FLEXIBLE MICROCRYSTALLINE SILICON SOLAR CELLS ON PERIODICALLY TEXTURED PLASTIC SUBSTRATES

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ABSTRACT: Roll-to-roll processing of thin film solar cells on flexible low cost substrates is an attractive option to lower the production cost of photovoltaic modules. Plastic substrates like PET or PEN are insulating which potentially offers advantages compared to conducting steel foils. However, plastic substrates require lower processing temperatures and novel schemes for efficient light trapping. In this paper we present results of microcrystalline solar cells on periodically textured substrates. Optical characterization of the back reflector revealed the presence of plasmon resonance effects which are mediated by the periodic structure. In TEM investigations we found that the structure is maintained congruently throughout the high index silicon layers. Microcrystalline silicon solar cells on the textured substrates reveal a gain in photocurrent of 27 % compared to flat reference cells. The gain is largely explained by an improved response in the spectral region between 650 and 1000 nm. The best cells on PEN substrates reached efficiencies of 8.2 %.
Keywords: Microcrystalline silicon, Light trapping, Optical losses

1 INTRODUCTION

Enhanced light absorption is a desirable feature of thin film silicon solar cells because it allows reducing the absorber layer thickness. In case of amorphous silicon thinner absorber layers show less light induced degradation, whereas in case of microcrystalline material enhanced absorption is desirable because its indirect band gap results in weak response to red and near IR light. An efficient way to enhance the absorption is light scattering at textured surfaces which results in a prolonged light path within the absorber layer. The effect is further increased by a highly reflective back contact which reflects weakly absorbed light back into the absorber layer.

Commonly thin film silicon solar cells and modules are fabricated in p-i-n structure on rigid glass substrates. The substrates are usually coated with a textured transparent front contact which also acts as a light scattering element. The surface texture is achieved by adapted growth processes [1,2] or by a texture etch after growth [3].

Flexible solar modules on plastic or steel foils, on the other hand, are an attractive alternative to rigid solar modules on glass. They are lightweight and easily applicable to building integration. Additionally, roll-to-roll deposition technologies hold considerable potential to lower the cost of module production. Flexible thin film silicon solar cells are usually fabricated in the n-i-p configuration, and different methods of incorporating light scattering surface structures are in use.

In this paper we report on flexible solar cells fabricated on plastic substrates with a periodically textured surface. Compared to flat reference cells they show a significantly enhanced photocurrent density.

2 EXPERIMENTAL

We use low cost plastic substrate materials like poly-ethylene-terephtalte (PET) or –naphtalate (PEN). The surface of the substrates is textured with a proprietary process which can produce a wide variety of surface structures and replicas of given morphologies [4]. The results presented here were obtained on periodically textured structures. They were covered with a reflector stack consisting of Cr-Ag-ZnO which was deposited by a roll-to-roll process in a large area multi-source sputtering system at the Fraunhofer Institut für Ionenstrahl und Plasmatechnik (FEP), Dresden [5]. Additionally, flat reflectors consisting of Cr-Ag-ZnO on glass (Schott AF 45) were deposited in house by sputtering and used as flat reference substrates.

Microcrystalline silicon was deposited in a single chamber system with base pressure in the lower 10^{-8} mbar range. The absorbers are grown in n-i-p sequence by plasma enhanced chemical vapour deposition at very high excitation frequencies (VHF-PECVD) between 70 and 140 MHz.

Finally, the transparent front electrode is deposited by low pressure (LP-) CVD [2]. It consists of boron doped ZnO which is deposited under conditions which result in a textured surface with an rms roughness of about 30 nm.

3 SOLAR CELL RESULTS

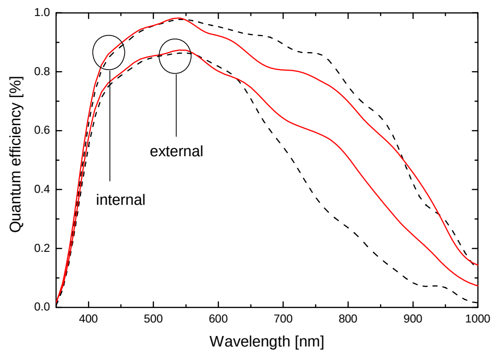

Figure 1: External and internal quantum efficiency of microcrystalline solar cells on textured PEN (full) and flat reference (dashed lines).

Figure 1 compares the quantum efficiencies of solar cells on textured and flat substrates in the spectral range from 350 to 1000 nm under short circuit conditions. The thickness of the microcrystalline n-i-p stack amounts to

1.55 μm. On the textured substrate the light conversion is greatly enhanced in the spectral region above 700 nm. The short circuit current densities are calculated by multiplying the spectral response with the AM1.5 spectrum and subsequent integration. We find current densities of 17.9 and 22.8 mA/cm^2, respectively, revealing a gain of 27%.

