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SLICING MECHANISM OF MULTI-WIRE SAWING USING ELECTROPLATED DIAMOND WIRE

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ABSTRACT

Multi-wire sawing, with fixed diamond abrasives, has been widely used for wafer mass production. However, the slicing mechanism has not been clarified completely, and the optimum slicing conditions are still determined through trial and error. In this study, the slicing mechanism of fixed abrasive wire sawing, using an electroplated diamond wire, was investigated experimentally. First, the diamond wire stiffness, and the relationship between normal cutting force and wire deflection, were discussed. Second, the influence of slicing conditions on cutting forces and the surface topography of the sliced wafer were investigated in detail. Third, a new analysis model based on a material removal method was proposed. The average abrasive cutting depth and the specific cutting energy were calculated at various slicing conditions namely, the wire speed, the feeding speed and the wire tension. Finally, the relationship of the average abrasives cutting depth to slicing characteristics and wafer quality were discussed. It was clarified that the average abrasive cutting depth is closely related to wafer quality and cutting characteristics. The material removal behavior changes with the average abrasives cutting depth. The size effect appears at a small cutting depth and brittle mode cutting becomes dominant at a large cutting depth.

KEYWORDS: diamond wire, silicon wafer, slicing, cutting force, abrasive cutting depth.

I. INTRODUCTION

Nowadays, silicon wafers are widely used in semiconductor and solar cell industries. Silicon wafers are manufactured by slicing silicon ingots. Some slicing technologies, such as the inner diameter blade method and the multi-wire saw method, have been developed and are used industrially for slicing a silicon ingot to silicon wafers. In recent years, some new cutting technologies, such as the wire electrical discharge machining method [1] and the laser slicing method [2], have been developed and their implementation is expected in the near future.

Multi-wire sawing is widely used in the slicing of various hard-brittle materials, such as silicon and quartz crystal. As a tool, the saw consists of an ultra-fine steel wire with a diameter of 0.2 mm or less, which are passed through grooves of guide rollers to several hundreds of iterations or more. In this process, only parts where the wire is routed are cut, and it is possible to simultaneously slice out a number of products corresponding to the number of iterations the wire has been wound around the machine. Currently, two slicing methods [3] exist: namely, loose abrasive slicing and fixed abrasive slicing. Loose abrasive slicing is a slicing method by which slurry (a suspension of abrasives and oil) is applied to a steel wire running at high speed. The ingot is cut by the rolling motion of abrasives between the wire and the workpiece. However, the environmental impact of slurry is considerable. Therefore, a diamond wire fixed with diamond abrasives is used in the fixed abrasive slicing method. High-efficiency slicing makes it possible to process large of wafer numbers in one slice process. Furthermore, as a water-soluble coolant is only used in the slicing process, the working environment is better and the washing process of sliced wafers is easy to carry out.

In recent years, the fixed-abrasive diamond wire sawing technology has had a rapid development and has been applied in the processes for slicing silicon and sapphire ingots into wafers [4], due to the diamond wire production technology having improved and the cost of diamond wire having declined. Diamond-wire slicing has high potential for thin wafer slicing due to using thinner wires. In addition, it can increase production efficiency and achieve a lower production cost. Therefore, the application of the diamond-wire technology in slicing polycrystalline silicon wafer production has not been very successful over the past years. One of the reasons is that the saw marks, generated by the diamond wire, cannot be removed in the subsequent etching process. Another reason is the high production cost of the electroplated diamond wire, which has caused a significant increase in the demand for electroplated diamond wire in slicing polycrystalline and monocrystalline silicon panels, due to the production cost of the diamond wire having reduced in recent years.

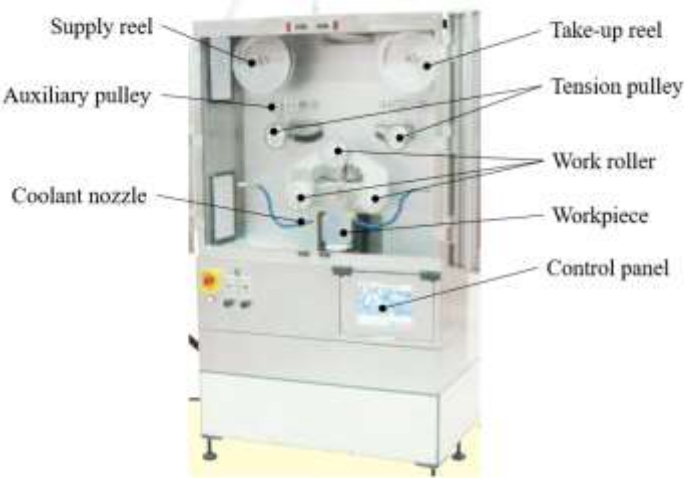
In this study, with regard to the abovementioned viewpoint, the author employed the diamond-wire technology in order to slice a polycrystalline silicon ingot, for the purpose of spreading the industrial use of diamond-wire sawing technology in various cutting fields. The influence of slicing conditions on cutting characteristics is discussed in detail. Cutting forces, specific cutting energy, and average abrasive cutting depth, were investigated by changing the wire running speed, workpiece feeding speed and wire tension. Wafer surface quality was also observed and analyzed.

