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Correlation between the open-circuit voltage and recombination loss at metal-silicon interfaces of crystalline silicon solar cells

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A B S T R A C T

For screen-printed silicon solar cells, optimization of the contact characteristics between the front metal electrode and silicon is very significant for realizing high efficiency. As technology advances, the solar cell efficiency has been steadily increased. Especially, as surface recombination becomes more important in high efficiency solar cells, understanding and controlling recombination in the metal contact area are necessary. Recombination at the metal-silicon interface is a major cause of the drop in the open-circuit voltage (V_{oc}) of a solar cell. Thus far, the study of electrodes in silicon solar cells has been largely aimed at reducing the series resistance, and few studies on recombination due to electrodes have been performed. Quantitatively evaluating the recombination in electrodes to assess the effect on the efficiency is expected to become more important in the near future. In this paper, the contact characteristics of a screen-printed silver electrode and silicon interface were analyzed using saturation current density (J_o) measurements according to the surface doping concentration and firing temperature. The effects of the contact characteristics on V_{oc} and recombination were also investigated. Experimental results showed that $J_{o.pass}$ decreased with decreasing surface doping concentration and $J_{o.metal}$ increased with increasing surface doping concentration and firing temperature. For quantitative analysis of $J_{o.metal}$, the size and distribution of Ag crystallites were observed using SEM and TEM, and the Ag concentration was analyzed by ICP-OES measurements. The larger $J_{o.metal}$ was, the higher the Ag crystallite concentration, indicating that the Ag crystallites under the electrode increased $J_{o.metal}$. The effect of $J_{o.metal}$ on the electrical characteristics of the solar cell was analyzed by calculating the change in the surface recombination velocity and the decreased width of V_{oc}. Through this study, the recombination in the metallized area, which is expected to become increasingly important, and particularly the effects of the doping profile of the emitter region and silver crystallites on the surface recombination were quantitatively assessed. The amount of silver crystallites on the silicon wafer was quantitatively analyzed.

1. Introduction

In crystalline silicon solar cells, the front metal electrode seriously affects the series resistance, shadowing loss, fill factor and short-circuit current. The metal-silicon interface contributes to the surface recombination velocity (S_{eff}) of minority carriers, which limits the open-circuit voltage (V_{oc}) and achievable efficiency [1–5]. To minimize S_{eff} in metallized areas, controlling not only the doping concentration but also the contact characteristics between the metal and the diffused silicon is important [6–8]. A heavily doped silicon emitter has a low contact resistance with an electrode, but its use can diminish the electrical characteristics of a solar cell due to the increased Auger recombination, the low blue response, and recombination via crystal defects on the dead layer [9–13]. Decreasing the surface doping concentration is important for reducing surface recombination, but a reduction in the surface doping concentration may increase the contact resistance at the metal-silicon interface; therefore, optimization is necessary. Recently, many studies have been carried out to improve the contact characteristics in the low doping regime [14–19]. The carrier recombination for various doping concentrations in the emitter layer is characterized by the emitter saturation current density ($J_{o.emtter}$). $J_{o.emitter}$ consists of the saturation current densities in the passivation area ($J_{o.pass}$) and in the metallized area ($J_{o.metal}$) [5]. $J_{o.pass}$ depends on the doping concentration and can be obtained from quasi-steady-state photoconductance

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