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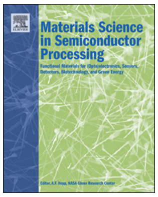

Improvement in the light conversion efficiency of silicon solar cells by pure hydrogen annealing

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ABSTRACT

In this report, the effects of pure hydrogen gas annealing on series resistance (R_s), shunt resistance (R_{sh}), open circuit voltage (V_{oc}), short circuit current (I_{sc}), fill factor, and efficiency were investigated systematically using standard, commercially available poly-silicon solar cells. Improvements on the electrical characteristics, fill factors, and efficiency of the solar cells were observed after annealing by pure hydrogen gas at 350 °C for 15 min. In the best case, the conversion efficiency was raised by nearly 1% point. Judging from our experimental evidences, the improvement on cell performance could be mostly attributed to the reduction of R_s and improvement in Ag grid/emitter contact resistance in the cells during the annealing process.

1. Introduction

Cost reductions on the development solar cells can be achieved either by a reduction of manufacturing costs or by an increase in solar cell efficiency. Silicon (Si) is a dominant material used in the commercial production of low-cost solar cells, and various cost competitive, relatively cheaper processing steps have been developed to make these solar cells more energy efficient. The lifetime of minority charge carriers is a widely accepted material parameter, which influences the conversion efficiency of the p–n junction silicon solar cells [1]. The main factors responsible for reducing the lifetime of the charge carriers are defects and impurities present in silicon wafers. Dangling bonds on the surface are the main trapping centers for the charged carriers. Hydrogen atoms play a vital role in the deactivation of those recombination centers. There are numerous established methods of hydrogen passivation, such as hydrogen ion implantation [2], hydrogen plasma injection [3], plasma enhanced chemical vapor deposition (PECVD) of hydrogenated silicon nitride [4] and forming gas (mixture gas of H_2 and N_2) annealing (FGA). Among all these, FGA is a much simpler and cost effective method for hydrogen passivation.

For enhancing conversion efficiency in solar cell applications, the treatment using hydrogen forming gas at an appropriate temperature can interact with impurities and improve the grain boundary to achieve better efficiency. There have been several reports on the enhanced conversion efficiency of low-cost solar cells after annealing in forming gas at elevated temperature [5–10]. Improvements in solar cell efficiency after FGA on silicon nitride-coated surfaces have been readily demonstrated by Kishore et al. [10] and Hanoka et al. [11]. The behavior of silver film contacts on n-type silicon after nitrogen post-metallization annealing was investigated in [12,13]. The beneficial effect of the FGA on the fill factor of Si solar cells with screen-printed Ag contacts has been found to be thermally activated at a temperature above 300 °C; this effect has also been found to be irreversibly stable in time [14]. It has been shown that the annealing method affects the current

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path between silver crystals and fingers, and lower contact resistance is suggested as the mechanism for improving efficiency.

In this report, we did not study how hydrogen passivation affected the SiN_x:H layer during or after the PECVD process. Instead, the effects of pure hydrogen gas anneal on series resistance (R_s), shunt resistance (R_{sh}), open circuit voltage (V_{oc}), short circuit current (I_{sc}), fill factor, and efficiency were investigated systematically using standard and commercially available polysilicon solar cells. Improvement on the electrical characteristics, fill factors, and efficiency of solar cells were observed after the hydrogen annealing process at 350 °C.

2. Materials and methods

Our studies were performed using standard, commercially available industrial solar cells on six-inch p-type Cz-polysilicon wafers. Cell surfaces were roughened using HF and HNO_3 saw damage etch with no additional texturisation. A $POCl_3$ diffusion process was carried out to obtain sheet resistance of 65 Ω/sq. The SiO_2 residues on the cell surfaces were removed through Phosphorus Glass (PSG) etching system. A SiN_x anti-reflection coating was deposited on the cells with a plasma enhanced chemical vapor deposition (PECVD) system. The front and rear side finger and bus bar contacts were screen-printed with a standard, commercially available lead containing Ag paste, Al paste, and Ag+Al paste. After drying at 200 °C, the cells were fired in a fast firing conveyor belt furnace at an optimal firing temperature of 850 °C to make fingers and bus bars come in contact with the N- and P-type regions for maximum performance. Finally, the cell edges were isolated using laser cutting.