II. EXPERIMENTAL APPARATUS

A requirement for precision slicing machines has risen in conjunction to the progressive development of LED and silicon/power semiconductors. Several types of diamond-wire saws have been developed for increasing the quality of workpieces. In this experiment, the single diamond-wire saw, seen in Fig. 1, was employed for slicing silicon ingot. Fig. 2 shows the detailed schematic of the wire saw slicing a silicon ingot. Machining was performed as follows. A diamond wire was wrapped alternately around a supply reel and a take-up reel. The reciprocating movement of the wire was achieved by changing the direction of movement of wrapping reels. The wire was wrapped around a supply reel, two auxiliary pulleys, two tension pulleys, and a take-up reel. The wire tension was adjusted to stable values by using the left and right tension pulleys, which swung back and forth and were controlled by an air system. The axis distance of the work rollers was set to 310 mm. The diamond wire was around the 3 work rollers, for 3 times, and 2 sheets of silicon wafers were cut out in one slicing process. A silicon ingot, fixed on a dynamometer, was fed perpendicular to wire movement direction. The cutting forces were recorded by a dynamometer.

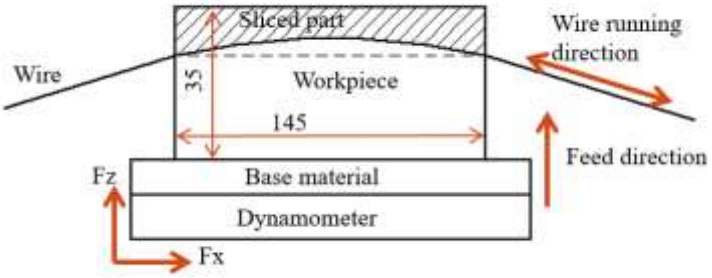
The cutting force is the sum of the reaction force, Fz, in the feeding direction of the workpiece, and the frictional force, Fx, in the running direction of the wire since the deflection of the diamond wire was determined to be negligible. The flexible diamond wire deflects because of the cutting force in the feed direction of the

Figure 1:



Appearance of diamond-wire saw

Figure 2:



Schematic of diamond-wire saw

workpiece during the cutting process. The relationship between the deflection of the diamond wire and the normal cutting force was determined. The diamond wire was immobilized under a constant tension, and the workpiece was fed to the wire in increments of 1 mm. As shown in Fig. 3, the cutting force, Fz, increased commensurately to the deflection distance and the wire tension. The diamond wire stiffness was evaluated by bending stiffness as Fz/W. It was found that the higher the wire tension was, the larger was the cutting force, Fz, and the larger was the wire stiffness. The wire stiffness remained virtually unchanged at different wire deflection distance. It is thought that slicing accuracy improved when the deflection distance of the diamond wire was reduced. The deflection distance could be reduced by increasing the tension of diamond wire. The cutting force and the kerf loss could be reduced by using a thinner diamond wire; however, the tension, which can be sustained by a thinner wire is limited.

The sliced wafer surface was observed and measured by a SEM (VE-8800, Keyence) and a contact type surface profiler (Form Talysurf PGI840, Ametek). Total thickness variation (TTV) was measured by a generalized mechanical thickness gauge.

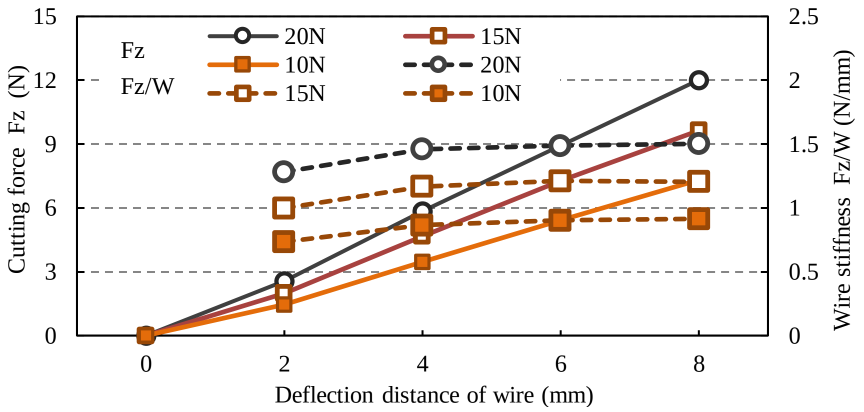
III. SLICING EXPERIMENTS

Slicing conditions and evaluation method

The slicing conditions reflect slicing abilities and wafer quality. In this section, different slicing conditions were applied to the slicing experiments. Table 1 presents the key slicing parameters when slicing a silicon ingot by a single diamond-wire saw. The slicing test was conducted on a 135-mm-long silicon ingot. The slicing parameters (wire speed, feeding speed and wire tension) reflect the cutting ability of the wire tool and affect the cutting forces and wafer quality.

