SAND99-0750C

ADVANCED SILICON SPACE SOLAR CELLS USING NANOTECHNOLOGY

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ABSTRACT

Application of nanotechnology and advanced optical structures offer new possibilities for improved radiation tolerance in silicon solar cells. We describe the application of subwavelength diffractive structures to enhance optical absorption near the surface, and thereby improve the radiation tolerance.

INTRODUCTION

Silicon space solar cells have been used reliably in satellites for over forty years and silicon solar cells are likely to remain the least expensive solar cell technology for many years due to the maturity of silicon technology. Silicon is also a highly versatile material that offers the possibility of integration with other functional elements of a satellite. For example, it may be possible to integrate energy storage and energy management functions with a silicon solar cell--which could be very useful in nanosatellites [1].

The main disadvantages of silicon compared to GaAs-based space solar cells are its low conversion efficiency and poor radiation tolerance. Both of these disadvantages are related to silicon's indirect-bandgap structure. Indirect-bandgap semiconductors have relatively weak optical absorption. One result of the weak absorption is that thick (e.g., several hundred microns for solar cells with planar surfaces) layers of silicon must be used to fully absorb the light. Thick silicon cells are a disadvantage for satellites due to their large mass. A second result of the weak absorption is long minority-carrier diffusion lengths are necessary to collect the photogenerated carriers from weakly absorbed photons. The cell conversion efficiency decreases rapidly as the minority-carrier diffusion length is degraded from radiation-induced damage.

It has long been recognized that the optical absorption of any material can be increased through structuring of the surfaces [2]. The surface structure increases the optical absorption by obliquely coupling the light into the material. Oblique coupling of light increases the path length by $1/\cos(\theta)$, where θ is the angle between the surface normal and the propagation vector. The path length of some of the obliquely coupled light can be further increased due to "optical confinement," which occurs when the light is confined within the material by reflection at one of the surfaces.

Most work to date has used anisotropic chemical etches of silicon that reveal the (111) crystallographic planes. The (111) surfaces form four-sided pyramids on a (100)-oriented silicon crystal surface. The pyramids are typically large (several microns) relative to the optical wavelengths of interest (300 – 1200 nm). The optics of these structures are therefore described by geometrical optics. The optical performance is not a strong function of the wavelength and is mostly determined by the crystallographically defined geometries.

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*Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

This paper describes some preliminary work on using diffractive optics rather than geometrical optics to enhance the radiation performance of silicon solar cells. The paper will first describe some potential advantages of using diffractive optics. The formation of diffractive optical structures in silicon will be described next. Finally, some preliminary experimental results will be presented.

DIFFRACTIVE OPTICS FOR SOLAR CELLS

The minority-carrier diffusion length in silicon degrades to around 25 μm after a fluence of 10^{15} 1-MeV electrons per cm^2 [3]. For planar-surface silicon solar cells, the photocurrent from photons with absorption lengths greater than 25 μm will be significantly degraded. The radiation tolerance of silicon solar cells can be improved by implementing optical structures that reduce the optical absorption depth of these weakly absorbed photons (roughly 850 to 1200 nm) to less than 25 μm. Photons with wavelengths shorter than about 850 nm are already absorbed within 25 μm of the surface, so it is not necessary to optically enhance the absorptance of these short-wavelength photons.

Geometrical optical surfaces with crystallographically defined surfaces can only enhance the optical absorption by about 35%. Diffractive optical surfaces can potentially achieve superior performance through two mechanisms (Figure 1). In the first approach, an appropriately designed surface texture is used to couple energy out of the transmitted zero order inside Si to diffraction orders propagating parallel to the surface. This approach is similar to the blazed gratings used in spectroscopy in which the top surface blazed angle and profile is designed to couple almost 100 % of the incident energy into a propagating diffraction order [4,5]. Diffractive optics has long been used for a similar application--coupling of light into waveguide modes [6]. This approach is likely to use shallow (grating depth less much less than incident optical wavelength) gratings.