The finished cells were then annealed in a belt furnace under hydrogen atmosphere at different temperatures ranging from 200 to 600 °C for 15 min. After annealing, samples were first isolated from the heat source to cool them down slowly in order to reduce the thermal shock. At the second stage, the temperature of the samples was further reduced to ambient temperature with cooling water. The performance parameters of the sample cells were again determined from *I*–*V* characteristic curves under illuminated condition using an AM 1.5 Global spectrum. The data from the comparative analysis of the performance parameters of a group of samples before and after hydrogen gas annealing are presented in the next session.

3. Results and discussion

In order to understand the effects of the H_2 annealing temperature on the conversion efficiency of the cells, the temperature was varied during the hydrogen gas annealing although the dwell time was kept at 15 min throughout the entire experiment. The development of the efficiency of solar cells, fired at optimal temperature of 850 °C for the screen-printed contacts, was plotted versus the hydrogen annealing temperature (Fig. 1). Efficiency did not show significant improvement until a temperature of 300 °C was reached. When the annealing temperature reached above 400 °C, cell performance began to degrade, and the average efficiency dropped by 0.62% at a temperature of 450 °C. This indicates that pure hydrogen gas annealing worked best at 350 °C. Above that temperature, the efficiency of the cells began to decrease due to the increase in surface dangling bonds and surface recombination loss at higher temperature. In addition, dwell time longer than 15 min did not improve the cell performance. On the contrary, annealing processes performed in nitrogen atmosphere under the same experimental conditions only show deteriorated or no improvement in cell performance, which indicate that the hydrogen gas indeed plays an important role in annealing.

In Fig. 2, we plot the efficiency rates before and after H_2 annealing at 350 °C for 15 min of 24 sample cells with efficiency rates ranging from 14.4% to 15.6%. Although some of the samples' efficiency rates were greatly improved, not all of them were improved after H_2 annealing. The reason for this will be discussed later. The gains of the V_{oc} and I_{sc} of the samples tested are also plotted in Figs. 3 and 4, respectively. Although we observed a slight increase in both V_{oc} and I_{sc} after annealing, the amount of increase was neither proportional nor strongly correlated to the increase in efficiency. Hydrogen is well known to have the ability to diffuse in Si

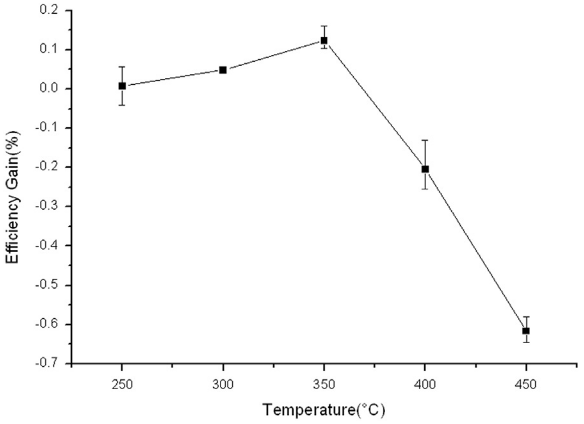

Fig. 1. Temperature dependence of the averaged efficiency gain of solar cells at temperatures ranging from 250 to 450 °C.

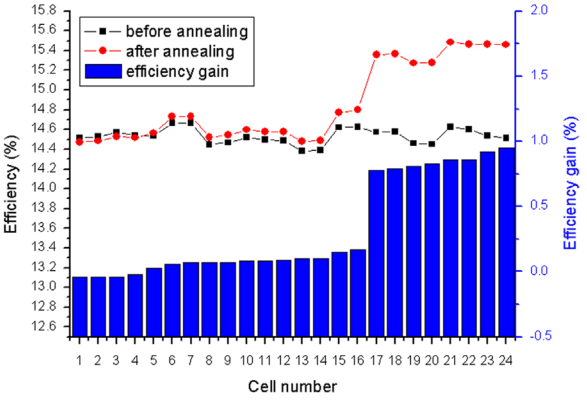

Fig. 2. Plots of efficiency and efficiency gain before and after H_2 treatment.