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An optimized prismatic cover design for concentrator and nonconcentrator solar cells

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Recently, the performance of both solar cells and photovoltaic systems have been considerably improved by the use of a prismatic cover applied to cell surfaces. This cover steers light away from the metal contact fingers on the top surface of the cell that would normally obscure the cell surface. Although the experimental advantages of this approach are now well documented, there is no published analytical treatment of these covers. This paper investigates their design for both concentrating and nonconcentrating application and clarifies the potential and limitations of the approach.

I. INTRODUCTION

Recent experimental results show the performance benefits to be gained by applying prismatic covers to silicon solar cells designed for use in concentrated sunlight. These covers have produced "module-ready" silicon concentrator solar cells of energy conversion efficiency of up to 25.2%,[1] an efficiency of 21% for the combination of a single cell and lens,[2] and, more recently, an efficiency of 20.4% for a 12 cell concentrator photovoltaic module.[3] This is believed to be the first time the 20% efficiency barrier has been exceeded by any photovoltaic module, although much higher efficiencies seem feasible in the future.

The prismatic cover cell structure which contributed to the above-mentioned achievements is shown in Fig. 1. The prismatic cover is made of transparent silicon polymer and has a refractive index of about 1.5. The hemispherical shaped domes of the cover concentrate the incident light onto the active areas of the cell, avoiding the metal fingers. Hence, all the finger shading loss is eliminated, and much larger coverage of the cell surface by metal fingers is allowed. By avoiding metal shading losses, cells with prismatic covers should have the same limiting efficiency as the rear contacted cell designs such as the rear point contact cells developed by Sinton *et al.*[4]

There are many different designs which have been suggested for these prismatic covers. Covers have been designed having the shape of a sawtooth,[5] hemisphere,[6,7] and more sophisticated geometries.[8,9] The cover used for the 25.2% efficient cell previously mentioned allows 15% metal finger coverage.[1] This is much more metal than can be tolerated for a conventional bifacially contacted concentrator cell which is generally limited to values of less than 10%.[10] However, even 15% metal coverage produces appreciable conductive loss in the fingers for large-area cells operating at high concentration levels. Better cover design is needed to allow further increases in the finger metal coverage so as to improve the cell performance and reduce restrictions on cell processing.

This paper discusses the optimization of the prismatic cover design to maximize the allowable finger metal coverage. The resulting uniformity of illumination of the cell surface was also considered for the designs studied.

II. COVERS FOR NONCONCENTRATED INCIDENT LIGHT

An assumed general shape of the cover is shown in Fig. 2(a). Only half of a unit cell is considered. This half-cell lies between the center of the metal finger to the center of active area between fingers. The metal finger is to the left of the origin (0,0) point. The incident light hits the point (X,Y) of the cover surface with an incident angle θ_1 to the normal to the cover surface as shown. It is then refracted into the cover at an angle θ_2 to the normal. The two angles are simply related:[11,12]