Fig. 4 shows a typical change in cutting forces (Fx and Fz), during the entire slicing process, by using the diamond wire saw. An accumulation phenomenon caused a transient state in the initial slicing process, in which the normal force, Fz, increased rapidly. The cutting force, Fz, gradually levelled and stabilized to a small range

Figure 3:



Influence of wire deflection on cutting force and wire stiffness at various wire tensions

Table 1. Basic slicing conditions

Diamond wire	Diameter: ϕ 0.15 mm, Grain size of diamond abrasive: 12-25 μm
Workpiece	Polycrystalline silicon, Cross section: □145×35 mm
Running speed of diamond wire	600 m/min
Recycle time of wire	60 s
Feeding speed of workpiece	0.75 mm/min
Tension of diamond wire	20 N
Coolant	Water-soluble type

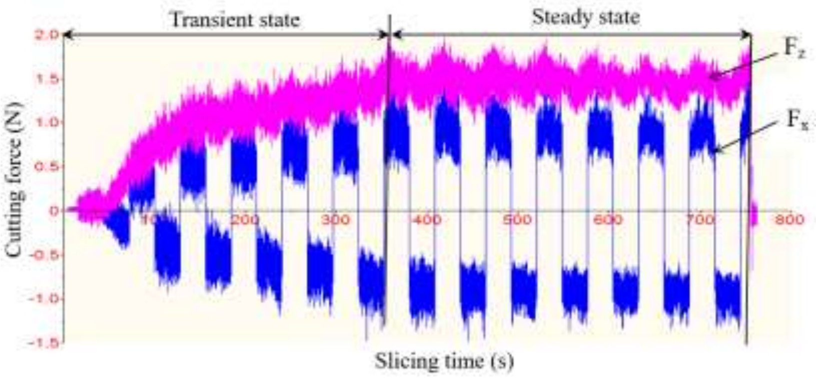
of values, and the slicing process entered its steady state. A balance between the slicing speed and the workpice feeding speed was established and no external adjustments were required. Even when the slicing speed became smaller than the feeding speed of the workpiece, the cutting force, Fz, would quickly increase, causing, in turn, the slicing speed to increase and approach the feeding speed. The vector of the cutting force, Fx, changed alternately because the running direction of the diamond wire had a reciprocating action. The absolute value of Fx increased gradually in the transient state because the slicing speed and the material removal rate both increased gradually. Thus, Fx represents the frictional forces between the wire and the workpiece, while Fz represents the deflection distance of the diamond wire and the abrasive force acting on the workpiece. In this study, the steady state cutting forces were used to evaluate slicing characteristics.

Influences of wire speed on cutting forces and wafer quality

Fig. 5 shows the relationship between the cutting forces (average horizontal and normal cutting forces) and the running speed of the diamond wire. The normal and horizontal forces decreased linearly as wire speed increased. The feeding speed of the workpiece was the same. The material removed by every diamond abrasive decreased at a higher wire speed, because longer diamond wire was used. At low wire speeds, the average material amount removed per abrasive was larger in the slicing process, which explains the high cutting forces. What is more, the deflection distance of the diamond wire decreased at high wire speed, because the cutting force, Fz, decreased.

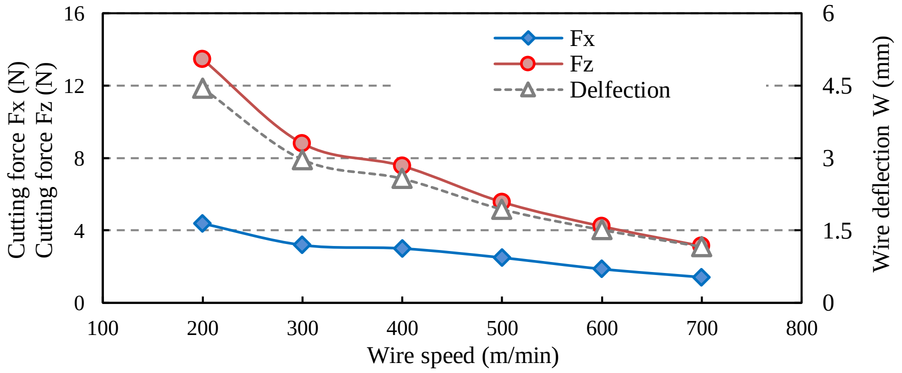
Fig. 6 shows the appearance of silicon wafer sliced by the diamond wire saw and the sample surface profile of the wafer on the feeding direction. The parallel saw marks are present on the surface of all wafers. Saw marks are a feature of the fixed abrasive wire sawing process. During the slicing process using diamond wire, the wire runs forward and backward repeatedly for 60 s. The workpiece feeding rate was constantly set to 0.75 mm/min. The saw marks repeat in a cycle of approximately 0.75 mm, which is equal to the feed quantity per cycle time of the reciprocating diamond wire. This is consistent to the result in previous studies [5]. This phenomenon has also confirmed in experiments where he feeding rate was changed.

