 mA/cm^2 short-circuit current density [1]. The stable efficiency of the tandem amorphous-microcrystalline silicon (micromorph) cells is 12%. This is possible thanks to textured layers, produced by VHF-plasma deposition, that absorb more light than similarly thin (2-4 µm) layers of single crystalline silicon. In previous work [2,3] we have shown that this enhancement of the optical absorption is mainly due to light scattering effects. It is of importance for future technological work to distinguish between light scattering through crystallite structure (columnar growth) in the bulk of the layer and light scattering from the rough surface. Here, for the first time, we are able to discriminate between these two contributions to the light scattering.

We have applied a complex optical characterization methods to these layers (either textured, as grown, or subsequently polished, mirror-like) to distinguish between both contributions. Transmittance, reflectance and absorptance (with the help of Constant photocurrent method, CPM) have been measured in a broad spectral range to determine the surface roughness σ and surface scattering, bulk scattering and the true optical absorption coefficient α. Increase in light absorption in the microcrystalline solar cell has been modeled as a function of surface texture (roughness).

2. EXPERIMENTAL

Microcrystalline silicon layers and solar cells were deposited by the very high frequency glow discharge method, VHF-GD, using high dilution of silane in hydrogen, with and without a purifier [1,3,4]. Layers were deposited on AF45 glass, under similar conditions as the corresponding cells. The typical film thickness was around 2 µm. As grown textured layers were chemomechanically polished up to a mirror-like surface to observe the influence of the rough surface on the optical properties. In some cases, also additional hydrogenation and annealing was used to eliminate small subsurface damage.

A computer-controlled single-beam spectrometer was used for the transmittance/reflectance measurements in the 0.6 - 3 eV spectral region. The light beam diameter was limited to 1 mm in order to suppress the influence of possible variation of the layer thickness on modulation depth of interference fringes.

The absorptance was measured directly with the help of the Constant photocurrent method, CPM. CPM was used both in the standard mode and as "Absolute CPM" [5]. Layers were equipped with coplanar Al or Cr electrodes evaporated with the interelectrode spacing varying from 30 µm to 3 mm. The contribution of the scattered light to the CPM signal is changed by this way and the "true" optical absorption coefficient α can be calculated [6].

3. EXPERIMENTAL RESULTS

3.1 Transmittance/reflectance measurement on smooth and textured layers, evaluation of surface roughness and light scattering

The spectral dependence of the specular transmittance / reflectance of a typical layer is shown in Fig. 1.

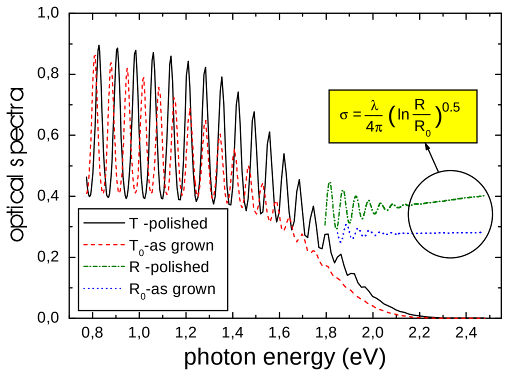

Fig.1 Transmittance and reflectance spectra of the :c-Si:H, measured on the sample with as grown textured surface and after chemomechanical polishing

The detector (or the integrated sphere with a detector) is placed far behind the sample. In the case of textured surface, the modulation depth of interference fringes is reduced due to light scattering. The “scalar scattering theory”, which considers just the phase modulation of the incident and outgoing light by the height variations along the surface, has been used to interpret the data and evaluate the root mean square (rms) surface roughness σ [7-10]. Roughness was also computed from the ratio of reflectance of the smooth and textured side [9], in the region of complete absorption and checked by the atomic force microscopy, AFM. We have observed rms roughness of microcrystalline silicon in the range 0 – 40 nm for layers of about 2 μm thickness. Typically, (220) textured layers have a rms surface roughness in the range of 15 – 35 nm.

