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Investigation on the Effect of Nano-Cutting Liquid on the Cutting Quality of Large Diameter Silicon Wafer

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To enhance the effective penetration of cutting fluid into the depth of the cutting joint, a nano-cutting liquid atomization method has been proposed to improve the cutting quality of diamond wire sawing. A six-inch large diameter silicon wafer (150 mm diameter) diamond wire saw cutting experimental platform was constructed. The base liquid, nano SiO2, and nano SiC cutting liquid were utilized as the cutting fluids, and various cutting solutions were employed to compare the cutting quality of large diameter silicon wafers. The temperature field change, surface roughness of the silicon wafer, surface morphology, and warping of the silicon wafer were measured as evaluation indexes, and the impact law of different cutting solutions on the cutting quality of diamond wire saw was analyzed. The results indicate that nano-cutting fluid can reduce the roughness of silicon wafers and improve the surface morphology of silicon wafers. Mixing multiple nanoparticles can produce cutting fluids that further enhance wire saw cutting performance in actual diamond wire saw cutting technologies.

Keywords: Diamond Wire Saw, Nano-Sio_2 Cutting Fluid, Nano-Sic Cutting Fluid, Silicon Wafer

1 Introduction

Silicon wafer is the basic material of the semiconductor industry, and its quality and quantity constrain the development of the downstream terminal industry. Large diameter silicon wafer will increase the production efficiency of semiconductor, reduce the manufacturing cost, large silicon wafer has become an inevitable trend [1-3]. Cutting is the first process in the production of silicon wafer. Its quality has a direct impact on the thickness, warping and other parameters of the silicon wafer, and this impact will also spread to the subsequent cleaning, polishing, velvet making and other links [4]. With the trend of large-size silicon wafer slice processing, it brings some challenges to the cutting process, and the silicon wafer cutting technology. needs to be further improved by [5] Diamond wire saw cutting is the current mainstream cutting technology, its principle is similar to grinding, mainly using the grinding grain to the silicon plow removal to achieve the silicon wafer cutting [6-7]. Line saw cutting liquid is a key factors impacting the quality and efficiency of silicon wafer cutting, especially in the face of large size, ultra-thin polycrystalline silicon wafer cutting, cutting liquid is particularly critical, many scholars have focused on this topic.

Li et al found that the film thickness of the slurry is closely related to the diameter of the abrasive in the wire and ingot [8]. Gao and other scholars believe that the thermal expansion of the silicon eventually impact the warping of the silicon wafer, and that the cooling effect of the cutting liquid can obviously impact this [9]. Qiu et al scholars proposed to use the cutting liquid water tank to immerse the diamond wire saw to cut the whole process. The results found that compared with the traditional liquid supply condition cutting, the cutting quality and saw wire life were significantly improved by [10]. Zheng and others found that the cutting liquid will produce liquid bridge (Liquid bridge), especially with the decrease of the saw diameter and spacing, the liquid bridge becomes significant, thus affecting the loss of saw seam and section thickness, and reduce the cutting quality [11-12]. Karimi et al. conducted an intensive heat transfer study on the nanoffluidics added SiC. And found that adding nanoparticles enhances the heat transfer capacity of nanoffluidics, and the heat transfer of nanofluidics increase as the ratio of nanoparticles in the nanofluidics increases [13].

In the study of diamond wire saw cutting fluid, there are still few studies on new cutting fluid and effective supply from the addition of nanoparticles. Therefore, in this topic, nanoparticle material is added to the basic cutting liquid of diamond wire saw, compared with the cutting performance of different nanoparticle cutting liquid, so as to enhance the liquid lubrication and cooling property, and to coolen the cutting zone, and reduce the surface warping of silicon wafer.

