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Light Trapping for Thin Silicon Solar Cells by Femtosecond Laser Texturing

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***Abstract* — Femtosecond laser texturing is used to create nano- to micron-scale surface roughness that strongly enhances light-trapping in thin crystalline silicon solar cells. Light trapping is crucial for thin solar cells where a single light-pass through the absorber is insufficient to capture the weakly absorbed red and near-infrared photons, especially with an indirect-gap semiconductor absorber layer such as crystalline Si which is less than 20 µm thick [1-2]. We achieve enhancement of the optical absorption from light-trapping that approaches the Yablonovitch limit [3].**

***Index Terms* — light trapping, laser texturing, epitaxial silicon, femtosecond laser, Lambertian.**

I. INTRODUCTION

The development of epitaxial, thin, crystalline Si solar cells has the goal of approaching the high efficiency of wafer-based Si cells, while using only a fraction as much Si [1-2]. The expectation is that these thin silicon cells will have dramatically lower production costs, and good potential for scalability to large areas. A key challenge for these ~2-20 µm thick cells is achieving sufficient photocurrent, which can be improved by capturing more of the weakly absorbed red and near-infrared incident sunlight.

Light trapping can increase the path-length of light, using total internal reflection to keep light inside the cell. A cell with a randomly textured surface giving Lambertian light-scattering can theoretically achieve the Yablonovitch light-trapping limit [3]. For weakly-absorbed light, the Yablonovitch path-length enhancement factor is $4n^2 \sim 50$x in Si ($n \sim 3.5$) for infrared photons near the bandedge.

KOH etching is a proven, industrial method of texturing Si; it produces random pyramids that can enhance light-trapping to near the Yablonovitch limit [4]. However, KOH etching typically removes many microns of Si, which may not be economical for thin silicon cells. Moreover, it only works well on (100) oriented Si.

Two alternative methods are texturing Si with plasma etching [5] or laser pulses. Here, we demonstrate the potential of femtosecond laser pulses for creating a nearly ideal random texture on Si; our laser texture can greatly enhance light-trapping while simultaneously decreasing reflectivity.

II. FEMTOSECOND LASER TEXTURING

A variety of surface morphologies can be obtained from fs laser treatments, depending on laser parameters and the ambient gas environment [6-7]. We target wavelength-scale and larger features to: a) reduce reflectivity by directing reflected light to neighboring valley walls; and b) scatter light at large angles, resulting in light-trapping due to total internal reflection.

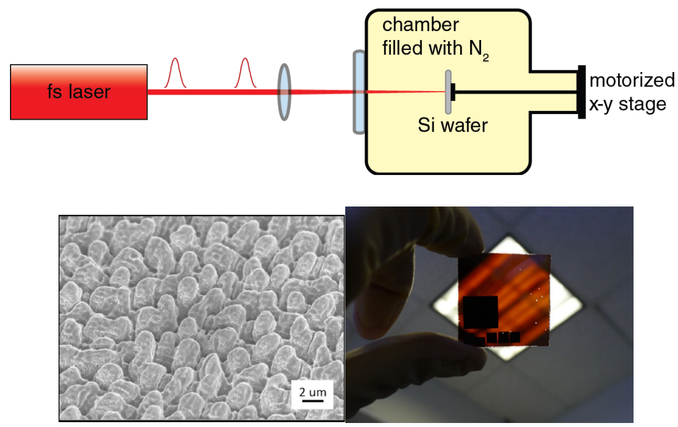

Fig. 1. (a) Schematic of femtosecond laser texturing apparatus. (b) SEM image of laser textured Si. (c) Thin (~2 µm) crystalline Si film on glass. Dark areas have been laser-textured.

We scan fs-laser pulses over the surface of a Si sample, with the sample located inside a vacuum chamber with motorized stage (Fig. 1a). Each fs laser pulse locally melts Si at the surface, which rapidly resolidifies. Optical interference effects cause rippling in the re-formed Si surface. Successive irradiation with laser pulses causes these instabilities to grow into "hills and valleys." Importantly, this change in morphology happens with negligible loss of material from ablation.

Texturing was done in N_2 gas ambient, with 4 kJ/m^2 laser fluence, 800 shots/area and 800 nm center wavelength. We generated ~0.1-1 µm scale features with a large degree of random roughness (Fig. 1b). The laser texturing dramatically modifies the optical properties of thin Si films. In Fig. 1c, we see that while untextured 2-µm-thick crystalline Si is mostly transparent, the textured areas are opaque due to the enhanced absorption by light-trapping.

III. Optical Properties

We investigate the absorption of laser-textured Si quantitatively, in order to determine the benefit of texturing to both light-trapping and also reduced reflectivity. Optical transmission and reflection measurements were performed using a Varian Cary 6000i spectrophotometer, equipped with an integrating sphere to collect diffusely transmitted/reflected light. The absorption was calculated by A = 1-T-R.

