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Fracture strength of silicon wafers sawn by fixed diamond wire saw

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ABSTRACT

A larger breakage ratio occurs with the decrease of wafer thickness due to the decrease of fracture strength for as sawn silicon wafers, which is a severe problem to limit the production yield of silicon wafers. It is necessary to understand the fracture behavior of as swan silicon wafers for increasing the wafer yield. In this paper, a predictive model for wafer fracture strength is proposed according to the linear-elastic fracture mechanics. The simulation results are comparable with the experimental results from references, indicating the correctness of this proposed model. Besides that, influences of surface crack parameters on the fracture strength of silicon wafer are discussed. Results indicate that the fracture strength of silicon wafer changes less when the surface crack inclination angle between the crack plane and saw mark is between 0 and 25°. However, the fracture strength increases with the increase of the surface crack inclination angle when the angle is larger than 25°. This proposed model can predict the strength distribution of silicon wafers, and it is very helpful to understand the fracture behavior of silicon wafers.

1. Introduction

Silicon crystal is widely applied in the manufacture of the integrated circuit and photovoltaic cells due to its excellent semi-conductive properties. Eighty percent of solar cells are fabricated by single crystal silicon and polycrystalline silicon. However, processing of silicon wafers occupies a large percentage of total machining costs. Some strategies have been adopted to solve this problem. For instance, thinner and larger silicon wafers are developed, and processing technologies are optimized, etc. The silicon wafer for photovoltaic cells has been developed to 100-μm-thick based on the Barbara Terheiden et al.'s work (Terheiden et al., 2015). While, reducing wafer thickness leads to a higher breakage rate, which aggravates the material loss and the manufacturing cost. Consequently, it is very essential to understand the fracture behavior of the silicon wafer.

As a kind of brittle material, the fracture strength of silicon wafers has been studied by lots of researchers (Cook, 2006; Popovich et al., 2011, 2013; Rupnowski and Sopori, 2009). The fracture strength, representing the ability of resistance to fracture for material, defines the limit of energy before two single atoms are separated from the atomistic view. According to the Orowan equations (Clarke, 1992), elastic modulus, surface energy, and lattice constant of material, all have influences on the fracture strength. The fracture strengths for silicon wafers along different material directions are varied due to the anisotropy of monocrystalline silicon. The actual value of material strength is generally lower than the theoretical one owing to various defects of different types and sizes within material (Schoenfelder et al., 2007). Due to the brittle nature of silicon at room temperature, it is very sensitive to the defects such as cracks and stress concentration. Brittle materials cannot release high stress, which is concentrated at the crack tip. Consequently, cracks will propagate through the material, and the silicon wafer will fracture if stress in the silicon is larger than critical stress (Anderson, 2005). Therefore, it can be said that the fracture strength of the silicon wafer is correlated to the defects, particularly the crack.

Distribution and size of defects have distinct influences on the strength of silicon wafer, which leads to different distributions of fracture strength for wafers (Burghartz, 2010). It is difficult to determine a single strength value of fracture strength because of a larger scattering of strength for brittle material. For this reason, the statistical approach is commonly adopted to study the fracture strength of wafers. Furthermore, the weakest link model proposed by Peirce is usually used to interpret the fracture strength of the silicon wafer (Peirce, 1926). Weibull developed a probability model to investigate the fracture strength of material based on the weakest link model (Weibull, 1951). Based on their theories, the fracture strength of one system composed of multiple links depends upon the fracture strength of the weakest link. Hence, it can be said that the fracture strength of a silicon wafer depends on the minimum critical stress which relates to the parameters of crack.

Wire sawing, the first step of processing silicon ingot, generates

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machining damages in the surface or subsurface of the sliced silicon wafer inevitably (Sopori et al., 2013). These machining damages include micro cracks, dislocation, residual stress, etc. Three kinds of failure modes can be grouped for silicon wafers: bulk, surface, and edge mode. Such as, the surface failure mode is mainly owing to the surface or subsurface defects. And the bulk and edge failure mode occur in the cases of a failure initiates induced by bulk and edge defects in wafer respectively. Because the silicon wafer is small in volume, and the size of the bulk defect is usually small as well, the bulk failure mode can be neglected. Before wire sawing, the silicon block is ground to remove damage for each face. And then, edges of silicon wafers are generated after wire sawing, which are from these ground faces. Consequently, the damages have been removed from the edges of sawn wafers, and the edge failure mode can be neglected as well (Rupnowski and Sopori, 2009). For the sake of simplicity, it is assumed that the dominant mechanism of wafer breakage is the surface failure mode in this paper.

Various wire sawing techniques, such as slurry wire sawing and fixed diamond wire sawing, induce distinct distribution types of surface crack and generate different fracture strength distributions for sawn wafers (Funke et al., 2005; Wu et al., 2014; Buchwald et al., 2014). A regional high pressure is developed, which generates crack damage with different orientations during diamond wire sawing. Wu et al. (2012) studied the effect of subsurface crack orientation on the stress intensity factor by using the finite element method. Their results indicated that the subsurface crack with angle 0–45° has little effect on the fracture strength of silicon wafers compared with the experimental results obtained by the uniaxial bending test.

