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Subsurface crack damage in silicon wafers induced by resin bonded diamond wire sawing

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ABSTRACT

In order to optimize the process of wire sawing, this work studied the subsurface crack damage in silicon wafers induced by resin bonded diamond wire sawing using theoretical and experimental methods. A novel mathematical relationship between subsurface crack damage depth and processing parameters was established according to the indentation fracture mechanics. Sawing experiment using resin bonded diamond wire saw was performed on a wire saw machine. The validity of the proposed model was conducted by comparing with the experimental results. At last, the influences of processing parameters on subsurface damage depth were discussed. Results indicate that the median cracks are mainly oblique cracks which generate the subsurface crack damage. On the diamond wire saw cross section, the abrasives with the position angle 78° between abrasive position and vertical direction generate the largest subsurface damage depth. Furthermore, abrasives, generating the subsurface damage, tend away from the bottom of diamond wire with the increase of wire speed or decreases with the increase of feed rate. However, the wire speed and feed rate have opposite effects on the subsurface crack damage depth. In addition, the subsurface crack damage depth is unchanged when the ratio of feed rate and wire speed does not change.

1. Introduction

Wire sawing is the first step in silicon ingot processing, which accounts for a large proportion of the total cost of silicon wafer manufacturing. To reduce the cost of wire sawing, resin bonded diamond wire saw is developed and considered as a novel slicing technique. Compared with slurry wire saw, the resin bonded diamond wire saw has the advantages of higher cutting efficiency, lower machining cost, and higher cutting quality. However, subsurface damage (SSD) is unavoidable during wire sawing, including micro-crack, amorphous layer, residual stress, dislocation, and other types of damage. Hed et al. [1] first developed the subsurface damage model for optical material as shown in Fig. 1, which was often used in the studies of subsurface damage for silicon wafers induced by wire sawing. SSD may impact on the function of silicon wafer in three major aspects: mechanical property, optical property, and electronic property. SSD deteriorates the mechanical property of silicon wafer, reduces the fracture strength, provides sites for light-absorbing contaminants to reside, causes atoms at or near fracture surfaces to be more easily ionizable (by changing the chemical or electronic environment), and/or modulates locally the electromagnetic field [2]. Therefore, the SSD must be eliminated in order to improve the property of silicon wafer.

The material removal mechanisms for slurry wire saw and fixed diamond wire saw are dissimilar, which results in the different types of subsurface crack damage in silicon wafers sawn by these two techniques. Funke et al. [3] observed the crack damage in silicon wafers sawn by slurry wire saw. They found out that the distribution of crack location was random. Moreover, these crack depths decreased gradually along the direction from wire inlet to wire outlet. However, Würzner et al. [4] revealed that cracks distributed along the direction of sawing grooves and appeared periodically in silicon wafers sawn by fixed diamond wire saw. A further difference found by Möller [5] was that the amorphous layer appeared locally on the wafer surface sawn by fixed diamond wire saw. Kang et al. [6] compared the subsurface crack damage depth of these two kinds of silicon wafers. They inferred that the quality of silicon wafer sawn by fixed diamond wire saw was superior to that sawn by slurry wire saw. Furthermore, the subsurface crack depth induced by slurry wire sawing was larger than that induced by fixed diamond wire sawing. In addition, Watanabe et al. [7] showed the similar conclusion via experiment and argued that the resin bonded diamond wire saw was suited for the fabrication of ultra-thin silicon wafers.

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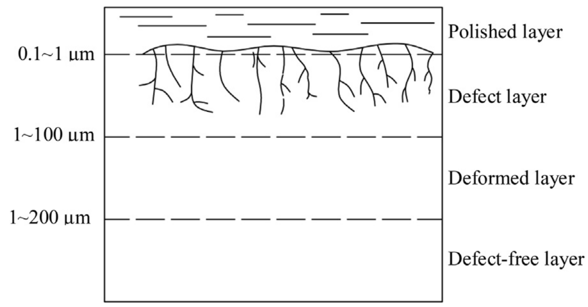

Fig. 1. Schematic of subsurface damage for optical material [1].

