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Reducing the stress concentration of back contact solar cells: Optimizing the process of drilling☆

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ABSTRACT

Drilling is important for back contact solar cells, which form a good ohmic contact between a front surface and a rear surface. However, drilling causes increases of breakages and cracks in a back contact solar cell when the silicon wafer is thinner and larger than that of conventional cells. In the present paper, the node value method of finite element post-processing, including a stress concentration factor, a Von Mises stress and a sub-model, is used to achieve a quantitative analysis involving the stress concentration of a silicon wafer with multiple holes under thin film residual stress. The results show that drilling which changes the stress field distribution in a silicon wafer generates a stress concentration around the holes. This stress concentration can be reduced by increasing the thickness of a silicon wafer, decreasing the drilling ratio and replacing the morphologies of trapezoidal holes with those of cylindrical holes. The results of the simulation are in accordance with the experimental results adopted by Raman spectra and three-point bending tests. Our results provide a beneficial reference for decreasing stress concentration in back contact solar cells.

1. Introduction

As the trends of decreasing costs, shadowing losses and increasing packing module density continue, there will be demand for thinner and larger silicon wafers [1,2]. In order to meet these demands, a back contact solar cell is designed, which has many holes on a silicon wafer to interconnect a front surface with a rear surface, as it is mostly the thin metal "fingers" or power-conveying busbars which are moved to the rear surface of the solar cell. For instance, there are about 200 holes in a metal wrap through (MWT) solar cell. For emitter wrap through (EWT) solar cells, up to 25,000 of these holes are required in each silicon wafer. Based upon our literature search [3,4,5], however, it was observed that using a thinner wafer with holes caused the increase of breakages and cracks in the solar cell, due to the fact that these holes create stress concentration, thereby affecting further mechanical strength when the wafer is under tension, as a result of thin film or Al back field residual stresses [6]. Bharatish et al. [7] evaluated the thermal residual stresses in laser drilled alumina ceramics by means of Micro-Raman spectroscopy, and confirmed that laser drilling with a high laser power and low scanning speed caused great damage to the holes and crack formation. Furthermore, using the wafer with micro-cracks resulted in an increase of the recombination current density in the depletion region of the solar cells [8].

In conventional solar cells, the methods of controlling the cooling temperature after Al paste sintering [9], changing the geometric configuration of a screen printing [10], and using an Al adhesive with low elastic modulus [6] have been adopted to reduce the stress concentration. In addition, significant research efforts have been dedicated to characterizing and investigating the relationship between laser drillings in back contact solar cells and their mechanical strength. Cereceda et al. [11] and Barredo et al. [12] observed that increasing the hole diameter results in the loss of mechanical strength. This mechanical strength loss could be reduced via designing different laser parameters [13] or carrying out chemical treatment [5].

However, in the studies we reviewed, the authors did not completely take into account the silicon anisotropy, drillings or post-processing, among which were deposited film and printed Al back field. Some of their models neither considered multiple holes, nor solved a precise solution of stresses, and only analyzed locally by ring-on-ring tests, thus lacking an integral analysis regarding a model with multiple holes. Therefore, it is necessary to further study the influence of the drilling on the stress distribution in a back contact solar cell after depositing thin films and printing Al back field. In the present paper, a stress concentration factor, a Von Mises stress [14] and a sub-model are adopted via the node value method of FE post-processing, in order to accomplish the quantitative analysis of stress distribution on an EWT solar cell after deposited thin films and Al back field. Our results provide a reference for reducing mechanical strength loss, breakages and cracks in back contact solar cells.

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2. Material and methods

2.1. Calculating the stiffness coefficient of a mono-crystalline silicon

A mono-crystalline silicon, which is one most of the important material in photovoltaic modules, is an anisotropic elasticity in <100> orientation. Based on linear elasticity in an orthotropic material and generalized Hooke's law, the matrix of the stiffness coefficients c_{ijkl} is shown in Eq. (1) in the crystal axes coordinate system [15]:

$$\left[c_{ijkl}\right]=\begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{44} \end{pmatrix} \tag{1}$$

Where $c_{11}=1.657\times10^{12}$ dyn/cm^2, $c_{12}=0.639\times10^{12}$ dyn/cm^2, and $c_{44}=0.796\times10^{12}$ dyn/cm^2 [16].

