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Optically enhanced amorphous silicon solar cells

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We describe the first application of optical enhancement to thin-film ($\sim 0.75\ \mu$m thick) amorphous silicon solar cells and define cell geometries which maximize enhancement effects. We observed that due to the improved infrared absorption the external AM1 short circuit current increases by 3.0 mA/cm^2 in cells constructed in accordance with the principles of optical enhancement.

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The idea of trapping light inside a semiconductor by total internal reflection had been proposed[1] as early as 1965. Recently, in a statistical mechanical analysis[2] of the light trapping problem, it was shown that the effective absorption of a textured semiconductor sheet could be enhanced by as much as a factor $4n^2 \approx 60$ over a plane parallel sheet, where n is the semiconductor index of refraction. The sixtyfold enhancement for textured sheets is a much larger effect than had previously been suspected. In a recent article,[3] it was shown that an amorphous silicon (a-SiH$_x$) film deposited on a sandblasted surface already experiences a photoconductivity enhancement factor of 25 in the vicinity of the absorption threshold.

In this article, (i) we describe more sophisticated texturing techniques which permit a closer approach to the statistical limit ($4n^2$), (ii) we deal with the practical problem of parasitic optical absorption in the electrode contacts which hinders the enhancement process, and (iii) we describe the construction of an a-SiH$_x$ solar cell whose AM1 short circuit current was increased by 3 mA/cm^2 due to optical enhancement. Improvements in short circuit current lead to proportionate improvement in cell efficiency since open circuit voltage and fill factor were unaffected by optical enhancement. We found that the keys to achieving these results experimentally were (1) production of textures which internally randomize and trap light in a 1-μm-thick semiconductor layer without shunting the cell, (2) utilization of cell geometries which minimize parasitic optical absorptions, and (3) production of a carrier collection width approximately equal to the cell thickness.

Light trapping requires that the plane parallel symmetry of the semiconductor film must be broken. To approach the statistical mechanical limit of $4n^2$, however, there is the additional requirement that the surface texture must fully randomize the light rays within the semiconductor so as to fill the internal optical phase space. As a general rule, the approach toward the statistical limit will be incomplete. Only a fraction β of the incoming light will be scattered to fill the internal optical phase space in the semiconductor sheet, while a fraction $(1-\beta)$ of the light will behave nonergodically, experiencing only a single pass through the sheet. For any given surface texture, we have found it necessary to determine β, empirically, from the following experiment. We measure[4] the experimental absorption enhancement fractor $E_{\rm exp}$ in the limit of weakly absorbed light and in the absence of parasitic electrode absorption. Then

$$\beta \equiv E_{\rm exp}/4n^2 \qquad (1)$$

measures the degree to which the statistical limit is approached.

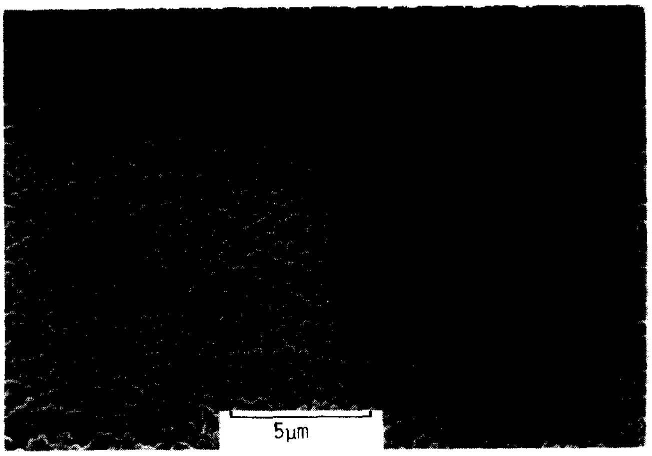

FIG. 1. Randomly packed 0.3-μm microcolumnar structures fabricated on glass substrate using natural lithography. The texture shown produced complete internal randomization of light; i.e., $\beta = 1$.

Such a measurement in a recent article[3] showed that β was equal to $25/4n^2 \approx 0.5$ in the case of a sandblasted surface texture. To produce an internal randomization fraction β more nearly equal to 1, we have developed a new lithographic method called "natural lithography"[5] and used it to fabricate identical randomly packed microcolumnar structures on the surface of a glass substrate. Materials forming *PIN* solar cells were deposited over the textured surface. Figure 1 shows one of the textures used to enhance cell performance. Precise control of microstructure dimensions allowed optimization of cell performance by varying the diameter, height, and profile of individual microcolumnar structures. In Ref. 4 it was found that optimum textures have dimensions somewhat greater than the wavelength of light in the semiconductor. If the lateral dimension of the microstructures is too large, light is specularly reflected and the internal randomization fraction β decreases. If the lateral dimension of the microstructures is less than the wavelength of light, then the microstructures do not effectively scatter light and β again decreases.