Many factors influence the subsurface crack damage depth during wire sawing, such as the feed rate of the workpiece, wire speed, slicing orientation, abrasive size, etc. Sopori et al. [8] researched the effects of various processing parameters on the subsurface damage. They found out that the subsurface crack depth mainly depended on the feed rate, wire speed and abrasive size. Würzner et al. [4] investigated the effect of wire speed on the surface damage for silicon wafers sawn by fixed diamond wire saw. Their results indicated that the maximum crack length decreased when wire speed increased. Teomete [9] found out that the subsurface crack depth increased with the increase of feed rate, and increased as the wire speed decreased. However, it was unchanged when the feed rate and wire speed increased or decreased proportionally. These conclusions show that a smaller subsurface crack damage depth and a higher material removal rate can be obtained through increasing feed rate and wire speed proportionally.

A large number of empirical and semi-empirical relationships between subsurface crack damage depth and surface roughness have been established according to the experimental results of machining optical materials. Preston [10] firstly found out that the subsurface crack damage depth was two or three times of the surface roughness for ground surface. After that, Lambropoulos et al. [11] obtained a linear relationship with a proportional coefficient between subsurface crack depth and surface roughness. Gao et al. [12] developed a nonlinear theoretical model for these two machining damages according to the Lambropoulos's model.

However, it is still difficult to predict the crack damage depth directly when processing parameters are known using the above method. Hence, a novel mathematical relationship between subsurface crack damage depth and processing parameters was proposed on the basis of indentation fracture mechanics in this paper. The validity of this model was conducted by comparing with the experimental results obtained through the bonded interface section technique and SEM. This proposed model can be used to evaluate the subsurface crack damage depth in a quick, accurate and no destructive way, which is benefit to optimize wire sawing process, reduce processing cost, and lower the probability of wafer fracture in latter machining process.

2. Model of subsurface crack depth

2.1. Crack system in resin bonded diamond wire sawing

The process of resin bonded diamond wire sawing is shown in Fig. 2. The wire and workpiece move along two perpendicular directions with the speeds v_s and v_f respectively. Abrasives, forced normal force P and tangential force Q, make the motion of sliding and plowing on the workpiece surface to achieve the material removal, which is similar to the scratching of moving indenter, as shown in Fig. 3. Brittle fracture behavior is considered as the main way of material removal during wire sawing. Crack is formed by the tensile and shear stress which are the result of interaction between indenter and material during scratching. The moving indentation usually involves two primary cracks: lateral crack and median crack.

There are normal force P and tangential force Q acting on the sharp indenter which taper angle is 2α. A plastic zone and crack system will emerge when the normal force exceeds a certain value. The indentation is surrounded by a nearly hemispherical plastic zone under which contains median crack and lateral crack propagating toward to subsurface and surface respectively. In the following analysis, the depth of median crack is defined as the subsurface damage depth (SSD).

Experimental results of scratching process indicate that the lateral crack depth is approximately to the plastic zone size. According to the study of Lambropoulos et al. [13], the lateral crack depth can be expressed as the size of the plastic zone:

$$C_{li} = b_i = 0.43(\sin\alpha)^{1/2}(\cos\alpha)^{1/3}(\frac{E}{H})^{1/2}(\frac{P}{H})^{1/2} \tag{1}$$

where C_{li} is the lateral crack depth; b_i is the plastic zone size; α is the half taper angle of indenter; E is the elastic modulus of single crystal silicon; H is the hardness of single crystal silicon; P is the normal force on diamond abrasive.

According to the study of Lawn et al. [14], the theoretical depth of median crack can be expressed as:

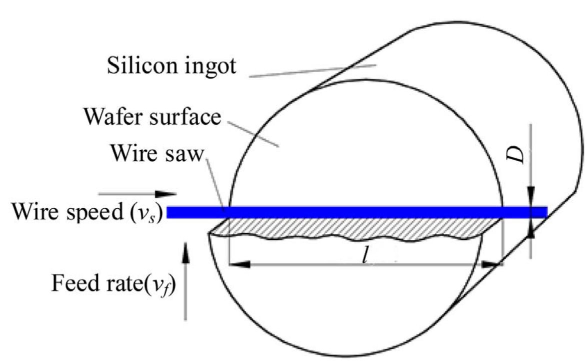

Fig. 2. Resin bonded diamond wire sawing.