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Effect of dislocation density on the efficiency of multicrystalline silicon solar cells

Z. BENMOHAMED*, M. REMRAM

Département d'Electronique, Université Mentouri de Constantine, 25000, Algeria

The behaviour of structural defects is still one of the major problems in multicrystalline silicon. The properties of solar cells made from these materials are mainly determined by dislocations, grain boundaries and intragrain defect impurities such as oxygen and carbon. Interactions between dislocations and impurities are also an important factor influencing the minority carrier diffusion length and then multicrystalline solar cells performances. In this paper, the effect of dislocations on minority carrier diffusion length is analysed and discussed. We carried out the calculation on the cell efficiency of multicrystalline silicon solar cell obtained from wafers cut out of ingots grown by Polix of Photowatt and Sitix of Sumitomo. A comparison between solar cells efficiency for the two materials outlined above is presented. Performances of the cells are estimated according to the last technological processes developed. The analyses have also been carried out to optimize solar cell performances by combining the effect of a double antireflection coating and back surface field.

Key words: *multicrystalline silicon; efficiency; dislocation; impurity; antireflection coating*

1. Introduction

Multicrystalline silicon (mc-si) which can be produced by different techniques is a low-cost material for photovoltaic applications. It was shown that structural defects together with the impurities present in solar grade material directly influence its electrical properties and therefore solar cell performance [1, 2]. Impurities such as oxygen and carbon are of particular importance because of their complex interactions with structural defects which may modify their electrical activity and then affect considerably photovoltaic properties of mc-si solar cells.

In recent years, there has been a growing interest in large grained multicrystalline silicon solar cells obtained by several growth process such as wafers cast out of ingots supplied for Polix of Photowatt or Sitix of Sumitomo. Because of different growth methods, the properties limiting dislocations can be present in different concentrations, structural defects can behave differently as well, and then the properties of solar cells produced from mc-si wafers show a significant variation [3]. The purpose of this work is to clarify a part of this variation; this may help to minimize the variation as much as possible, e.g., through an optimised ingot growth. Hence, the optimal solar cell fabrication processes have also to be developed and optimised individually.

The usual electrical and structural characterization techniques have been used, the minority carrier diffusion length was evaluated by steady state surface photovoltage (SPV) method, and the dislocation density was determined by selective etching.

PC1D simulator was used in order to calculate solar cells performances under standard illumination (AM1.5G, 100 mW/cm^2). The technological parameters were selected according to the recent development in solar cells fabrication.

2. Experimental procedures

In order to study the effect of structural and electrical parameters on the multicrystalline solar cells efficiency, we have used two series of P-type multicrystalline silicon wafers cut out of ingots grown respectively by Polix of Photowatt and Sitix of Sumitomo with the boron concentration of about 1×10^{16} cm^{-3}.

The two materials have been two side polished. The dislocation densities were determined by selective etching on polished surfaces, the etch pits were automatically counted by an image processing system.

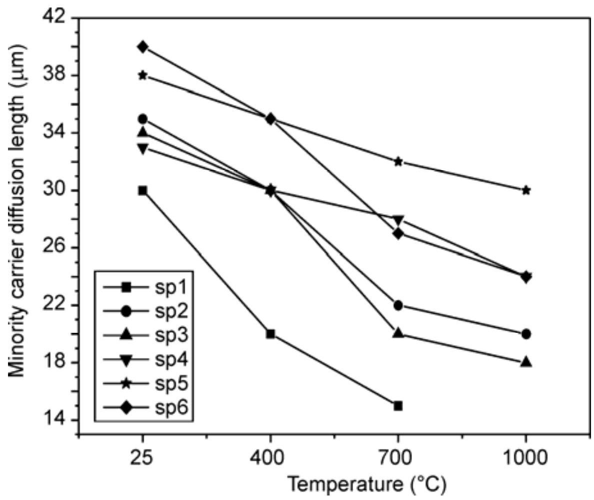

Fig. 1. Variation of minority-carrier diffusion length (µm) after RTP in Polix wafers in function of RTP temperature

