Minority lifetime degradation of silicon wafers after electric zone melting

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ABSTRACT

The degradation of minority lifetime of mono- and multi-crystalline silicon wafers after electric zone melting, a simple and contamination-free process, was investigated. The thermal-stress induced dislocations were responsible to the degradation; however, the grain size also played a crucial role. It was believed that the grain boundaries helped the relaxation of thermal stress, so that the degradation was reduced as the grain size decreased. In addition to lifetime mapping and etch pit density, photoluminescence mapping was also used to examine the electrically active defects after zone melting.

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1. Introduction

The wafer quality is crucial to the conversion efficiency of silicon solar cells. Thermal stress and impurities during crystal growth are the two major factors that affect the wafer quality, which is often characterized by the minority carrier lifetime [1]. Understanding the interplay of the thermal stress/impurities and the lifetime during crystal growth is very important to find a way to grow the crystal with a better quality at lower cost. On the other hand, with the increasing slicing cost, the kerf-free ribbon growth, either the edge-defined fed-film growth (EFG) [2] or the string ribbon growth [3], remains a promising technology for future cost reduction. However, the low-lifetime issue is still the key obstacle for its applications. In addition to the thermal stress, the contamination from the mold or string is also responsible to this issue; the precipitation could induce dislocations as well. The electric zone melting (EZM) [4–8], a simple contamination-free process, developed by Lisbon University is an ideal process that could be used to study the lifetime degradation during the ribbon growth. The dislocations are simply induced by thermal stress, while the grown in defects are usually several-order smaller; the impurities are further reduced after zone melting as well. This process could be easily setup and operated at a low energy budget. More importantly, the in-situ observation and thermal measurements during crystal growth are rather easy.

The EZM of multi-crystalline wafers have been studied [5–7]. Thermal measurement and the overall minority lifetime as a function of drifting velocity and electric current have also been investigated [5,6]. However, the lifetime degradation for different wafers considering mono or multi-crystalline wafers having different grain sizes has not yet been investigated. Such a study would be helpful to get a deeper understanding of the thermal stress-induced defects and the possible mechanisms of stress relaxation due to defect or grain formation. The role of grain boundaries could also be investigated. In the next section, the experimental setup and the characterizations are described. Section 3 is devoted to results and discussion, followed by conclusions in Section 4.

2. Experimental

The EZM setup was similar to the one reported by Costa et al. [5], as shown in Fig. 1(a). The p-type wafers, the resistivity being about 1.2–1.7 Ω-cm, were obtained commercially; the thickness was about 200 μm. Two types of high-performance multi-crystalline (mc) wafers [9,10] were considered; one was near the seeds having small grains (about 1.5 mm) and one was near the top of the ingot having large grains (about 4.0 mm). The resistivity of the small- and large-grain mc-wafer was about 1.7 and 1.2 Ω-cm, respectively. The wafer was cut by laser into the sample size of 5 cm × 12 cm for the EZM experiment. Before experiment, the wafers were rinsed by 10% HF solution for 5 min to remove the surface oxide. Two 3 cm × 10 cm mc wafers near the water-cooled aluminum electrodes were used for heat dissipation, and this was important to keep the molten zone away from the electrodes. To enhance the electrical contact, graphite felt was used to

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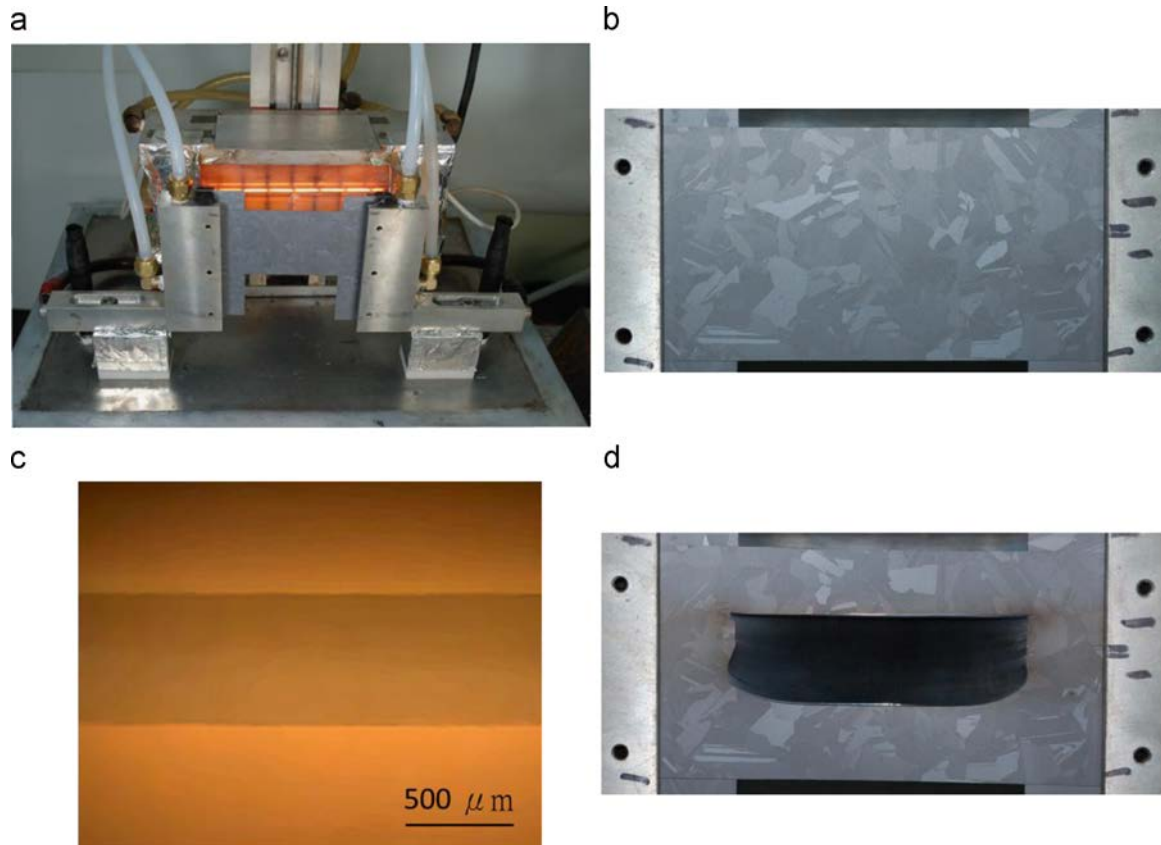 *E-mail address:* cwlan@ntu.edu.tw (C.W. Lan).

