Wire EDM Slicing of Monocrystalline Silicon Ingot

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1. Introduction

Monocrystalline silicon is one of the most important materials in the semiconductor industry because of its many excellent properties as a semiconductor. The manufacturing process of IC chip consists of various fine precision machining techniques, including monocrystallizing of silicon, slicing of ingot, lapping and polishing of wafer, photolithography and etching for integrated circuits, dicing and so on. In the slicing process, further improvements of efficiency and accuracy are strongly required, since the final flatness of wafer is significantly determined by this process.

Conventionally, inner diameter(ID) blade has been used for slicing silicon ingot1). However, some problems in efficiency are existed, that is, kerf loss is relatively large and the maximum crack of about 30µm in depth is generated on the sliced surface resulted from mechanical machining. Moreover, this method is difficult to apply for larger-scale wafers of 12 or 16 inches diameter expected to be used in the near future. Then, multi wire saw has been gradually applied2). This method is performed by feeding thin piano wire to workpiece with slurry consisting of abrasives and cutting oil. In the method, many wafers can be sliced at the same time, kerf loss is relatively small, and it is applicable to large-scale wafer. However, there still remain the problems of slurry treatment and contamination of sliced surface.

From the above mentioned viewpoints, a new slicing method of monocrystalline silicon ingot by wire electrical discharge machining (WEDM) is proposed in this study. A silicon wafer used as substrate for epitaxial film growth has low resistivity in the order of 0.01Ω·cm, which makes it possible to cut silicon ingot by WEDM3)-5). And it is expected that the crack on the machined surface might be reduced, since the material removal is performed by repetition of micro crater due to a single discharge and the machining force acting on the workpiece in WEDM process is extremely small compared with that in conventional slicing methods. In this study, the possibility of slicing of silicon ingot by WEDM was discussed, and the machining properties such as cutting speed and surface roughness were experimentally investigated. Furthermore, the accuracy of wafer and the contamination on the machined surface was evaluated.

2. Experimental Procedures

Fig.1 shows the schematic diagram of experimental apparatus. In this machine, the discharge current pulse made by transistor switching circuit has relatively long duration and low intensity, different from conventional one made by condenser circuit. Therefore, it is expected that the electrode wear becomes very small. Then, the wire electrode used once is rewound around the drum and reused repeatedly, as shown in the figure. P-type monocrystalline silicon ingot of 40mm in thickness whose resistivity is 10^{-2}Ω·cm is used as a workpiece. Main machining conditions are shown in **Table 1**. The experiment using conventional WEDM with condenser circuit is also done for comparison. In this case, large discharge current for 1st cut and small one for 2nd cut are applied.

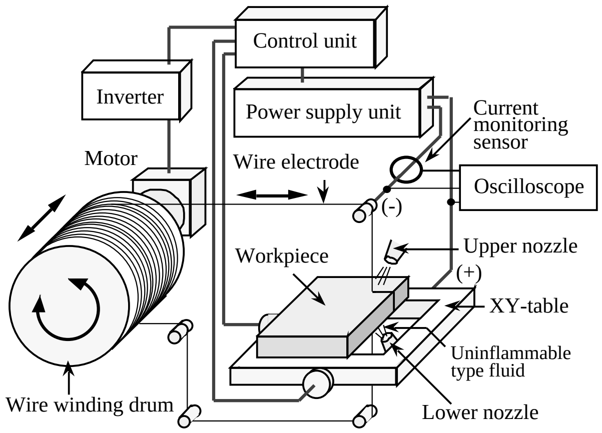


Fig.1 Schematic diagram of experimental apparatus

Table1 Machining conditions

Electrode	Molybdenum (180μm in diameter)
Polarity	Electrode : (-)
Dielectric	Deionized water (10^6Ω·cm)
Gap voltage	u_i=100 [V]
Discharge current	i_e = 3, 12, 22 [A]
Discharge duration	t_e = 5, 10, 20, 40, 75 [μs]
Duty factor	Df = 15 [%]
Wire feed rate	F_W=10.0 [m/s]
Wire tension	F = 0.6 [kgf]

3. Machining Properties

Fig.2 shows the variations of removal rate with discharge duration for various discharge currents. As can be seen in the figure, the removal rate increases with an increase of discharge current. And the removal rate takes maximum at about 20μs in pulse duration, just like die-sinking EDM process. On the other hand, in case of conventional WEDM, they were 104mm^2/min and 10mm^2/min under 1st cut condition and 2nd cut one respectively. It was made clear that the removal rate of monocrystalline silicon by relatively long duration and low intensity current with transistor switching circuit was as large as that in conventional WEDM with condenser circuit. It was reported6) that the Joule's heat generation played an important role in material removal in EDM for high resistance material. Also in this case, it is considered that the Joule's heat generation in addition to the heat conduction from arc column made a great contribution to material removal.