2 Materials and methods

2.1 Synthesis of the nanometer cutting solution

When preparing the nano-cutting solution, nano-SiO_2 or SiC is a nano-additive, CMC-Na and PEG2000 as dispersants, deionized water as the base liquid, using magnetic stirring and ultrasonic shock. The mass ratio of selected CMC-Na and PEG2000 is 0 wt%, 6 wt%, respectively. The mass fraction of nanoparticles is 0, 0.1, 0.2, 0.3, 0.4 wt%, respectively. The main preparation steps are described as follows:

- (1) Nano SiO_2 is determined according to the desired mass fraction2The required mass of particles, nano SiC, CMC-Na, PEG2000 and deionized water is weighed by high-precision electronic balance.
- (2) Add PEG2000 to the deionized water, and stir through a magnetic stirrer for 0h, so that it is completely dissolved in the water to form a solution.
- (3) Nanoparticles and CMC-Na are added to the mixed solution in (2), and stirred through a magnetic stirrer for 0.5h.
- (4) Ultrasonic oscillation of the nano-cutting liquid for 1 h through the ultrasonic cleaning instrument.
- (5) Use the reagent bottle to store the prepared nano-cutting solution quietly.

2.2 Cutting Experiments and conditions

The experimental equipment setup is mainly composed of cutting experimental platform, experimental measurement system and liquid supply cooling device. Among them, the cutting test platform adopts diamond wire cutting double wire tube machine tool (Taizhou Chenhong CNC Equipment Manufacturing Co., Ltd., C HSX5620-XW type). The machine tool is a reciprocating cutting machine. The cutting wire is 300m length. The area temperature of the experiment is 24 (±1) °C and the relative humidity is 55% (±5) %. The experiment analyzes the surface temperature field of the silicon wafer by photographing the surface temperature change during cutting. Fig. 1 exhibit the flowchart of the experimental equipment.

The diamond saw wire radius is 0.125 mm, the consolidated diamond grinding size is 10~20 μm, and the distribution grain size density is 40~50 /mm. The monocrstalline silicon cylinder is six inches (diameter 150 mm), the single cutting thickness is 1 mm. The cutting fluid includes 0.3 wt% nano SiO_2, 0.2 wt% nano-SiC cutting solution and base fluid. Specific cutting parameters were exhibited in Tab. 1.