The second approach typically requires a deep grating where the grating depth is greater than the incident optical wavelength. In this case, enhanced absorptance is achieved by trapping of light within the grating grooves. The rectangular grating profiles act as individual wave-guides with enhanced light interaction for linewidths ~ λ/n, where n is the refractive index of the semiconductor material [7].

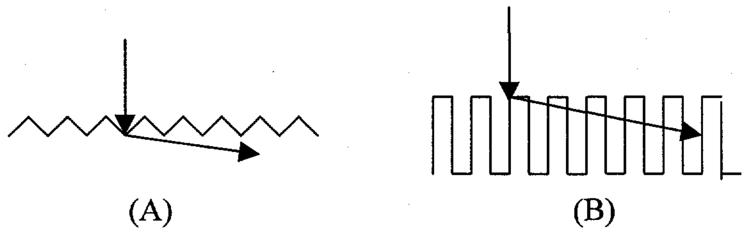


Figure 1. Illustration of use of surface gratings to (A) couple light into a shallow propagation mode with a shallow grating, and (B) couple light into the grating itself with a deep grating.

NANOSCALE TEXTURE FORMATION

The diffractive optical structures have subwavelength features that require application of nanoscale fabrication techniques. We have investigated both randomly textured and periodically textured nanoscale surfaces. Reactive ion etching (RIE) is used to etch the silicon surface. RIE provides very precise, repeatable, and anisotropic etching that is independent of Si crystalline orientation. The degree of anisotropy is controllable. These RIE features are critical to the formation of nanoscale features. Random texture is obtained with either a sacrificial masking layer or through control of the RIE ambient. Periodic texture is obtained with a photoresist mask. The photoresist is patterned using laser interferometry lithography [8]. A detailed description of the experimental techniques is presented by Zaidi [9].

Randomly textured surfaces were produced using SF_6/O_2 RIE. The silicon samples were mounted on an Al electrode, and the distance from the Al electrode to the sample surface was found to be critical (Figures 2 and 3). In this particular experiment, sputtered Al particles are believed to act as random etching masks--which causes the strong dependence of the texture features on the sample dimensions. The external reflectance of the samples with the larger texture features was greatly reduced (Figure 4).

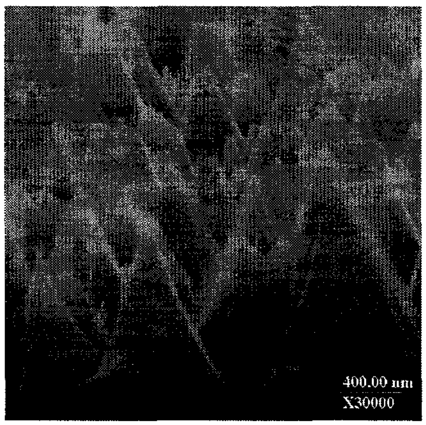


Figure 2. SEM picture of a black Si RIE-textured surface.

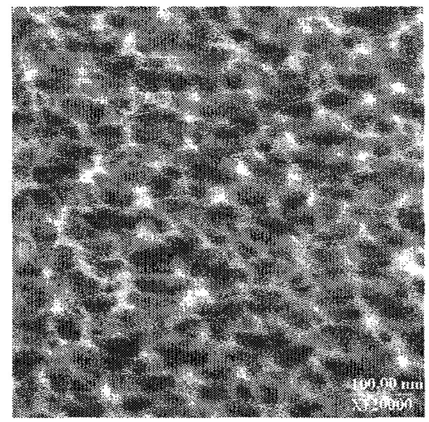


Figure 3. SEM picture of a lightly absorptive Si RIE-textured surface.