Figure 1 also includes the internal quantum efficiencies where the external data have been corrected by data from reflection measurements of the different solar cells. It is observed that the textured cell suffers from some loss in the spectral region between 650 and 800 nm. A possible origin could be increased absorption in the reflective back contact; surface textures have been reported to increase the absorptive losses of silver and other metallic layers [6].

On the textured substrates we also frequently observe slightly reduced values of open circuit voltage and fill factor, but the gain in current more than balances the losses in terms of solar cell efficiency. Table I compares the parameters of cells on textured plastic and the flat reference substrate. The table includes results obtained from a process in a double chamber system which reduces the amount of cross contamination between the doped and intrinsic layers [7]. These results clearly show the potential of using the investigated substrate texture.

Table I: Performance parameters of the textured and flat solar cells in figure 1. A recent result from a two chamber system is included.

	V_{oc} [mV]	I_{sc} [mA/cm^2]	FF %	η %
textured	491	22.8	69	7.7
flat	515	17.8	74	6.7
(double chamber)	*531*	*22.2*	*70*	*8.2*

4 FILM MORPHOLOGY

For high efficiency cells and better utilization of the solar spectrum, we also develop micromporph tandem n-i-p cells. In this case, the surface of the microcrystalline cell acts as textured "substrate" for the amorphous top cell. In order to study the development of morphology on the textured substrates we prepared a cross sectional sample of a micromorph tandem cell for TEM analysis.

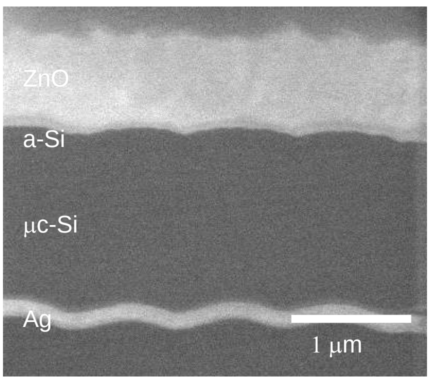

Figure 2: Cross section of a micromorph tandem solar cell after preparation by focussed ion beam (FIB).

A snapshot of the cross section sample preparation is shown in Figure 3. Compared to the substrate, the peak to valley depth at the surface of the microcrystalline and the amorphous silicon films is slightly reduced. The in plane periodicity, however, is clearly maintained throughout the silicon films.

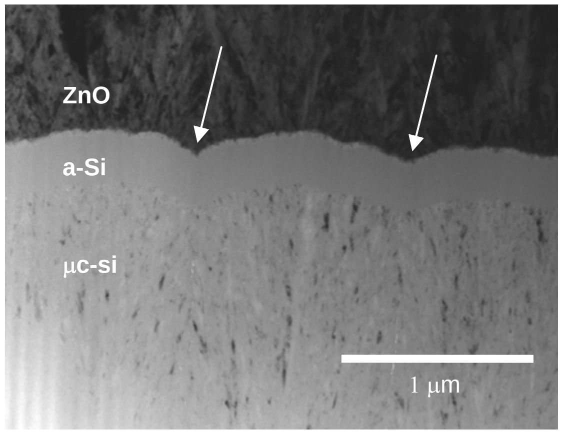

Figure 3: TEM cross section through the upper part of a micromorph tandem solar cell. In the middle is the amorphous i-layer, the upper dark part represents the ZnO front contact.

In the TEM image in Figure 3 it is observed that the surface of the microcrystalline layer forms more pointed valleys (see arrows) while the curvature of the peaks becomes slightly shallower. Nevertheless the interfaces of the high index silicon films exhibit a laterally coherent periodicity. The situation seems analogous to diffractive gratings where phase relations are predominantly based on the lateral properties and only to a lesser extent by the vertical dimensions. We conclude that coherent scattering of light waves will have substantial influence on the optical properties of this solar cell structure.

5 REFLECTIVE PROPERTIES OF THE TEXTURED BACK CONTACT

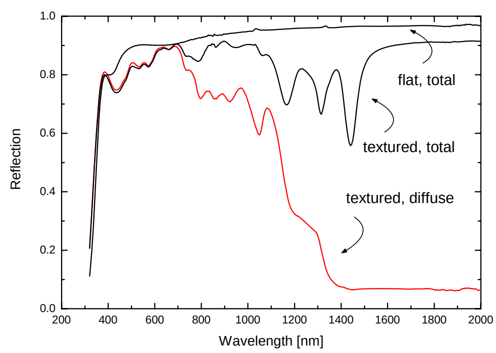

Figure 4: Reflective properties of the Cr-Ag-ZnO back contact. Compared to the flat reference, the reflector on the textured substrate shows several dips in the total reflection.

