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REDUCTION OF REFLECTION LOSSES OF PV-MODULES BY STRUCTURED SURFACES

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Abstract—Structuring the transparent cover of solar cell modules reduces reflection losses, particularly at large angles of incidence. Relevant aspects are good transmission efficiency independent of wavelength and a low sensitivity to pollution. The macroscopic, linearly grooved structure proposed in this article shows good performance only in combination with a textured cell because large angles are likely to occur inside the structured cover. A classification is made with the concept of annual averaged transmission efficiency for the climatic zone of Freiburg. Calculations and measurements for different combinations of smooth and structured covers and solar cells are presented. From the calculated 97.8% entering the structured glass cover, a measured 93.2% can be coupled into a pyramidal textured monocrystalline solar cell. This is an absolute improvement of 17% compared to a smooth, uncoated solar cell with a smooth glass cover. Outdoor measurements showed that a textured solar cell with a structured cover has between 5 and 10% higher values of short-circuit current than a textured cell with a smooth cover.

1. INTRODUCTION

On its way into the solar cell material, a part of the incoming sunlight is reflected and cannot take part in the conversion process inside the cell. It is thus an important task to get as much sunlight into the solar cell as possible (i.e., to reduce reflection losses).

Transparent antireflection coatings are commonly used in present-day solar cell fabrication to reduce reflection losses. By choosing the appropriate refractive index and thickness, reflection losses can be suppressed totally for one wavelength (usually 600 nm for silicon solar cells) and one direction of the incoming light (usually normal to the solar cell surface). The unwanted dependence on wavelength and direction can be reduced but not avoided by combining two or more antireflection coatings, as shown by Green (1986). Reflection losses of 4% for usable sunlight at normal incidence can be obtained.

In a simple model, a part of the light reaching the solar cell is reflected due to sudden changes of the optical density or the refractive index. A smooth, uncoated silicon surface exposed to air has such a refractive index change with a value of about 3.5 and reflects about one third of the incoming sunlight at normal incidence.

The amount of reflected light depends strongly on the value and on the steepness of the change of the refractive index. If we constructed a transparent cover of a solar cell in which the refractive index varies continuously from air (n = 1.5) to silicon (n = 3.5), no light would be reflected and 100% of the incoming sunlight could take part in the conversion process inside the solar cell. Because such a cover has not yet been developed, other (less effective) mechanisms must be used to reduce reflection losses.

In all practical applications, the solar cells are covered with a transparent glass plate. Such a glass cover (with n = 1.5) not only protects the solar cell against damage, but, assuming that there is good optical contact to the cell, also divides the large change of refractive index into two smaller ones. Reflection losses are reduced to about 20% (without antireflection coating) at normal incidence.

Using this simple model, a structured surface has an average refractive index that rises continuously with depth. The sudden change in the refractive index is thus smoothed and reflection is reduced.

Structuring the surface of $\langle 1, 0, 0 \rangle$ oriented, monocrystalline silicon solar cells by means of a selective etch (i.e., texturing the solar cell surface) has become an established method to reduce reflection losses not only for high-efficiency laboratory solar cells. These textured cells have, compared to antireflection coated ones, the advantage of low reflection for all usable wavelengths and over a wide range of directions of the incoming light. This article also discusses structuring the transparent glass cover.

2. BASIC PRINCIPLE

On a structured surface, incoming light rays are reflected several times, giving them several chances of being refracted into the material. The simplest case is a randomly roughened surface. Such a surface is not suitable for a cover of solar modules because pollution (e.g., dust particles) would give rise to an inverse effect (i.e., an increase of reflection and absorption losses). Possible angles of incidence of direct solar radiation onto a stationary surface tilted toward the south by the geographic latitude angle are $-90° < \alpha < 90°$ in the east–west and $-23.45° < \alpha < 23.45°$ in the north–south directions, respectively (α being the angle of incoming light rays with respect to the normal to the surface).