Figure 4:



Example of cutting forces during slicing process

Figure 5:

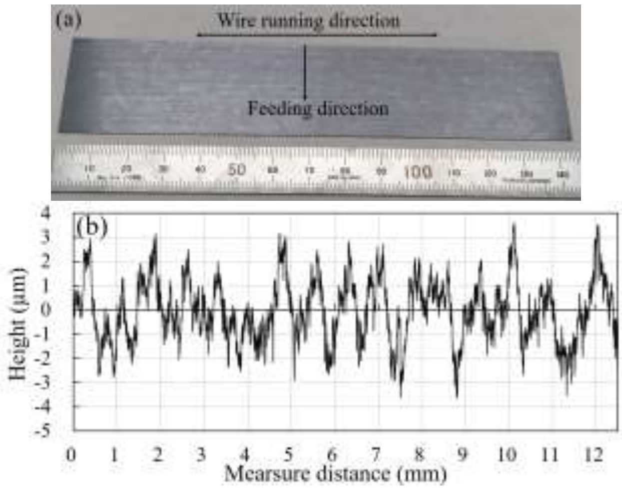


Influence of diamond wire running speed on cutting forces and wire deflection distance

Fig. 7 shows the SEM micrographs of sliced silicon wafer surface topography at different wire running speeds. There exist some long scratches, brittle crashes and lots of micro pits, as reported by Gao et al. [6] and Suzuki et al. [7] The scratches appear deep, in a visual sense, at lower wire speed. The size of micro pits is smaller and the pits are less at higher wire speed. In the case of 200 m/min, it is confirmed that the micro pits connect and become big to micro cracks in various places.

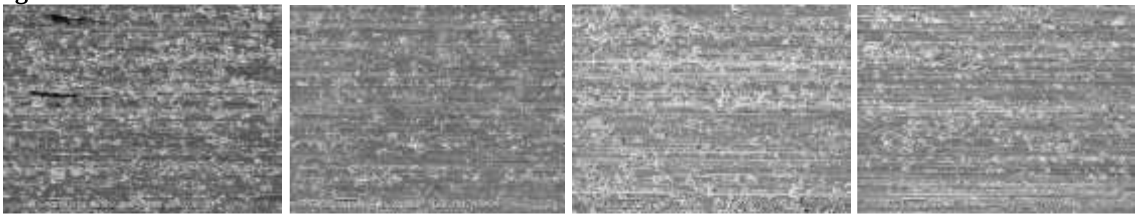
Fig. 8 shows the influence of the diamond wire running speed on TTV and the surface roughness of sliced wafers. The surface roughness improved as wire speed increased. This is due to the number of abrasives acting on the workpiece being large and the cutting depth per abrasive being shallow. The value of TTV decreased as the wire speed increased; however, wafer thickness increased. The thickness of wafers depends on wire pitch and the abrasive diameter, except from when a diamond-wire vibration occurs. The experimental result showed that the diamond wire vibrated with a high amplitude at low wire speed, because the cutting forces and the deflection distance of diamond wire were large. The diamond-wire vibration represents lack of stability and affects the TTV of sliced wafers.

Figure 6:



Appearance of sliced silicon wafer and sample profile curve on feeding direction

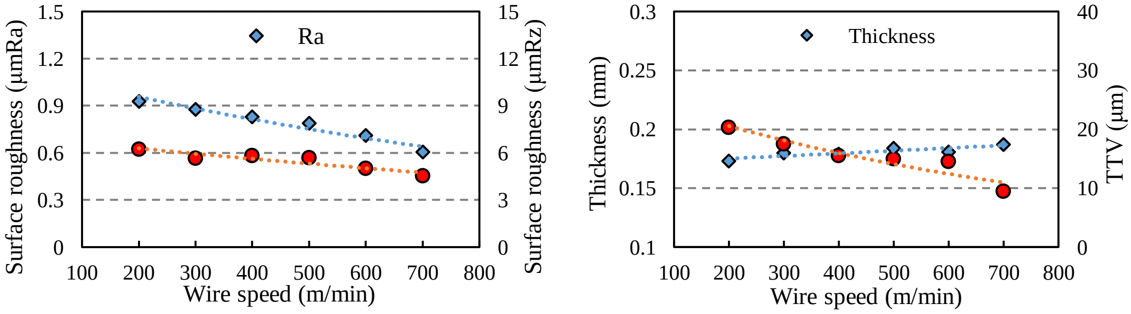
Figure 7:



(a) 200 m/min *(b) 300 m/min* *(c) 500 m/min* *(d) 700 m/min*

Surface topography SEM micrographs of silicon wafers sliced at various wire running speeds

Figure 8:



(a) Surface roughness *(b) TTV and wafer thickness*

Influence of wire running speed on TTV and surface roughness of wafers

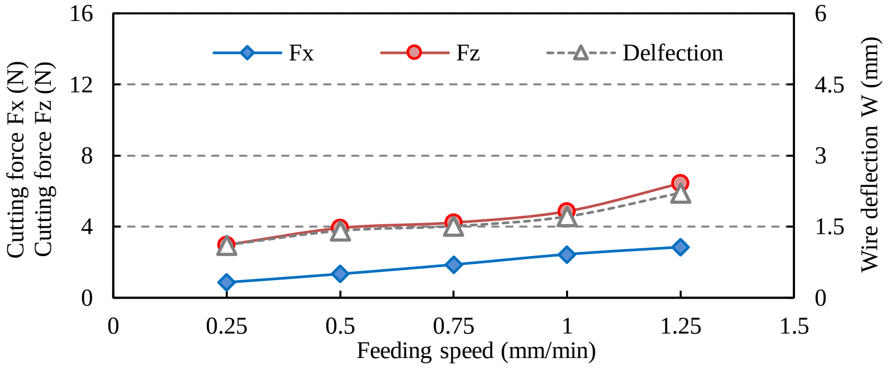
Influence of workpiece feeding speed and wire tension on cutting forces and wafer quality

The relationship between cutting forces and the workpiece feeding speed is shown in Fig. 9. The cutting forces increased as the feeding speed increased. The total amount of removed material was greater at higher feeding speeds, at constant machining time. The load on diamond wire increased with feeding speed, as shown by the increased cutting forces.

