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Adequate Method for Decoupling Bulk Lifetime and Surface Recombination Velocity in Silicon Wafers

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In this paper, we present an appropriate method of decoupling surface and bulk recombination processes in silicon wafers. The study was carried out using the surface passivation of multicrystalline silicon wafers by ethanolic solution of iodine at different molarities varying between 0.01 M and 0.1 M. The effect of the concentration of ethanolic iodine solution on surface passivation effectiveness was investigated by using quasi steady state photo-conductance technique. Reproducible experiments have shown that the best passivation is reached for a molarity of around 0.02 M. The carrier lifetime after passivation at 0.02 M has been improved by more than one order of magnitude, compared to that of the same wafer before the passivation. Using an adequate modeling of minority carrier lifetime curves $\tau(\Delta n)$, based on Hornbeck-Haynes model, surface recombination velocity was calculated. The minimum values of surface recombination velocity have been found to be approximately 120 cm/s for 0.02 M. The modeling results indicate that the minority carrier lifetime improvement can be easily correlated with the decrease of the surface recombination velocity for a fixed bulk lifetime $\tau_b = 115$ μs.

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1. Introduction

In semiconductor and solar cell technologies the inspection of the bulk minority carrier lifetime τ_b is a crucial step for monitoring the material quality, determination of the cleanliness of furnaces, and establishing the effects of various process steps during device processing [1]. However, a reliable measurement of τ_b is not easy and involves careful preparation of the wafer. One of the essential requirements for an appropriate measurement of τ_b is that the wafer surfaces and edges be well cleaned and passivated, especially in the case of wafers that have higher electrical quality.

Currently, two main techniques are used by the photovoltaic community to inspect the electrical quality of silicon wafers; microwave photoconductance decay (μ-PCD) and quasi steady state photo-conductance technique (QSSPC). In spite of the fact that the μ-PCD is an effective technique to study the carrier lifetime distribution, the QSSPC still remains an advantageous technique in terms of simplicity of use and short measurement time. Nevertheless, since recombination occurs in the bulk as well as on both surfaces of the wafers, the measured lifetime is an effective value τ_{eff} that has contributions from the bulk τ_b and the two surfaces τ_s. It can be described by

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

where

$$\tau_s = \frac{W}{2S} + \frac{1}{D_n}\left(\frac{W}{\pi}\right)^2, \tag{2}$$

S is the surface recombination velocity, W is the wafer thickness and D_n is the diffusion constant of minority carriers.

When the surface undergoes a good passivation; $\tau_{\text{eff}} \approx \tau_b$. The recombination activity can be reduced either through thin films deposition such as SiO_x, Si_xN_y, Al_2O_3, a-Si:H and a-SiC:H or by formation of a floating N/P junction, or by immersion in chemical solution using hydrofluoric acid (HF) and iodine in ethanol or methanol (I-E or I-M) solution. The first kind of passivation techniques requires an important thermal budget that can't be avoided [2, 3], accompanied by bulk properties modification more or less significant. Therefore, chemical passivation route seems to be fast, simple, not expensive and more adequate to inspect the bulk quality and then to predict the final solar cell efficiency. Chhabra et al. [4] and Swain et al. [5] have, respectively, used quinhydrone- and iodine-methanol to passivate silicon and germanium, and have obtained high passivation qualities. Another study carried out by Stephens and Green [3] demonstrated that good surface passivation can be achieved using 0.08 M iodine-ethanol solution.

In the present work, we report a systematic study of decoupling of bulk lifetime and surface recombination velocity in silicon wafers. It refers to a semi-empirical method based on the modeling of experimental results obtained by QSSPC.