It is desirable to find a structure that transmits light falling within these angles and is not sensitive to con-

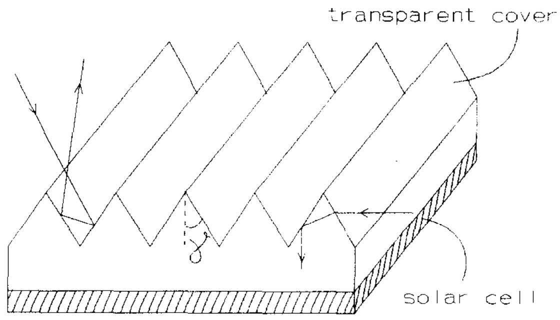

Fig. 1. Grooved structure on a transparent cover of a solar cell.

tamination. We suggest the grooved, prism-shaped structure shown in Fig. 1. Such a structured transparent cover is mounted with the grooves pointing in north-south direction. If the whole solar cell module is then tilted toward the south—on a rooftop, for instance—rainwater can run down the grooves, cleaning them effectively (Goetzberger, 1990). The structure is of arbitrary but macroscopic scale so that geometric optics are valid. This ensures (ignoring dispersion effects) independence from the wavelength.

The apex half-angle γ should, on the one hand, be as small as possible to ensure several reflections for incoming rays from all directions. On the other hand, light that has entered the glass should not be refracted outward again. So a light ray coming from the most extreme direction of incidence (i.e., $\alpha = 90°$) must undergo total internal reflection after being refracted into the glass (Fig. 1). This leads to the following formula for the apex half-angle γ:

$$1/n = \sin(2\gamma - \arcsin(\sin\gamma/n))$$

For a refractive index of $n = 1.5$, $\gamma = 32°$ is found.

3. PERFORMANCE

Using a ray-tracing procedure, Scheydecker *et al.* (1991) calculated the transmission of such a structured

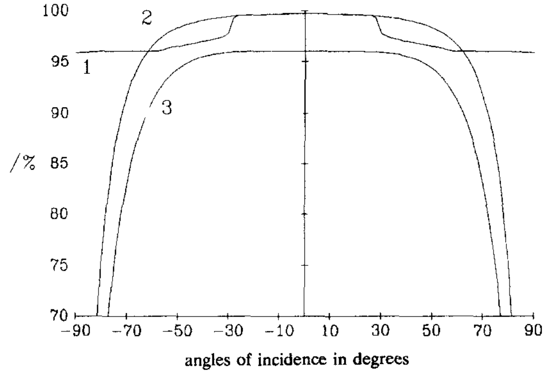

Fig. 2. Transmission versus angle of incidence for a structured surface, perpendicular (1) and parallel (2) to the grooves and for a smooth surface (3).

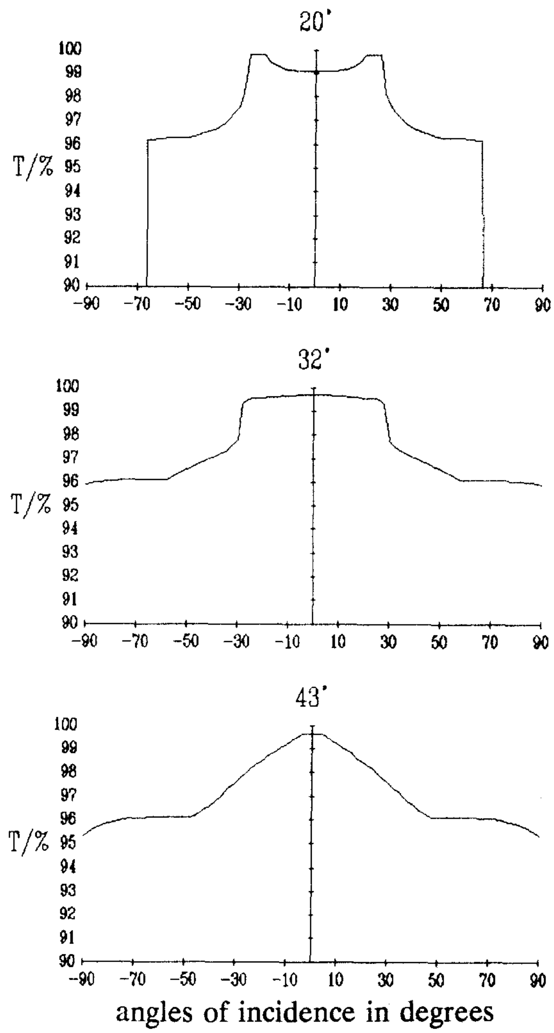

Fig. 3. Transmission versus angle of incidence perpendicular to the grooves for different apex half-angles, $\gamma = 20°$, $32°$, and $43°$ ($n = 1.49$).