$$n_1 \sin\theta_1 = n_2 \sin\theta_2, \tag{1}$$

where n_1 and n_2 are the refraction indices of the medium

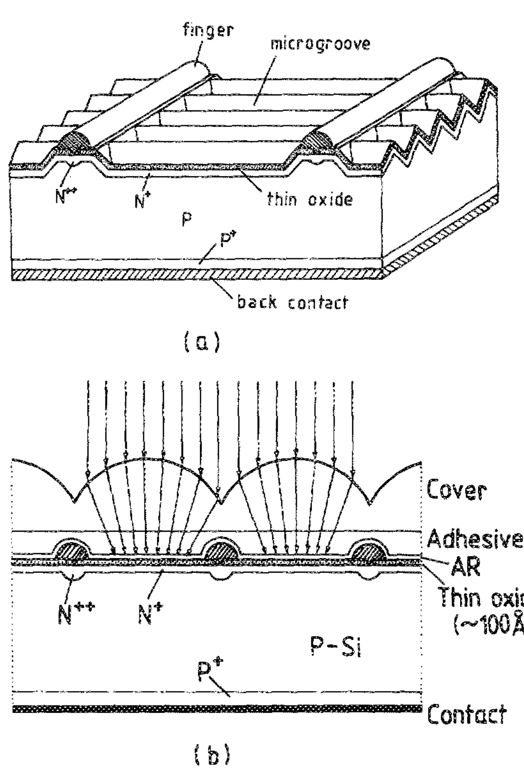

FIG. 1. Solar cell covered by a prismatic cover to steer light away from the top contact fingers.

from which the light is coming and the cover material, respectively. The cover material is chosen so that n_2 is higher than n_1. When the cover is used as the cell encapsulation, n_1 equals 1. However, $n_1 > 1$ if another layer of material is used to encapsulate the cover into a module, as discussed in the next section.

It is essential in the present case to steer all the light incident from all possible directions onto the active areas of the cell surface, since nonconcentrated sunlight contains a significant diffuse component. Hence, one limiting condition is when the light hits the point (X,Y) tangentially ($\theta_1 = 90°$). Any light incident with a greater angle will hit another point to the right of the point (X,Y). If the correct surface angle of the cover is chosen, the tangential light is then assumed to be refracted to the point (0,0) to just avoid the metal finger. Light incident with any less oblique angle will be refracted further away from the metal finger.

Figure 2(a) can be redrawn as Fig. 2(b). If α is the angle of the cover surface with respect to the horizontal x axis (y axis is vertical), then

$$\tan \alpha = dy/dx \tag{2}$$

where dy and dx are surface increments. Also,

$$\beta + \arctan(Y/X) = 90° \tag{3}$$

and

$$\theta_2 = \alpha + \beta, \tag{4}$$

where θ_2 is given by Eq. (1). From Eqs. (1)–(4), the increment dy becomes

$$\begin{aligned} dy &= \tan[\arctan(Y/X) - 90° + \theta_2]dx \\ &= \tan[\arctan(Y/X) - 90° + \arcsin(n_1/n_2)]dx, \end{aligned} \tag{5}$$

where $\sin \theta_1 = 1$ was used, since $\theta_1 = 90°$. Equation (5) was solved numerically by computer. The step length dx was set to 0.1 μm to ensure the accuracy of the calculation. However, increasing this step size to 1 μm would give very little difference.

The starting point (X_0, Y_0) was selected as $(-30,80)$. This location was based on four considerations. First, Y_0 is where the cover is thinnest. This thickness should be between 50 to 100 μm to maintain good mechanical strength for the cover. A value of 80 for Y_0 allows the results to be applied to the case where the length units are micrometers. Second, the ratio $-Y_0/X_0$ determines the angle of the light path from (X_0, Y_0) to the (0,0) point, the edge of the metal finger. Some of the light from (X_0, Y_0) would hit the hemispherically shaped finger shown in Fig. 2. However, the larger the ratio $-Y_0/X_0$, the smaller is the fraction of the light striking the metal finger. This would mostly be reflected onto the active region of the cell for the case shown. The third consideration is the angle of the calculated curve at the (X_0, Y_0) point. A very large angle would make it difficult to fabricate the cover. The ratio $-Y_0/X_0$ also affects the overall shape of the calculated curve. It was found that the larger the ratio, the smaller is the allowable finger metal coverage.

As a compromise between the last three effects, a value of $-8/3$ was selected as the $-Y_0/X_0$ ratio for the present study.

Figure 3 shows the calculated result. A value of 1 was used for n_1. Three different values of n_2 were used and corresponding results are shown in the figure. It can be seen that the higher the value of n_2, the narrower the permissible spacing between fingers. This is desirable since it makes it possible to further reduce the finger conductive loss, to increase the sunlight concentration, or to increase the cell area. Thinner covers are also needed for higher n_2 values.