The periodic structure of the textured substrate strongly influences the reflective properties of back contact. In Figure 4 almost completely diffuse reflection up to wavelengths of 700 nm is observed, followed by a plateau around 80% between 700 and 1100 nm. For longer wavelengths the diffuse part rapidly decreases and above 1400 nm the properties are completely governed by specular reflection. Figure 4 also compares the total reflection of the textured substrate and that of the same reflector stack on flat substrate. There are three distinct dips in the wavelength range from 1150 to 1500 nm and several less clearly resolved features at lower wavelengths.

Dips of this nature have earlier been reported for reflection from periodically structured metal surfaces. They are attributed to the excitation of plasmon resonances which are mediated by the surface structure [8,9]. The description of plasmons usually considers with the properties of the flat surface and treats the surface structure as perturbation. When electromagnetic radiation is incident on a flat metallic surfaces the charge distribution is modulated in the manner of waves propagating along the surface. These surface waves are also called surface plasmon polaritons; they are described by the following dispersion relation:

$$k(\omega) = \frac{\omega}{c}\sqrt{\frac{\varepsilon'(\omega)}{\varepsilon'(\omega)+1}}$$

Here, ω and k, denote the angular frequency and the wavevector of the surface wave, c represents the speed of light and $\varepsilon'(\omega)$ is the real part of the dielectric function of the metal. The relation $k(\omega)$ is given instead of $\omega(k)$ because the dielectric functions are normally tabulated in dependence of the angular frequency. For example, Figure 5 shows $\varepsilon'(\omega)$ of ideal metals according to the Drude model, and of silver [10]. The square root of the dispersion relation has real solutions for values of $\varepsilon'(\omega)$ below -1, for silver this is the case up to 3.65 eV.

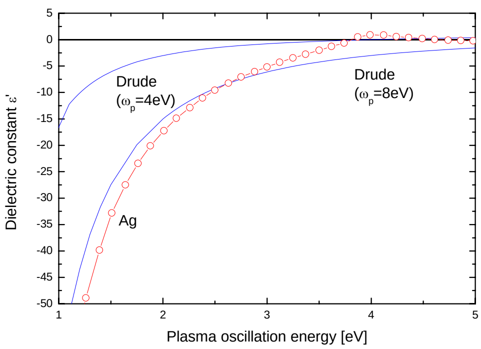

Figure 5: Real part of the dielectric function for silver (open symbols) [10]. The lines represent the theoretical relationship according to the Drude model for Plasma energies of 4 and 8 eV, respectively.

The dispersion relation for the silver surface has been calculated from the reported dielectric function and is shown as continuous line in Figure 6. For photons the dispersion relation is given by the linear relationship $\omega(k)=ck$. In the present context it is always the in-plane component k_x that should be considered. If θ is the angle with respect to the surface normal, it is given by the following equation:

$$k_x = k_{\text{Photon}} \cdot \sin\theta$$

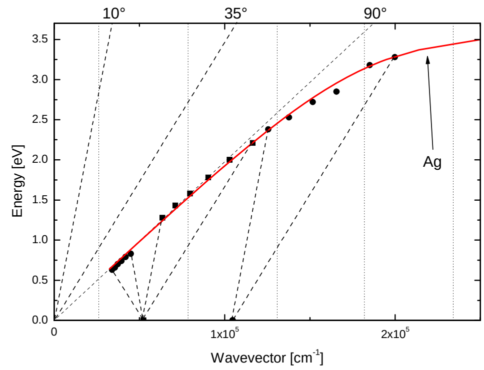

Figure 6: Dispersion relation of the plasmon of a flat silver surface (full line). The dashed straight lines represent the energy $\hbar\omega$ versus k_x of photons under different angles of incidence. Measurements on a textured substrate coated with Ag are represented by full symbols. The vertical dotted lines represent the Brillouin zone boundaries of the reciprocal lattice.

In a dispersion diagram like Figure 6 photons are represented by straight lines through the origin, and different angles of incidence correspond to different slopes. Interactions between a photon and a surface plasmon are only possible if energy and momentum are conserved at the same time which is the case when the characteristics intersect. Figure 6 shows that this condition is never fulfilled on an ideally flat surface; the plasmon curve is always below the photon line, even for the limiting case of grazing incidence (θ=90°).

On real surfaces with roughness the situation is different; particularly on surfaces with periodic texture a reciprocal lattice can be defined like in the case of crystalline materials. It is then possible to realize momentum conservation by adding a reciprocal lattice vector $G=2\pi/L$ where L is the period of the structure.

