Study on the Diamond-Coated Wire Sawing Process of Silicon with Minimum Quantity Lubrication

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Keywords: Diamond-Coated Wire Saw; Minimum Quantity Lubrication; Nano-Fluid; Silicon Wafer

Abstract. Wire sawing is the first machining process in prime wafer manufacturing. The performance of the wire sawing would affect subsequent grinding, lapping, and polishing processes. With the development of coating technology, the diamond-coated wire saw, also known as fixed abrasive diamond wire saw, is replacing the slurry wire saw in wafering, especially for very hard materials such as Sapphire and Silicon Carbide. The diamond-coated wire removes material as a fixed abrasive cutting tool, in which two-body abrasion is the major material removal mechanism as grinding. In grinding, Minimum Quantity Lubrication (MQL) has been studied and its performance showed the benefit to reduce the grinding force, working temperature, and surface roughness. However, the study of using MQL in diamond-coated wire sawing process is still absent. In this study, experiments of MQL in wire sawing process were conducted using customized desktop reciprocating wire saw machine. Three different lubricating conditions, Flood, Mist with a flow rate of 75 mL/hr, and Mist with a flow rate of 150 mL/hr, were applied. In addition, the nanofluid with alumina nanoparticles were also employed in the MQL. The results show that the lubrication of the Mist with a flow rate of 150 mL/hr can reduce the slicing force efficiently. The tool wear and surface roughness of the three lubrication conditions are comparable. The addition of nano alumina particles in MQL can further reduce the cutting force. However, the nanoparticles increased the wear rate of diamond grains and degraded the performance of slicing after a period of usage.

Introduction
Wafer substrate manufacturing processes include ingot growth, slicing, flattening, and cleaning. Slicing is the first machining process to cut an ingot into a number of wafers. At one time, ingots were sliced into wafers piece by piece using an inner diameter saw. As reported by Nasch and Sumi, slurry wire sawing was introduced in the 1980s. In this process, piano wire is wound on wire guides and slurry is spread on the wire net during operations [1]. Hundreds of wafers can be obtained after a single operation of slicing, such that this process dramatically increased the yield and decreased material loss. Because of these advantages, wire saw has become the most common tool for slicing ingots of various materials including silicon, sapphire, and silicon carbide for semiconductor and photovoltaic wafers.

The cost associated with slicing ingots is high enough to drive most manufacturers using diamond wire sawing instead of slurry wire sawing. Pauli et al. demonstrated that the cost of abrasive grits and cutting fluids occupies about 79.5% of the total cost of slurry wire sawing, and diamond wires can reduce processing time by 70% [2]. Developments in this area have driven down costs, such that diamond wires are now widely used for materials including monocrystalline and polycrystalline silicon ingots for solar wafers. Goodrich et al. predicted that the use of diamond wire sawing could reduce the cost of solar wafers by USD $11 per square meter, and the total manufacturing cost of which is USD $76 [3]. It is inevitable that diamond wire sawing will entirely replace slurry wire sawing processes in the near future. Nonetheless, even with a reduction in the cost of diamond coated wires, diamond wire sawing remains an expensive process.

The usage of cutting fluid in machining occupies a large portion of total cost, which includes the cost of cutting fluid and disposal fee. In order to reduce the cost and the impact to environment, the principle of minimum quantity lubrication (MQL) has been proposed. In grinding, it is also called
near-dry grinding (NDG). The general guide for conventional fluid usage in grinding is 1 l/min of fluid per 1 mm of grinding wheel width. In contrast, MQL fluid consumption is typically 30-100 mL/hr [4]. Although it is not superior to conventional flood supply method in the surface quality and temperature, MQL does dramatically reduce the usage of coolant and tangential grinding force [5, 6]. In addition, the utilization of nanofluid in MQL further reduces the force and increases tool life in grinding [7]. Nanofluid is the fluid which contains nanoparticles. Many nanoparticles including graphite [8], molybdenum disulfide (MoS$_2$) [7, 9], alumina (Al$_2$O$_3$) [10], and diamond [11], have been studied. However, there is no such study in wire sawing process.

In this study, diamond wire sawing using MQL was investigated. Two difference mist flow rate, 75 and 150 mL/hr, were applied in the experiments and compared to the conventional flood lubricating method. In addition, nano-alumina particles were mixed in the lubrication to study the effect of nanofluid in lubrication. The results showed the benefit of MQL of a flow rate of 150 mL/hr which reduced the slicing forces. The addition of nanoparticles improved the surface roughness of sliced wafers. However, The slicing forces were increase after a period of operation because of the tool wear.

**Experimental Setup**

The experiments were conducted using the customized wire saw machine developed in our laboratory, as shown in Fig. 1. This machine can slice 10 wafers at the same time. The maximum wire speed is 6 m/s. The slicing samples are monocrystalline silicon ingots, which were prepared with the size of 40×15×70 mm. The slicing length was 40 mm and the depth was 15 mm. The pitch between wire sections was 1 mm, which means that the thickness of sliced wafer would be less than the difference of 1 mm and the diameter of diamond-coated wire. A diamond-coated wire with the diameter of 250 µm was employed to slice the silicon ingot. The size of the diamond grains coated on the wire were 30-40 µm according to the SEM images.