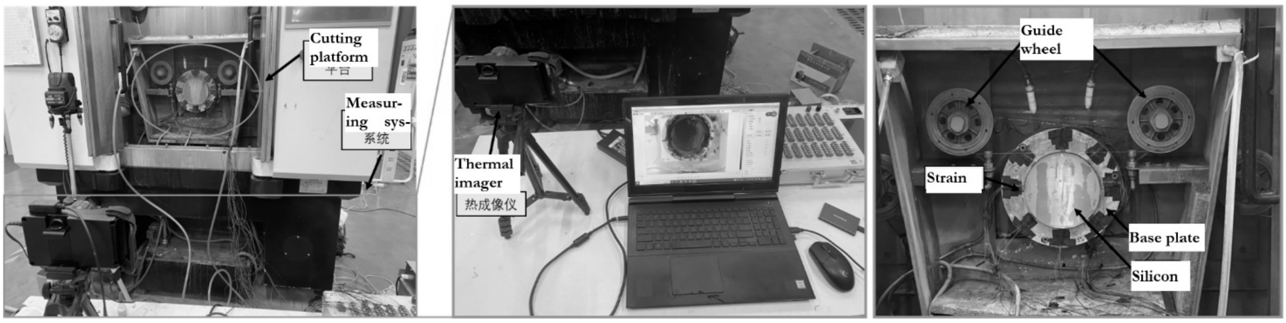


***Fig. 1** Diamond Wire Saw Cutting Experimental Measurement System and Cutting Experiment Platform*

***Tab. 1** Cutting parameters*

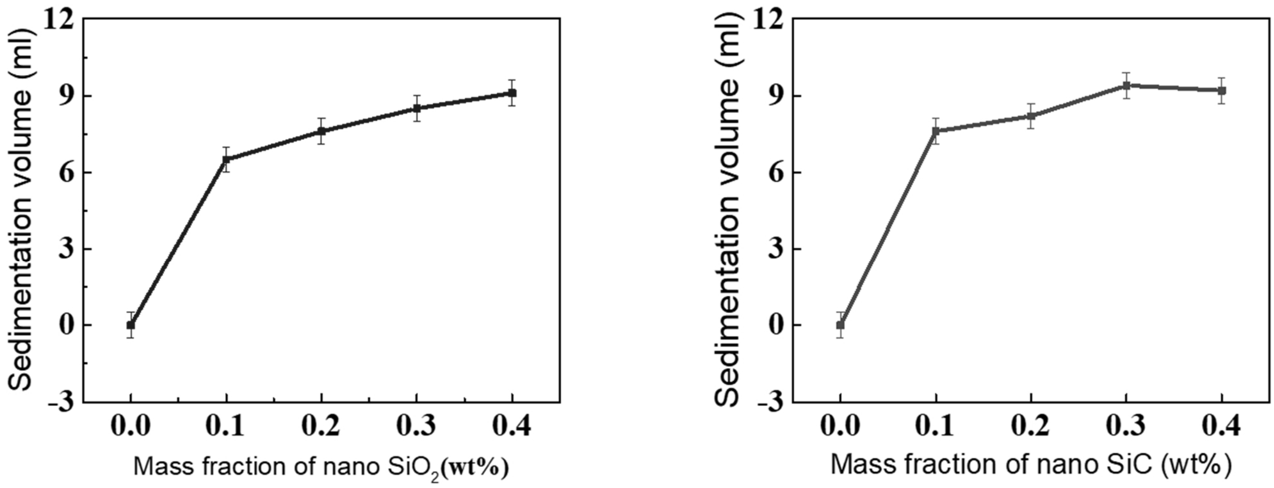
Parameter	Parameter values
Wire radius (mm)	0.125
Wire speed (m/s)	10.0
Feed speed (mm/min)	0.75
Wire length (m)	300

3 Results and analysis

3.1 Stability evaluation of nano-cutting solution

Stability is an important evaluation standard of cutting fluid. Only with good stability can cutting fluid be applied to experiments and even actual cutting. This gravity settlement method is used to evaluate the stability. Gravity sedimentation method mainly observes the settlement status of the nanoparticles in the cutting liquid by holding the cutting liquid for a period of time, and evaluates the sedimentation volume. The different mass fraction of nano-SiO_2 cutting solution and nano-SiC cutting solution were allowed to stand for 30 days to observe the dispersion of the cutting solution.

Fig. 2 gives the results of the nano-SiO_2/nano-SiC cutting fluid sedimentation volume at different mass fraction actions. The larger the sedimentation volume of the nanocutting solution, the higher dispersion performance. It can be known that the prepared cutting solution has good dispersion stability. While compared to nano SiO_2 the cutting solution, the nano SiC cutting solution has better stability, larger sedimentation volume under the same mass fraction, and PEG2000 and CMC-Na as dispersants have better auxiliary dispersion effect on the nano SiC cutting solution. The prepared cutting solution has good stability and can be used for subsequent experimental studies.



(a) Nano-SiO_2 cutting solution (b) Nano-SiC cutting solution

Fig. 2 *Settlement Volume of Cutting Fluid with Different Mass Fractions*

3.2 Temperature field results and analysis

To research the influence of different cutting liquid on the cooling process the wafer cutting, the temperature distribution of the cutting surface was recorded by FLIR315 thermal imager. To better analyze and compare the temperature changes on the silicon wafers surface, the trend of the highest temperature at cutting zone with cutting fluids changing with the cutting position was exhibited in Fig. 3.

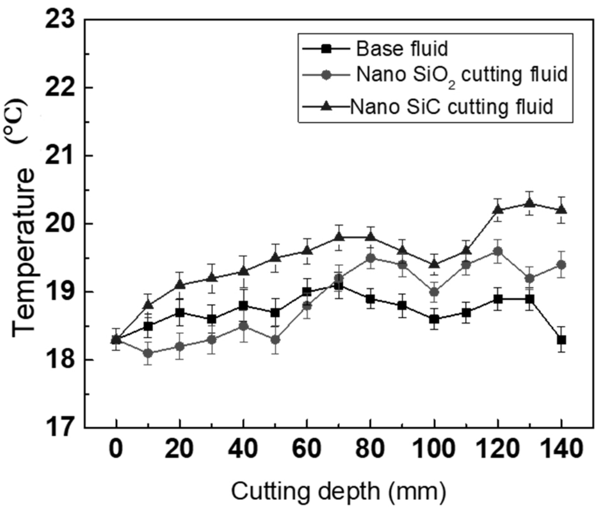


Fig. 3 *The Variation Trend of the Maximum Temperature of Cutting Area with The Change of Cutting Position Under the Action of Different Cutting Fluids*