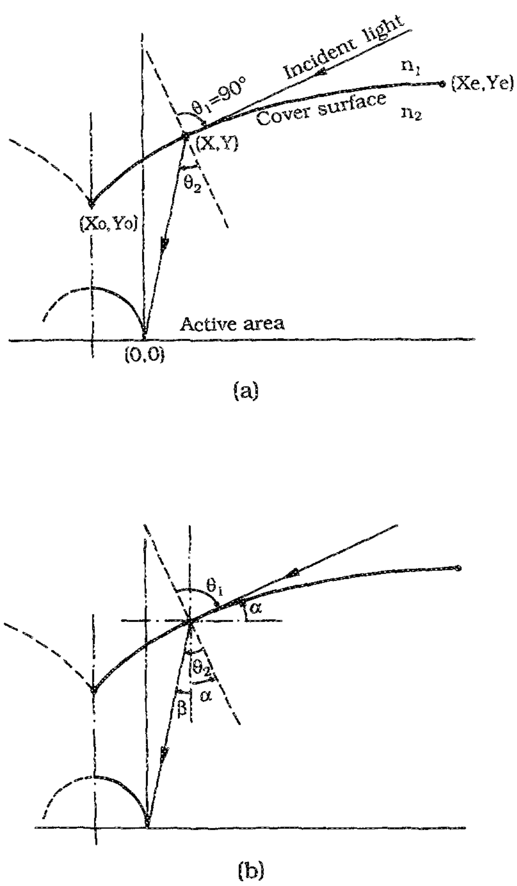

FIG. 2. (a) Optimized prismatic cover design assumes that the incident light from the right limit angle is refracted to the left edge of the cell active area. The limit angle is 90° for one-sun cells. (b) The angular relations used in the solution.

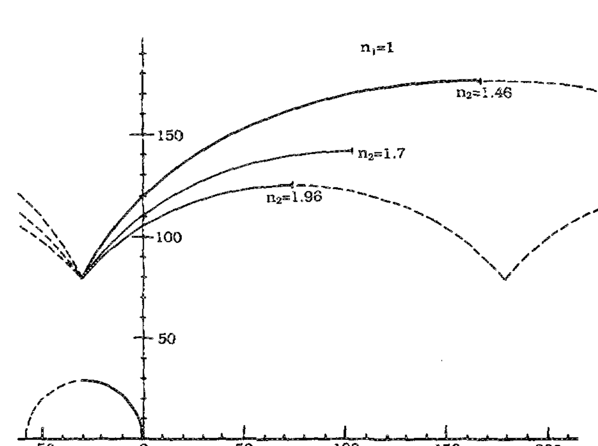

FIG. 3. Calculated shapes of prismatic cover designs for one-sun cells which accept incident light from all directions.

Because all incident light will illuminate only the area to the right of the (0,0) point, the area on left side of that point can be used to make metal fingers as shown. An Ag plating technique would commonly be used to make these metal fingers.[13] The plated silver can be 3 times as thick as for 4-cm^2 nonconcentrating cells such as the recent one-sun PERC cells with efficiency of 23.2%.[14] At the same time, the spacing between fingers could be halved, if n_1 is equal to 1.46 and the units in Fig. 3 are taken as micrometers.

The fractional power loss p from the metal resistance of the finger is given by the following expression, assuming that the contact width is much smaller than the Ag plating radius r:[15]

$$p = \frac{2\rho_m J_{mp} S L^2}{3\pi r^2 V_{mp}}, \tag{6}$$

where ρ_m is the silver conductivity, L and S are finger length and spacing, and J_{mp} and V_{mp} are the current density and voltage at the maximum power point.

If the fractional power loss p is to be held constant, then

$$L = Ar\sqrt{1/S}, \tag{7}$$

where A is a constant for a fixed illumination level.

