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Laser induced quasi-periodical microstructures with external field modulation for efficiency gain in photovoltaics

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ABSTRACT

The overall reflectivity of silicon is decreased by 10% altering the surface topology by ultra-short pulsed laser ablation and resulting in an efficiency increase of solar cells. The size of quasi-periodical μm-structures on the surface can be defined by the applied laser parameters. The topology is additionally adapted in size and distance of the microstructures at constant laser parameters with a specifically applied external electrical field leading to a cone-like microstructure with an adjustable light-trapping geometry. On large scale multicrystalline silicon solar wafers with a laser generated μm-scale surface topology were processed into cells with an absolute efficiency gain.

1. Introduction

The mechanical, chemical, and optical properties of materials can be optimized for many applications by a tailored surface topology. For example in medical applications the wettability of water on a metal surface can be set to hydrophobic [1]. The electrochemical performance of lithium cobalt oxide for Li–ion batteries is enhanced by an enlarged active electrode area with e.g. μm-sized cone like surface features [2]. The surface topology alters in optical applications the luminous emittance of organic [3] and anorganic surfaces [4]. Therefore, the lighting characteristics can be changed in terms of the scattering angle and luminosity for organic and anorganic LED's. In the case of photovoltaics the electro-optical efficiency of solar cells is limited by the surface reflectivity of silicon, which is also a function of the wavelength of light [5].

Different techniques can be applied on silicon wafers to reduce the spectral dependent reflectivity, e.g. coating with antireflective layers [6], and texturing by isotropic etching or laser processing [7–10]. A topology characterized by μm-scale surface features can be produced by laser ablation with distinct laser parameters and processing gases at different laser pulse durations [7,9,11].

In this article, we describe the generation and modification of μm-sized surface features for reflectivity reduction in photovoltaics. The generation of sub-μm sized laser induced features called ripples can be described by a plasmon model based on surface plasmon polaritons (SPP) [12,13].

The SPP are coherent oscillations of electrons at the substrate surface, and resulting in an electromagnetic field at the surface boundary [14]. The quasi-periodical structures described here in more detail are induced at laser fluencies of up to several 10-folds of the ablation threshold while ripples are induced close to the ablation threshold. We expect that the quasi-periodical μm-sized surface features are also generated by laser induced SPP and can therefore be controlled with laser radiation by applying additional electromagnetic fields. In our approach the quasi-periodical structures are generated on the surface of silicon by laser ablation in ambient atmosphere and not in halogenic atmosphere [7]. Further, ultra-short pulsed laser structuring has been achieved at large area velocities (processed area per time) with repetition rates in the order of several hundreds of kHz. To parallelize the laser processing optional diffractive optical elements (DOE) have been applied for beam splitting [15]. In addition to our approach, external electromagnetic fields have been generated using conductive silver electrodes on the silicon sample to control the formation of the quasi-periodical structures during laser processing, which is explained in detail in Section 3, Fig. 3. With this method it is possible to design and shape the topology for different applications. In case of photovoltaics a topology is favourable with different structure distances and heights to decrease the reflectivity over a broad spectral range. 5-Inch silicon wafers have been finally structured for producing silicon solar cells.

2. Theoretical description for plasmon propagation

We propose a description of a modified plasmon propagation approach to explain the generation of quasi-periodical μm-sized surface features with a distinct average distance Λ. The electromagnetic wave function (SPP), here the electrical field only at the surface boundary is described [14]

$$\vec{E} = \vec{E}_0 \cdot e^{i(k_x \cdot x - k_z \cdot z - \omega \cdot t)}, \tag{1}$$

with $\vec{E}_0$ being the electrical field component, k_x and k_z the wave vectors in x and z direction, ω the angular frequency, and t the time (Fig. 1).

The attenuation of the electrical function of the SPP at $1/e$ is described by the lateral plasmon propagation length

$$L_i = \frac{1}{2 \cdot k_x''} \tag{2}$$

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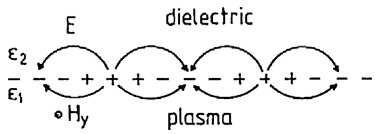

Fig. 1. Surface plasmon polaritons at the boundary of a two layer system with the dielectric constants ε_1 and ε_2; schematic illustration of the electric charges (+ −); H_y *y*-component of the magnetic field; *E* and arrows direction of the electrical field of the *p*-polarized wave [14].

with k_x'' being the attenuation coefficient. Two primes correspond to the imaginary part of a complex function and one prime represents the real value. The attenuation coefficient k_x'' depends on the angular frequency of light ω, the velocity of light c, and the complex dielectric functions of the two boundary materials ε_1 and ε_2 and equals to [14]

$$k_x'' = \frac{\omega}{c}\left(\frac{\varepsilon_1' \cdot \varepsilon_2'}{\varepsilon_1' + \varepsilon_2'}\right)^{3/2} \frac{\varepsilon_1''}{2(\varepsilon_1')^2}. \qquad (3)$$

