SIMULATION OF LIFETIME CHARACTERIZATION OF TEXTURED SILICON AND COMPARISON WITH EXPERIMENTAL RESULTS

[1]Ruhani DADASHOV, [1]Jan VOVES, [2]Deep Pakki ABHINAV

[1]*Department of Microelectronics, Faculty of Electrical Engineering, Czech Technical University in Prague (CTU), Czech Republic, EU, dadasruh@fel.cvut.cz*

[2]*Department of Electrotechnology, Faculty of Electrical Engineering, Czech Technical University in Prague (CTU), Czech Republic, EU, pakkiabh@fel.cvut.cz*

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Abstract

We present the surface lifetime characterization of the textured silicon surface for the application in solar cells. The measurement by the Sinton WCT-120 PL lifetime tester is compared with the simulation by the Silvaco TCAD software to get possible values of the surface recombination velocity. The n-type silicon textured surface wafers were used as the substrate. In the first experiment, the carrier lifetime was measured and simulated of the pure textured surface. The second experiment was done after deposition of aluminum oxide by the Atomic Layer Deposition on the textured surface. The thermal method was used with TMA as a precursor. The two-dimensional TCAD calculation was realized on the silicon structure with textured surface. The surface profile was determined by the AFM measurement. Two electrodes were placed on both sides of the structure to calculate the current flow generated by the light pulse. The real Sinton optical source spectrum was approximated by the five beams in the range 690 - 830 nm with different intensities. The current decrease connected with the decay of the optical intensity was simulated. The comparison of experimental results with the TCAD simulation gives the possibility to distinguish between the bulk carrier lifetime and surface recombination velocity. The coincidence of the measured and simulated graphs by the fitting the simulation parameters result in the realistic value of the surface recombination velocity. It can be used for the classification of the silicon surface passivation influence on the solar cells' efficiency.

Keywords: Surface recombination velocity, carrier lifetime, textured silicon

1. INTRODUCTION

The knowledge about the surface recombination velocity (SRV) and charge carrier lifetime of silicon is necessary for an analysis of the semiconductor material quality and the efficiency of the work power of solar cells. [1]. Charge-carrier lifetime can be described as the characteristic time τ describing how long an excess charge carrier remains in a conductive state before becoming immobilized due to trapping or recombination. It is clear that τ is of essential importance for electronic and optoelectronic devices because the performance of these devices is mainly determined by the efficiency of the transport of excess charge carriers injected by light or contacts [2]. Surface recombination can affect devices in two ways: by increasing saturation currents (decreasing output voltage) and by decreasing short circuit currents [3]. The surface recombination velocity S_r is defined as the number of carriers recombining on the surface per unit area per unit time of excess carriers at the surface or interface [4]. For extremely pure Si samples, the bulk lifetime τ_b is so high that surface recombination dominates the effective lifetime. However, for lower quality, i.e., low resistivity or solar grade silicon wafers, the lifetime is lower and both τ_b and S_r must be determined. Photoconductance decay, surface photovoltage, and quasi-steady state photoconductance are widely used for characterizing the minority carrier lifetime and diffusion length. Separation of bulk and surface recombination is possible by varying the sample thickness or by evaluating the initial decay modes of photoconductance decay [5]. The overall goal of this work was to find reasonable efficiency values for effective carrier lifetime and surface recombination velocity by comparison of Silvaco TCAD simulation results and compare them with the experimental part measurement of carrier lifetime by Sinton WCT 120 photo-conductance lifetime tester. All simulations and experiments are carried out on randomly textured silicon wafers with a thickness of 140 µm and approximately 1 ms bulk carrier lifetime. We measured wafers with a 9.6 nm deposited passivation layer of Al_2O_3 [6] applied via the Atomic Layer Deposition machine Sentech Si 500 and without a passivation layer for comparison.

