Nano-polishing of silicon wafers using ultra-dispersed diamonds

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In the present study, two new methods are proposed for polishing of silicon wafers using the ultra-dispersed diamonds (UDD). The first proposed polishing method uses a polishing tool with an ultra-fine abrasive material made by electrophoretic deposition of UDD onto a brass rod. Dry polishing tests showed that the surface roughness of the silicon wafer has been reduced from $R_a = 107$ to 4 nm after polishing for 30 min. The second method uses a new polishing pad with self-generating porosity. By polishing using the new pad in combination with the polycrystalline UDD in water suspension, it is possible to achieve the specified surface roughness of the silicon wafer rather faster than using a conventional pad made of foamed polyurethane. The tests showed that the surface roughness of the silicon wafer has been reduced from $R_a = 107$ to 2 nm after polishing for 90 min.

1. Introduction

To improve the surface roughness and remove residual damages of subsurface layers of silicon wafers after cutting, conventional polishing technologies use the chemical-mechanical polishing (CMP) methods. The CMP has comparatively low productivity because it uses abrasive materials with soft grains, such as colloidal silica or oxidized cerium.

To increase the efficiency of polishing of hard materials, several alternative approaches propose to use the ultra dispersed diamonds (UDD) as abrasives. The UDD produced by detonation of explosives with negative oxygen balance [1] can be obtained after chemical treatment in forms of pastes, powders, and water suspensions with various types and sizes of grains. For example, the typical sizes of the monocrystalline UDD grains in water suspensions lie in range of 4–50 nm, and the polycrystalline UDD in water suspensions have the grain sizes of several micrometers. The UDD-based slurries showed superior chemical stability and lubricity, however these slurries have not been applied widely for precise polishing on the mass-production basis.

In the current study, we proposed two new methods for precise polishing using the UDD in water suspensions and investigated its polishing characteristics by a number of experiments.

The first proposed method uses a new grinding wheel with an ultra-fine abrasive material made by electrophoretic deposition of the monocrystalline UDD onto an electrode [2]. In this series of experiments, we tested various types of grinding wheels and evaluated its characteristics for precise polishing of silicon wafers.

The second proposed method uses a new polishing pad, in which the porosity can be generated naturally during polishing. In this series of experiments, we compared the polishing performances using the new polishing pad and a conventional foamed polyurethane pad in combinations with the monocrystalline UDD in water suspension and the polycrystalline UDD in water syspension for precise polishing of the silicon wafers.

2. Experimental equipment

The polishing experiments conducted using laboratory-scale equipment. The polishing machine consisted of two rotary shafts independently driven by electric motors and a container filled with abrasive materials. The silicon wafer was fixed on the bottom of the container associated with Spindle *B*. The abrasive grinding wheels and the polishing pads were fixed on Spindle *A*, where the polishing load of 2 N was applied. The profiles of finished surfaces were measured using a diamond stylus (measuring machine: Taylor Hobson „Talysurf 4").

3. Precise polishing using ultra-fine abrasive grinding wheels

3.1. Experimental conditions. In this series of tests, we evaluated the characteristics of the ultra-fine abrasive grinding wheels for dry polishing and wet polishing of the silicon wafers.

The grinding wheels were made using the electrophoresis phenomenon. The monocrystalline UDD grains, put into sodium alginate or into a mixture of sodium alginate with carboxymethylcellulose (CMC), deposited during 60 min on a brass electrode rotating with a speed of 50 rpm. An applied electric potential was varied within the range of 10–100 V. The grinding wheel was dried and machined.

Upon the type of solutions and the concentration of UDD in the solutions, the maximum thickness of abrasive UDD material reached 1.5 mm. The manufacturing conditions are summarized in Table 1.

3.2. Experimental results and discussions. Polishing tests with manufactured ultra-fine grinding wheels were conducted in two different environments: wet and dry. It was found that the surface roughness decreased gradually with polishing time for both cases, however the absolute values of surface roughness were larger in the case of wet polishing than in the case of dry polishing.

