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Atmospheric Components and Dopant Carry-Over Influence During Laser Ablation

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Abstract

In order to improve the efficiency of multi-crystalline (mc)-silicon solar cells, laser ablation as a non-contact tool is highly suitable for various processes. Apart from the laser and scanning parameters frequently reported in the literature, other factors exist upon which the observable results of laser ablation depend. In addition to laser and scanning parameters, the influence of various atmospheres on the laser ablation process is investigated in this work. The laser edge isolation process is used to demonstrate these effects. The impact on the dopant concentration in the generated laser groove is investigated using the shunt resistance of the solar cells. From these investigations the most suitable laser is determined as well as ambient parameters for the ablation of mc-silicon.

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Keywords: atmospheric components; laser ablation; dopant carry-over

1. Introduction

Within the photovoltaic industry today lasers are used e.g. for edge isolation, marking and cutting. Laser edge isolation is currently an established application for producing Si solar cells. In this application the phosphorus doped surface layer is removed on the edge to obtain the pn-junction isolation. In this paper different types of lasers with corresponding wavelengths and pulse durations have been investigated [1, 2, 3, 4]. The wavelengths for the studies range from the near infrared (NIR) to the ultraviolet (UV) parts of the spectrum and pulse durations have been applied between a few picoseconds and several hundred nanoseconds. The edge isolation process is applicable for mc-Si solar cells using these types of laser sources. The laser parameters do not describe the impact on the mc-Si solar cells completely. Other factors have to be considered, in particular the initial dopant concentration of phosphorus at the surface and the ambient atmosphere during laser processing [3].

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2. Experimental

The mc-Si solar cells are typically doped to a depth of approx. 500 nm. With the aid of specific resistivity over dopant concentration, it is possible to estimate the shunt resistance over the groove depth if no dopant diffusion occurs during the generation of the groove.

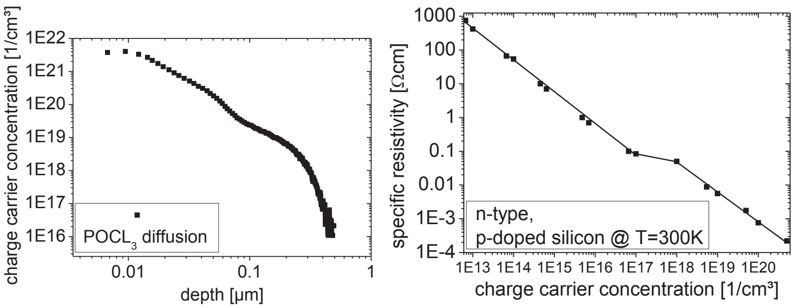


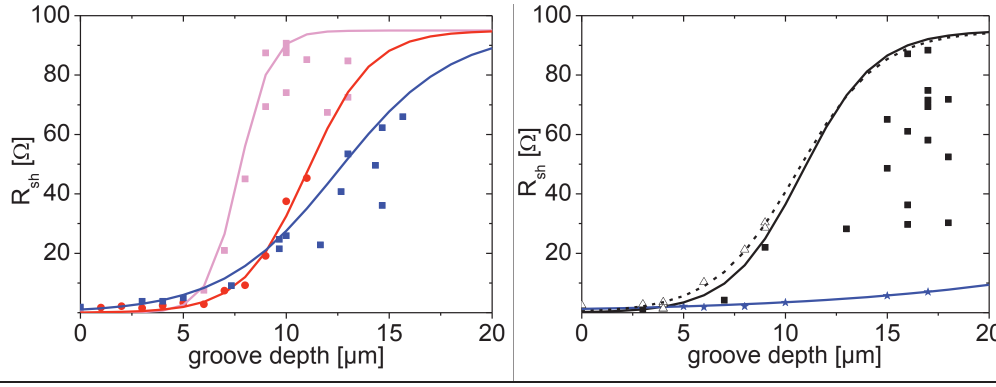
Fig. 1 Charge carrier concentration and the corresponding specific resistivity, data from Schott Solar AG; the specific resistivity versus charge carrier concentration is subdivided into three regimes in the right image, data taken from [5]

The mc-Si solar cells are laser edge isolated by a variety of laser sources from pico- to nanosecond pulse durations with near infrared and green wavelengths. The relatively large working field for processing 6-inch solar cells requires a long focal length of the corresponding f-theta lens. For the investigations, optics with focal lengths of 255 mm and 250 mm have been used. With these laser sources, different groove depths have been generated and measured with optical microscopy and their corresponding shunt resistance values are determined by dark I-V measurements.

In addition several gases as processing atmospheres are tested according to their suitability for the laser edge isolation process. These experiments are done with a picosecond laser with a wavelength of $\lambda = 515$ nm at a repetition rate of $f_{rep} = 400$ kHz. These gases are normal ambient atmosphere, oxygen, nitrogen, and argon. Three characteristic laser parameter ranges are tested for edge isolation. The first is the thermal ablation regime [3] at a high scanning velocity, corresponding to a relatively low overlap. The two others are in the optical regime [3], but at low and very low scanning velocities and corresponding to very large overlaps. The structural and chemical investigations are performed with secondary electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX).