2. EXPERIMENTAL

The first step of the experiment started with characterising the pure wafer's surface with 2.5 Ω·cm base resistivity via Atomic Force Microscopy (AFM) and using these pictures to observe the roughness of the textured wafer surface and how to is the surface deposited by Al_2O_3 affected as shown in **Figure 1**. These images were used to determine the dimensions of pyramids and to get the average size for one shape to apply to the simulation for the next steps. Deposition of Al_2O_3 was executed by thermal ALD using TMA precursor and 120 deposition cycles. The layer thickness per cycle is 0.8 Å. The aim of the deposition was to create an additional thin sheet which has a passivation role on the surface. The effective carrier lifetime was measured by the Sinton lifetime tester immediately before and after the deposition of the passivation layer. The results are in **Table 1**.

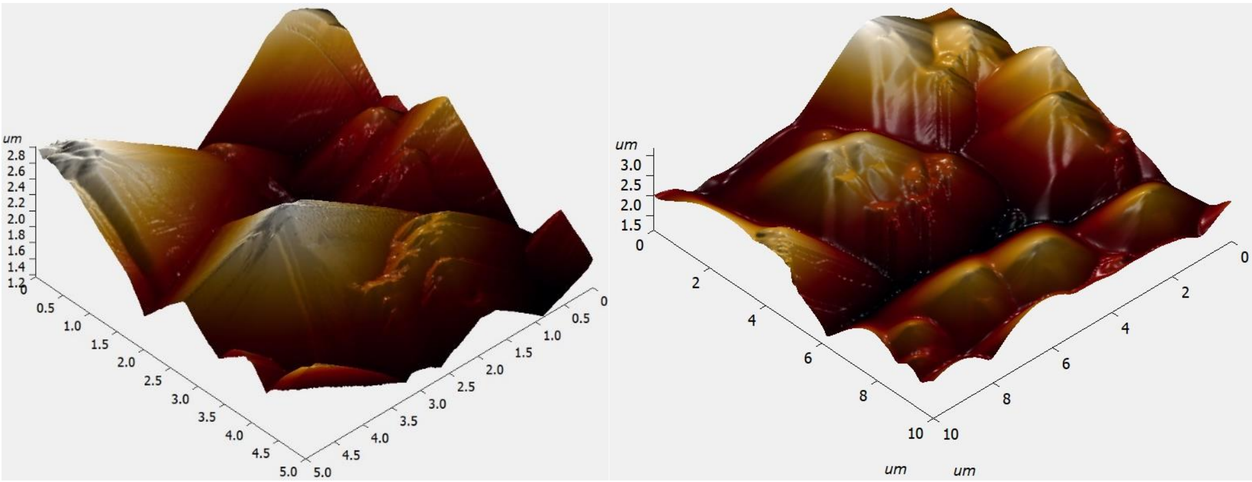

Figure 1 AFM picture of pure silicon surface (left), and silicon surface with passivation layer (right)

Table 1 Comparison between Sinton WCT-120 PL lifetime tester results before and after deposition of the passivation layer to the surface

	Maximum value of photoconductance (siemens)	Minority carrier lifetime (µm)	Minimum minority carrier density (cm^{-3})	Maximum minority carrier density (cm^{-3})
Before	0.0026	1.16	8.88e+12	6.82e+14
After	0.0082	3.26	6.68e+13	2.14e+15

3. MODELING

The simulation was based on creating a part of the silicon model (20000 µm x 140 µm) and adding two electrodes for both sides of it to apply a small voltage to see the current drop produced by carrier recombination during the illumination drop. We measured the optical spectrum of the Sinton optical source by means of the spectrometer Ocean Optics USB 2000 (**Figure 2**) to acquire the wavelengths and intensities of five optical beams (**Table 2**) to approximate the real spectrum. These beams in the range 690-830 nm at different intensities we applied in a perpendicular direction to the wafer surface. Turning off the light with an exponential decrease of light power during 0.015 ms time was simulated on the pure and passivated wafer surface. We calculated the relative beam intensities and for the final beam intensity we used the definition that 1 sun is equal to 0.1 W/cm^2 [7]. The constant voltage of 0.1 V was applied between side electrodes during transient simulation to obtain the resulting photocurrent decay. We kept a constant bulk lifetime for both electrons and holes (10^{-3} s) and mainly focused on calibrating for the near value of SRV to get an accurate graph for both minority and majority carriers.

