Fundamental Characteristics of Grooving Aiming at Reduction of Kerf Loss Using an Ultrafine Wire Tool

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Abstract. Thinning of silicon wafers and reduction of kerf loss can minimize the manufacturing costs of semiconductor products. Currently, the volume of kerf loss is about the same as the volume of the wafer itself. Therefore, we study slicing techniques for silicon wafers that result in reduced kerf loss by using an ultrafine wire tool and fine abrasive grains. As a first step, grooving characteristics using an ultrafine tungsten wire tool and fine abrasive grains are investigated in this paper. A borosilicate glass is used as the work material. The main conclusions are as follows: Precision machining using ultrafine wire tool is possible and the kerf loss decreases because the groove width decreases. However, a larger diameter of the wire tool results in a deeper groove. A faster relative speed produces a shorter wire tool lifetime, but a deeper groove. To supply enough abrasive grains to the machined portion, it is necessary to use abrasive grains having a suitable particle size for the specific diameter of the ultrafine wire tool.

1. Introduction

Multi-wire sawing is an excellent slicing method for hard and brittle materials, such as silicon ingots, magnetic materials, ceramics, and sapphire [1]. Multi-wire sawing has become the mainstream slicing system for large-diameter ingots in recent years.

Presently, the volume of kerf loss is about the same as the volume of the wafers when several thin wafers are sliced from a silicon ingot using a multi-wire saw [2]. Thinner wafers and a decrease in kerf loss can minimize manufacturing costs [3]. Additionally, from the viewpoint of resource savings, drastic reduction of kerf loss is desired. The diameter of the wire tool and particle size of the abrasive grain that are used for slicing greatly affect the volume of the kerf loss. In other words, when the wire tool is thin and the abrasive particles are small, the kerf loss can be drastically reduced. However, there are few research reports of slicing performance using the fine wire tool because of frequent breaking of the wire tool and deterioration in slicing performance. On the other hands, the slicing method of silicon wafers using electric discharge machining or chemical processing, such as etching to reduce kerf loss, have been proposed [4, 5]. However, these methods still have problems because it is difficult to slice a high resistance material or use a high processing speed. Therefore, these methods are still not practical for regular use.
The main purpose of this study is to reduce kerf loss using multi-wire sawing. Therefore, the possibility of using an ultrafine wire tool and fine abrasive grains as the slicing tool for multi-wire sawing are examined. Both slicing and grooving methods are applied using the relative motion of the wire tool and the work material. In other words, both machining mechanisms are the same mechanism. Therefore, as a first step to realize slicing with less kerf loss, we discuss the fundamental grooving characteristics using ultrafine wire tools and fine abrasives in this paper.

2. Experimental procedure

Figure 1 showed the schematic of the slicing experimental setup and the experimental conditions and materials used for the experiments were summarized in Table 1. A jig that held the wire tool under constant tension was installed on the table of a computerized numerical control (CNC) milling machine. The work material was attached to the work holder, which was installed along the Z-axis of the CNC milling machine. Prior to the experiments, the work material was pushed 15 mm toward the wire tool and grooving experiments were conducted using rotational motion of the spindle, as shown in Figure 2. A borosilicate glass round bar with a diameter of 10 mm was used as the work material, and the rotational speed of the work material was set to 28 m/min and 228 m/min. Previous studies demonstrated when the contact length of the wire tool and the work material (the length of the wire tool contributing to grooving) were short, the wire tool was damaged in a short amount of time due to wear [6]. In this study, to increase the length of the wire tool contributing to grooving, the X-Y table reciprocated at a low speed (278 mm/min) in the X-axis direction. The X-Y table movement distance was 90 mm. Therefore, the length of the wire tool contributing to the grooving was 90 mm. In addition, a free software (Mach 3, Artsoft USA) was used as the numerical control (NC) software.

The scanning electron microscope (SEM) image of the unused wire tools is shown in Figure 3. The diameter of each wire tool is 50 μm, 80 μm, 100 μm, and 140 μm. A wire tool with a diameter of 140 μm is a commonly used steel wire tool. Experiments are conducted using tungsten wire tools with diameters of 50–100 μm. The tension applied to the wire tools is 3.6 N. Green silicon carbide (GC)
with three different particle sizes is used as the abrasive and the mean diameters of the abrasives are 1.2 μm, 3.0 μm, and 6.7 μm. The abrasives are mixed with a water-soluble coolant and is based on polyethylene glycol, which is used as the water-soluble slurry. The supplied slurry includes 40 wt% of the abrasive. The feed amount is 50 mL/min.