3.2 Angular dependence of diffuse scattering

An ideal diffusing surface (Lambertian surface) has the property that the intensity of light originating in a given direction from a small surface component is proportional to the cosine of the angle between that direction and normal to the surface. With the help of a He-Ne laser and a goniometer we have checked several different microcrystalline samples with preferential (220) orientation and compared them with the Spectraflect diffuser (made by Labsphere, Inc.) and theoretical cosine distribution. Results for angularly resolved scattered intensity are presented in Fig. 2. We observe a small departure from the ideal behavior for all materials.

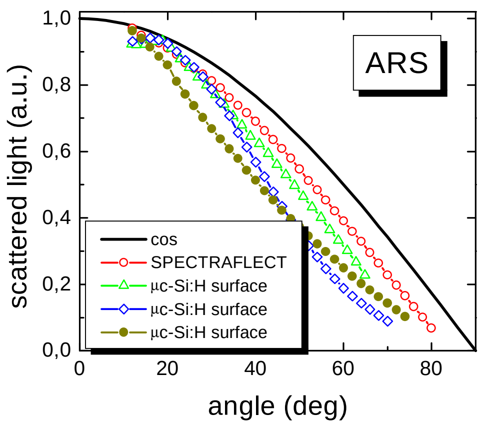

Fig.2 Angularly resolved distribution of the (reflected) scattered light of three different :c-Si:H textured surfaces, compared to the Spectraflect and theoretical cosine distribution

3.3 Study of textured and smooth layers by the Constant photocurrent method (CPM)

For the evaluation of the "true" α(E) and the defect-connected, (typically very low) subgap optical absorption in thin films of microcrystalline silicon deposited by VHF-GD, we need a method, which measures directly the absorptance in the film down to values of 10^{-6}. Both, PDS and CPM, well known from the field of amorphous silicon, can be used. They give us an "apparent" optical absorption coefficient $\alpha_{app}(E)$, influenced by scattering. We have preferred in this study to use CPM. CPM detects the light absorbed (either directly or after one or more scattering events) in between the electrodes used for the photocurrent measurement. By changing the spacing between the electrodes over two orders of magnitude, we can vary the contribution of light scattering upon the measured, "apparent" optical absorption coefficient α_{app}. For the case of weak bulk scattering we have presented a theory for the evaluation of true optical absorption coefficient α(E) in Ref. [11], for the case of multiple scattering in Ref. [6]. Details will be presented in Ref. [12], together with a theory for the surface scattering.

Here we present CPM data together with true α determined from T/R measurements [9,10] and from CPM data [6,12] for the samples with preferential (220) texture. Figs. 3a, 3b show the sample “A”, with the as grown (textured) and polished (mirror-like) surface. We can see that the effect of light scattering on CPM spectra disappeared after polishing, hence, the sample has negligible bulk scattering and we directly measure true optical absorption coefficient.

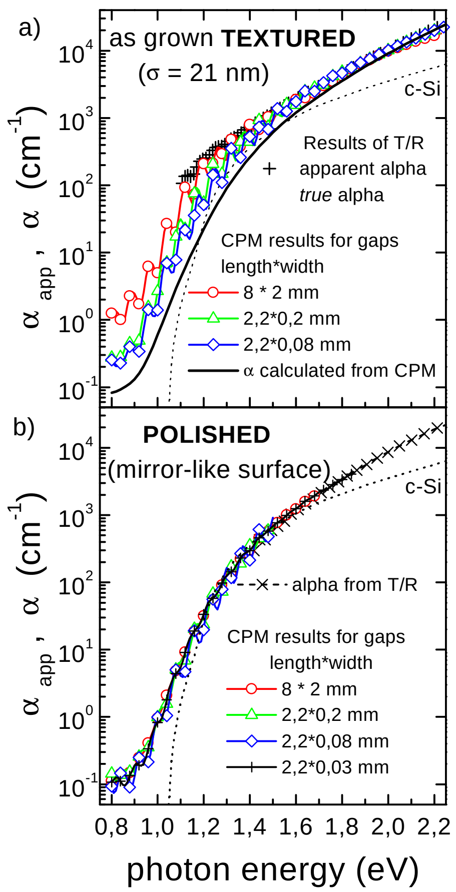

Fig.3 Apparent optical absorption coefficients of the sample “A” measured by CPM with different interelectrode spacing (gap) and calculated from T/R measurements: a) in the as grown state with TEXTURED surface and b) after chemomechanical POLISHING. Evaluated spectral dependence of the *true* absorption coefficient ∀(E) is shown by full line as the main result; ∀(E) of crystalline silicon is shown for comparison