Fig.3 shows the variations of surface roughness. The surface roughness increases with the increases of discharge current and discharge duration. On the other hand, it was 21.5μm for 1st cut and 7.6μm for 2nd cut in conventional WEDM. It is reported that the surface roughness is about 20μm in multi wire saw slicing applied so far. Furthermore, the removal of crack layer is actually performed after slicing process, and the thickness is more than 30μm. Considering these results with the removal rate shown above, large discharge current and short pulse duration are suitable conditions, which leads to large removal rate and small surface roughness.

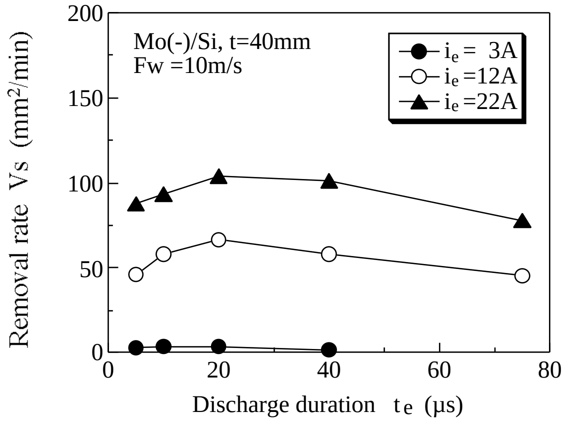


Fig.2 Variations of removal rate

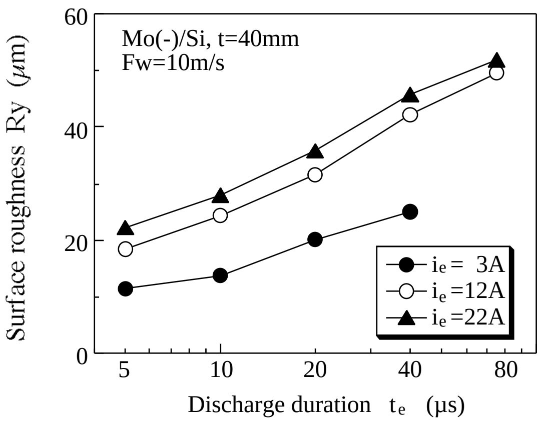


Fig.3 Variations of surface roughness

4. Surface Integrity

Fig.4 shows one of the longest cracks generated in sliced surface by WEDM. The crack length is about 20μm as shown in the micrograph. On the other hand, they are about 20-30μm in cases of ID blade and multi wire saw slicing. Therefore, this method is effective for high efficiency manufacturing of IC, since thinner crack layer leads to the shortening of time to remove the layer.

In order to investigate the contamination of machined surface, XPS(X-ray Photoelectron Spectro-scopy) analysis was carried out. **Fig.5** shows the results of analysis. The contamination layers such as oxidized layer and carbonized layer which had been generated by atmosphere after machining were removed by argon ion etching in the measurement chamber before analysis.As shown in the figure, oxygen exists on the machined surface in both cases. It is considered that the machined surface is oxidized by electrical discharge in deionized water or in air. Of course, contamination by oxygen is not desirable in semiconductor manufacturing process. However, it is allowable to some extent, since a few process for removing oxygen are actually performed after slicing process. In case of conventional WEDM, copper and zinc from wire material exist. Copper is one of the most undesirable materials in semiconductor manufacturing process, since it tends to diffuse into the inside of silicon. Therefore, conventional WEDM is never applicable. On the other hand, molybdenum of wire material hardly adhere to the machined surface in case of this WEDM. It is considered that adhesion or diffusion of wire material can be reduced because of discharge current waveform made by transistor switching circuit.

