Effect of laser annealing on defected silicon solar cells

AHJ Al- Mousawy

Department of Physics, College of Education (Ibn Al-Haitham), University of Baghdad, Adamiyah, Baghdad, Iraq.

E-mail: ajalmousawy@yahoo.com

Abstract. The effect of pulsed Nd-YAG laser annealing (λ = 1.06 µm), on the efficiency of defected polycrystalline silicon solar cells has been studied. Cells performance measurement and microscopic structure examinations of the surface using optical and scanning electron microscopy (SEM) have been done before and after irradiation with different laser fluences (2.3 – 25 J/cm²) and for successive times until a steady state has been reached. It is found that the annealing causes a change in the topography of the cells, resulting in an increase in grain size at low fluences and beginning of crystal growth at higher fluences up to an optimum value of 7.5 J/cm². These processes cause an improvement in the electrical output characteristics of the defect-rich solar cells; hence an increase in the cell efficiency is obtained. The maximum change in efficiency value is found to be about 5 times greater than its initial value. For fluences of more than 16 J/cm², SEM micrographs show slightly deeper melt front penetration which affects the junction interface and a reduction in light output characteristics of the cells has been detected.

1. Introduction
The development of laser processing technologies has shown great potential for innovative advances of cell fabrication [1-2]. The junction characteristics of solar cells could also be improved by using a suitable laser annealing power [3]. The lattice strain at the grain boundaries could be minimized, which is a consequence of an increase in electrical conductivity after laser treatment [4].

The goal of this study was to investigate the possibility of recovery of damaged polycrystalline Si solar cells after laser annealing by scanning electron microscopy (SEM). The photovoltaic performance and the efficiency of these cells are considered.

2. Experimental Work
Different types of polycrystalline Si solar cells, enriched in defects (or damaged) during manufacturing, have been selected. The laser irradiation has been performed with Nd-YAG pulsed laser (λ = 1.064 µm) with a Gaussian profile and 10 Hz repetition rate. The fluences used were in the range 2.3 – 25 J/cm². The sample was put on a movable stage and irradiated with successive overlapping pulses through the damaged region only. Microscopic examinations before and after laser irradiation were done using a JEOL SEM (JSM-6400).

3. Results and Discussion
In order to define the damaged region, an optical microscope was used to examine the surface of the solar cell before any laser irradiation. Figure 1a shows an optical micrograph of the interface between the undamaged and the damaged (defect-rich) region. Figure 1b represents an SEM micrograph of the defect-rich region irradiated with fluence 4 J/cm².
revealing the melt region caused by the annealing. Figure 1c is the defect-rich region irradiated with 6 J/cm$^2$, showing the increase in grain size while micrograph 1d is the defect-rich region irradiated with 9.6 J/cm$^2$, revealing recrystallization processes occurring due to annealing. The grain sizes, before and after irradiations for other fluencies, calculated from similar micrographs, are tabulated in Table 1.

Figure 1. (a) The optical micrograph showing the interface between defect-rich and the undamaged regions in the polycrystalline cell before irradiation. (b) SEM micrograph representing the defect-rich region irradiated with fluence 4 J/cm$^2$. (c) SEM micrograph for 6 J/cm$^2$. (d) SEM micrograph for 9.6 J/cm$^2$.

| Fluence (J/cm$^2$) | Average grain size (µm) |
|-------------------|-------------------------|
| before irradiation | 10                      |
| 2.3               | 13.5                    |
| 4                 | 25                      |
| 7.5               | 35                      |
| 8.7               | 26                      |
| 19.6              | 20                      |

Table 1. The grain size in µm for different fluences.

The change in AM1 efficiency $\Delta \eta = \eta_{after} - \eta_{before}$ after laser annealing with different fluences is shown in Figure 2, where AM1 (air mass one) is solar radiation of 925 W/m$^2$ and $\eta$ is the solar cell efficiency. The measurements in this figure have been repeated many
times, applying post treatment annealing (PTA) for different times until a steady state had been reached. It is clear from Figure 2 that, in general, there is an improvement in the solar cell performance, which appears as an enhancement of the efficiency for most of the fluences in the range 2 – 16 J/cm². However, there appears a peak in \( \Delta \eta \) at the particular fluence of 7.5 J/cm². Although \( \Delta \eta \) increases with increasing the PTA until a steady state is reached, the position of the peak is not affected by PTA. However, for fluences more than 16 J/cm² a slightly deeper melt front affects the cell junction and causes a reduction in the efficiency and solar cell deficiency.

![Figure 2.](image-url)

It is well known that grain boundaries play an important role in solar cell performance [4], due to the large densities of defects and segregated impurities at the grain boundaries. The boundaries are regions of strong recombination of electron and holes. This in turn reduces the charge collection efficiency of the solar cell [5, 6]. Therefore, the increase in grain size caused by the laser annealing of the damaged region, apparent from Table 1, could have a special effect on the cell performance as is clear from Figure 2. However, the enhancement of efficiency with PTA may indicate that metastable states are introduced during laser annealing process.

4. Conclusions
Laser annealing is a superior method for removing lattice damage even after manufacturing of the solar cell. Melting of the surface region followed by liquid-phase epitaxial regrowth is the most likely mechanism for the annealing process. Redistribution of the impurities and a reduction in the defected area may also result from laser annealing. Thus the efficiency of a damaged solar cell can be improved by using a proper optimum laser fluence for annealing.

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