Figs. 4a, 4b show the sample "B", prepared at a high deposition rate (over 1nm/sec), again with the as grown (textured) and polished surface. In the sample B there is a strong difference in CPM spectra, measured with a different distance between the electrodes also for the polished surface. Hence, also a strong bulk scattering has to be present [6,11,12]. Evaluated bulk scattering coefficient $\alpha_s = 28*E^4$, where E is the photon energy (eV).

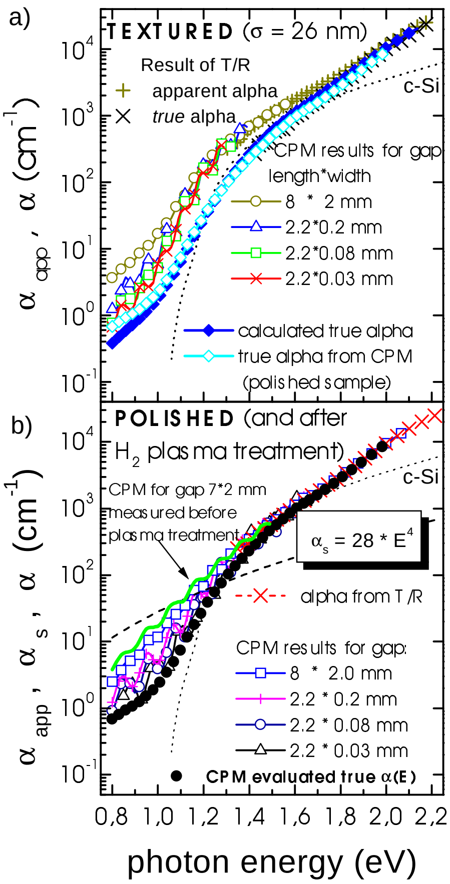

Fig.4 Apparent optical absorption coefficients of the sample "B" measured by CPM with different interelectrode spacing and calculated from T/R measurements: a) in the as grown state with TEXTURED surface and b) after chemomechanical POLISHING and plasma treatment. Evaluated spectral dependence of the *true* absorption coefficient ∀(E) is shown by solid circles or diamonds as the main result; ∀(E) of crystalline silicon is shown for the comparison.

4. DISCUSSION

Surface texture of microcrystalline Si thin films and thin solar cells is quite different from the surface texture of solar cells based on thick Si wafers. Height variations of the microcrystalline Si surface are smaler than the wavelength of light, in contrast to the pyramidally textured and grooved surfaces of Si wafers with height variation larger than the wavelength. We have mentioned typical rms surface roughness of 220 textured layers to be below 40 nm. The needle-like grains in the layer, in the direction of growth, have a diameter of the order of tens of nanometers. Hence, we can use the scalar scattering theory for random rough surfaces, as described in Ref. [6]. Application of this theory for evaluation of transmittance/reflectance data is in Refs. [8-10] and for CPM data in Refs. [6,12]. A crucial parameter, which describes diffuse scattering at random rough surface with a small correlation distance, is the scattering factor S [8,9]. The amplitude of specularly reflected wave is modified by this factor S, given for the case of external (internal) reflection by eqs. 1 and 2 and for the case of transmitted wave by eq. 3 (see Fig. 5).

$$S_{ext} = \exp\left\{-\frac{1}{2}\left(\frac{4\pi\, n_0\, \sigma}{\lambda}\right)^2\right\} \quad (1)$$

$$S_{\rm int} = \exp\left\{-\frac{1}{2}\left(\frac{4\pi\, n\sigma}{\lambda}\right)^2\right\} \quad (2)$$

$$S_t = \exp\left\{-\frac{1}{2}\left(\frac{2\pi\,(n-n_0)\,\sigma}{\lambda}\right)^2\right\} \quad (3)$$

where λ is the wavelength in vacuum, σ is rms surface roughness, n and n_0 is the index of refraction of Si and air.