It can be known that this index in the cutting area under the action of the three cutting fluids generally increases first and then decreases with the depth of the cutting position. This is because as the depth of the cutting position increases, the length of the cutting seam first increases and subsequently reduces. On the one hand, the increase in the length of the cutting seam will reduce the amount of cutting fluid distributed to each cutting area at the same time [14]. On the other hand, the amount of cutting fluid carried by the saw wire will decrease more, causing a sharp decrease in the amount of cutting fluid in the cutting area, especially in the middle area, a significant decrease in cooling effect, and an increase in temperature. Therefore, the highest temperature in the cutting area shows this trend of change. Before the cutting position reaches 60 mm, the highest temperature rise when using SiC cutting fluid is the largest, followed by the base fluid, and the rise of nano SiO_2 cutting fluid is the smallest. This can reflect that adding nano SiO_2 particles helps to enhance the cooling effect. Nano SiO_2 particles have a small size effect, which contributes to micro convection between liquid and particles, enhancing heat transfer. The largest rise of nano SiC solution may be due to the participation of nano SiC particles in the auxiliary cutting process, increasing heat generation and causing temperature rise [15]. As the cutting continues, the highest temperature under the nano SiO_2 cutting fluid increases significantly, and at the cutting position of 100 mm, there is a significant upward trend in the highest temperature under the nano SiO_2 cutting fluid and nano SiC cutting fluid, reaching the highest temperature at one point. This may be due to the aggregation and accumulation of nano particles, some of which reach the cutting area under the action of gravitational potential energy, resulting in an increase in the mass fraction of nano SiO_2 cutting fluid and nano SiC cutting fluid. This not only weakens the small size effect, but also promotes friction and wear during the cutting process due to aggregation, increases heat generation, and leads to a sharp rise in temperature.

3.3 Surface roughness analysis

In the experiment, a digital microscope (Hangzhou Full Spectrum Laboratory Equipment Co., LTD., DSX1000) was applied to detect the surface roughness of the resulting silicon wafer, and the magnification of 640 was selected. In the experiment, the six-inch silicon wafer was divided into nine areas along the cutting direction, and five points in every position were detected, and the mean surface roughness of five points was taken as the surface roughness of that area, and then the average surface roughness of nine areas was used as the surface roughness of the whole wafer. Each group of silicon wafer was measured three times repeatedly, and the measurement area was as shown in Fig. 4. In this paper, we compare the surface roughness of different silicon wafer to evaluate the cutting quality and reflect the lubrication effect of diamond wire saw cutting.

The surface roughness of silicon wafer under different cutting solutions are shown in Tab. 2. According to Tab. 2, the surface roughness of silicon wafers under the action of nano SiC cutting fluid decreased by about 29.6% compared to the action of base fluid, and decreased by about 47.2% compared to the action of nano SiO_2 cutting fluid. This indicates that adding nano SiC particles to the cutting fluid during wire saw cutting of six inch silicon wafers still helps to improve the surface roughness and enhance the cutting quality [16-17]. This reflects that adding nano SiC particles helps to assist in grinding silicon crystals and improve the cutting lubrication effect. Adding nano-SiO_2 particles to the cutting fluid actually increases the surface roughness of the silicon wafer. This may be because SiO_2 particles have little auxiliary grinding effect on the silicon crystal, and instead have the opposite effect, exacerbating the scratching of the silicon wafer. Additionally, due to the possibility of adsorption and accumulation in the already cut area, the effective infiltration of the cutting fluid is reduced, further reducing the lubrication effect of the cutting fluid and increasing the surface roughness of that wafer.