surface depending on the angle of incidence of incoming light rays. The results are presented in Fig. 2. The curves parallel and perpendicular to the grooves of the structure and that of a smooth surface are plotted. A noticeable increase of 3.7% at normal incidence to almost 100% (99.7%) can be obtained in theory. Because the curve perpendicular to the grooves, corresponding to east–west directions, does not fall below 95% even for large angles, direct solar radiation will be transmitted through the surface effectively throughout any day of the year. (One must bear in mind that all transmission values presented in this article must be multiplied with the cosine of the angle of incidence to obtain realistic values, because only that part of the solar cell area is seen by the incoming light ray.)

Next we examined the influence of different apex half-angles on the transmission. Figure 3 shows the transmission versus angle of incidence curves perpendicular to the grooves for three different apex half-angles γ. With the small apex half-angle ($\gamma = 20°$), the transmission drops rapidly at large angles of incidence.

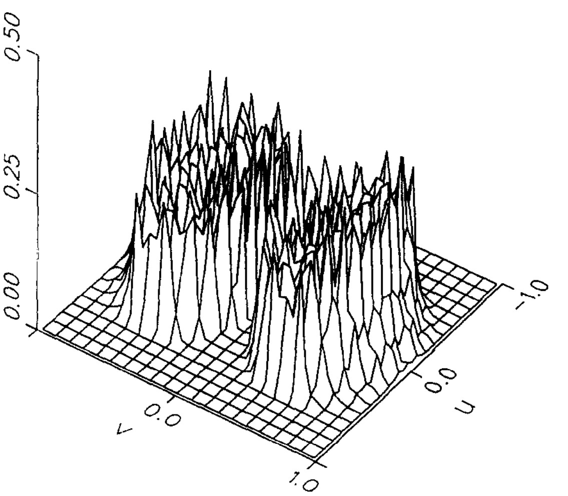

Fig. 4. Angular distribution behind the structure, summed over all possible angles of incidence (isotropic illumination). u and v are the direction cosines with the v-axis perpendicular to the grooves.

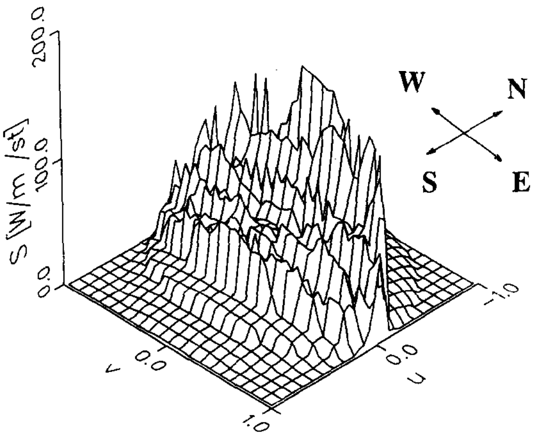

Fig. 6. Annual global radiation for Freiburg in dependence of the angle of incidence on a south-oriented surface, tilted 48°.

Light rays from these directions are not trapped inside the structured glass but are partly reflected outward again. With the large apex half-angle (γ = 43°), the plateau of highest transmission is smaller compared to the ideal apex half-angle (γ = 32°). The depth of the grooves decreases with increasing apex half-angle, and the shape of the structure approaches the smooth surface.

With an apex half-angle of γ = 43° in acrylic glass, good results are to be expected. The measurements and all the following calculations were carried out using this apex half-angle.

The angular distribution beyond a smooth surface, inside the cover, is restricted to angles inside a cone with an opening half-angle of 42° due to Snell's law of refraction. Using direction cosines (i.e., the projections of a unit vector pointing in the direction of the ray onto the x- and y-axes), these angles lie inside a circle in the x, y-plane with radius sin 42° = 0.67. This is not the case for a structured surface. Figure 4 shows the angular distribution behind the structure (γ = 43°) integrated over all possible angles of incidence. Angles larger than 42° occur whereas very small angles do not. The light rays passing through the structured surface are refracted toward larger angles compared to a smooth surface.

From this it can be seen that solar cells with absorption coefficients almost independent of the incoming direction are needed to ensure good transmission through the structured cover into the solar cell. This could be achieved with antireflection coated cells, but a more convenient way is to structure the solar cell surface as well, (i.e., to use textured cells).