Now, for the case previously mentioned, the finger plating radius r is increased 3 times, and finger spacing S halved. If p is unchanged, L can increase 4.24 times. Hence, 8.5×8.5-cm^2 one-sun cells are possible with no increase of power loss from metal finger resistance compared to that already demonstrated for 2×2-cm^2 cells. The power loss from the diffused layer at the front surface would actually decrease to a value only a quarter of its value without the cover. The cell fill factor should therefore actually increase.

Because the metal shading loss is effectively zero, the cell efficiency should increase about 4%, if reflection from the surface of the prismatic cover is not considered. It is therefore not impossible to make very large-area one-sun cells with efficiency over 24.1% with technology already demonstrated.

The refractive index n_2 has a large influence on the cover shape as seen from Fig. 3. If a material with higher refractive index is used, the cover can be made thinner, with even smaller finger spacing. Figure 3 also shows the use of a cover when $n_2 = 1.96$. For this case, the cell size can be increased to 12×12 cm^2 without any more power loss than already demonstrated for a 2×2-cm^2 cell.

III. COVERS FOR CONCENTRATOR MODULES

For concentrator modules, the direct component of the incident light is concentrated onto the cells. In this case, the incident angle is determined by the concentrator system. The maximum incident angle is around 30° to 60° depending on the system design. It is possible to have more space for metal fingers under the concentrated light than under nonconcentrated light. Figure 4 shows the relevant optical paths for this case. θ_1 is the maximum incident angle. It is assumed as in the last section that the incident light with the maximum incident angle θ_i hits a point (X,Y) on the cover surface. By appropriate design of the angle of the cover surface, the light is then refracted just to the right of the point (0,0)

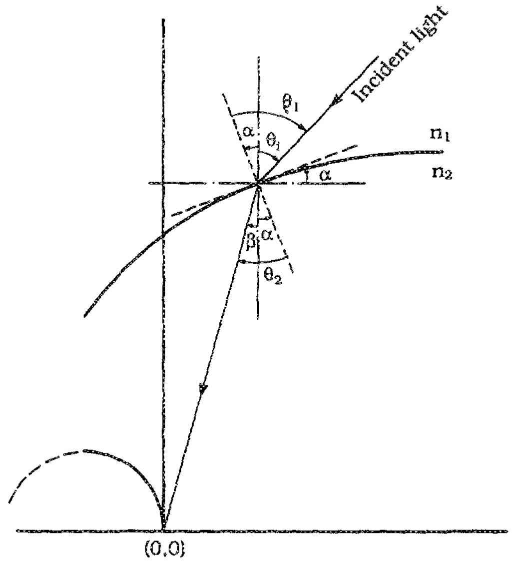

FIG. 4. The incident angle θ_1, is usually limited for concentrator cells by the primary optics. This allows more finger metal and reduced finger spacing.

to avoid the metal finger. Light with any smaller incident angle will be refracted further away from the metal finger. α, β, θ_1, and θ_2 have the same meaning as in the last section. Therefore

$$\theta_1 = \theta_i + \alpha, \tag{8}$$

$$\theta_2 = \beta + \alpha. \tag{9}$$

Combined with Eqs. (1)–(3), this yields

$$n_1 \sin[\theta_i + \arctan(dy/dx)] = n_2 \sin[90^\circ - \arctan(Y/X) + \arctan(dy/dx)]. \tag{10}$$

To calculate the shape of the curve, Eq. (5), appropriate for unlimited incident angle, is used initially as in Sec. II. When the angle of the cover surface α decreases to the maximum incident angle θ_i, Eq. (10) is then used for further calculations to calculate the cover surface angle in the case of limited acceptance angle.