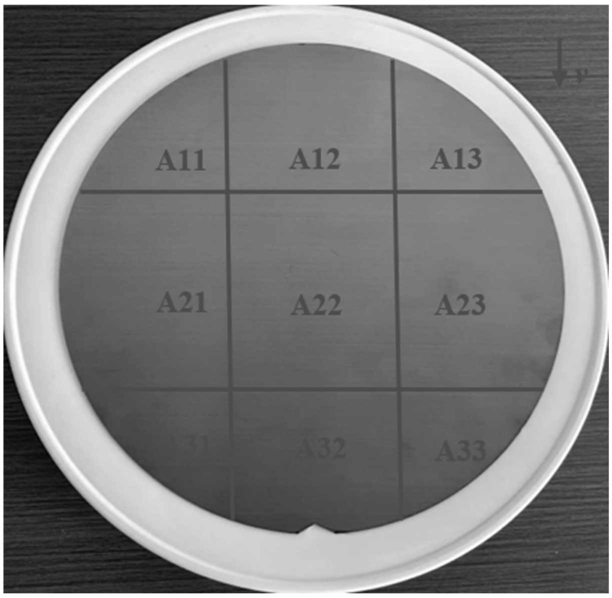


Fig. 4 *Schematic Diagram of the Six-Inch Silicon Wafer Measurement Area*

Tab. 2 *Measurement results of silicon wafer surface roughness under different cutting solutions*

Types of cutting fluid	Surface roughness Sq (μm)									
	A 11	A 12	A 13	A 21	A 22	A 23	A 31	A 32	A 33	Mean
Base solution	1.205	1.610	2.232	2.112	2.808	2.470	2.523	2.564	2.058	2.176
Nano-SiO_2	1.945	2.945	2.863	3.160	3.282	2.947	3.916	4.166	4.000	3.247
Nano-SiC	0.799	0.790	0.939	2.136	1.911	1.863	1.708	1.755	1.878	1.531

To further investigate the lubrication effect of different areas during diamond wire saw cutting, this article analyzes the surface roughness distribution from the vertical and horizontal directions. Take the average surface roughness of A11, A12, and A13 as the surface roughness of that at a vertical position of 35 mm. Similarly, obtain the surface roughness at vertical positions of 75 mm and 115 mm, and plot the variation curve of surface roughness along the vertical direction, as shown in Fig. 5 (a). Take the average surface roughness of A11, A21, and A31 as the surface roughness of that at a horizontal position of 35 mm. Similarly, obtain the surface roughness at horizontal positions of 75 mm and 115 mm, and plot the curve of surface roughness along the horizontal direction, as Fig. 5 (b).

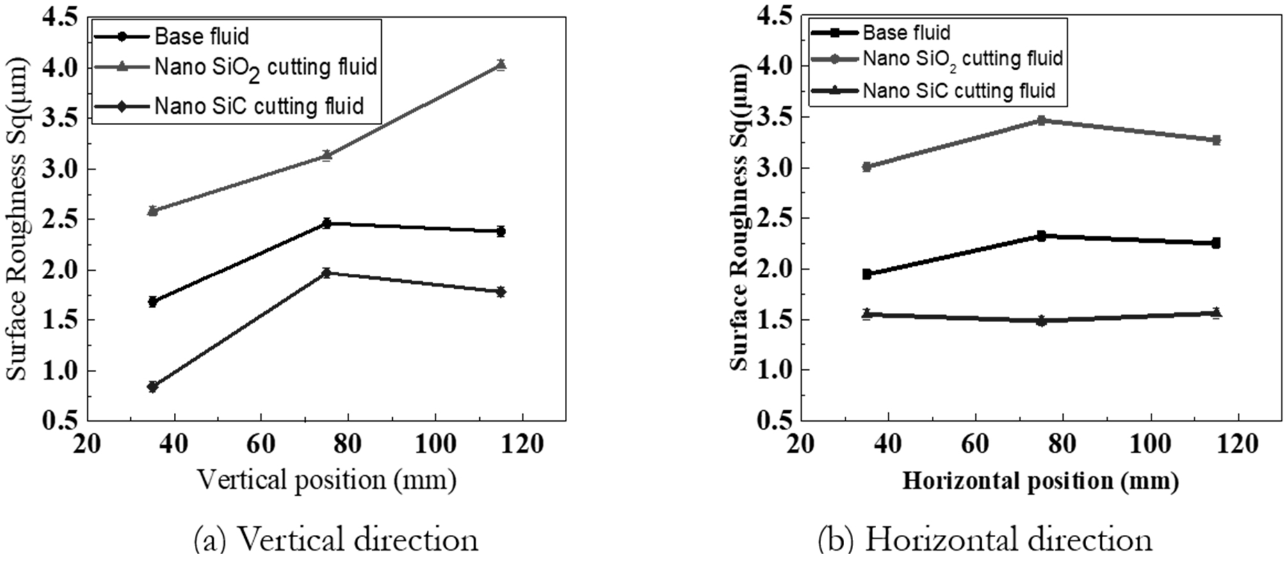


Fig. 5 *Variation Trend of Surface Roughness of Silicon Wafers Unde the Action of Different Cutting Fluids*

