Applied Surface Science 374 (2016) 177–182

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Time-resolved photoluminescence for evaluating laser-induced damage during dielectric stack ablation in silicon solar cells

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ARTICLE INFO

Article history:
Received 12 June 2015
Received in revised form 29 October 2015
Accepted 30 October 2015
Available online 11 November 2015

Keywords:
Laser processing
Ablation of dielectrics
Al_2O_3
SiN_x
Minority carrier lifetime
Photoluminescence
Silicon solar cells

ABSTRACT

Selective laser ablation of dielectric layers on crystalline silicon wafers was investigated for solar cell fabrication. Laser processing was performed on Al_2O_3, and bi-layers Al_2O_3/SiN_X:H with a nanosecond UV laser at various energy densities ranging from 0.4 to 2 J cm^{-2}. Ablation threshold was correlated to the simulated temperature at the interface between the dielectric coatings and the silicon substrate. Laser-induced damage to the silicon substrate was evaluated by time-resolved photoluminescence. The minority carrier lifetime deduced from time-resolved photoluminescence was related to the depth of the heat affected zone in the substrate.

1. Introduction

Laser technologies are gaining considerable attention for photovoltaics since they open ways to new structures with improved conversion efficiency. As an example, the rear-side of high efficiency silicon solar cells often includes rear-side passivation and local contacts produced by laser ablation of a dielectric stack. The challenge of laser ablation is to achieve complete removal of selected areas without causing detrimental damage to the surrounding material [1,2]. It is, therefore, necessary to control the surface quality after laser processing as laser-induced damage can reduce drastically the minority carrier lifetime in the substrate. Photoluminescence (PL) is a contactless and non-destructive technique to evaluate the effective minority carrier lifetime in semiconductors. Quasi steady-state and imaging PL techniques have been applied successfully to the characterization of solar cell fabrication including laser ablation steps [3,4]. It has also been shown that room temperature PL spectroscopy was a sensitive technique to evaluate qualitatively the laser-induced damage after ablation of SiN_x on silicon [5]. Recently, we have demonstrated that time-resolved photoluminescence (TRPL) measured by time correlated single photon counting (TCSPC) was well suited to extract the minority carrier effective lifetime in silicon [6]. It is a room temperature technique whose spatial resolution is limited by the dimension of the laser beam. In this work, we use TRPL to investigate the laser-induced damage in Al_2O_3 and bilayers Al_2O_3/SiN_X:H used as passivating and/or anti-reflection coatings in silicon solar cells. The ablation of these dielectric layers is challenging because their absorption at the laser wavelength is much smaller than that of the underlying Si substrate. Although laser ablation of SiN_x has been quite thoroughly studied for photovoltaics application for example in [1,2,7,8], ablation of Al_2O_3 has been less studied [9–11] despite the fact that it has become a widely used dielectric for Si solar cells particularly in combination with SiN_x for back surface passivation of p-type solar cells. In the present work, simulations were used to relate the experimental observations to the temperature evolution at the interface between the silicon substrate and the dielectric coatings. The effect of the ablation fluence on the effective carrier lifetime was measured by TRPL and related to the thickness of the heat-effected zone.

2. Sample preparation and preliminary characterization

Double polished high quality n-type FZ crystalline silicon wafers were used for the experiments. Wafers were 250 μm-thick with a resistivity around 10 Ω cm. Al_2O_3 layers (15 nm thick) were deposited by thermal Atomic Layer Deposition (ALD). SiN_X:H

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http://dx.doi.org/10.1016/j.apsusc.2015.10.230

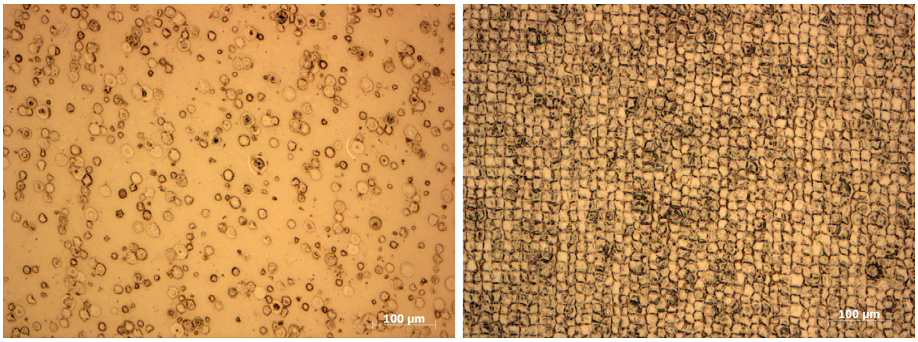

Fig. 1. Optical microscopy of a Si/Al_2O_3 sample irradiated with a 355 nm nanosecond laser at fluences 1 J cm^{-2} (left) and 2 J cm^{-2} (right).

layers (80 nm thick, refractive index around 2.01 at 635 nm) were deposited by PECVD on Al_2O_3 substrates. Layer thicknesses were close to the values commonly used for passivating anti-reflection coating in silicon solar cells.