The SEM micrographs, TTV, and surface roughness of silicon wafers, at different workpiece feeding speeds, are shown in Fig.10 and Fig. 11. The wafer surface roughness deteriorated as the feeding speed increased. Deeper scratches and larger micro pits could be observed, especially at higher feeding speeds. The wafer surface was formed mainly by brittle fracture. Then, however, the feeding speed decreased to 0.25 mm/min, the saw marks appeared evenly, and a portion of wafer surface was formed mainly by ductility mode cutting.

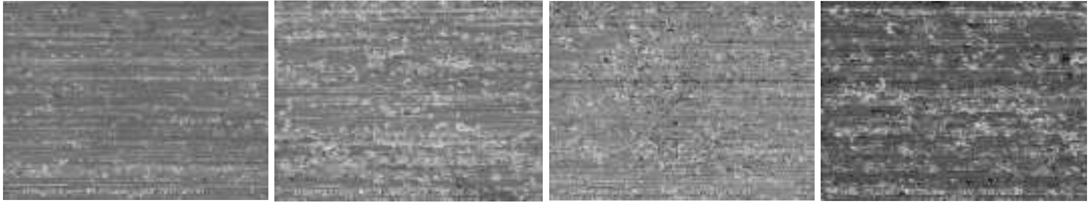
Fig. 12 shows the relationship between the cutting forces and diamond wire tension. Increased wire tension appeared to slightly decrease the wire deflection; however, the effect was smaller in magnitude, in comparison to the effect caused by changing the wire speed or feeding speed. It was confirmed experimentally that the wire tension does not have much influence on cutting forces. Fig. 13 shows the influence of wire tension on TTV, and the thickness and surface roughness of sliced wafers. The surface roughness of wafers deteriorated slightly as wire

Figure 9:



Influence of workpiece feeding speed on cutting forces and wire deflection

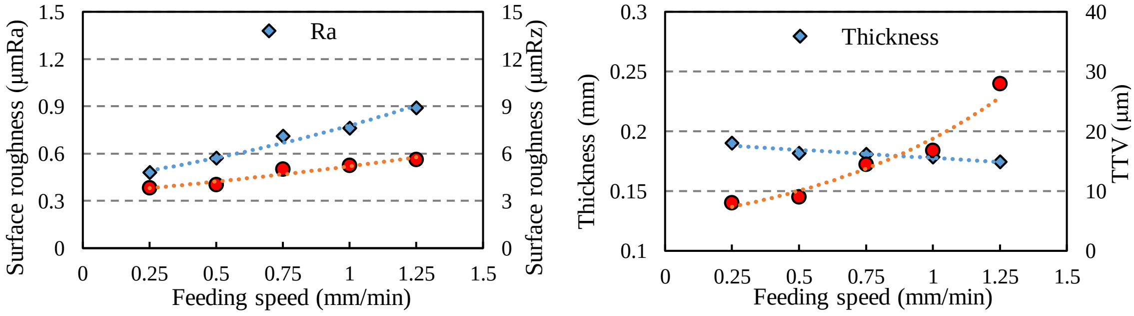
Figure 10:



(a) 0.25 mm/min *(b) 0.50 mm/min* *(c) 0.75 mm/min* *(d) 1.25 mm/min*

Surface topography SEM micrographs of silicon wafers sliced at various workpiece feeding speeds

Figure 11:



(a) Surface roughness *(b) TTV and wafer thickness*

Influence of workpiece feeding speed on TTV, thickness, and surface roughness of sliced wafer tension increased. The TTV values of wafer and wafer thickness show well at high wire tension. It is thought that the wire tension had an effect on vibration suppression and improved slicing accuracy. Therefore, the influence of wire tension on the quality of sliced wafer is small and a thinner diamond wire could be used in the slicing process. What is more, a smaller material kerf loss can be obtained by using a thinner diamond wire. It is forecasted that thin diamond wires will become mainstream in future.

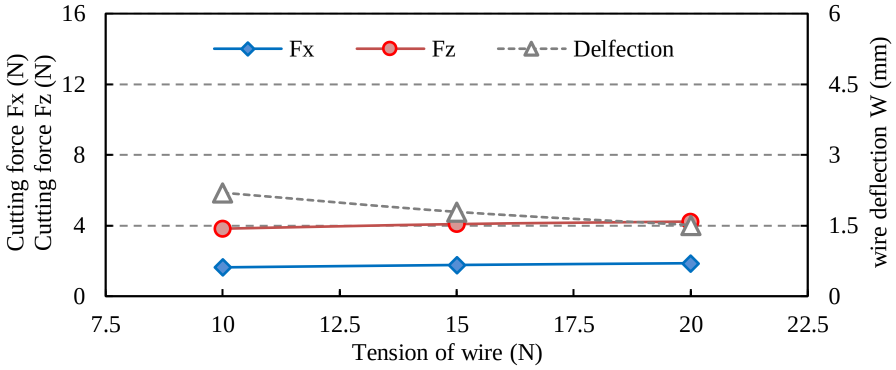
IV. ANALYSIS OF MATERIAL REMOVAL METHOD

Experiments have been conducted to analyze sawing characteristics. Therefore, there are not many theoretical analyses, and practical analyses are few [3][8][9][10]. In this study, the values for some parameters in in analytical model were assumed by the author as described follow.