Surprisingly, it is found that optimal textures do not create pinholes for shunts but significantly improve yields of good (nonshunted) devices. This counterintuitive result is attributed to a stress relief in the a-SiH$_x$ film caused by the texture. Measurements of the residual stress have shown that texturing can relieve both compressive and tensile stress in deposited a-SiH$_x$ solar cells.

The theoretical absorption probability F^{enh} can be calculated from an infinite geometric progression representing the multiple reflections of an average light ray scattered back and forth across the film. The Lambertian angle averaged path length of a randomized ray is twice the mean thickness l of the film. If internal randomization occurs immediately upon the light ray entering the front surface of the solar cell, the sum of the geometric progression representing absorption in the semiconductor is

$$F^{enh} \equiv \frac{1 - \eta e^{-2\alpha l} - (1-\eta) e^{-4\alpha l}}{1 - (1-\eta) e^{-4\alpha l} + [(1-\eta)/n^2] e^{-4\alpha l}}, \qquad (2)$$

where η is the parasitic absorption in the electrical contacts, n the index of refraction of the semiconductor, $1/n^2$ the angle-averaged probability of the light ray escaping from the front surface, and α the absorption coefficient of the semiconductor. The theoretical enhancement factor $E(\alpha, \eta)$ over single pass absorption is defined:

$$E(\alpha, \eta) \equiv F^{enh}(\alpha, \eta)/(1 - e^{-\alpha l}),$$

and Fig. 2 is a plot $E(o, \eta)$ the theoretical maximum enhancement factor obtainable for a given electrode absorption η. It is seen that if the parasitic absorption is only 6%, the maximum attainable enhancement factor will be only 1/2 that with no parasitic absorption.

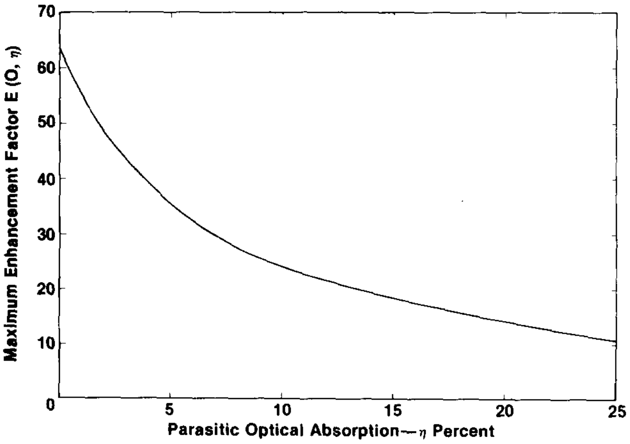

FIG. 2. Theoretical plot of the maximum attainable enhancement factor $E(o, \eta)$ plotted as a function of parasitic optical absorption (η).

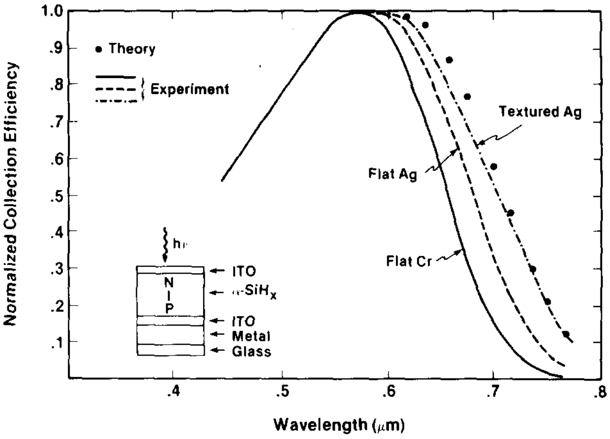

FIG. 3. Normalized collection efficiency for unenhanced (flat Cr), enhanced (textured Ag), and weakly enhanced (flat Ag) cells with an integral reflector structure. Normalized collection efficiencies are compared to remove differences in the antireflection properties of the cells (texturing can reduce front surface reflection). The theoretical model assumes $\eta = 22\%$.

Effects of parasitic absorption on optical enhancement were evaluated in cells with two different reflector configurations. The first utilizes a reflector which is integral to the cell and the arrangement of layers shown in the inset of Fig. 3. The metallic reflector layer is overcoated with a transparent conductor which acts as a diffusion barrier preventing migration of the metal during deposition of a-SiH$_x$. Effects of optical enhancement for this integral reflector structure were evaluated by comparing adjacent enhanced and unenhanced cells. Unenhanced cells contained a flat Cr layer in the reflector while enhanced cells utilized textured Ag. Due to a small amount of unavoidable residual roughness, the "flat" Ag reflector produced a small enhancement effect. The quantum efficiency observed for collection of carriers from enhanced (textured Ag), unenhanced (flat Cr), and weakly enhanced (flat Ag) cells are shown in Fig. 3. By modeling the curve for flat Cr, we conclude that the carrier collection width was about equal to the intrinsic a-SiH$_x$ layer thickness ($\sim 0.75\ \mu$m). The shape of the textured Ag curve was modeled from Eq. (2) by assuming full internal randomization of incoming light ($\beta = 1$) and parasitic optical absorption $\eta = 22\%$. The solid dots shown in Fig. 3 are the theoretical points.