2. Experimental details

A set of five adjacent gettered wafers (P6, P7, P8, P9 and P10) selected from the top region of ingot were

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used in this study. The wafers were 1.5 Ω cm, p-type, of multicrystalline silicon, grown by the heat exchanger method [6], with thickness of 300 μm. Firstly, wafers were chemically etched in NaOH:H_2O (30%) at 80 °C, followed by dipping in HF (10%) and rinsing in deionized water. Later on, wafers were placed in transparent polyethylene bags without I-E solution, and lifetime measurements were directly performed by QSSPC technique (Sinton Consulting, WCT-120 tester). The obtained results are considered as references (Ref.). After this step, the five wafers were passivated by adding the same concentration of I-E into the bags containing the wafers, and then the lifetime measurements were done again. Subsequently, the wafers were dipped in diluted HF, dried and passivated using another concentration of I-E. The cleaning-passivation-measure process was repeated for different I-E solution concentrations ranging from 0.01 M to 0.1 M.

3. Results and discussion

Figure 1 illustrates the evolution of measured minority carrier lifetime τ vs. injection level Δn curves obtained for wafer P6 without and with passivation at different I-E concentrations. We note that similar results were found for the rest of studied wafers (P7, P8, P9 and P10).

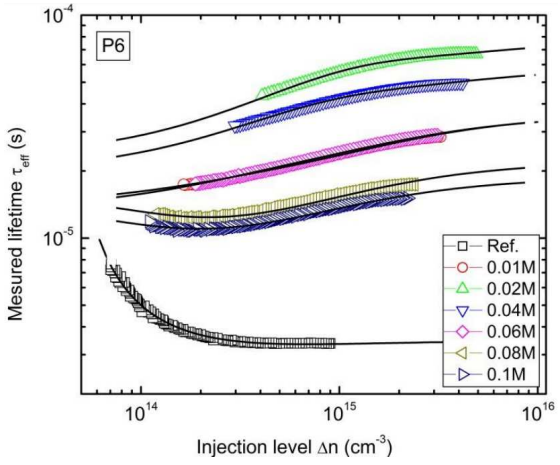

Fig. 1. Evolution of injection level dependent measured lifetime curves, obtained by QSSPC technique for wafer P6 after passivation at different concentrations of I-E solution. Solid lines represent fits made using Hornbeck-Haynes model.

We observe that I-E concentration has a notable effect on $\tau(\Delta n)$ curves. This effect can be clearly shown by the increase of the measured lifetime and also the shift of curves towards higher injection level Δn. This evolution is accompanied by a change in the curves slop, especially before and after the I-E passivation. Lifetime simulation demonstrates that the decrease of surface recombination velocity yields similar evolution of lifetime curves. Such observation leads us to assumption that the evolution of $\tau(\Delta n)$ is probably due to an effective surface passivation. For checking quantitatively this assumption, an adequate modeling of $\tau(\Delta n)$ has been done using Hornbeck-Haynes model [7–9]. In our previous study [10], the same model was employed to investigate bulk lifetime improvement after the gettering process.

During the modeling of lifetime curves, bulk parameters such as recombination centre density N_r and capture cross-sections σ_n and σ_p were carefully computed and fixed at appropriate values for all studied wafers (see Table I). The only parameter which has been considered variable is the surface recombination velocity (SRV). In the present study, SRV was assumed independent of injection level Δn.

TABLE I

Appropriate bulk parameters (N_r, σ_n and σ_p) used in modeling and the resulting bulk lifetime τ_b.

Bulk parameters	Computed values	Bulk lifetime [μs]
N_r	8×10^{11} cm^{-3}	115
σ_n	2×10^{-14} cm^2	
σ_p	3×10^{-16} cm^2	