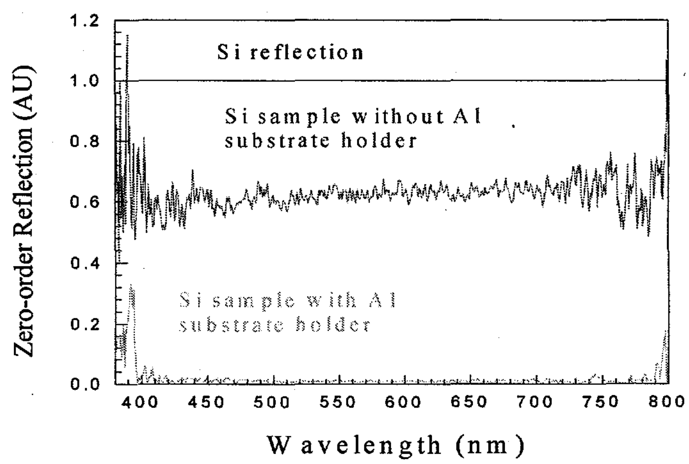
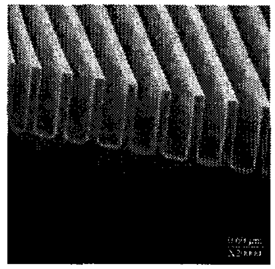


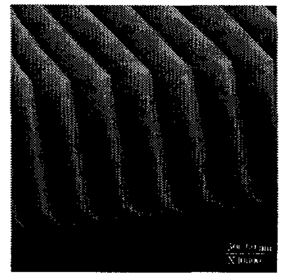
Figure 4. Normal incidence spectral reflectance from randomly etched Si structures with and without Al holders. The 100% baseline is the reflectance from a polished Si surface.

A wide variety of subwavelength deep gratings have been investigated [9]. An example of some of these gratings is presented in Figure 5. The reflectance data show some of the resonances due to the periodic grating structure and associated linewidth variation (Figure 6).

period ~ 1000 nm, linewidth ~ 330 nm



period ~ 500 nm, linewidth ~ 130 nm



period ~ 300 nm, linewidth ~ 50 nm

Figure 5. SEM photomicrographs of three RIE-etched Si surfaces with deep 1-D gratings.

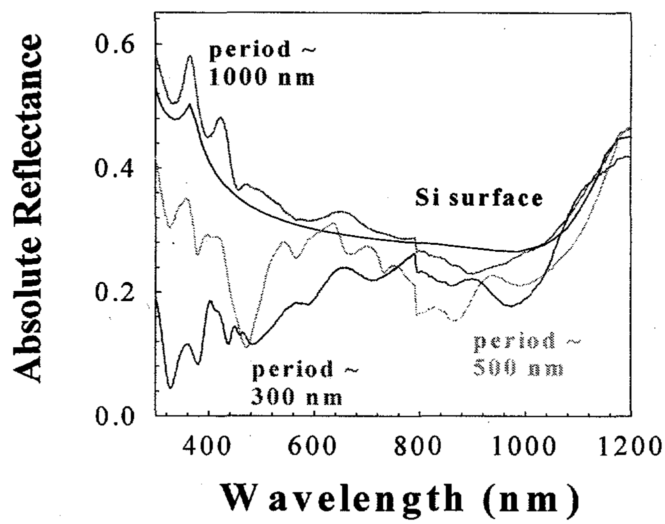


Figure 6. Hemispherical spectral reflectance from the three Si 1-D grating surfaces of Figure 5. Data for a polished Si surface is included for comparison.

The reflectance data does not give an indication of the absorption depth, which is important for the optimization of the radiation tolerance of a Si solar cell. Gratings were also fabricated in silicon-on-sapphire (SOS) samples. The SOS samples allowed for transmittance measurements, which allowed for calculation of the sample's optical absorptance. The SOS samples were obtained from a commercial source, and the silicon layers were only 1.6 μm. The absorptance of several different gratings was characterized (Figure 7). The absorptance of the thin Si samples was enhanced due to the grating structures.

Some very preliminary work has also started on integration of these nanoscale textures into complete solar cells. The internal quantum efficiency--which is the number of collected electrons per absorbed photon--gives an indication of the effectiveness of the nanoscale features to enhance the absorptance near the surface. The internal quantum efficiency spectra were found to be enhanced in the near infrared spectrum due to the use of either randomly or periodically textured surfaces (Figure 8).