The high parasitic optical absorption limits the maximum current increase attained from an integral reflector geometry to ~ 2.3 mA/cm^2. Parasitic optical absorption can be significantly reduced by using a novel detached reflector configuration shown in the inset of Fig. 4. By detaching the reflector from the rear surface electrical contacts, optical absorption in the reflector can be reduced because the reflec-

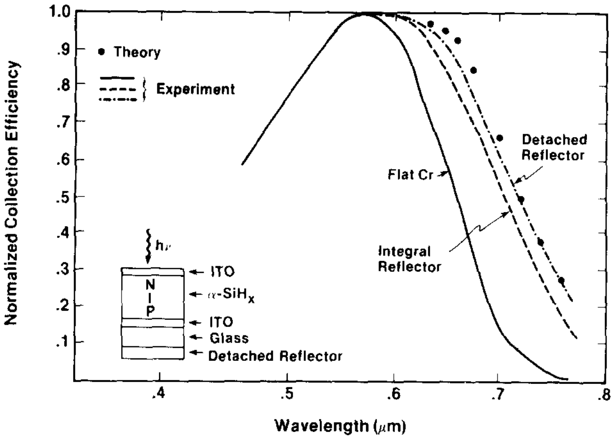

FIG. 4. Comparison of normalized collection efficiencies for unenhanced and enhanced cells having integral and detached reflectors. The theoretical model assumes $\eta = 14\%$.

tion function can be optimized separately from the electrical conductivity function. Figure 4 compares the performance of identically textured cells having integral and detached reflectors. The solid dots shown in Fig. 4 are a theoretical model [Eq. (2)] of detached reflector performance assuming complete internal randomization of light ($\beta = 1$) and a parasitic absorption of $\eta = 14\%$. Concomitant with reduction of parasitic absorption, we find that the short circuit current was increased by 3.0 mA/cm^2. The values of parasitic optical absorption for both integral and detached reflectors have been recently confirmed using photothermal spectroscopy.[4]

The improvement in external AM1 short circuit currents was measured by two methods: directly comparing the performance of 0.02 cm^2 enhanced and unenhanced cell fabricated from the same a-SiH$_x$ film (1) with a solar simulator and (2) by mathematically integrating the measured carrier collection efficiencies.[6,7] Depending on a-SiH$_x$ deposition conditions the open circuit voltages V_{oc} were 0.8–0.9 V, fill factors (FF) were 0.5–0.6, and the unenhanced short circuit currents were 11–13 mA/cm^2. Over this wide range of cell parameters V_{oc} and FF were unaffected by the enhancement process.

In conclusion, we have constructed optically enhanced thin-film solar cells which have significant improvements in infrared response. This leads to an increase of 3.0 mA/cm^2 in the AM1 short circuit current of otherwise identical a-SiH$_x$ solar cells. Further reduction in the parasitic optical absorption in the electrodes should permit enhancement factor approaching the upper limit imposed by statistical mechanics; namely, $4n^2 \approx 60$.

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High resistivity in *p*-type InP by deuteron bombardment

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High resistivity layers have been achieved in p-type InP using deuteron bombardment. A curve of average resistivity versus bombardment dose has been determined for p-type InP with an initial background carrier concentration of 1×10^{18} cm^{-3}. It has been shown that average resistivities of $10^9\,\Omega$ cm or higher can be attained reproducibly, over a dose range 3×10^{13}–1×10^{14} deuterons/cm^2.

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Ion bombardment is widely used in semiconductor device technology. For example, proton bombardment has been used to make the highly resistive regions in GaAs and AlGaAs[1–3] needed for the fabrication of bombardment-delineated stripe geometry lasers.[4,5]

In 1977 Donnelly and Hurwitz[6] reported using proton bombardment to make p-type InP highly resistive, but they observed that at high dose the bombarded layer converted to n-type material. This effect was observed by others and recently verified by Holden *et al.*[7] This technique has also been used to make stripe geometry lasers,[7–9] but the proton doses generally were of such a high flux as to convert the p-type InP to n type, thereby forming p-n junctions to confine the current. This type of confinement can allow sufficient leakage current across the reverse-biased junction to be deleterious to the device properties.

In 1980 Steeples *et al.*[10] reported using deuteron bombardment to make high resistivity layers in n-type GaAs. He