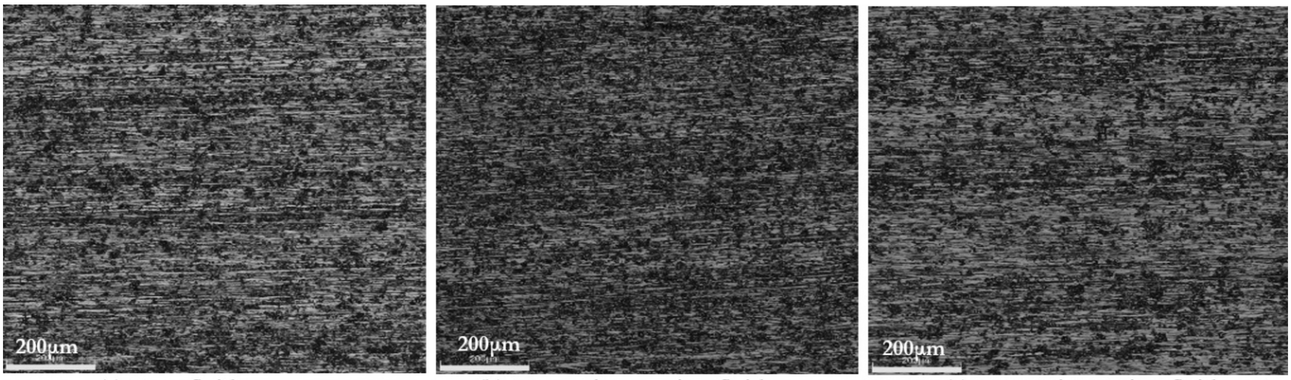
According to Fig. 5 (a), the surface roughness of the silicon wafer under the action of the base liquid and nano SiC cutting fluid first increases and then decreases with the vertical direction. The roughness is highest in the middle of wafer. Meanwhile, the surface roughness of the upper half of that wafer is smaller than that of the lower half. On the one hand, atomization can allow the cutting fluid to penetrate deeper, and the proportion of thin film lubrication in the boundary lubrication theory is larger, resulting in better lubrication effect. On the other hand, a better cooling effect can improve the shedding of abrasive particles on the saw wire, thereby avoiding the scratching of wafers by abrasive particles and reducing the silicon wafers roughness. However, under the action of nano-SiO_2 cutting fluid, the silicon wafers roughness increases. This may be due to the agglomeration of some nanoparticles in the cutting fluid during atomization, which adsorb and deposit in the already cut area during the cutting process, further increasing the difficulty of cutting fluid infiltration and significantly reducing the effective cutting fluid volume in the lower half area, resulting in a significant increase in roughness [18].

It was observed from Fig. 5 (b) that the silicon wafer roughness under the action of the base liquid and nano SiO_2 cutting liquid first increases and then decreases in the horizontal direction, and the roughness is also highest in the middle position of that wafer. This is because the variation in vertical direction corresponds to the change in cutting length, which first enhances and subsequently decreases. As the cutting length increases, the cutting area becomes larger, making it more difficult for cutting fluid to enter the cutting area. The amount of cutting fluid involved in lubrication decreases, resulting in lower lubrication effect and higher surface roughness. In addition, the phenomenon of lower surface roughness in the middle part of silicon wafers under the action of nano SiC solution may be due to the fact that nano SiC are more easily adsorbed on the saw wire compared to cutting fluid. As the saw wire moves, they are brought into the middle cutting area and are more likely to concentrate in the middle part. Nano SiC particles have a good auxiliary cutting effect, which enhances the lubrication effect and reduces the silicon wafers roughness [19-20]. Overall, the roughness on two boundaries of the silicon wafer in the horizontal direction does not change significantly under the action of the three cutting fluids. This is because the saw wire moves in a timed direction during cutting, and the distribution of cutting fluids on both sides is consistent overall.