Results calculated in this way are shown in Fig. 5. It is

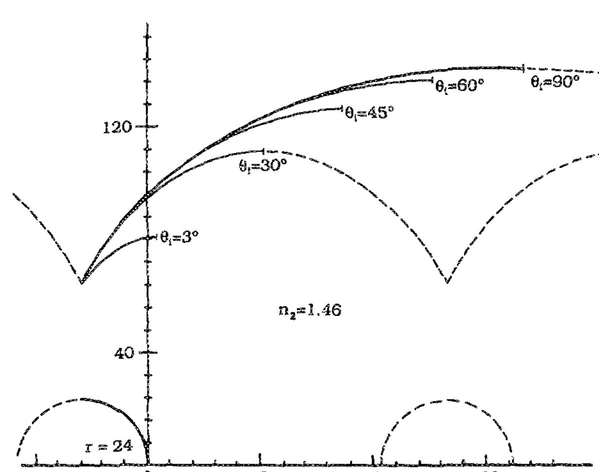

FIG. 5. Prismatic cover designs for different acceptance angles of the cover, θ_1.

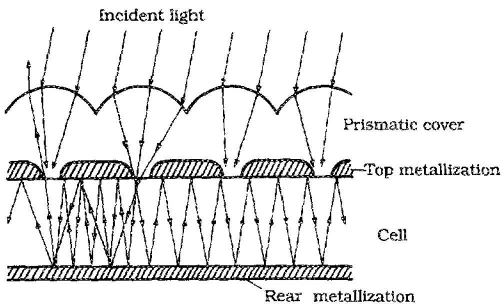

FIG. 6. Light trapping scheme arising from prismatic cover designs of small acceptance angle.

seen that the active area and the cover thickness need to decrease as the maximum allowable incident angle decreases. For 30° maximum incident angle, it is easy to maintain 125-μm finger spacing for the prismatic cover cells,[1] by decreasing the scale of Fig. 5 to 8 μm per division. According to Eq. (7), the finger length of the present prismatic cover concentrator cells could actually be increased 3 time while still keeping the power loss unchanged. The present cover design will also improve the cell efficiency by reducing the finger conductive loss as well as relaxing constraints on the cell processing.

To consider a limiting condition, the case of 3° maximum incident angle has been investigated. The results are also shown in Fig. 5. In this case, only an 8-μm-wide active area is required between metal fingers of 50 μm width. The

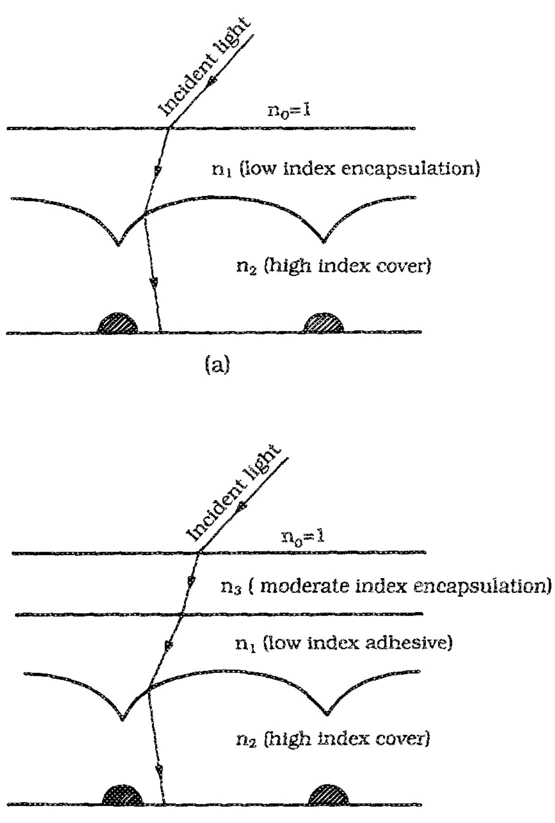

FIG. 7. (a) Prismatic cover can be encapsulated if cover and encapsulation materials satisfy $n_2 > n_1$; (b) alternatively, a layer of low-index adhesive n_2 can be used between the cover and encapsulation.