The cross section of the diamond abrasive was assumed to be hexagonal and the tip angle of abrasives was assumed to be 120° as shown in Fig. 14(a). It was also assumed that the abrasives were uniformly distributed on the diamond wire. Fig. 14(b) shows the schematics of the material removal mechanism in in slicing process.

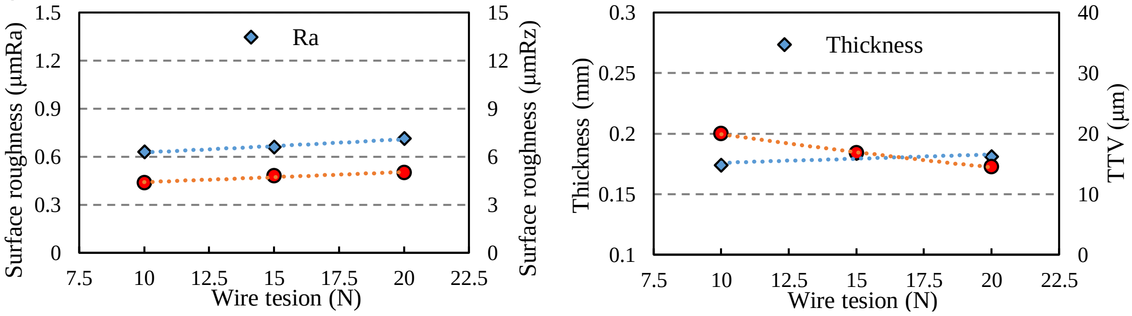
The cross-section area per abrasive S is described by the following function:

Figure 12:



Influence of wire tension on cutting forces and wire deflection

Figure 13:



(a) Surface roughness *(b) TTV and wafer thickness*

Influence of wire tension on TTV, thickness, and surface roughness of sliced wafer

Figure 14:

(a) Cutting area of abrasive *(b) Model for analyzing material removal*

Abrasive fixed on diamond wire and definition of model material removal

$$S = \sqrt{3} \cdot d_0^2 \quad (1)$$

where d_0 is the average cutting depth of abrasives. The volume of removal material by an abrasive V0 is given as the following function:

$$V_0 = B \cdot S \quad (2)$$

where B is the width of the silicon ingot. Only half of all abrasives on the diamond wire are assumed to cut the workpiece, since the upper half-side diamond wire does not make contact with it. The number of abrasives related to cutting process, Σn, is given as the following function:

$$\Sigma n = \frac{1}{2} \cdot v \cdot \Delta t \cdot \sigma \quad (3)$$

where v is the running speed of the diamond wire, Δt is a constant cutting time, and σ is the diamond wire's abrasive density. Thus, ΔV, which is the stock removal material by abrasives, is calculated as the following function:

$$\Delta V = V_0 \cdot \Sigma n = \frac{\sqrt{3}}{2} \cdot B \cdot v \cdot d_0^2 \cdot \Delta t \cdot \sigma \quad (4)$$

The volume of removed material ΔD can also be calculated from slicing conditions by the following function as shown in Fig. 14(b).

$$\Delta D = B \cdot \Delta H \cdot Dw = B \cdot f \cdot \Delta t \cdot Dw \quad (5)$$

where ΔH is the sliced distance in slicing time Δt, Dw is the diamond wire diameter and f is the workpiece feeding speed.

The total volume of stock cut material per abrasive ΔV is equal to the removal material by diamond wire ΔD. Thus, the average cutting depth of abrasives d_0 and the specific cutting energy k_s are calculated as the following calculation formula:

$$d_0 = \sqrt{\frac{2 \cdot f \cdot Dw}{\sqrt{3} v \cdot \sigma}} \quad (6)$$

$$k_s = \frac{Fx \cdot v \cdot \Delta t}{\Delta D} = \frac{Fx \cdot v}{B \cdot Dw \cdot f} \quad (7)$$