To prove this conclusion, Fig. 5 shows the calculated transmission versus angle of incidence curves for three different combinations of smooth and structured surfaces of the transparent cover and of the solar cell. Structuring the surface of the cover alone does not improve the transmission significantly. Only a combination of structured cover coupled to a good absorbing (textured) cell is promising.

4. MEASUREMENTS

An acrylic glass plate with the aforementioned structure, manufactured by 3M Optics Technology Center, Minnesota (S. G. Saxe & D. L. Wortman), was used for measurements. It was originally designed for light trapping in wave guides. The grooves are 0.3

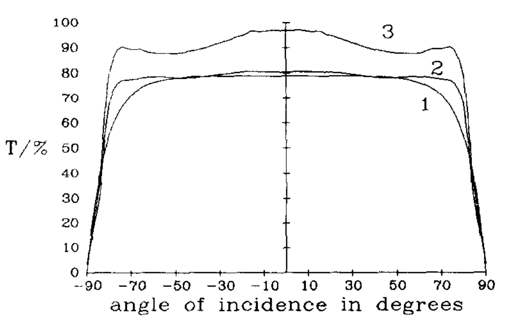

Fig. 5. Calculated transmission versus angle of incidence curves into a smooth solar cell with a smooth (1) and a structured (2) cover and of a micregrooved cell with a structured cover (3).

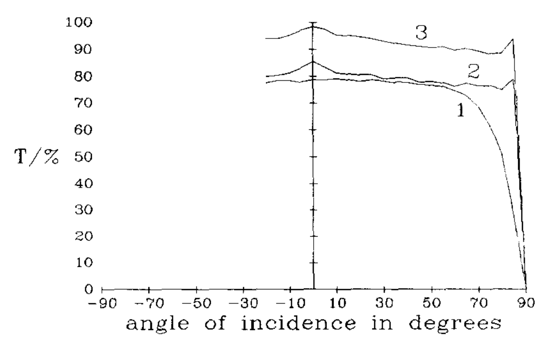

Fig. 7. Measured transmission versus angle of incidence curves of a smooth solar cell with a smooth (1) and a structured (2) cover and of a microgrooved cell with a structured cover (3).

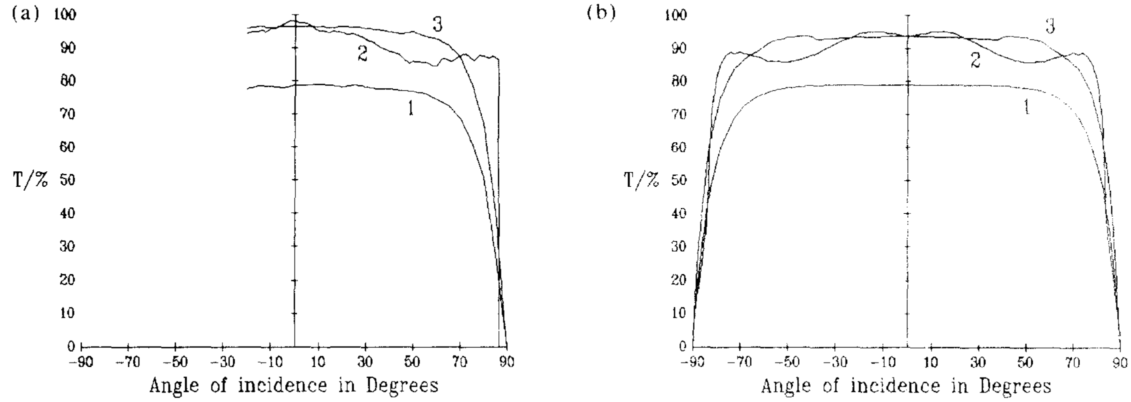

Fig. 8. Measured (a) and calculated (b) transmission versus angle of incidence for a smooth cover with a smooth cell (1) and a structured cover, perpendicular (2) and parallel (3) to the grooves, with a microgrooved textured cell.

to 0.4 mm apart. The apex half-angle of $\gamma = 43°$ is not ideal but is close enough to give reasonable results, as described earlier.