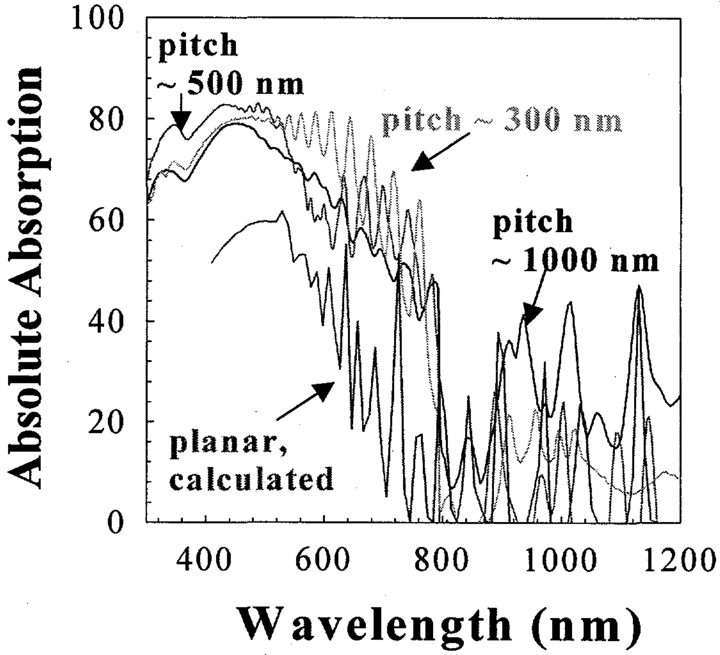


Figure 7. Hemispherical absorption in 1-D grating structures in SOS configuration. The planar sample is a calculated spectra.

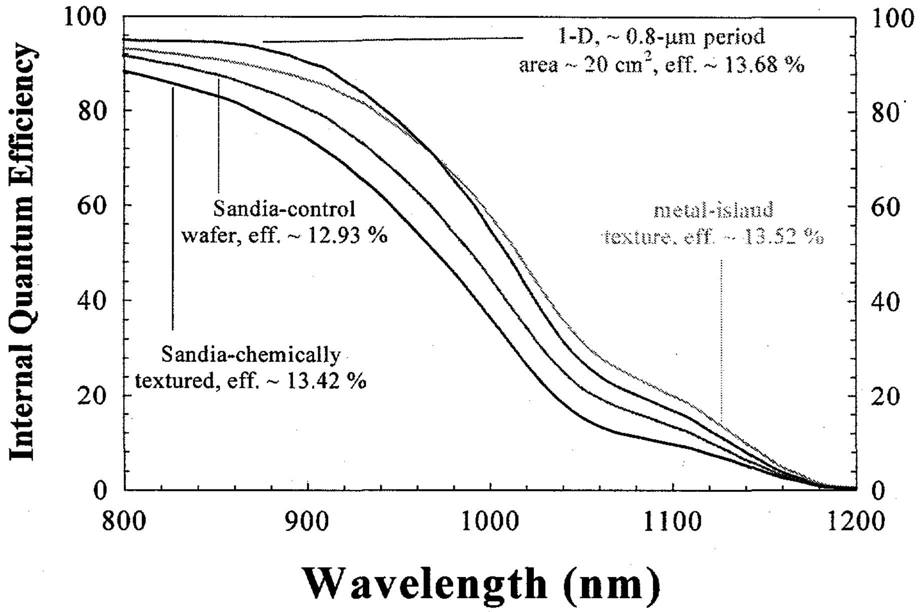


Figure 8. Internal Quantum Efficiency spectra of randomly and periodically textured solar cells in the near-infrared spectral range.

CONCLUSIONS

Diffractive optical structures offer the possibility of enhanced radiation tolerance for Si solar cells. The application of these structures and some preliminary experimental results are presented.

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