Yang et al. (2013a,b) used four-point bending test to analyze the fracture strength of silicon wafers sliced by fixed diamond wire saw and slurry wire saw. They focused on the influences of saw marks on the fracture strength. And also, Meng and Zhou (2014) studied the mechanical behavior of silicon wafers sawn by diamond wire saw. Their experimental results indicate that the fracture strength is various with the different directions of wire sawing. Moreover, surface crack with the inclination angle 20°–60° is the main reason for wafer breakage (Azar et al., 2016).

In this paper, a new model of predicting fracture strength of silicon wafers is developed. The fracture strength of the silicon wafer sliced by fixed diamond wire saw is studied under the condition of considering the characteristics of surface crack generated by diamond wire sawing. This research is meaningful to understand the fracture behavior of a silicon wafer comprehensively, and it is important to ensure the reliability of product.

2. Theoretical model

2.1. Strength of silicon wafer

As the discussion on the introduction part, three kinds of failure modes can be distinguished for silicon wafers: bulk, surface, and edge mode. Based on the work of Behnken et al. (2003), the probability that wafer does not break when a load σ is applied can be expressed as the following formula if the three failure modes are all considered:

$$F(\sigma) = F_V(\sigma)\cdot F_A(\sigma)\cdot F_L(\sigma) \tag{1}$$

where the $F_V(\sigma)$, $F_A(\sigma)$, $F_L(\sigma)$ are the probability of a wafer survival under the condition of bulk failure mode, surface failure mode or edge failure mode is only considered, respectively.

From the probabilistic fracture mechanics, the formula (1) can be rewritten as:

$$F(\sigma) = \exp\left(-\int_V \left(\frac{\sigma-\gamma_V}{\alpha_V}\right)^{\omega_V} dV - \int_A \left(\frac{\sigma-\gamma_A}{\alpha_A}\right)^{\omega_A} dA - \int_L \left(\frac{\sigma-\gamma_L}{\alpha_L}\right)^{\omega_L} dL\right) \tag{2}$$

where α_V, α_A, α_L, γ_V, γ_A, γ_L, ω_V, ω_A and ω_L are Weibull parameters.

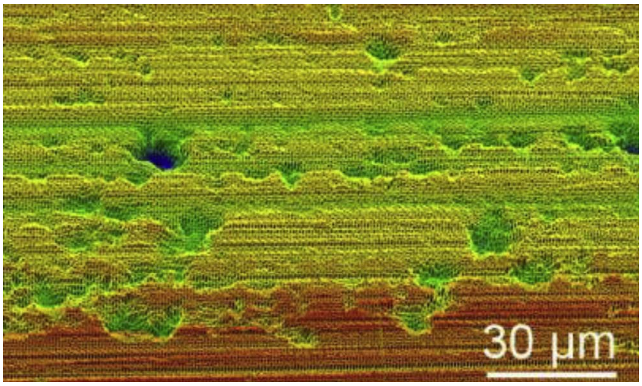

Fig. 1. The morphology of a silicon wafer sliced by fixed diamond wire saw (Möller, 2015).

According to the description of the three kinds of failure modes in the introduction part, it can be assumed that the dominant mechanism of wafer breakage is the surface failure mode to simplify the calculation mode. Therefore, the formula (2) can be rewritten as:

$$F(\sigma) = \exp\left(-\int_A \left(\frac{\sigma-\gamma_A}{\alpha_A}\right)^{\omega_A} dA\right) \tag{3}$$

Here, two-parameter Weibull distribution is used to instead of the Eq. (3) (Weibull, 1951):

$$F(\sigma) = \exp\left(-\int_A \left(\frac{\sigma}{\alpha_A}\right)^{\omega_A} dA\right) \tag{4}$$

2.2. The model of surface crack distribution

Diamond abrasives plow and scratch on the silicon block to remove material under the interaction of wire movement during fixed diamond wire sawing. This motion is similar to the scratch movement of moving indenter. Crack is formed by the tensile and shear stress, which is the result of interaction between abrasives and material during wire sawing. Fig. 1 is the typical morphology of the sliced surface for the silicon wafer sawn by fixed diamond wire saw. It can be seen that, lots of parallel grooves distribute along the moving direction of diamond wire saw. Furthermore, some pits appear in some local regions.

According to the study of Würzner et al. (2015), the distribution of surface crack shows some regularities in wafer surface sliced by fixed diamond wire saw, as shown in Fig. 2. It can be seen that, these cracks have the similar propagation directions. Furthermore, surface cracks distribute along the moving direction of diamond wire, and appear periodically along the feed direction. This kind of surface crack distribution is similar to the crack distribution generated by single-point

Fig. 2. Surface crack in silicon wafer sliced by fixed diamond wire saw (Würzner et al., 2015).