3.4 Surface morphology analysis of silicon wafer

In order to reflect the cutting quality of silicon wafer more intuitively and study the lubrication ability of wire saw, the surface morphology of silicon wafer was explored in this paper. Collecting the surface morphology of that by digital microscope yielded 2D/3D images, and a magnification of 320 was chosen to obtain the appropriate area size. In the experiment, the six-inch silicon wafer was divided into nine regions along the cutting direction (see Fig. 4). Five points were selected for each area, and each group of silicon wafer was collected three times. The surface morphology of the anterior central part of the wafer (area A 22) for each group of wafers was compared. The surface topography image of the silicon wafer under different cutting solutions is exhibited in Fig. 6.

From Fig. 6, it was observed that the silicon wafer mainly has three surface defect characteristics: scratches, deep grooves, and brittle cracking. The main reason for scratches and deep grooves is that the saw wire undergoes periodic reversals during the cutting process of the experimental equipment. During the reversals, the linear velocity changes and the cutting force changes accordingly, resulting in varying depths of scratches. Secondly, the diamond abrasive particles on the saw wire vary in size, and larger abrasive particles are more likely to cause continuous, long, and deep scratches. Thirdly, the abrasive particles on the saw wire may detach due to insufficient lubrication and heating, and rub against the surface of wafer again, resulting in shallow scratches. The main reason for brittle fracture is that single crystal silicon, as a hard and brittle material, is prone to brittle peeling during processing [21-22]. Under the action of nano-SiO_2 cutting fluid, silicon wafers exhibit the most obvious scratches and the highest number of brittle fractures. Under the action of the base liquid, the number of surface defects formed is second. Under the action of nano SiC cutting fluid, the scratches are relatively less obvious and the number of brittle fractures is also the least.



(a) Base fluid (b) Nano SiO_2 cutting fluid (c) Nano SiC cutting fluid

Fig. 6 *Image of Surface Morphology of Silicon Wafer Under the Action of Different Cutting Fluids*

The change trend of the height difference of the silicon wafer contour under different cutting solutions was exhibited in Fig. 7. As Fig. 7, the height difference between the nano-SiC cutting liquid is the smallest, followed by the base liquid2.The cutting solution was the largest. This also reflects that in terms of lubrication effect, nano SiC cutting liquid is the best and nano SiO_2.The cleavage solution was the worst.

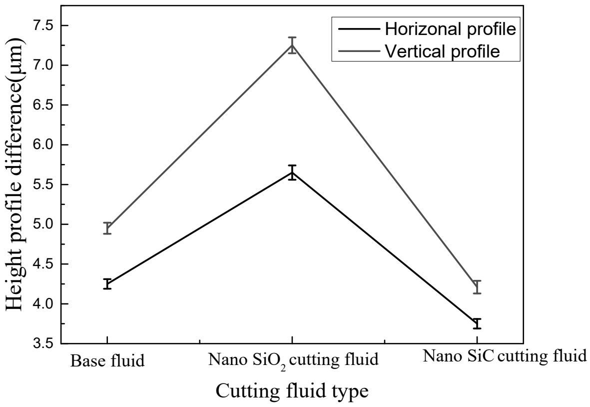


Fig. 7 *Variation Trend of Height Profile Difference of Silicon Wafers Under the Action of Different Cutting Fluids*

3.5 Warping analysis

The degree of silicon wafer warping refers to the bending degree of that in the vertical direction. The degree of such wafer warping reflects the strength of it and the quality of the manufacturing process. The warping of silicon wafer leads to the semiconductor equipment can not be installed correctly, thus affecting its normal working performance. Controlling the warping of silicon wafer is an important factor in manufacturing high-quality silicon wafer. Therefore, the silicon wafer cutting quality is evaluated by analyzing the warping size.

In this paper, the silicon wafer warping is detected by the large silicon wafer flatness detection system (Fabos Semiconductor Equipment Co., Ltd., TWS300). The main detection method of the detection system is: using laser rangefinder to scan the upper and lower surfaces of the silicon wafer respectively to obtain multiple sets of distance values; construct a median surface and correct the gravity effect as the least square datum; calculate the datum deviation (RPD) on each pair of measurement points, and the difference in the max reference deviation and the lowest datum deviation is the warping degree.