Three different solar cells were used, and all were monocrystalline silicon cells, $2 \cdot 2$ cm^2 in area. One had a smooth surface, whereas the others were textured cells fabricated in our institute. Selective etching of $\langle 1, 0, 0 \rangle$ surfaces with dilute KOH after photolithographic treatment led to $\langle 1, 1, 1 \rangle$ planes tilted 55° to the surface (Blakers, 1989). One of the two textured cells had a structure similar to that of the cover. The microgrooves were about 9 μm apart and oriented perpendicular to the lines of the top metal contact grid. The other had square-based pyramidal holes, again about 9 μm apart.

To ensure good optical contact of the acrylic glass plates ($n = 1.49$) to the solar cells and to be able to remove the cover from the cell, silicone oil ($n = 1.4$) was used.

The measurements were made using light from a 150-W halogen light source, 1.4 m away from a sample holder, which can be rotated in two directions with stepping motors. Accuracies of 2° in direction and of 2% in homogeneity over the cell area were obtained. Reference measurements with a photodiode ensured equal conditions for all measurements.

The light entering the solar cell is partly converted into electricity. The short-circuit current is proportional in first order to the light transmitted into the solar cell, independent of the angle of incidence. The short-circuit current is thus a good measure of the transmission through any optical apparatus into the solar cell. An absolute calibration for each solar cell was found by comparing the values of the short-circuit current with reflection measurements made with a goniometer in our institute.

5. SOLAR RADIATION DATA

For comparison and classification of different configurations of the solar cell and the cover, it is important to take realistic solar radiation data into account. This was done for a typical year in Freiburg, using solar radiation data from the Test Reference Year, or TRY (K. Blümel *et al.*, 1986). There, every hour throughout an entire year, 14 different parameters representing the mean characteristic weather in a climatic region were recorded. The data for direct and diffuse radiation were taken to calculate the solar irradiance in dependence of the incoming direction. Figure 6 shows the solar radiation (in $W/m^2/st$; st = steradian) summed over 1 yr on a surface tilted by 48° (the geographical latitude) toward the south. Again u and v are the direction cosines. Each point in the u, v-plane represents one direction of incoming light (or point of the sky dome) to which a value of yearly summed radiation is associated. The sum over all angles gives a total annual irradiance of 1156 $kWh/m^2/a$. One can easily distinguish the direct radiation from the two plateaus of diffuse radiation and ground reflection. In the area of direct radiation, the tracks of the daily movement of the sun from east to west (parallel to the v-axis) in winter (positive u-values) and in summer (negative u-values) can be reconstructed.

These solar radiation versus angle of incidence data can be convoluted with measured or calculated transmission versus angle of incidence data. This convo-

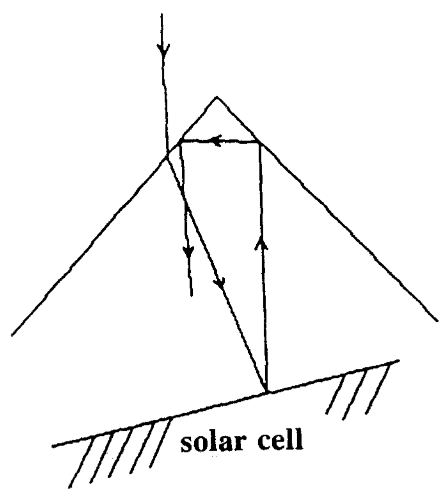

Fig. 9. If the solar cell is tilted by only a small angle, the light ray may be reflected back onto the cell.

Table 1. Annual average transmission efficiencies in % for different configurations

	Calculated	Measured
Entering through the structure into the glass	97.8	
Smooth glass with smooth solar cell	77.1	75.6
Structured glass with smooth solar cell	79.2	81.3
Smooth glass with microgrooved solar cell	91.5	86.9
Smooth glass with pyramidal textured solar cell		89.0
Structured glass with microgrooved solar cell		
Grooves parallel	90.5	90.8
Grooves perpendicular	92.4	92.7
Structured glass with pyramidal textured solar cell		93.2

lution leads to a number called the annual average transmission efficiency (which is a measure for the fraction of the solar radiation) that transmits through the transparent cover into the solar cell. This value allows a realistic classification of the transmission performance of any solar cell module to be used (e.g., in Freiburg).