The absorption of both 400 and 20 μm thick Si wafers show similar behavior (Fig. 2). The texture decreases reflectivity across the spectrum. This is its primary benefit at shorter wavelengths, <1000 nm and <800 nm respectively for the 400 and 20 μm thick wafers. The reduction in reflectivity, as compared to a flat wafer, is nearly as good as a 75 nm silicon nitride AR coating (n ~ 2).

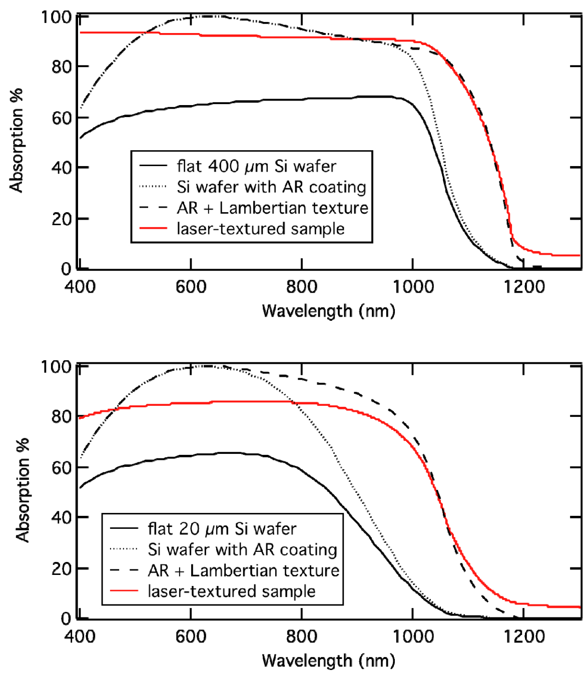

Fig. 2. Optical absorption of (a) 400 μm and (b) 20 μm thick Si wafers with laser-textured front side, as compared to theoretical absorption spectra for a flat wafer, a flat wafer with silicon nitride AR coating, and with Lambertian (Yablonovitch) light trapping.

The laser texture also significantly enhances the light-trapping in the long-wavelength region, >1000 nm and >800 nm respectively for the 400 and 20 μm thick wafers. This is particularly evident for the thinner 20 μm wafer (Fig. 2b). In both cases, the absorption enhancement is practically at the Yablonovitch light-trapping limit. We attribute this excellent light-trapping to the nearly ideal random texture created by fs laser treatment.

IV. Textured Solar Cell

To demonstrate the efficacy of fs laser texturing for solar cell devices, we study texturing of a thin, epitaxial crystalline Si cell. The Si was deposited by hot-wire chemical vapor deposition (HWCVD) hetero-epitaxial growth on a sapphire substrate [8]. First, a heavily n-doped bottom contact was grown 2 μm thick (Fig. 3a). Then, the 4-μm-thick lightly n-doped absorber layer was grown.

Subsequently, the surface of the epitaxial Si film was laser-textured. After laser-texturing, we performed various chemical cleaning steps. We are investigating the benefit of a wet chemical etch that can remove some thickness of Si which is damaged in the laser process. The cell junction is formed by depositing ~6 nm intrinsic and 15 nm p-doped amorphous Si, giving a Si heterojunction emitter. 75 nm indium tin oxide (ITO) is deposited as a top contact. A 0.05 cm^2 mesa cell was isolated by etching down to the highly-doped bottom contact. Light enters the cell through the top side and a silver back mirror is used at the bottom.