The effective minority carrier diffusion length was evaluated by steady state surface photovoltage technique (SPV) [4, 5]. The effective minority carrier diffusion length for

Sitix samples was evaluated at room temperature and it varied between 53 µm and 82 µm [6]. The Polix samples were treated by rapid thermal processing (RTP) during 20 s in an FV4 furnace of JIPILEC France, with a cooling rate of 50 °C/s at a temperature range from 400 °C to 1000 °C. The SPV results after thermal treatment are shown in Fig. 1. Effective minority carrier diffusion length decreases when the temperature increases. We also note that at a given temperature the samples present different minority diffusion lengths; this is attributed to the position of wafers in ingots where the concentration of oxygen and carbon change from the top to the bottom [7]. The measured length is only an effective value, which is not trivially related to any real diffusion length. This effective value is lower than the true one, because of the recombination of minority charge carriers at the backside of samples [8].

3. Effect of the dislocation density on diffusion length

The variation of diffusion length versus dislocations density for the two types of materials in particular at room temperature is illustrated by Fig. 2. We notice that the diffusion length decrease when the dislocation density increases from 10^3 cm^{-2} to10^5 cm^{-2} for the two series of wafers. Furthermore, the Sitix samples present diffusion length larger than the Polix samples. The degradation of minority diffusion length can be attributed to the presence of impurities (transitions metals, oxygen and carbon) and their segregation in the vicinity of dislocations. Thus the dislocation behaviour is influenced [9]. These have a direct consequence on the decreasing of minority-carrier diffusion length and their lifetime.

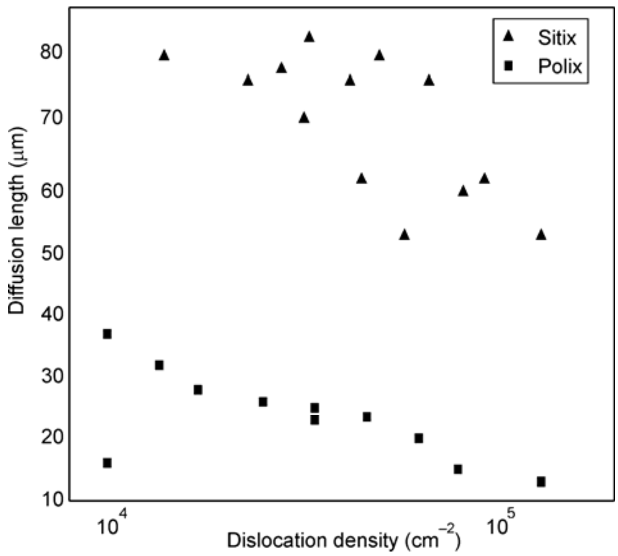

Fig. 2. Minority-carrier diffusion length versus dislocation density

Our results are in accordance with some mathematical models describing the diffusion length according to the structural parameters. Indeed, Yamaguchi et al. [10] described the minority carrier diffusion length with the equation:

$$\frac{1}{L^2} = \frac{1}{L_0^2} + \frac{1}{L_D^2} + \frac{1}{L_i^2} \tag{1}$$

where: L_0 is the bulk minority-carrier diffusion length. In addition to the effect of dislocations expressed by L_D, L_i describes the various possible interactions (grain boundaries dislocations, dislocation impurities) which can occur in material and deteriorate the minority carrier diffusion length.

We believe that the dislocation parameter remains limited to describe the carriers transport in multicrystalline silicon. However, such a phenomenon remains difficult to be quantified, considering the evolution of the unstable state of various interactions.

The results of electrical and structural characterization that we have obtained are used to calculate the efficiency of multicrystalline solar cells.