6. RESULTS

Figure 7 shows the measured transmission versus angle curves corresponding to the calculated ones in Fig. 5. The conclusions drawn from the calculated curves are confirmed. Only a combination of structured cover and structured solar cell surface leads to high transmission values. The accuracy of the measurements decreases with increasing angle because the absolute signal is lowered proportional to the cosine of the angle of incidence, as mentioned earlier.

Figure 8 gives three measured curves [Fig. 8(a)] and the corresponding calculated curves [Fig. 8(b)]. Curves 1 repeat the transmission through a smooth cover into a smooth cell. Curves 2 and 3 show the transmission through a structured surface into a microgrooved cell, perpendicular and parallel to the grooves of the structured cover. The grooves of cover and cell are parallel to each other.

A comparison of Figs. 8(a) and 8(b) again shows that the measured curves behave as predicted. The textured cell succeeds in collecting all rays up to large angles of incidence compared to Fig. 2.

All measured curves perpendicular to the grooves (Fig. 7, curves 2 and 3 and Fig. 8, curve 2) show higher transmission values than predicted around normal incidence. An explanation of this could be the following (Fig. 9): If the solar cell surface is tilted by only a small angle, that part of the light ray which is reflected at the solar cell surface may be completely reflected back onto the cell surface due to total internal reflection at the structured surface of the cover. The trace of such a ray is indicated in Fig. 9. Tilting the back surface to trap the weakly absorbed "red" light inside the solar cell is used in high-efficiency silicon cell design, as shown by Campbell (1990).

Table 1 summarizes calculated and "measured" (measured transmission convoluted with TRY data) annual average transmission efficiencies. The first line gives the value for the structured acrylic surface alone (i.e., with ideal coupling into the solar cell). The second line gives the annual average transmission efficiency for a smooth cover coupled to a smooth, uncoated solar cell. All other values shown in the table lie in between these two limits. The upper limit of 97.8% from line 1 is approached more and more closely as the structure of the solar cell surface is improved. In the end an absolute improvement of about 17% compared to the unstructured and untextured (and uncoated) case is obtained.

It is notable that an annual average transmission efficiency close to 90% can be reached with a smooth cover coupled to a textured cell. The refractive index change (and with this reflection losses) from air to glass ($\Delta n = 0.5$) is smaller than that from glass to silicon ($\Delta n = 2$). Reducing reflection losses at the solar cell surface is thus effective.

Until now there has been no attempt to add an antireflection coating to the solar cell surface. As mentioned earlier, the angles of incidence on the solar cell

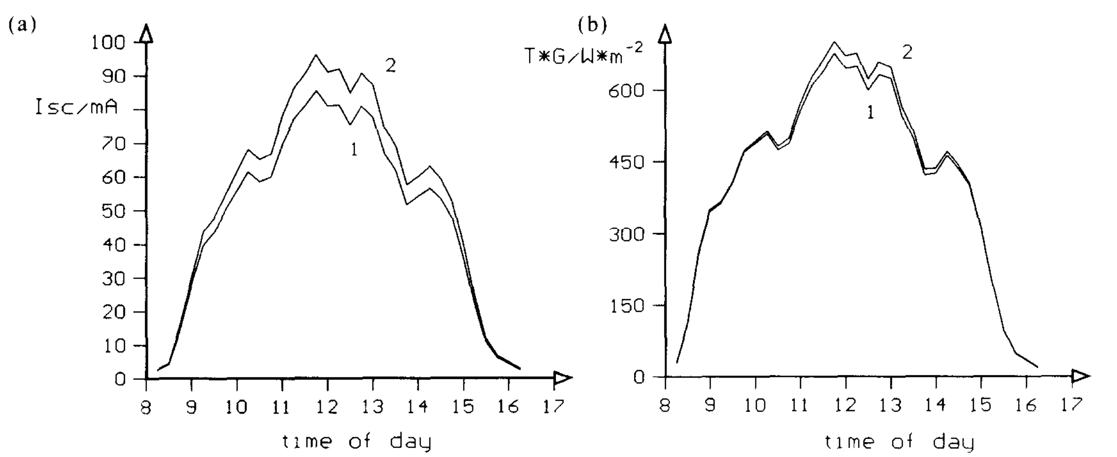

Fig. 10. Measured short-circuit current (a) and calculated transmitted radiation (b) versus time of the day for textured cells with smooth (1) and structured (2) cover on a sunny day.