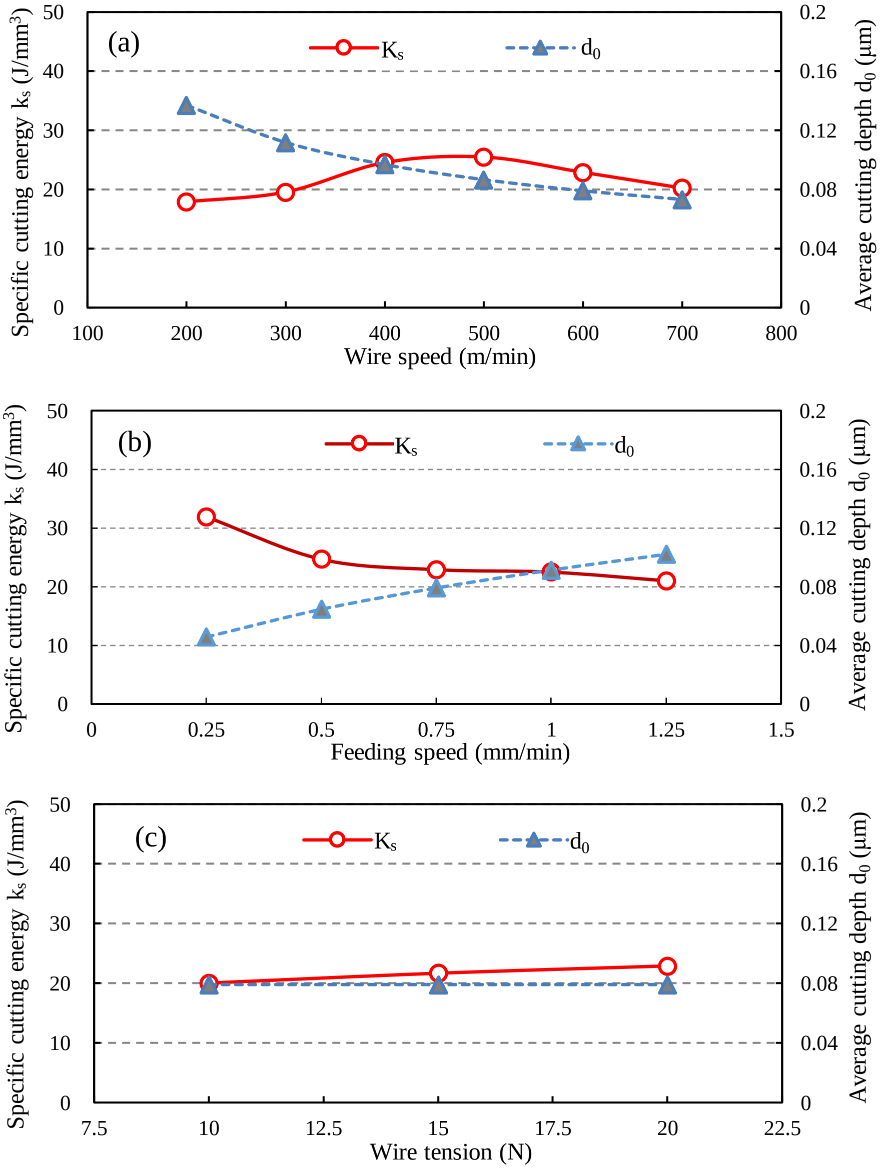
The specific cutting energy and average abrasive cutting depth at various slicing conditions, was calculated by formula 6 and 7. Fig. 15(a) shows the wire speed influence on specific cutting energy and average abrasive cutting depth, which decreases linearly with wire speed, while the specific cutting energy shows a peak at a wire speed of approximately 500 m/min, and the abrasive cutting depth approximately 0.1 μm. The author suspects that the machining mechanism of a hard brittle material, such as silicon, is different and depends on the cutting depth of abrasives. At shallow abrasive cutting depth (less than approximately 0.1 μm), the material is cut smoothly by diamond abrasives and the specific cutting energy appears low. However, at higher abrasive average cutting depth, the hard brittle material is crushed by abrasives, and this "crush energy" is advantageous in cutting the workpiece. This leads to a low specific cutting energy at lower wire speed and also explains the maximal value of specific cutting energy at different wire speed.

The influences of workpiece feeding speed on specific cutting energy and abrasive average cutting depth are shown in Fig. 15(b). The average abrasive cutting depth increases, and specific cutting energy decreases, as the feeding speed increases. The change range of specific cutting energy, at a higher feeding speed, from 0.5 mm/min to 1.25 mm/min, is small. While at the low feeding speed of 0.25 mm/min, the specific cutting energy increased significantly. It is speculated that the "size effect" facilitates the increase of specific cutting energy at lower abrasive cutting depth. The specific cutting energy, and average abrasive cutting depth, show no appreciable variation, due to the tension of diamond wire, as shown in Fig. 15(c). In other words, the tension of diamond wire has a negligible effect on cutting behavior.

The brittle-ductile transition mechanism, in single crystal silicon cutting, has been investigated by many researchers [11][12]. The critical cutting depth of the ductile mode is approximately 0.092-0.153 μm which changes on different crystal plane. The partial state of ductile mode cutting can be observed in the wafer surface macrograph, shown in Fig. 10(a). The average abrasive cutting depth, d_0, at a feeding speed of 0.2 mm/min, is approximately 40 nm, which is smaller than the critical cutting depth of the ductile mode. However, diamond abrasives of variable size were fixed on the diamond wire and the height of the abrasive cutting edge was not equal, which led to an incomplete wafer ductility mode machining surface, since the average abrasive cutting depth, d_0, is smaller than the critical cutting depth of the ductile mode. While the average abrasive cutting depth is over 0.1 μm, brittle fracture occurs actively and the surface of sliced wafers becomes coarse.