Fig. 1. (a) System setup of the EZM; the wafer was clamped by two water-cooled electrodes and the linear halogen lamp on the back was focused by a polished parabolic mirror, which was mounted on a translation system; (b) a close-up view of the silicon wafer; (c) a molten zone image (at 20.5 A) and (d) the sample after electric zone melting.

fix the sample inside the groove of the electrodes. The close-up view of the silicon wafer is shown in Fig. 1(b), and the lamp and the cooling wafers were on the back side. The heating for concentrating the electric current was carried out by a mirror-focused linear halogen lamp (1 kW). This elliptic mirror (20.5 cm long) was machined and polished from an aluminum block having the long- and short-axis of 40.00 and 31.22 mm; the focus distance was 25.00 mm. The mirror was mounted on a translation system having a precision screw (40 pitches/inch), driven by a micro-stepping motor. The initial position was set at 1 cm below the upper edge of the wafer. To avoid oxidation, a Plexiglas chamber with a quartz view window was slightly vacuumed and then flushed continuously with argon. The electric current to generate the molten zone was controlled by a power supply (Sorensen DC 55 V 55 A 3 kW).

To start the experiment, the electric voltage of the power supply needed to be increased to about 50 V first, while the lamp power was increased slowly. As the lamp power was at about 530 W, the electric current started to increase to a few A, while the voltage was dropped quickly. With further increase of the lamp power, the electric current increased and a molten zone was initiated near the edge of the cooling wafers. At the lamp power of 900 W, a stable molten zone of about 400 to 500 μm could be established at the current of around 19 to 20 A. The zone length increased with the applied current. In this paper, the current was fixed at 24.5 A. As a stable molten zone was established (about 750 μm), the lamp was moved downward at a setting speed. Three speeds, 2, 4 and 6 mm/min, were considered here. Fig. 1(c) shows the observed molten zone after 100 s of the lamp movement at 2 mm/min. The zone length as shown was very uniform and stable at about 600–650 μm until the end of the experiment. The sample after zone melting is shown in Fig. 1(d). A major problem of the

electric zone melting was on the control of zone edges. The edge variations during zone melting could cause fluctuations in the solidification speed and the zone length.

During zone melting, a mono-color pyrometer with a spot size of 0.3 mm (Sensortherm Gmbh Metis MS 90) was used to measure the temperature of the sample. The temperature gradients could be obtained as the zone position was recorded simultaneously. The measured temperature profiles as a function of time are summarized in Fig. 2(a), where the measured spot was fixed and located below the initial molten zone. Because we set the emissivity to be 0.58 for the measurement at the wavelength of 900 nm [11], the temperature inside the molten zone was lower due to the lower emissivity of the melt (about 0.22 [11,12]). The variation of emissivity near the melting temperature was small. In addition, due to the finite spot size (0.3 mm), the maximum temperature inside the molten zone could not be revealed; the mono-color pyrometer tended to average the temperature inside the spot. By measuring the position of the melting and solidification interfaces, we could estimate the local speeds of the interfaces. With the speeds, the interface positions could be obtained by integration, so that the position of the measured spot could then be estimated. Having such information, we could calculate the temperature profile as a function of distance. The thermal profiles at different lamp speeds with respective to the lamp position are as shown in Fig. 2(b). As shown, the effect of lamp speeds on the thermal gradient at the solidification side was small. The estimated thermal gradient was about 180 K/mm.

After zone melting, the wafers were chemically etched (HNO₃: HF=6: 1) for subsequent characterizations. The etch pit density (EPD) was revealed by Secco etching [13] for about 3 min [14]. The minority carrier lifetime was measured by the microwave photo-conductivity decay technique (μ-PCD) (Semilab WT2000), while