4. Simulation

The cell structure used to calculate the solar cell efficiency assumes an n^+pp^+ junction, the cell area is 1 cm^2 consisting of a thin n emitter region (0.15 μm) doped at 10^{20} cm^{-3}, a P base region with the thickness of 20 μm and a 5μm thick p^+ layer serving as a back surface field (BSF); the latter being expected to play an important role under the condition $L_n >> d$. The doping of p and p^+ regions is fixed at 10^{16} cm^{-3} and 5×10^{18} cm^{-3}, respectively. PC1D simulator version 5.0 is used to calculate the solar cell efficiencies under standard illumination (AM1.5G, 100 mW/cm^2). The material parameters used in the calculation such as the electric permittivity, refractive index and absorption coefficient are the program default settings. No special light-trapping structure is used so that the internal reflectance was assumed to be 10%. The front and rear surface recombination velocities are set to be 100 cm/s and 500 cm/s, respectively.

5. Results and discussions

5.1. Effect of dislocation on the efficiency

Figures 3 and 4 show the evolution of multicrystalline silicon solar cells efficiency with the cell thickness as a function of dislocation density, elaborated by Sitix and Polix techniques, respectively. As expected, the increase of the dislocation density from 10^3 cm^{-2} to $5\cdot10^5$ cm^{-2} reduces significantly the energetic efficiency. This degradation is more important for Polix solar cells compared to Sitix solar cells. Moreover for the two series of solar cells, there is an optimum cell thickness for energetic efficiency. For this result, a multicrystalline Sitix solar cells conversion efficiency of

16% is feasible. For Polix solar cells 13% is obtained even at a cell thickness of 20 μm if the dislocation density is less then 10^5 cm^{-2}.

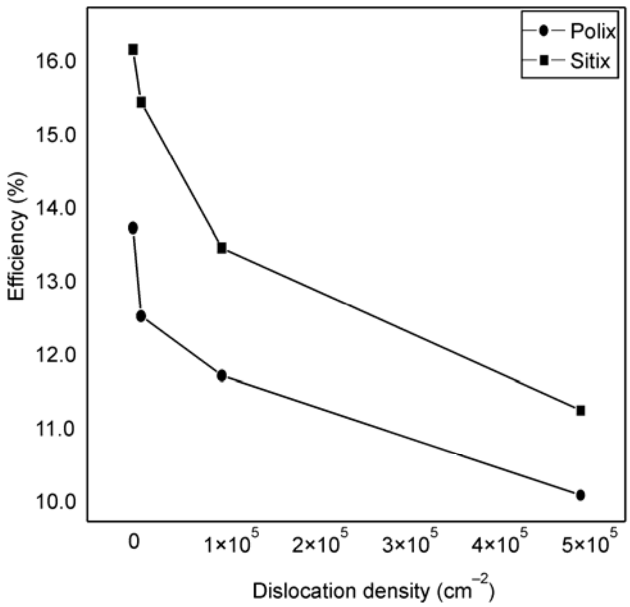

Fig. 3. Sitix solar cells conversion efficiency vs. dislocation density

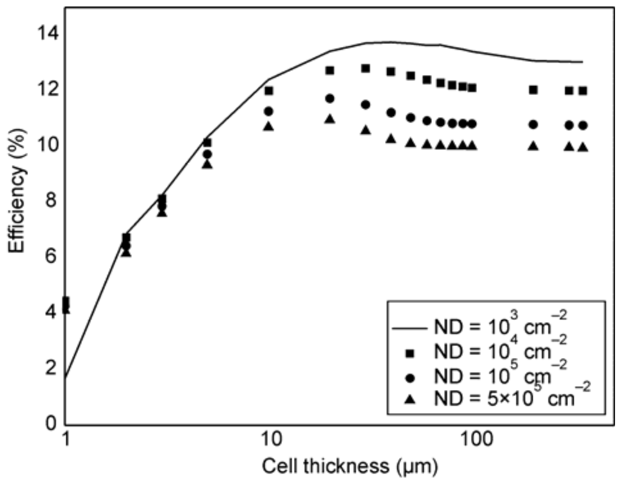

Fig. 4. Polix solar cells conversion efficiency vs. dislocation density

We also notice that energetic efficiency profile show different paces for the two series of samples. Indeed, one remarkable point is that when the dislocation density increases, the efficiency degradation is more pronounced for Sitix solar cells compared to Polix solar cells. One can assume, however, that impurities will diffuse to the dislocation and decorate them. As a result, dislocations may have different recombination behaviours depending on the degree of decoration.