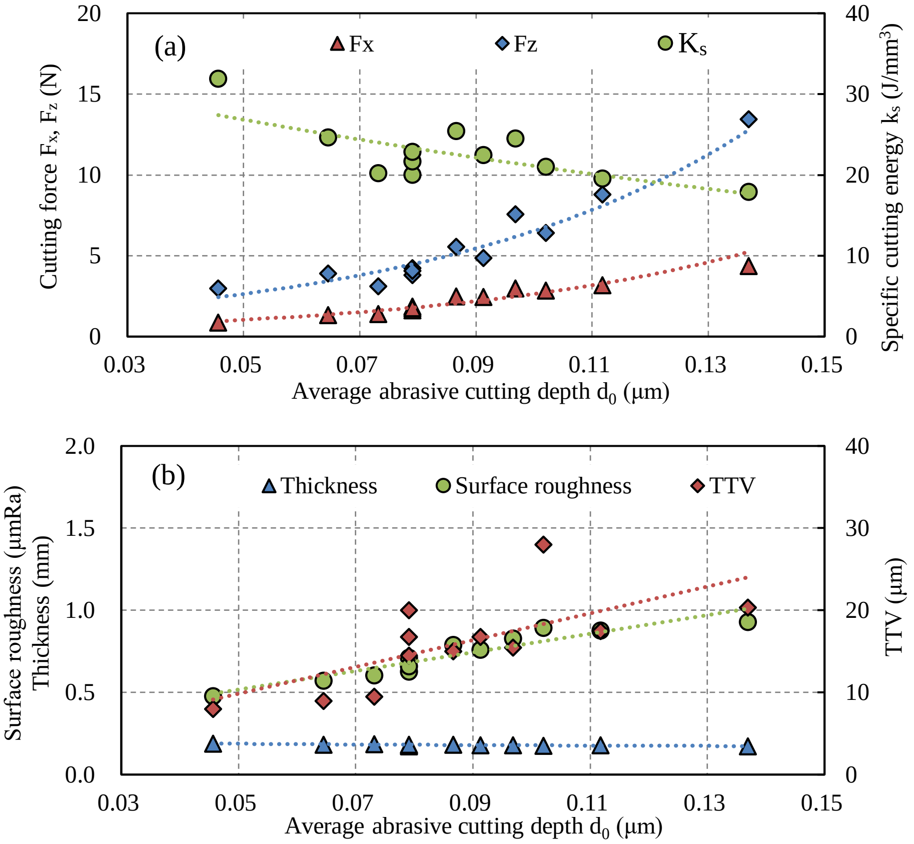
Fig. 16(a) shows the influence of average abrasive cutting depth on slicing characteristics. A larger abrasive cutting depth affects material removal behavior by causing a brittle fracture mode, and subsequently leads to higher cutting forces and lower specific cutting energy. From this result, it was clarified that the average abrasive cutting depth is an important factor when selecting the slicing conditions or reducing the cutting force in the slicing process. The average abrasive cutting depth is also correlated to wafer quality, as shown in Fig. 16(b). A higher average abrasive cutting depth leads to worse TTV, surface roughness, and thinner wafer. This is thought to be due to the vibration of the diamond wire gathering in a high abrasive cutting depth. The evaluation of wire vibration will be discussed in a subsequent paper. In future work, thinner diamond wires should be used in the slicing process. The diamond wire's finite tension strength must be applied at high wire speed, or at low feeding speed, in order to reduce cutting resistance, even when the specific cutting energy is high. It also needs to reduce the cutting depth of abrasives, in terms of slicing wafer quality such as TTV, kerf loss (thickness opposition) and surface roughness.

Figure 15:



Influence of slicing conditions on specific cutting energy and average abrasive cutting depth

Figure 16:



Influence of average abrasive cutting depth on wafer quality and cutting characteristics

V. CONCLUSION

In this paper, experiments utilizing a diamond-wire saw to slice silicon ingot are presented. The influences of slicing parameters on cutting forces and wire deflection were investigated. The surface quality, TTV, and thickness of the sliced wafer were considered. A new analysis model was proposed and the average abrasive cutting depth, and specific cutting energy, were analyzed. The relationship between slicing conditions and slicing characteristics, as well as the average abrasive cutting depth were also discussed. The following conclusions were reached:

1) The deflection of diamond wire is proportional to normal cutting forces. The diamond wire stiffness is affected by wire tension, but is not affected by the deflection of wire, because the diamond wire is too thin to the distance of work rollers.
2) There are numerous visible scratches and micro pits on the sliced wafer surface, under the slicing conditions of low wire speed or high workpiece feeding speed of. As wire speed increases, or feeding speed decreases, surface roughness and TTV improve and the quality of the wafer increases. The influence of wire tension on wafer quality is small.
3) A new analysis model, based on a material removal method, was proposed. The average abrasive cutting depth and the specific cutting energy were calculated under various slicing conditions. As wire speed increased, or feeding speed decreased, the cutting depth of abrasives became shallow and the specific cutting energy increased. The material removal behavior, which changes with the average abrasive cutting depth, is different due to the surface topography of the sliced wafer. The size effect appears at a small abrasive cutting depth and brittle mode cutting becomes dominant at large abrasive cutting depth.
4) It was clarified that the average cutting depth of abrasives is closely related to wafer quality, e.g. TTV, surface roughness, and slicing characteristics such as kerf loss, cutting force and specific cutting energy.

I. ACKNOWLEDGEMENT

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