Table 2 Used intensities of beams with different wavelength according to **Figure 2**

Wavelength (nm)	690	714	735	763	830
Intensity (a.u.)	250	350	380	450	700
Relative intensity (%)	0.12	0.16	0.18	0.21	0.33

The simulation and experiment give us only the effective lifetime:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{1}{\tau_s} \tag{1}$$

where the surface carrier lifetime τ_s can be replaced by the surface recombination velocity S_r where W is the wafer thickness and D is the diffusion constant of the minority carriers (in $\mathrm{cm}^2\mathrm{s}^{-1}$) [8]:

$$S = \frac{W}{2\left(\tau_S - \frac{1}{D}\left(\frac{W}{\pi}\right)^2\right)} \tag{2}$$

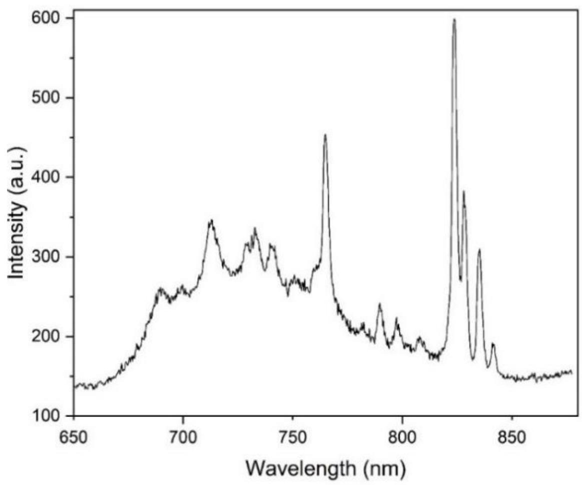

Figure 2 The spectrum of Sinton optical source measured via spectrometer Ocean Optics USB 2000

Our other goal was to optimize the SRV value and to obtain the simulated photocurrent curves most close to the experimental ones.

4. RESULTS

The experimental results (**Figure 3)** show approximately 3.1 times increase in the maximum value of photoconductance between the clean surface and the surface with deposited passivation layer. The optimized simulation results have almost the same amount of increase as shown in **Figure 4**.

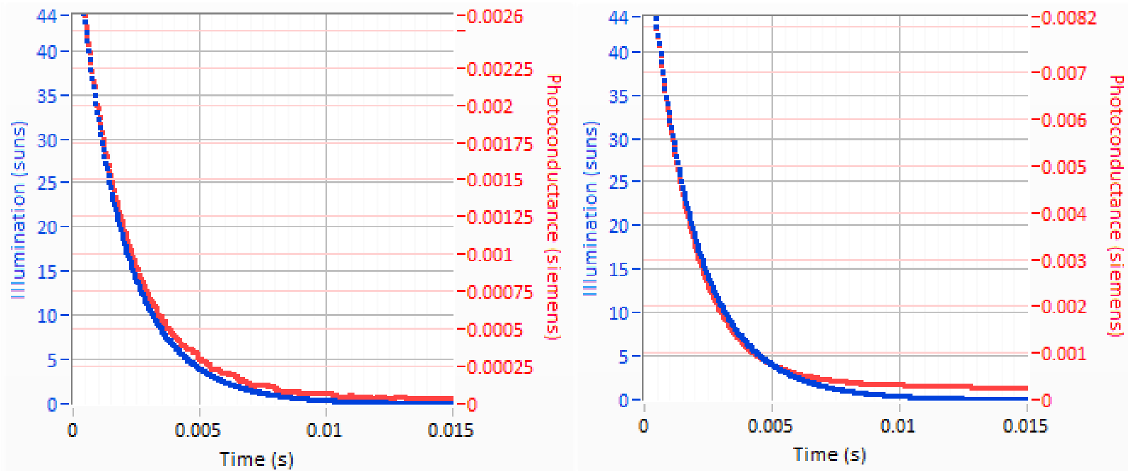

Figure 3 Photocurrent dependence during the turning off the light according to results of Sinton WCT 120 photo-conductance lifetime tester. The surface without Al_2O_3 (left), with Al_2O_3 (right)