In order to investigate the effect of MQL on diamond wire sawing process, three different lubricating methods were applied: Flood with a flow rate of 8 L/hr, MQL with a flow rate of 75 mL/hr (MQL75), and MQL with a flow rate of 150 mL/hr (MQL150). The coolant (DWS-435) was purchased from MDWEC, Taiwan. In addition, the nano-alumina particles with average size of 50 nm were mixed and dispersed in the cutting fluid and spread on the wire net using MQL lubricating method to study the effect of nanofluid. The ratios of nano-alumina particles in the cutting fluid were 0.5, 1.0, and 1.5 wt%, respectively. Three experiments were conducted for each set of parameters.

The slicing parameters were kept constant for the comparison of lubricating methods. The feed rate was 0.4 mm/min. The wire tension was set as 20 N. The maximum wire speed was 5 m/s. Because
of the reciprocating motion, there were acceleration and deceleration of the wire. The moving wire length with maximum wire speed (5 m/s) was kept 15 m long in each cycle. In order to record the slicing forces, a 6-axis load cell (Memstec, Sri-V-151230-D) was installed under the stage on which the silicon ingot was fixed. The used diamond-coated wire and sliced silicon wafers were observed using SEM (JEOL, JSM-6390LV). The sliced wafers were examined using surface profilometer (Mitutoyo, SJ210) for surface roughness.

Table 1 Weight percentage of nano-aumina particles and lubricating method of each test.

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<th>Test 1</th>
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**Results and Discussion**

**Minimum Quantity Lubrication without Nanofluid.** The experimental results of different lubricating methods including Flood and MQL with flow rates of 75 and 150 mL/hr are presented in this section. Other experimental results using nanofluid will be presented in the next section. Figure 2 shows the cutting force in horizontal and vertical directions, which represent the slicing force (in X direction) and trust force (in Z direction), respectively. Because there were four wire sections slicing the silicon ingot at the same time, the measured forces are the summation of the four wire sections. From the results, MQL150 reduced the slicing force and trust force after a period of time. However, the higher forces were with the lubricating condition of MQL75. This observation shows that MQL can help to reduce the slicing forces with sufficient lubrication.

![Figure 2](image)

Figure 2  Slicing forces in (a) x-axis and (b)z-axis using lubrication without nanofluid.

The SEM images of used diamond coated wires are in Fig. 3. It can be observed that the tiny sliced debris were stuck to the wire. This could be one of the reasons why the slicing force of MQL75 is greater than the lubricating conditions of Flood and MQL150. The debris can reduce the slicing efficiency and increase the forces. Using MQL with enough flow rate, such as 150 mL/hr, the debris on the wire would be blown away to keep the slicing efficiency. The reduction of extrusion heights of the diamond grains on the wire were examined using the SEM images, which represent the wear of diamond grains. The results are illustrated in Fig. 3(d). Although the average value of MQL150 is slightly higher than other two lubricating conditions, there is no significant difference statistically.

The average surface roughness (Ra) of the sliced silicon wafers were measured and presented in Fig. 4. The flood lubrication results in the best surface condition among the three lubricating methods, and MQL75 produced the worst surface.
Figure 3  SEM images of used diamond-coated with (a) Flood, (b) MQL75, and (c) MQL 150 lubricating conditions and (d) the height reductions of used diamond grains.

Figure 4  (a) Image of sliced wafer and (b) average surface roughness (Ra) of sliced silicon wafers.

**Minimum Quantity Lubrication with Nanofluid.** The experimental results of nanofluid minimum quantity lubrication with a flow rate of 150 mL/hr are presented in this section. Figure 5 shows the cutting forces. The results show that the addition of nano-alumina particles can further reduce the slicing force in the first 12 minutes and trust force in the first 30 minutes. The forces exceeded those without nanoparticles after a period of operation. Although the aggregation of nanoparticles and debris were not observed in the SEM images, the diamond grains were worn because of the nano-alumina particles. This also reduces the cutting efficiency and increases the slicing forces.

Figure 6 shows the wear of diamond grains with different mixing ratio of nano-alumina particles in the lubrication. The increase of the weight percentage of nanoparticles enhances the wear rate of diamond grains. This is a disadvantage of the nanofluid in the application of MQL. Comparing the surface roughness of sliced wafers in Fig. 7, it can be found that the increase of nanoparticles in the fluid reduces the roughness of sliced silicon wafers. The nanoparticles shared the loading of each diamond grain during the slicing process to reduce the concentration of the loading, which helps to smooth the wafer surfaces.
Figure 5  Slicing forces in (a) x-axis and (b) z-axis using MQL150 with nanofluid.

Figure 6  SEM images of used diamond-coated with MQL150 and nanofluid with (a) 0.5 wt%, (b) 1.0 wt%, and (c) 1.5 wt% nano-alumina particles and (d) the height reductions of used diamond grains.

Figure 7  Average surface roughness (Ra) of sliced silicon wafers using MQL150 with nanofluid.
Summary

The application of MQL in fixed abrasive wire sawing process was investigated in this study. The results show that the slicing force can be reduced and without degrading surface roughness and tool wear with sufficient flow rate of MQL. It shows the feasibility to employ MQL as lubricating method in wire sawing process. The addition of nano-alumina particles in the lubrication could further reduce the slicing force and surface roughness of the wafer surface. However, because of the wear of diamond abrasives on the wire, the slicing efficiency would be reduced after a period of operation and the slicing force would increase continuously. Therefore, the lubrication with minimum quantity lubrication with a flow rate of 150 mL/hr is recommend based on the results in this study.

References