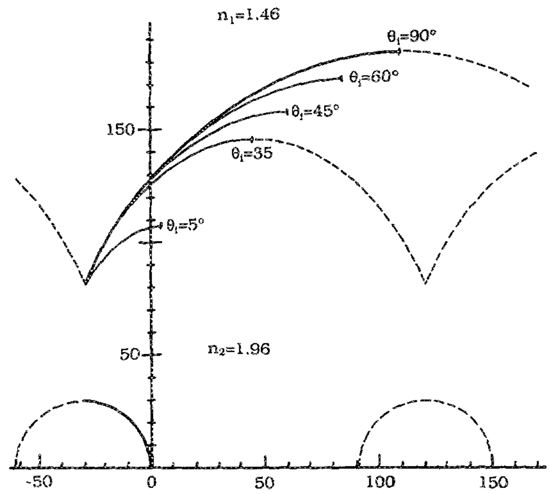

FIG. 8. Calculated prismatic cover designs under encapsulation. A large refractive index of the cover material ($n_2 = 1.96$) is preferred for such designs.

metal coverage would be over 85% of total front area in this case. These design features are not only important for good conductivity from the fingers and diffused layers, but also for light trapping purposes.[16] All the incident light would be concentrated and enter the substrate through the very narrow active area windows. The light would then be reflected from the rear metal surface, if it is highly reflective. When the light reaches the front surface again, there is a very little chance (15%) for it to hit the active area and thereby leave the substrate. About 85% of it will be reflected back into the substrate by the front metal fingers as shown in Fig. 6. Hence, it forms a very effective light trapping scheme.[16] Incident angles as small as 3° can be achieved by a linear primary lens.[2]

IV. FLAT-PLATE PV MODULES

Most one-sun cells designed for nonconcentrated light have to be encapsulated into a module. It might seem impos-

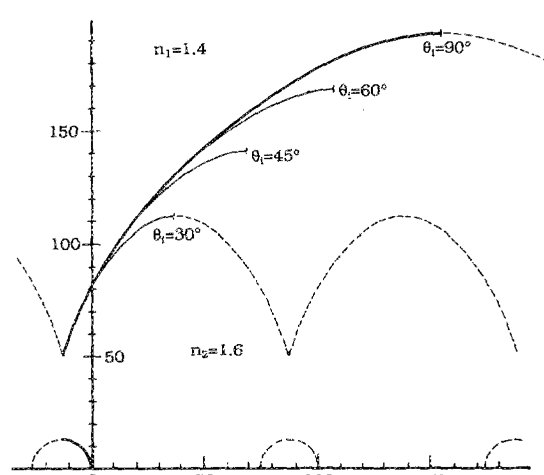

FIG. 9. Calculated prismatic cover designs with small index ratio of encapsulation ($n_1 = 1.4$) to cover material ($n_2 = 1.6$). Much thicker covers are required and less finger metal is allowed.

sible to incorporate prismatic covers into such modules. However, it is actually possible if two different refractive index materials are used for the cover and the module encapsulation. This approach is shown in Fig. 7(a). The two layers of materials are chosen so that $n_2 > n_1$. The only change from the previous calculation is that the incident angle in the n_1 layer is smaller than in the n_0 layer due to the different refraction which is determined by Eq. (1). The corresponding results are shown in Fig. 8. Even smaller finger spacing is possible than without encapsulation (see Fig. 5).

Ideally, n_2 would be much higher than n_1, but it might be difficult to find such high-index materials that are sufficiently nonabsorbing. Hence, the case where $n_1 = 1.4$, $n_2 = 1.6$ is also calculated. The results are shown in Figure 9. It is found that a thicker cover is needed, and only smaller coverage can be achieved because of the small n_2/n_1 ratio.