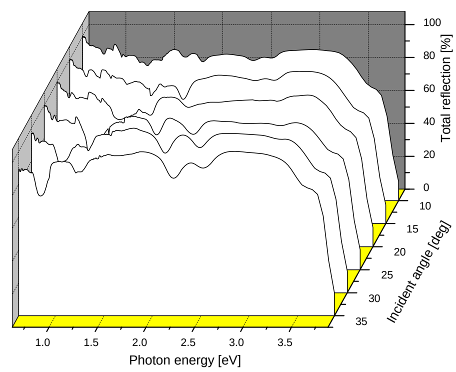

Figure 7: Total reflection of a Cr-Ag on the textured substrate with for incidence between 10° and 35°.

We tried to relate the reflection dips in figure 4 to excitations of surface plasmon resonances. Figure 7 shows angle resolved reflection measurements between 10° and 35° of a somewhat simpler system where the ZnO layer was removed from the reflector. It is observed that the positions of the dips change systematically with the angle of incidence. By recording the energy of each dip (or shoulder) in a series versus the k-value of its corresponding in-plane wavevector, we are able to sample points where the dispersion relation of the incident photon intersects with the dispersion relation of the surface plasmon. The dispersion relation of the surface plasmon can be reconstructed by adding or subtracting integer multiples of the reciprocal lattice vector G.

The procedure is illustrated in Figure 6 where we assumed that the two series with the lowest energies require a shift of at least one reciprocal lattice vector. The dashed lines originating from the centre of the second Brillouin zone represent the limiting angles of 10° and 35° for two series where increasing the angle of incidence shifts the dips to lower and higher energies, respectively. For a third series at higher energy we assumed a shift into the third Brillouin zone. The resulting data is found to be in excellent agreement with the plasmon dispersion relation of silver.

6 EFFECT OF THE TEXTURE ON THE CURRENT COLLECTION

In the previous section it was found that the periodically structured substrate shows a strong influence on the angular reflection properties of the back reflector. Therefore, the periodic structure is also expected to influence the current collection in the spectral region between 700 and 1100 nm where light can pass all the way to the back reflector due to the weak absorption of silicon. Figure 8 compares the short circuit current density of a textured solar cell and the flat reference for angles of incidence between 0 and 65°. For a better assessment of gain in photocurrent collection the data have been corrected for the purely geometric $\cos\theta$ dependence of oblique incidence.

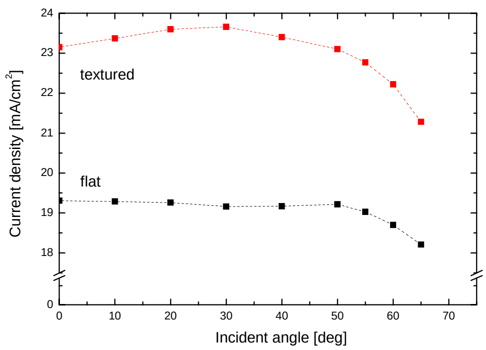

Figure 8: Short circuit current density of a textured solar cell and its flat reference with respect to the angle of incidence.

It is observed that collection of the flat cell shows little changes up to 50°, for higher angles the reflection from the front surface results in lower currents. On the textured cell there is a clear increase for higher angles with a maximum at 30°. The same tendency has been observed on a cell where the rough ZnO front contact was replaced by a nominally flat ITO layer. Based on geometric optics we expect that refraction will reduce the actual range of angles in the silicon layer to less than 15° compared to the bare reflector. Further experiments are required to explain whether the increased current density is a consequence of better light trapping by total internal reflection within the silicon layer, a texture enhanced coupling of light into a guided mode, or reduced absorption loss of the plasmon resonance on the silver surface.

7 CONCLUSIONS AND OUTLOOK

We presented the development of microcrystalline thin film silicon solar cells on flexible plastic substrates with a periodic surface texture. An investigation of the back reflector structure revealed distinct absorption phenomena. These are related to the excitation of surface plasmons which is mediated by the periodic structure of the substrate. Cross sectional analysis of the solar cell structure showed that the lateral dimensions of the periodic substrate structure is reproduced in all interfaces throughout the solar cell stack. We presented angle resolved measurements on the influence of the periodic structure on the current collection in the solar cell where we found increased light conversion for incident angles of 30°. Under standard perpendicular illumination conditions the solar cells on textured show a current enhancement of 27% compared to the flat reference.

In future we will perform more detailed investigations of the unique optical properties of solar cells on the textured substrate. For further improvements it is necessary to understand the relation between the morphology of the solar structure and the light conversion.

8 ACKNOWLEDGEMENTS

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