In order to pursue high precision, the detection system divides the entire silicon wafer surface into hundreds of regions. Among them, when detecting a six inch silicon wafer, the surface is divided into 896 regions. The detection results of silicon wafer warpage under different cutting fluids are shown in Fig. 8. According to Fig. 8, the silicon wafer with the base liquid has the smallest warpage, about 49.254 μm. The warpage of silicon wafers using nano SiO_2 cutting solution is second, about 65.511 μm. The maximum warpage of silicon wafers using nano SiC cutting fluid is about 94.404 μm. When using the base solution, the curvature of the silicon wafer decreased by about 24.8% compared to the nano SiO_2 cutting solution, and by about 47.8% compared to the nano SiC cutting solution. One reason is that some nanoparticles in the nano cutting fluid undergo particle aggregation during the atomization process, making it difficult for some cutting fluid to penetrate through the capillary formed by chips and abrasive particles,thereby enhance the quality of it. As the cutting process progresses, they adsorb and deposit in the already cut area, thereby reducing the effective amount of cutting fluid and reducing the lubrication and cooling effect on the cutting area. Secondly, nanoparticles have the function of assisting cutting, especially nano SiC particles. During contact with the workpiece, friction occurs, exacerbating the generation of thermal stress and increasing the degree of silicon wafer warping and deformation [23-24].

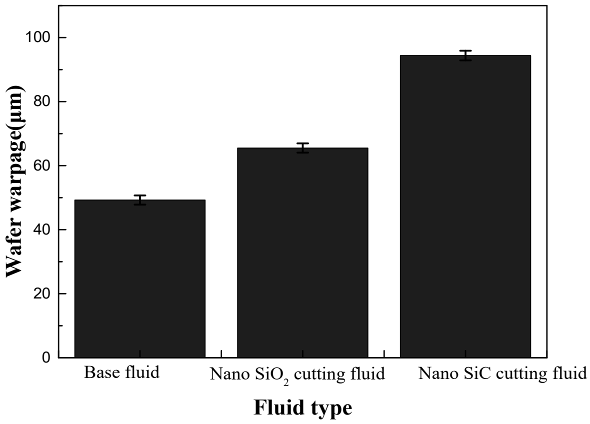


Fig. 8 *Measurement of Silicon Wafer Warping Under Different Cutting Solutions*

4 Conclusions

This article mainly uses different cutting fluids for large-diameter diamond wire saw cutting experiments. Using temperature field changes during cutting, silicon wafer surface roughness, silicon wafer surface morphology, and silicon wafer warpage as evaluation indicators, analyze the impact of different cutting fluids on the cutting quality of diamond wire saws. The main results are as follows:

In terms of temperature field changes, before the cutting position reaches 60 mm, the changes are most uniform under the action of nano-SiO_2 cutting fluid, followed by the base fluid, and the change amplitude of nano-SiC cutting fluid is the largest. However, as the depth of the cutting position continues to increase, the temperature rise amplitude under the action of nano-SiO_2 cutting fluid and nano-SiC cutting fluid increases significantly. In terms of surface roughness, the nano SiC cutting fluid has the best effect on silicon wafers roughness, reducing it by about 29.6% compared to the base fluid and about 47.2% compared to the nano SiO_2 cutting fluid. In terms of surface morphology, the scratches on silicon wafers are most obvious and the number of brittle fractures is the highest under the action of nano SiO_2 cutting fluid, followed by the base fluid. The surface morphology of silicon wafers is the best under the action of nano SiC cutting fluid. In terms of curvature, the silicon wafer has the smallest curvature under the action of the base liquid, which is reduced by about 24.8% compared to the nano SiO_2 cutting liquid and about 47.8% compared to the nano SiC cutting liquid. The results indicate that silicon wafers cut with nano SiO2 cutting fluid exhibit the least warpage, yet suffer from the poorest surface roughness and surface morphology. Nano-SiC cutting fluid, on the other hand, enhances the surface roughness and morphology of silicon wafers to a certain degree, but results in the greatest warpage. It is challenging for cutting fluids that utilize only a single type of nanoparticle to excel in all aspects of cutting quality. Consequently, combining two or more nano cutting fluids can improve the cutting quality of silicon wafers. These findings offer practical reference value for enhancing the diamond wire saw cutting process of large-diameter silicon wafers.

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