The ablation was achieved using a frequency tripled Nd:YAG laser (Rofin RSM 20E THG) with a Gaussian profile, a wavelength of 355 nm and a pulse duration of 10 ns [12]. The penetration depth of the UV laser in silicon was around 10 nm. The laser spot diameter at the sample surface was around 25 μm. The scanning speed of the laser beam was chosen to have no overlap between the spots. Small areas (6 mm × 6 mm) were ablated at different laser fluences F_{laser} ranging from 0.4 to 2 J cm^{-2}. After ablation, samples were etched for 10 s in 5% water diluted HF to remove the dielectric coatings that were locally ablated. Substrates were finally passivated on both sides by a 15 nm-thick Al_2O_3 and annealed at 400 °C for 10 min before minority carrier lifetime measurements.

Optical microscopy was used as a simple means to assess the ablation threshold and the surface quality. Ablation threshold of Al_2O_3 and Al_2O_3/SiN_X was observed around 0.85 and 0.95 J cm^{-2}, respectively. Optical microscope observations after ablation of a 15 nm layer of Al_2O_3 on silicon are shown in Fig. 1 for two laser energy densities 1 and 2 J cm^{-2}. Partial removal of dielectrics at these fluences was attributed to the lack of pulse-to-pulse repeatability of the laser that is very critical close to the ablation threshold. Damage at the surface is attributed to the ablation of silicon that occurs around 1 J cm^{-2}. Severe damages with ablation of the silicon surface were observed at 2 J cm^{-2} for both stacks.

3. Ablation mechanism

Laser ablation of dielectrics has been shown to result from the vaporization of the material due to heat [7,12]. The thermal expansion of the underlying substrate and its vaporization has also been used to explain SiO_2 and SiN_x ablation on a Si substrate [2]. If the material has a small absorption coefficient at the laser wavelength, as it is the case for Al_2O_3 and stoichiometric SiN_x in the UV range, ablation can still take place due to absorption in the highly absorbing silicon substrate. Due to the low absorption coefficient of Al_2O_3 and SiN_x at 355 nm ($\alpha_{Al2O3} \sim 0$ and $\alpha_{SiNx} \sim 3.5 \times 10^2$ cm^{-1}) compared to Si ($\alpha_{Si} \sim 10^6$ cm^{-1}) the laser absorption in the dielectric layers under study is negligible. Consequently the Si substrate behaves as a heat source after having absorbed the laser energy. The heat absorbed in Si is transferred by conduction in a few nanoseconds to the adjacent layers. While other complex mechanisms may occur during laser-matter interaction, ablation of the dielectric coatings under study can be explained by a vaporization mechanism when the temperature reached in the layer is of the order of the boiling temperature (respectively, around 3253 K for Al_2O_3 and 2150 K for SiN_x).

Table 1
Thermal properties of the materials under study [11].

	Al_2O_3 (crystalline)	Si_3N_4	Si (crystalline)
Melting point/sublimation temperature (K)	2343	2150	1683
Boiling point/vaporization temperature (K)	3253	NA	2628
Thermal conductivity solid state (W m^{-1} K^{-1})	18	25	150
Thermal conductivity liquid state (W m^{-1} K^{-1})	1–5.5	NA	200–370

Modelling of a single laser pulse interaction with the dielectric coatings on a Si substrate was done using the commercial software COMSOL Multiphysics [12]. The heat-transfer equation was solved for the two structures Si/Al_2O_3 and Si/Al_2O_3/SiN_x. Simulated thicknesses of the Al_2O_3 and SiN_x layers were 15 nm and 80 nm, respectively. The main thermal properties of the dielectric layers and silicon used in the simulation are given in Table 1. However, the thermal properties commonly available for Al_2O_3 are those of the bulk material that are expected to differ from those of thin films. The maximum fluence used in the simulation is 1 J cm^{-2} which corresponds to the ablation threshold of Si. Fig. 2 shows an example of the temperature versus time at the Si surface of a stack Si/Al_2O_3/SiN_x submitted to a single pulse of fluence of 0.5 J cm^{-2}.

In a similar way, the maximum temperature at the Si surface was computed for the different stacks and different laser fluences. Results are reported on Fig. 3. The relevant melting and boiling

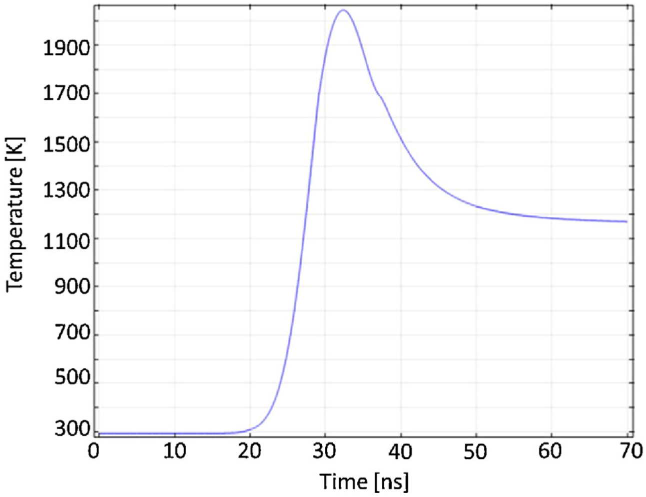

Fig. 2. Comsol simulation of the time evolution of the temperature at the Si/Al_2O_3/SiN_x interface for a laser fluence of 0.5 J cm^{-2}.