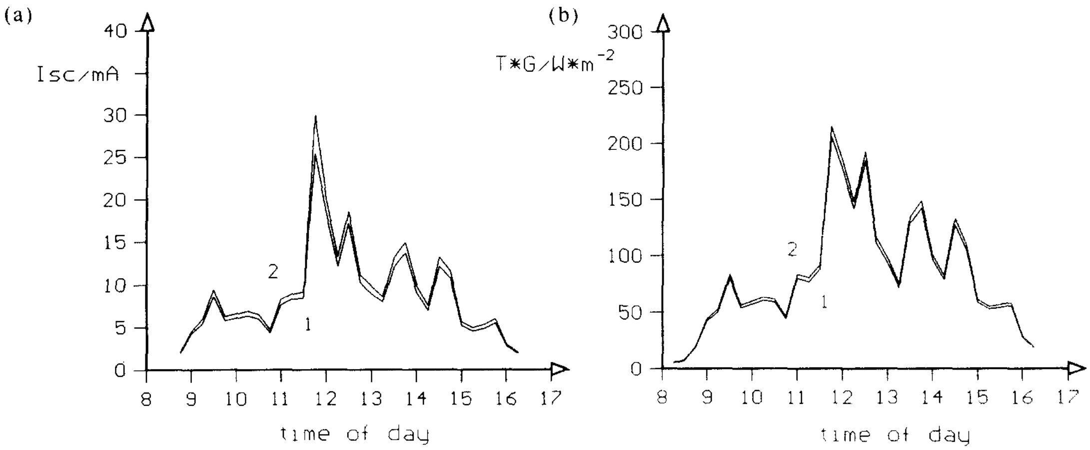

Fig. 11. Measured short-circuit current (a) and calculated transmitted radiation (b) versus time of the day for textured cells with smooth (1) and structured (2) cover on a cloudy day.

surface behind the structured glass cover a wide range (up to 90° inside the structured glass; see Fig. 4). Thus, an antireflection coated surface with its transmission dependent on wavelength and angle of incidence cannot improve the transmission values significantly in this case. A texturing of the silicon surface is much more effective.

In autumn of 1991 outdoor measurements were carried out with two (almost) identical, pyramidal textured, monocrystalline silicon solar cells. One of them was covered with a smooth glass plate, whereas the other was covered with the structured acrylic glass plate mentioned earlier.

Figures 10 and 11 show measured (a) and calculated (b) results for a sunny day (diffuse radiation less than 15%) and a cloudy day (100% diffuse radiation). The modules were tilted by 45° toward the south. Figures 10(a) and 11(a) show the measured short-circuit current versus time of the day. From the measured values of direct and diffuse radiation (averaged over every 15 min), we calculated the radiation transmitted through the cover into the solar cell [Figs. 10(b) and 11(b)]. Because again this radiation is proportional to the short-circuit current, a relative comparison of Figs. 10(a) and 11(a) with 10(b) and 11(b) is possible.

A measured improvement in transmission of about 10% in comparison to a calculated one of about 5% (both constant over both days) for a structured cover is obtained. The much higher measured value is due primarily to two factors: First, microgrooved cells were used for calculations, whereas the better pyramidal textured ones were used for the measurements. Second, the aforementioned effect of higher transmission values around normal incidence must be expected here, too. Both effects are likely to explain at least part of the differences between measurement and calculation.

To study the self-cleaning effect of the structured cover, the two solar cells (with the smooth and structured covers, respectively) were left outdoors for a period of 3 months. A comparison of the efficiencies of the solar cells with contaminated and clean covers led to the conclusion that there was no substantial difference in the degree of contamination between the structured and the smooth cover. This is a first indication that the self-cleaning of the structure works as predicted.

7. CONCLUSION

Reduction of reflection loss was achieved with structured surfaces over a wide range of angles and independent of wavelength. The concept of annual average transmission efficiency was used for classification. The structure of the transparent cover was designed to be kept clean by rainwater and to collect direct solar radiation effectively. A combination of the structured cover and pyramidal textured solar cell yields the best results. Calculating the annual average transmission efficiency for other radiation conditions may lead to different results but will not alter the basic conclusions. Further outdoor measurements are being carried out to confirm the results reported here and to find out how well the self-cleaning of this macroscopic structured cover by rainwater works.

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