3. Experimental results and discussion

3.1. Possibility of grooving using ultrafine wire tool
First, it is investigated whether grooving can be performed with ultrafine wire tools when borosilicate glass is used as the work material. Figure 4 shows an example of the work material after grooving. The diameter of the ultrafine wire tool is 50 μm and the particle size of the abrasives is 6.7 μm. The rotational speed of the work material is 28 m/min. From Figure 4, it is sufficiently possible to groove the material when using ultrafine wire tools.

3.2. Influence of diameter of ultrafine wire tool
The influence of the diameter of the ultrafine wire tool on the grooving characteristics is investigated while maintaining a constant particle size of the abrasives at 6.7 μm. Figure 5 shows the processing time necessary to break the ultrafine wire tool. It is clear from this figure that increasing the diameter of the wire tool, the processing time up to the breaking is increased. In addition, as the relative speed increases, the processing time that produces a broken tool is shortened. However, when the relative
When the speed was fast, the influence of the wire diameter appears slightly. This is because the wire tool breaks in a very short amount of time when the relative speed is high.

Figure 6 shows the influence of the diameter of the ultrafine wire tool on the groove depth. When the diameter of the wire tool increases, the groove depth tends to deepen. When the diameter of the wire tool is larger, the processing time to break the wire tool increases. However, as the relative speed increases, the groove depth tends to deepen although the processing time to break the wire tool decreases. This is due to the improvement of the cutting performance of individual abrasives when there is an increase in relative velocity.

Figure 7 shows the influence of the diameter of the ultrafine wire tool on the groove width (kerf width). Naturally, the width of the groove is directly related to the volume of kerf loss. The empirical formula for the groove width is known [7]. Therefore, the calculated groove width is given by Equation 1.

\[ W = 3G \]  

(1)

Figure 5. Influence of wire diameter on processing time, until the wire tool breaks.

Figure 6. Influence of wire diameter on groove depth.

Figure 7. Influence of wire diameter on the groove width.

Here, \( W \) is the calculated groove width, \( T \) is the diameter of the wire tool, and \( G \) is the particle size of abrasives. \( W \) is called a calculated value (calcd) in this study and it is indicated by a dashed line in the figure. Generally, the groove width in the experiments tends to be larger than the calcd because it is influenced by the accuracy of the experimental apparatus. It is clear from this figure the groove width does not depend on the relative speed, but depends on the diameter of ultrafine wire tool. In addition, a larger diameter of the wire tool creates a greater difference between the experimental value
and the calcd. This is the result of the particle size of the abrasives remaining constant irrespective of changes in the diameter of the wire tool. Therefore, when the diameter of the wire tool is small, a sufficient number of abrasives cannot be conveyed to the processing part and the experimental value becomes smaller than the calcd.

3.3. Influence of particle size of abrasives

The influence of particle size of the abrasives on grooving characteristics is investigated while the diameter of the ultrafine wire tool is kept constant at 50 μm. Figure 8 shows the influence of particle size of abrasives on processing time, running until the wire tool breaks. A larger particle size produces a shorter time necessary for the wire tool to break. This is due to increased damage to the wire tool by the abrasives. Additionally, the faster the relative speed, the time necessary to break the wire tool is shortened.

Figure 9 shows the influence of the particle size of the abrasives on the groove depth. As the particle size of the abrasives increases, the groove depth tends to deepen. Additionally, a faster relative speed creates a deeper groove depth.

Figure 10 shows the influence of the particle size on the groove width. No clear relationship is found between the different particle sizes of the abrasives, the difference in relative speed, and the groove width. Additionally, when the particle size of the abrasives is 6.7 μm, the experimental value is smaller than the calcd. This phenomenon is particularly noticeable when the relative speed is fast. The particle size is too large relative to the diameter of the ultrafine wire tool (50 μm), and it is not able to carry enough abrasives to the processing part. A larger particle size for the abrasives makes it easier to fall off from the ultrafine wire tool. Therefore, it is believed the amount of slurry adhering to the ultrafine wire tool decreases. In other words, it becomes clear the balance between the wire diameter and the particle diameter greatly influences the grooving characteristics. Therefore, to supply enough abrasive grains to the machined portion, it is necessary to use abrasive grains having a size suitable for the specific diameter of ultrafine wire.

It is clear from Figure 10 that groove width can be reduced to about 60 μm by using an ultrafine wire tool and fine abrasives.
4. Conclusions
We investigated grooving characteristics using an ultrafine wire tool. The main conclusions obtained from this study showed the larger the diameter of the wire tool, the deeper the groove depth became. Additionally, a faster relative speed resulted in a shorter lifetime of the wire tool, but a greater groove depth. The groove width did not depend on the relative speed, but depended on the diameter of ultrafine wire tool used. To supply sufficient abrasives to the machined portion, it was necessary to use abrasives that had a particle size suitable for the diameter of the wire tool used. In this study, we could reduce groove width (kerf width) to about 60 μm by using a fine wire tool and precision abrasive.

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