In order to carry out the coefficients transformation from crystal axes coordinate system to an arbitrarily oriented coordinate system, one must revert to tensor notation transformation. The L_2 rotated axes are chosen as the transformation axis in a crystal axes coordinate system, and the transformation results are shown in Eq. (2).

$$\left[c'_{ijkl}\right]=\begin{pmatrix} 3.781 & 3.254 & 2.851 & 3.340 & 0 & 0 \\ 3.254 & 3.725 & 2.828 & 3.302 & 0 & 0 \\ 2.851 & 2.828 & 2.859 & 2.691 & 0 & 0 \\ 3.340 & 3.302 & 2.691 & 4.487 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.624 & 0.587 \\ 0 & 0 & 0 & 0 & 0.587 & 1.208 \end{pmatrix} \tag{2}$$

2.2. Calculating the residual stress of a thin films system

The Stoney Equation [17], shown in Eq. (3), is a powerful tool for solving the residual stress of thin films:

$$\kappa=\frac{6\sigma_m h_f}{M_s h_s^2} \tag{3}$$

where κ is a deformational curvature of a silicon base caused by film stress, σ_m represents film stress, M_s is an elasticity modulus of a silicon base, and h_f and h_s are the thicknesses of a film and a silicon wafer, respectively. In our study, there are 80 nm SiO_2 film and 120 nm SiN_x film on the front of a back contact solar cell, and 500 nm Al back field on the rear of it. In addition, σ_m can be derived from Eqs. (4)–(6).

$$\varepsilon_m=(\alpha_s-\alpha_f)\Delta T \tag{4}$$

$$\sigma_m=\varepsilon_m M_f \tag{5}$$

$$M_f=E_f/(1-\upsilon_f) \tag{6}$$

where ε_m indicates a strain, α_s is the thermal expansion coefficient of silicon <100>, α_f is the thermal expansion coefficient of a film, M_f is an elasticity modulus of a film, E_f indicates a Yong's modulus of a film, and υ_f is a Poisson's ratio of a film.ΔT is the temperature gradient, which is calculated by room temperature of 27 °C and sintering temperature of 800 °C. Their mechanical properties parameters [13,18] are shown in Table 1.

The film stress was set at −881 MPa in both the X and Y directions on the interface between the films and the silicon wafer. The center of the wafer was fixed in the Z direction.

Table 1
Summary of material models for characteristic values at room temperature.

Material	Thermal expansion coefficient α [°C^{-1}]	Yong's modulus E [GPa]	Poisson's ratio υ
Si	3.137×10^{-6}	130	0.28
SiO_2	0.584×10^{-6}	71	0.16
SiN_x	0.92×10^{-6}	280–310	0.22
Al	23.64×10^{-6}	70	0.35

2.3. Wafer model geometry

According to a typical demand for a back contact solar cell, there are 25,000 holes in a 125 mm^2 EWT solar cell [19,20]. Thereby, in this paper a model consists of a matrix of 5 × 5 holes, with a distance of 2 mm between the centers of the adjacent holes, and its area is 3.8 × 3.8 mm^2.

2.4. Material characterization

A Renishaw in a Via Raman microscopic instrument is used for measuring a Raman spectrum by a typical accumulation time of 20 s for each spectrum. Its power of an excitation laser with 514.5 nm is 3.6 mw. A breaking strength is measured using a Zwick-Roell Z2.5 electronic universal testing machine, with a constant span length of 6.5 mm. The bone is positioned horizontally with the anterior surface facing upwards, centered on the supports, and the pressing force is directed vertically to the midshaft of the bone, with a constant speed of 0.5 mm/min until failure.

3. Results and discussion

The influence of drilling ratio which is a drilling area divided by a total area, hole morphology and wafer thickness on the stress distributions in silicon wafers with multiple holes after depositing of thin films and Al back field is discussed.

Figs. 1 and 2 show the displacement vector sums of silicon wafers with multiple holes of 150 μm and without holes under the same thicknesses of 160 μm. Both form saddle shapes after being loaded with film stress, which accounts for the anisotropic nature of the mono-crystalline silicon wafer. This signifies that their maximum and minimum displacements are at the top corner and center of the silicon wafers, respectively [21]. These can be further described by the fact that

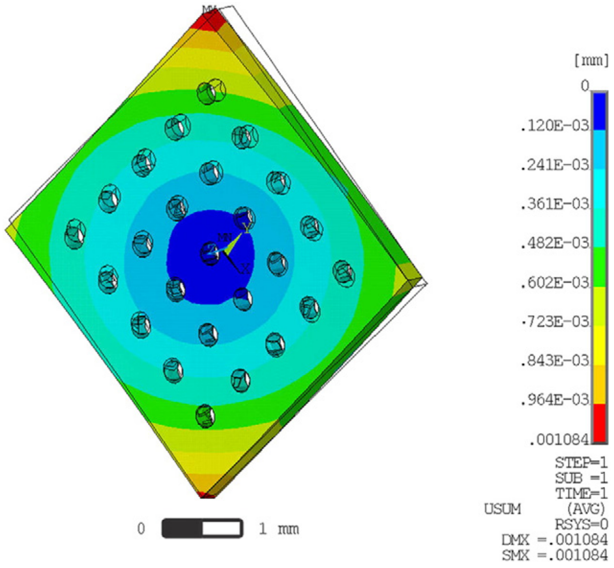

Fig. 1. Displacement vector sum of silicon wafer with multiple holes of 150 μm.