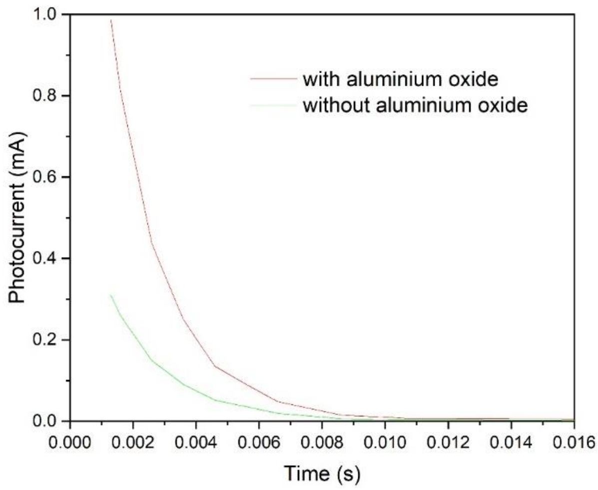

Figure 4 Photocurrent dependence during the turning off the light by means of Silvaco TCAD

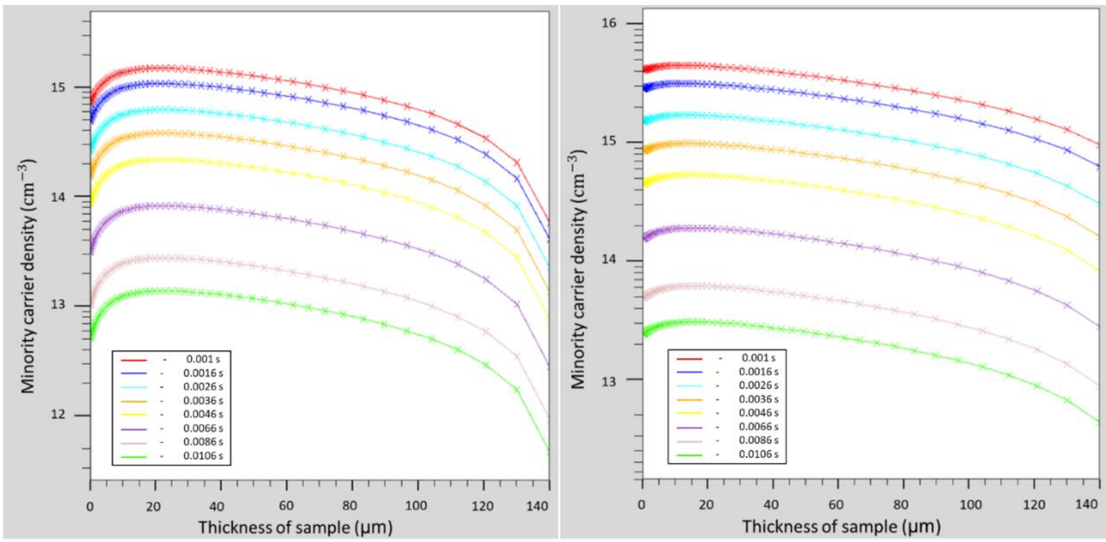

Figure 5 Minority carrier density (holes) during the turning off the light. The surface without aluminum oxide (left), with aluminum oxide (right)

During photocurrent change, we tried to keep the same values for minority carrier densities compared with experimental results as shown in **Table 1** by calibrating surface recombination velocity for both minority and majority carriers for passivated and pure surfaces. We found the near-optimal values for surface recombination velocities for electrons and holes is 3.45 .10^4 cm/s for the pure surface, and 6.79 .10^3 cm/s for surface with the passivation layer. The results are shown in **Figure 5**.

5. CONCLUSION

The comparison of the Sinton WCT lifetime measurement with the Silvaco TCAD simulation allowed us to obtain unknown values for surface recombination velocities for both electrons and holes. The ability to distinguish between the bulk lifetimes and surface recombination velocities would help to improve the efficiency of solar cells. It can be used for optimizing the choice of the different materials for the surface passivation and for the shape of the surface.

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