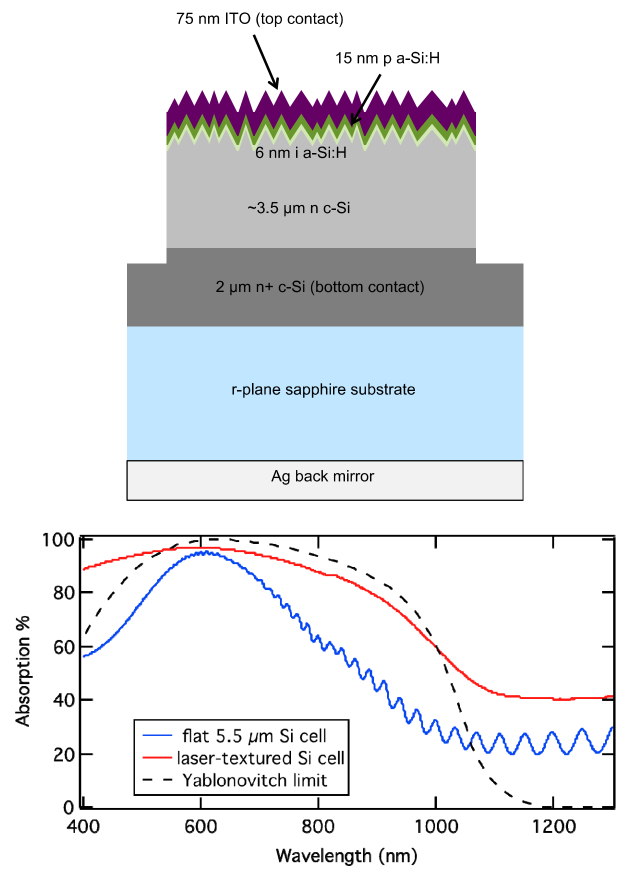

Fig. 3. (a) Schematic cross-section of epitaxial crystalline Si solar cell grown on sapphire substrate, with front side laser texture. (b) Optical absorption of flat and textured epitaxial Si solar cells, as compared to the Yablonovitch Lambertian theory.

The optical absorption was determined, in the same way as with the Si wafer samples (Fig. 3b). Thin-film interference fringes are visible for the flat cell, but are absent for the textured cell because of diffuse scattering. Similar to the Si wafer samples, we see good reduction in reflectivity and also enhancement in light-trapping to nearly the Yablonovitch limit. The decreased reflectivity is most evident in the short-wavelength region <600 nm, while light-trapping is enhanced for longer wavelengths. We additionally see some parasitic absorption in both flat and textured cells at >1100 nm wavelength. This is due to free carrier absorption in the highly-doped bottom contact layer. Light-trapping also enhances the parasitic absorption.

We performed external quantum efficiency (EQE) and current-voltage (I-V) measurements on both flat and textured cells having the same physical thickness. The shape of the EQE curve for the textured cell is qualitatively similar to its optical absorption (Fig. 4a), except for parasitic free-carrier absorption that doesn't contribute to current. However, the EQE is quite low with very poor collection of photocarriers. This is likely due to a poor Si heterojunction on the laser-textured surface. We are currently investigating methods to remove some thickness of laser-damaged Si, which should improve performance. Notably, despite the overall poor EQE, we still see a small enhancement in the infrared as compared to the flat cell (dashed oval in Fig. 4a).

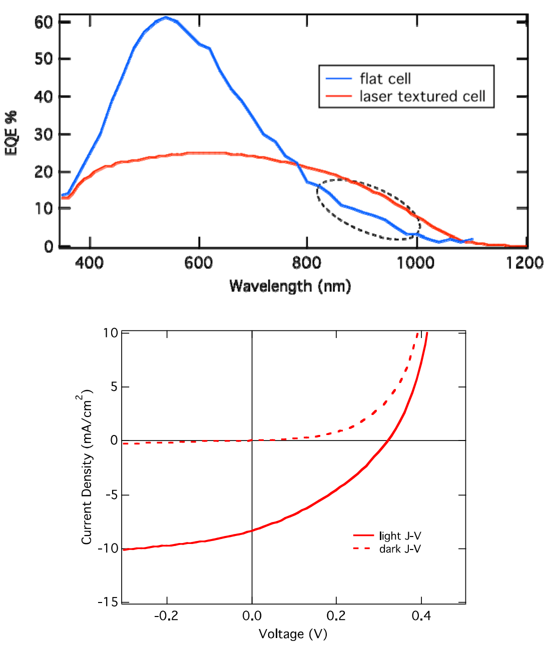

Fig. 4. (a) External quantum efficiency of flat vs. textured epitaxial Si cells. Dashed oval shows infrared QE enhancement of the textured cell. (b) J-V characteristic of textured epitaxial Si cell.

Consistent with the EQE results, the laser-textured cells have low V_{OC} ~ 0.3 V and J_{sc} ~ 8-12 mA/cm^2. We also see a problem with low shunt resistance in the J-V curve (Fig. 4b), which also points to problems with the junction. We will discuss these issues in subsequent publications and are working on solutions that should give significantly improved cell performance.

V. Conclusion

Femtosecond laser treatment allows us to create a nearly ideal, randomly-textured surface on Si. Significant reductions in reflectivity and light-trapping absorption enhancements approaching the Yablonovitch limit have been achieved by texturing. We have fabricated working solar cell devices from hetero-epitaxial Si grown on sapphire substrates by HWCVD. The cells have poor EQE, V_{OC} ~ 0.3 V and J_{sc} ~ 8-12 mA/cm^2. We believe we understand the problem of laser-induced damage, and have methods to significantly improve cell performance in the future. Importantly, these initial results with relatively poor laser-textured cells nonetheless show increased quantum efficiency (vs. un-textured cells) for infrared photons, due to enhanced light-trapping.

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