There is another solution to the problem of requiring a large difference between n_2 and n_1. A layer of low refractive index (n_1) adhesive can be applied between the module surface encapsulation layer (n_3) and the prismatic cover (n_2) as shown in Fig. 7(b). It is still required that $n_1 < n_2$. It does not matter what value n_3 has since the calculation is independent of the n_3 layer. Only the n_1 and n_2 layers are considered, exactly as for the case shown in Fig. 7(a). The n_3 layer would cause a little extra loss (about 2%) due to reflection from the interface between n_3 and n_1, provided n_3 is not much higher than n_1. This loss can be also reduced by grooving this interface perpendicular to the finger direction due to a "double bounce" reflection effect. Most of the light reflected from the cell surface would also be completely reflected back to the cell due to these grooves.[17]

The prismatic cover technique could be also applied to the outer encapsulation surface to steer the light so that if also avoided the gaps between cells and the interconnect busbar as well as the fingers.

V. ILLUMINATION UNIFORMITY

It is essential that all the incident light hits the active area of the cell for any prismatic cover design. The curve defining the shape of the prismatic cover surface was calculated to ensure that the light from the right side at maximum incident angle hit the right edge of the metal finger. Light with smaller incident angle will go further towards the center of the active area. However, it remains to be examined whether the light will hit another metal finger to the right of the active area as shown in Fig. 10, if the incident angle changes to the left maximum angle. The distribution of illumination on the active area is also important. A good prismatic cover design should have a uniform light distribution. For nonuniform cases, it is preferable to have higher illumination at the edge of the active area than at the center to reduce the loss due to lateral conduction through the surface diffused layer. Hence, the light distribution was also calculated at the same time the previous curves were calculated. For a well-designed square or a rectangular primary Fresnel lens, the incident light is nearly uniformly distributed over the range of incident angles between the maximum positive and negative. A typical light distribution calculated in this way is shown in Fig. 11 for a concentrator cell with limiting incident angle of 30°.

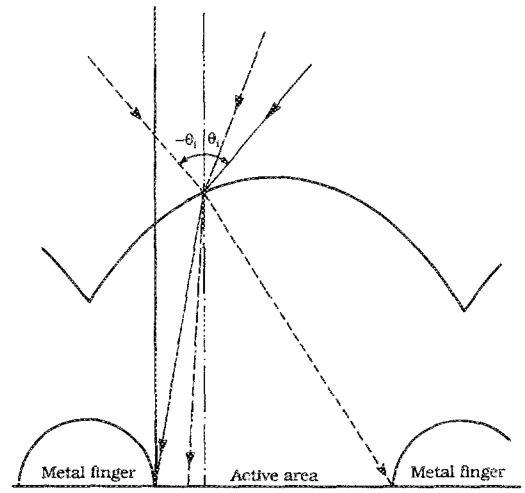

FIG. 10. In the optimum design, incident light will illuminate the left edge of the active area when incident from the right side at the limiting angle (solid lines). Light with smaller incident angle will illuminate further into the cell active area (dash and dot lines). It was found that such a design will cause the light incident from the left at the limiting angle to strike the right edge of the active area (dashed lines).

It is found that all the light does illuminate only the active area for concentrator cells if the maximum incident angle is smaller than 83°. Component I in Fig. 11, represented by the dotted curve, is the intensity distribution contribution from the light that illuminates the left half-dome of the cover (the calculated curve) with incident angles from 0° to θ_i, where θ_i is defined in Fig. 10. Component II, represented by the difference between the dashed and dotted curves, is the intensity distribution contribution from the light that illuminates the left half-dome with incident angles from 0° to $-\theta_i$. Component III, represented by the difference between the solid and dashed curves, is the intensity distribution from