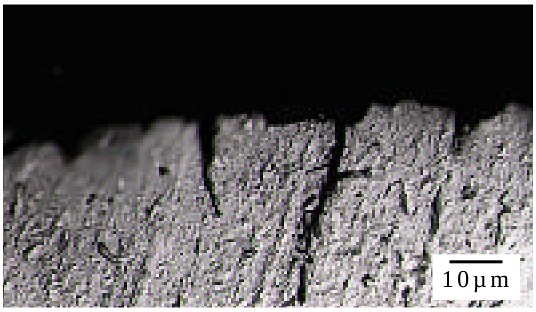
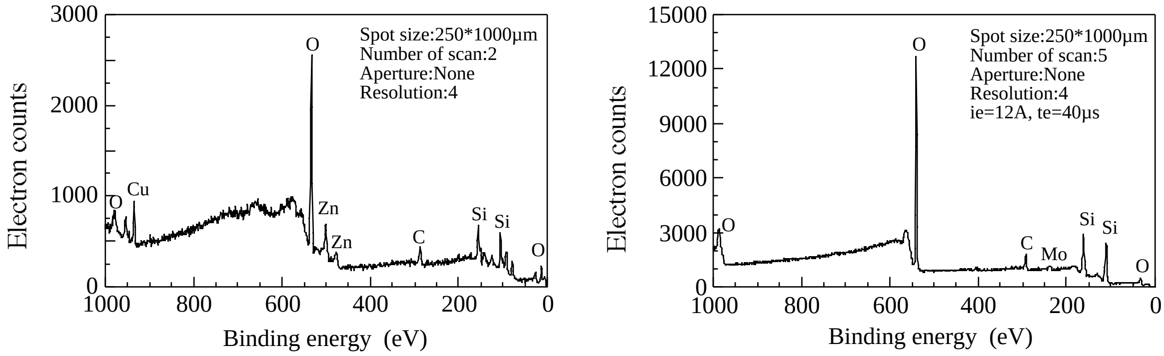


Fig.4 Cross section of sliced surface



(a)Conventional WEDM with condenser circuit (b)WEDM with transistor switching circuit

Fig.5 Results of XPS analysis of sliced surface

5. Slicing of 6 inches Ingot

Next, slicing of 6 inches silicon ingot was carried out. **Fig.6** shows the relationship between displacement of wire and machining time. As shown in this figure, slicing speed decreases with an increase of workpiece width, and it takes about 140 min to slice 6 inches silicon ingot. That is, the average slicing speed is about 1.1mm/min. In the case of multi wire saw, it is 0.2-0.3mm/min . If multi slicing, in which many wafers are sliced at once can be realized like wire saw slicing, this WEDM slicing method is applicable as a high efficiency slicing method of silicon ingot.

Fig.7 shows TTV(Total Thickness Variation) and Warp of 6 inches wafer sliced by WEDM. Both values are the important dimensional parameters of wafer, that is, TTV is the difference between the maximum and minimum thickness, and Warp is defined as the difference between the maximum and minimum distances from a reference plane, as shown in the figure. Both values in the case of WEDM are almost the same as those in the case of wire saw. In addition, the kerf loss was about 250μm, which is almost the same value as wire saw,too.

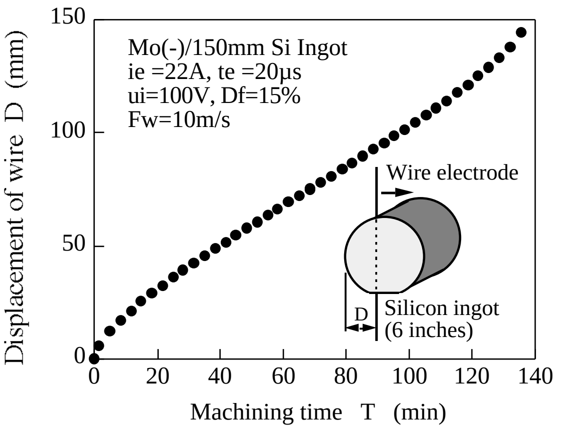


Fig.6 Displacement of wire in slicing of 6" ingot

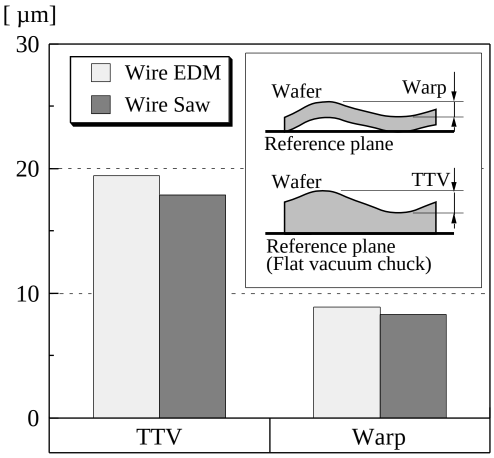


Fig.7 TTV and Warp of sliced 6" wafer

6. Conclusions

Main conclusions obtained in this study are as follows:

(1)Wire EDM has a possibility as a new slicing method of monocrystalline silicon ingot.

(2)The surface roughness by WEDM is as small as that by multi wire saw method used conventionally.

(3)Contamination due to adhesion and diffusion of wire electrode material to machined surface can be reduced by WEDM under the condition of low current and long discharge duration.

(4)The accuracy of wafer by this slicing method is almost the same as that by multi wire saw method. And, higher speed slicing is possible if a multi type WEDM slicing can be realized.

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