In Fig. 5 we plotted the square of these factors because the intensity is proportional to the square of amplitude. For the case of internal reflection (e.g. at the back reflector of solar cell) and rms surface roughness in the range 40-50 nm the specular part of reflection vanishes because $(S_{\rm int})^2$ approaches to zero and we have just the diffuse reflection. This is not the case for transmission through a surface of the same roughness, as it can be deduced from Fig. 5.

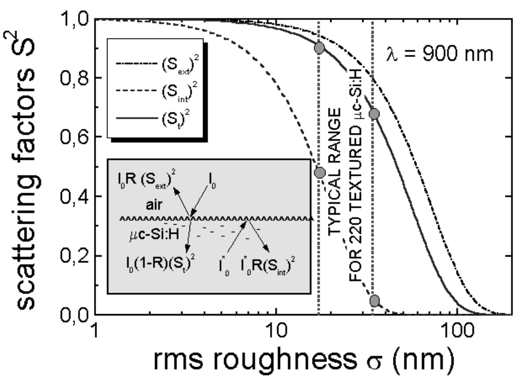

Fig.5 External and internal reflection and transmission scattering factors of a rough surface, plotted versus the rms surface roughness, for wavelength 8=900 nm

In Fig. 6 we present results of computer modeled absorption in microcrystalline Si solar cells. The modeled cell consists of a 3.5 µm silicon film deposited on flat front TCO window, rough microcrystalline Si surface is covered with silver (95% reflectance). The rms surface roughness of the textured microcrystalline Si layer is a parameter. We see a strong improvement of infrared response due to light scattering, it saturates at reasonably moderate rms surface roughness (40 nm). In our model, a real angular distribution of the scattered light can be used instead of the theoretical cosine distribution and TCO roughness can be included.

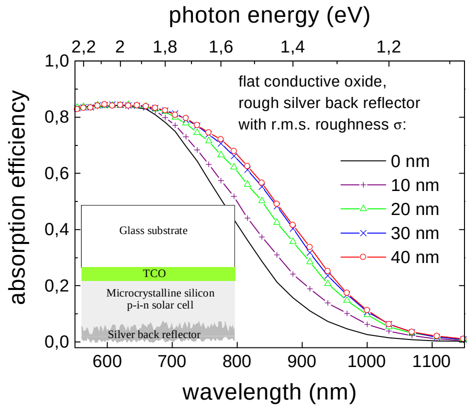

Fig.6 Calculated spectral dependence of the absorption efficiency for 3.5 :m thick microcrystalline solar cell without antireflection coating, with a different texture of the back reflector

5. CONCLUSIONS

We have experimentally demonstrated that an absorption enhancement in (220) textured microcrystalline silicon thin film solar cells in the infrared region comes mainly from the surface scattering. Surface roughness of about 40 nm (root mean square value) is sufficient for complete diffuse scattering for the case of internal reflection (solar cell with diffusive back reflector). If the light is coming through a rough surface then the same roughness is not sufficient for an efficient scattering.

Bulk scattering, due to heterogeneity of microcrystalline silicon, contributes significantly in the subgap spectral region, where both kinds of scattering can create the maximum possible absorption enhancement (for an ideal diffuse scattering it is given just by the indices of refraction, in the negligible-absorption region [13]).

Low defect density (characterized by a "true" optical absorption coefficient α smaller than 0.1 cm^{-1} at about 0.8 eV) and a distinct surface texture with rms roughness over 30 nm is characteristic for our fully microcrystalline, thin solar cells having efficiency over 7%.

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