The imaginary part of the complex dielectric function of the material is given by

$$\varepsilon_1'' = 2n \cdot \kappa \qquad (4)$$

with n representing the refraction index and κ the extinction coefficient. The parameter κ is on the other hand coupled to the absorption coefficient

$$\alpha = 2\kappa \frac{\omega}{c} \qquad (5)$$

The absorption of laser radiation in material is determined by the absorption coefficient α, which is a function of the temperature T, the laser wavelength λ [16], and the applied laser fluence $H_p = 4 \cdot E_p \cdot \pi^{-1} \cdot d_{fok}{}^{-2}$ with E_p representing the laser pulse energy and d_{fok} the focal diameter [17]. In a first approximation the reciprocal absorption coefficient, respectively the optical penetration depth is set to be equal to the ablation depth per pulse a_p as a function of the laser fluence H_p

$$\frac{1}{\alpha} = a_p(H_p) \qquad (6)$$

and with Eq. (6) one can estimate ε_1'' and determine L_i. The attenuation coefficient k_x'' of Eq. (3) equals with Eqs. (2)–(6) to

$$L_i = \frac{1}{2 \cdot ((\varepsilon_1' \cdot \varepsilon_2')/(\varepsilon_1' + \varepsilon_2'))^{3/2}(n/(2(\varepsilon_1')^2 \cdot a_p(H_p)))} \qquad (7)$$

The laser–material interaction width d_{lmi} scales with the laser fluence H_p and the focal diameter d_{fok} by

$$H_p = H_{thr} \cdot \exp\left[\frac{4 \cdot d_{lmi}^2}{d_{fok}^2}\right] \qquad (8)$$

and therefore defines the boundary of the propagation for the SPP, too, Fig. 2.

Furthermore the lateral propagation length of the SPP can be described by the product of the attenuation time τ_i and the drift velocity of the electrons v_D [14]

$$L_i = |\vec{v}_D| \cdot \tau_i, \qquad (9)$$

whereas the drift velocity v_D is given by electron mobility μ_e and the electrical field strength $\vec{E}$

$$\vec{v}_D = \textbf{micro;}_e \cdot \vec{E}. \qquad (10)$$

The definition of the lateral plasmon propagation length with Eqs. (2) and (9) is equivalent and therefore we expect an effect of the electric field during laser ablation.

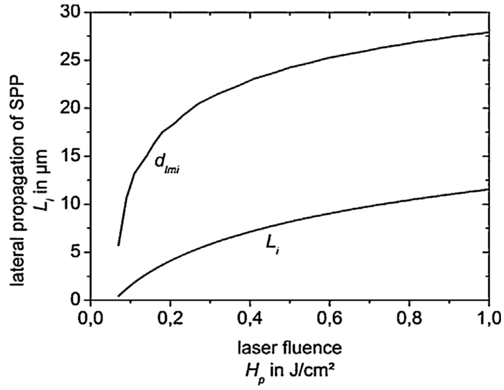

Fig. 2. Lateral plasmon propagation length L_i as a function of laser fluence H_p, redetermined with the ablation depth per pulse a_p for silicon at a laser pulse duration of t_p = 7 ps; d_{lmi} laser–material interaction width; d_{fok} = 23.6 µm.

3. Experimental procedure

The experiments are carried out with a laser machining set up consisting of an ultra-fast laser source with a second harmonic generator (t_p = 7 ps, λ = 515 nm, f_{rep} = 400 kHz), a three times beam expander, and a galvanometric scanner system to deflect the laser beam with a scanning velocity v [11]. The scanner system is equipped with an *f*-theta lens. The spot diameters are measured with a Primes MicroSpotMonitor with $d_{fok} \approx 20$ µm at $1/e^2$ and M^2 = 1.19 (focal length f_{foc} = 255 mm) and $d_{fok} \approx 23.6$ µm at $1/e^2$ and M^2 = 1.06 (focal length f_{foc} = 292 mm). The laser fluency has been varied from H_p = 0.023 J/cm² to H_p = 2.286 J/cm² and the number of pulses per point $N_{ppp} = d_{fok}\, f_{rep}/v$ has been set up to $N_{ppp} \leq 100$ to determine the proper parameter values to induce µm-scale cone like quasi periodical structures.

In addition external electric fields are applied during laser processing on the sample to realize the new procedure. The external electrical fields are initiated by conductive silver electrodes on the silicon sample surface, which are connected with a DC-power supply, Fig. 3.

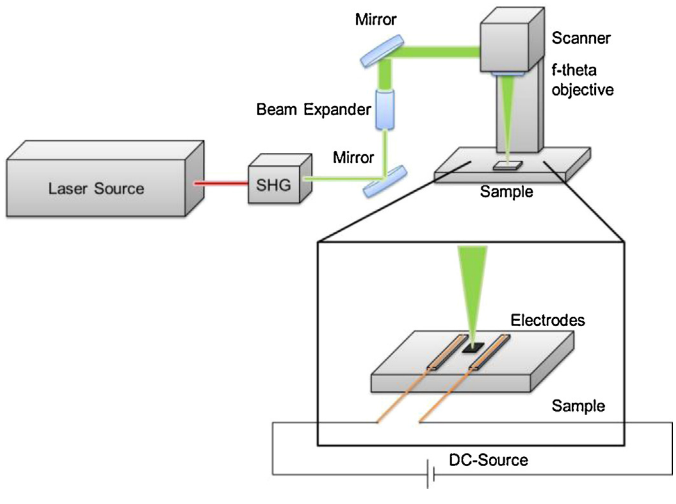

Fig. 3. Experimental setup with laser source, beam guidance and a detailed layout of the external application of electric fields.

The drift velocity v_D of the collective electrons is a function of the applied electrical field E. The lateral plasmon propagation length L_i is changed by applying external electrical fields. The external electrical parameters (electrical field strength E (V/m) and electric current I (A)) have been altered at a set of constant laser parameters, e.g. laser fluence H_p and number of pulses per point N_{ppp} to induce quasi-periodical µm-scale cone like structures on silicon, Figs. 4 and 7.