3. Results and Discussion

The achieved shunt resistances at particular depths are lower than expected from the theoretical description [4]. The systematic differences are due to laser processing with different laser parameters, impurities, and non-ideal behavior of the mc-Si solar cells. Laser processing yields heat input into the material due to the irradiation itself as well as the indirect heating by plasma plume after the laser pulse. The laser energy in the material accumulates with consecutive laser pulses until energy diffusion and energy input reach a balance. This energy accumulation raises the temperature of the material thus yielding diffusion of the dopants into the bulk material as described by Fick´s laws. However, the discrepancy of the ideal shunt values at a certain depth and the investigated ones can be due to a variety of physical phenomena, like the mentioned dopant diffusion, but also re-deposition of particles and surface topology. Figure 2 demonstrates the curve evolution for the parameters of the laser systems (dots) as well as for the determined fit parameters (lines). The fitted curves are determined due to Schütz, et.al. [4].



Laser type	RSM E20	RSM E20	TruMicro5X50	TruMicro5X50	YLP-1-120-50-50	YLPM-1-A4-20-20
t_p (ns)	7	13	0.007	0.007	120	20
λ (nm)	532	532	515	1030	1064	1064
f_{rep} (kHz)	15	40	400	400	50	100
Ov (%)	85	85	93.3	97.3	75	85
sign	■	●	■	★	■	△

Fig. 2 Shunt resistance versus groove depth for various laser systems with wavelengths in the near infrared and green spectra [4], Ov is the overlap, λ is the laser wavelength, t_p is the laser pulse duration, and f_{rep} is the repetition rate of the laser system

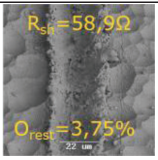
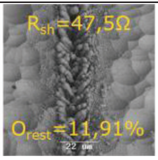
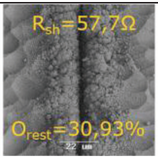
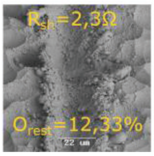
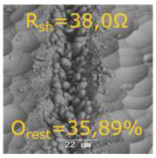
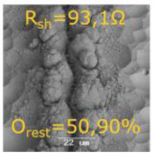
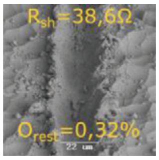
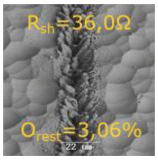
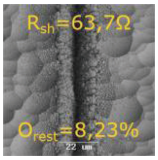
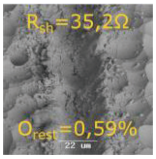
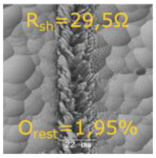
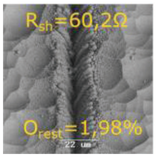
A significant increase of the shunt resistance is achieved for groove depths deeper than approx. 7 µm and not as estimated of approx. 500 nm [4]. One of the main conclusions according to these curves is that the laser parameter mainly influencing the process is the repetition rate. A decrease of the repetition rate for a ns-system yields a higher shunt resistance, despite a three order of magnitude lower laser pulse duration at the same groove depth.

For efficient laser edge isolation and in series a higher solar cell efficiency an exemplary optical setup is equipped with a f-theta lens with a focal length of z_{lens} = 292 mm and a collimated raw beam diameter of d_{raw} = 5.5 mm at $1/e^2$. The laser source should provide a median output power of P_m = 23.1 W at a repetition rate of f_{rep} = 30 kHz, a pulse duration of t_p = 7 ns at a laser wavelength of λ = 532 nm on the substrate to achieve a scribing velocity of v = 624 mm/s for a 6-inch solar cell with a charge carrier concentration profile mentioned in Fig. 1.

In addition, three characteristic laser parameter sets are chosen for the laser edge isolation in different ambient gases. With these parameter settings three groove structure types are distinguished. In the thermal ablation regime and at a relatively low overlap, typical ns-pulse duration groove geometries are obtainable. In the optical regime at high and very high overlaps, a cone-like structure and a deep narrow groove are generated respectively.

Corresponding to different atmospheres and scanning velocities, varied remaining oxygen concentrations in the silicon remain.

Table 1 Different groove types for three characteristic laser parameters, isolated in ambient atmosphere, O_2, N_2, and Ar; f_{rep} = 400 kHz; d_f = 23.4 µm; R_{sh} is the shunt resistance of the solar cell, O_{rest} is atomic oxygen content in the laser groove, H_p is the laser fluence, and Ov is the overlap

H_p (J/cm²) Ov (%)	14 93.33	1 99.63	1 99.91
ambient atmosphere			
O_2			
N_2			
Ar			

Argon and nitrogen atmospheres yield lower shunt resistances in each parameter regime. In the case of industrial-relevant laser parameters, the most suitable atmosphere is the normal ambient one. Increasing the oxygen content in the case of picosecond laser pulse durations is counterproductive for the laser edge isolation. Edge isolation in the optical regime and at a slower scanning velocity and therefore at larger overlaps yields higher shunt resistances, but isolating with these parameters is far too slow and thus further research is necessary to obtain industrial relevant scanning velocities. Furthermore, the ideal atmosphere is a matter of the laser and scanning parameters as well as the remaining oxygen concentration in the groove.

4. Summary

Various laser sources with different pulse durations and wavelengths have been tested due to their suitability for the edge isolation process. It is possible to achieve good edge isolation in terms of the shunt resistance with all laser sources, but at different repetition rates, laser fluencies, and in series different groove depths. Further different ambient atmospheric conditions have been tested. Due to the different atmospheric conditions varied oxygen concentrations remain in the groove and in series different shunt resistances after laser processing with the same laser and scanning parameters. In the case of industrial-relevant laser parameters the most suitable atmosphere is the normal ambient one.

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