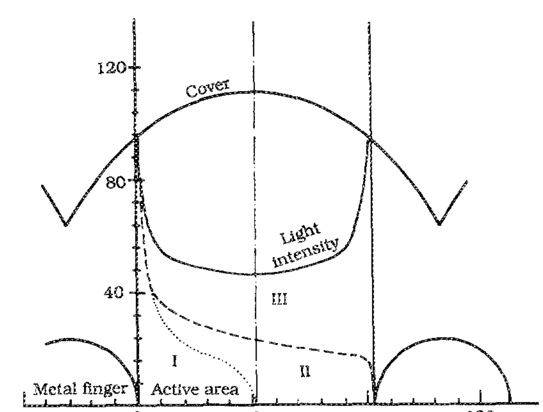

FIG. 11. Calculated illumination distribution for a typical prismatic cover cell, which has a 30° limit on incident angle and 1.46 index of cover material. Component I, represented by the dotted curve and Component II, represented by the difference between the dashed and the dotted curves, show the light intensity distribution arising from light hitting the left half-dome of the cover. Component III, represented by the difference between the solid and dashed curves, shows the corresponding distribution from light hitting the right half-dome of the cover.

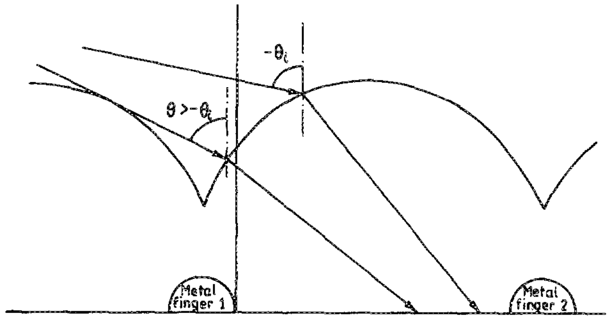

FIG. 12. For the case with very large incident angles θ_i, part of the cover is shaded by another section.

the light contribution which illuminates the right half-dome (symmetrical image of the calculated curve) with the incident angles from θ_i to $-\theta_i$. The top curve is the sum of these three components and therefore represents the total illumination intensity on the active area. It is seen that most light will hit the edge of the active area. This is good for concentrator cells, because the light will generate carriers close to the metal fingers and the voltage drop along the top diffusion layer will be smaller. Actually, manufacturing tolerances will smooth the illumination intensity distribution. Metal fingers should be made a little narrower than the designed value to accommodate such tolerances.

These results confirm the validity of the present design approach. It is not totally unexpected that all the incident light is concentrated only onto the active areas of the cell. At the center of the dome, symmetry dictates that light at both angular extremes will fall at the edges of adjacent metal fingers.

If the incident angle is unlimited from $-90°$ to $90°$ as for a one-sun cell, or limited at close to $90°$, a new element enters the calculation as shown in Fig. 12. The left maximum angle is smaller than the designed maximum angle for some sections of the curve because the left dome shades some incident light from the left side as shown.

At such angular extremes, it was found that some incident light with left incident angle does illuminate the metal finger 2, outside of the active area. However, this light only goes out of the active area a small distance. The distance is about 1.5% of the finger spacing for the cover index ranging from 1.46 to 1.96, if the incident angle is unlimited at $90°$. For $n_2 = 1.46$, there is no incident light out of the active areas if the maximum incident angle is smaller than $85°$. This limit angle decreases to $83°$ with n_2 increasing to 1.96.

However, it is easy to solve the problem by inserting a short flat section at the dome top of width equal to 1.5% of the finger spacing. It is not necessary to consider this effect for concentrator cells because all the concentrator cells have a maximum incident angle much smaller than $85°$.

VI. DISCUSSION

The method developed to optimize the design of prismatic covers for solar cells has been described. The optimized cover would allow much more finger metal on the top surface of the cell. This would improve the cell efficiency, allow a higher concentration level and larger cell area, and relax tolerances on cell processing. The optimized cover could be used for concentrator or nonconcentrator cells, and flat-plate modules. Designs with very small incident angle ranges of light would also form the basis of a very good light trapping scheme. The optimized cover design described would also supply a rather favorable illumination distribution onto the cell active area.

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