A comparison between solar cells efficiency for the two series of samples is illustrated by the Fig. 5. Variation efficiency between 11% and 16% is reached for multicrystalline silicon solar cells grown by Sitix, whereas that obtained for solar cells based of Polix samples vary from 10% to 13%.

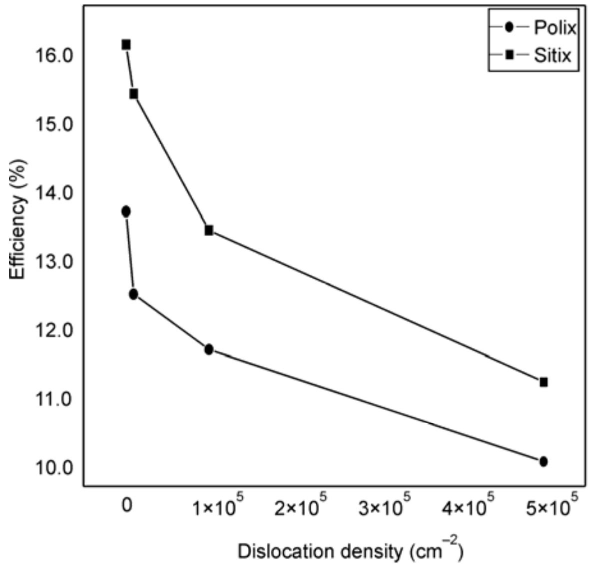

Fig. 5. Comparison of conversion efficiency for the two series of solar cells

We also notice that the efficiency obtained for Polix samples decreases little when the density of dislocation increases of two decades, compared to the Sitix samples where the efficiency variation is larger. That confirms the non-linearity of the mc-si solar cells efficiency versus the minority carrier diffusion length.

5.2. Effect of antireflection coating

The cell described in section 4 has a double antireflection coating, MgF_2 (106 nm) on a top of ZnS (56 nm) with the refractive index equal to 1.4 and 2.4 respectively; an analysis is made to identify the major areas for further improvements in solar cell properties. The results of simulation are summarized in Table 1.

An improvement in short-circuit current is observed. Short-circuit current increases from 23.5 mA/cm^2 to 31.18 mA/cm^2. This improvement is due to the reduction of optical losses from the front surface of the cell. Also it can be seen that further increase in solar cell efficiency can be reached by reducing recombination and reflection losses. An increase in diffusion length to 200 µm depends on further improvements in both growth material conditions and solar cell fabrication; with these factors improved, the efficiency of about 17.4% would be feasible for the Sitix solar cells.

Table 1. Results performance of areas improvement for Sitix solar cells

Structure	Performance		
	J_{sc} (mA/cm^2)	V_{oc} (V)	Efficiency (%)
n^+p	23.5	539.5	10.3
n^+pp^+	28.6	624.7	14.82
n^+pp^+ with MgF_2/ZnS	31.04	626.9	16.02
Improved L_n to 200 μm	31.18	672.6	17.49

6. Conclusion

In this study, we present and discuss the effect of dislocation density on electrical properties of multicrystalline silicon grown by Polix of Photowatt and Sitix of Sumitomo. The results show that the behaviour of the dislocations in both series of wafers differs. We assume that this is due to a different degree of contamination. Dislocations are not the major factor influencing electrical properties of material. Inactive impurities were already present in the grown material, in particular oxygen precipitates. The electrical activation of these impurities in an inhomogeneous distribution is also a principal source of deterioration of multicrystalline silicon solar cells efficiency. The effect of various impurities on the device performances is not completely analysed yet, but there is substantial evidence that these intragrain defects have to be taken into account. By a further optimisation of growth material and cell processes, high mc-si solar cells efficiency can be attained.

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