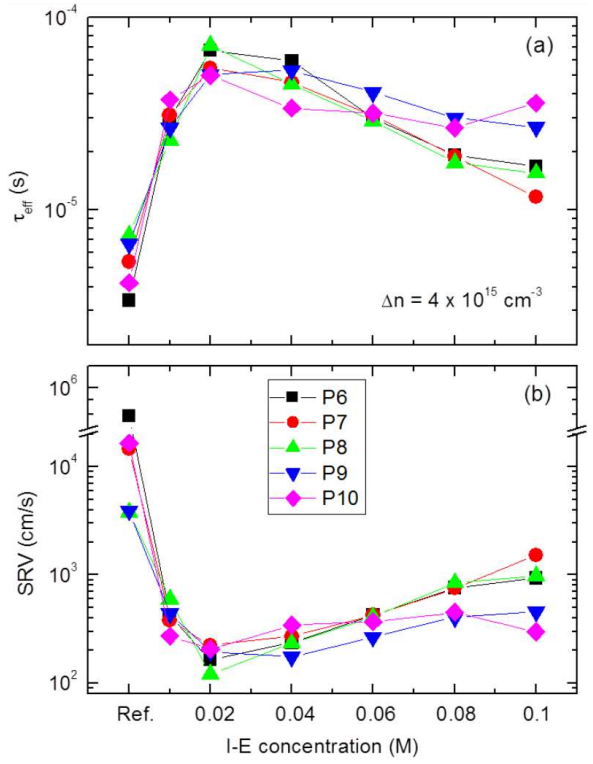

Fig. 2. Variation of the effective lifetime of all studied wafers (a) and the associated surface recombination velocity (b) as function of concentration of the I-E solution.

The effect of I-E solution concentration on the effective lifetime and SRV, estimated by fitting, is presented in Fig. 2a and b, respectively. We observe an obvious reproducibility of passivation experiment, where all wafers showed a similar lifetime variation with I-E

concentration. The lifetime reached maximum values for I-E concentration of around 0.02 M, with an increment of $\sim 900\%$ compared to the lifetime measured without passivation. This increment of lifetime is accompanied by a clear degradation of calculated SRV. The minimum SRV (~ 120 cm/s) is reached at 0.02 M. Correlation between experimental and modelling results leads us to conclusion that the lifetime improvement is due to an effective surface passivation. Same inverse variation of SRV with lifetime can be observed beyond 0.02 M, confirming the above explanation.

Figure 3 summarizes the obtained results for all studied wafers; P6, P7, P8, P9 and P10. It shows the variation of effective lifetime τ_{eff} measured by QSSPC at $\Delta n = 4 \times 10^{15}$ cm^{-3} as function of SRV determined by fitting. The solid line represents an appropriate theoretical curve τ_{eff} (SRV) plotted employing Eqs. (1) and (2). The bulk lifetime $\tau_b = 115$ μs used in plotting the curve was calculated from bulk parameters (see Table I). This figure shows clearly a good consistency between the experimental data and modeling findings. It demonstrates also a reliable decoupling of SRV and τ_b for all measured values of τ_{eff}.

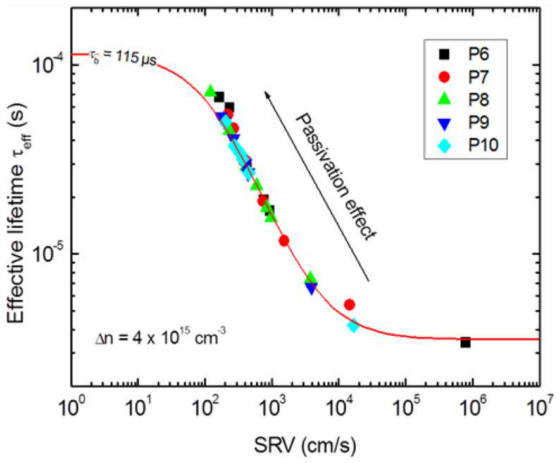

Fig. 3. Variation of the effective lifetime τ_{eff} as function of surface recombination velocity SRV obtained for all studied wafers. Solid line is the theoretical plot of τ_{eff} (SRV) for $\tau_b = 115$ μs.

4. Conclusions

In the present work, we report a systematic investigation of surface passivation made on p-type multicrystalline silicon wafers using different iodine-ethanol molar concentrations. Measurements of the minority carrier lifetime τ were made for iodine-ethanol molarity varying from 0.01 M to 0.1 M. Reproducible experiments showed an effective surface passivation at the optimal I-E molarity of 0.02 M. At this particular molarity the surface recombination velocity was estimated by modeling to be around 120 cm/s, and the bulk lifetime was found to be equal to 115 μs (at $\Delta n = 4 \times 10^{15}$ cm^{-3}). This study has demonstrated the potential of the used method for decoupling surface recombination velocity and bulk lifetime from the measured effective lifetime.

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