Table 1. Experimental conditions (ultra-fine abrasive grinding wheel)

Abrasive grain	UDD (0.5 wt.%)
Binder	a) Sodium alginate (0.25 wt.%) b) Sodium alginate (0.2 wt.%)+CMC (0.5 wt.%)
Work piece	Silicon wafer
Polishing load	2 N
Spindle *A*	450 rpm
Spindle *B*	165 rpm
Polishing conditions	a) Wet polishing b) Dry polishing
Polishing time (max)	90 min

In the first series of tests, we used the grinding wheels made with a mixture of the monocrystalline UDD and sodium alginate without addition of CMC. The test results are shown in Fig. 1. The minimum surface roughness achieved after 80 min of dry polishing was $R_a = 6$ nm. In the case of wet polishing, the grinding wheel broke suddenly after 60 min.

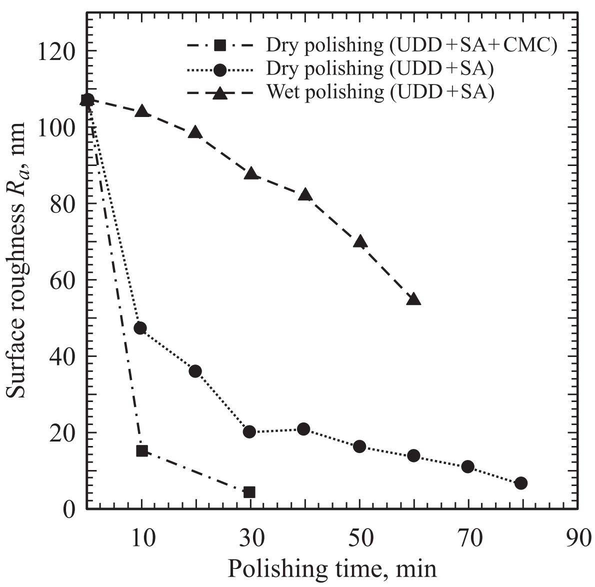

Figure 1. Results of polishing tests using ultra-fine grinding wheels.

Another series of tests was performed with the grinding wheel made with the monocrystalline UDD grains in the mixture of sodium alginate and CMC. As it is shown in Fig. 1, the surface roughness of the silicon wafer in this case reduced from $R_a = 107$ to 4 nm after dry polishing for 30 min.

For small-size silicon wafers, the method showed relatively good polishing performance, however the overall performance of this method was unsatisfactory due many uncertain factors, which influenced of the manufacturing process of the ultra-fine abrasive grinding wheel. It was found that the quality of the grinding wheels strongly affected by such parameters as the adhesiveness of UDD to the brass electrodes. The wet polishing was not found effective in comparison with the dry polishing. Certainly, this method requires many improvements.

4. Precise polishing using pads with self-generating porosity

4.1. Experimental conditions. The polishing tests were conducted using the new-type polishing pad on the equipment described in Section 2 of the current paper. The experimental conditions are listed in Table 2.

Table 2. Experimental conditions (new polishing pad)

Pad	a) Foamed polyurethane pad b) New pad with self-generating porosity
Work piece	Silicon wafer
Slurry	a) Monocrystalline UDD in water suspension b) Polycrystalline UDD in water suspension
UDD in slurry	5 wt.%
Polishing load	2 N
Spindle *A*	250 rpm
Spindle *B*	50 rpm
Polishing time (max)	180 min

Made from petroleum pitch mixed with halite, the new pad with self-generating porosity has high manufacturability. The molten petroleum pitch was mixed with the pulverized halite grains of the uniform size and later was solidified and flattened by turning operations in order to create a flat polishing pad. The optical micrographs of the pad are shown in Fig. 2. Self-generation of porosity was achieved in the boundary layer of the pad when the halite grains protruded of the surface of the pitch were dissolved by the UDD slurry during polishing. It was found that the pad with self-generating porosity and the foamed polyurethane pad had similar visco-elastic and mechanical characteristics.

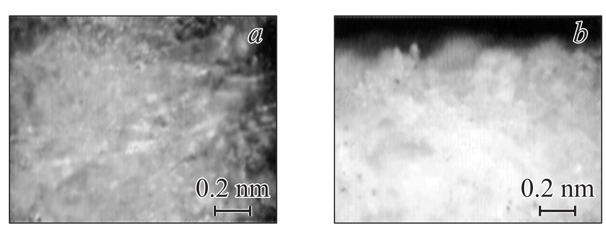

Figure 2. Optical micrographs of new pad with self-generating porosity. *a* — surface, *b* — cross-section.

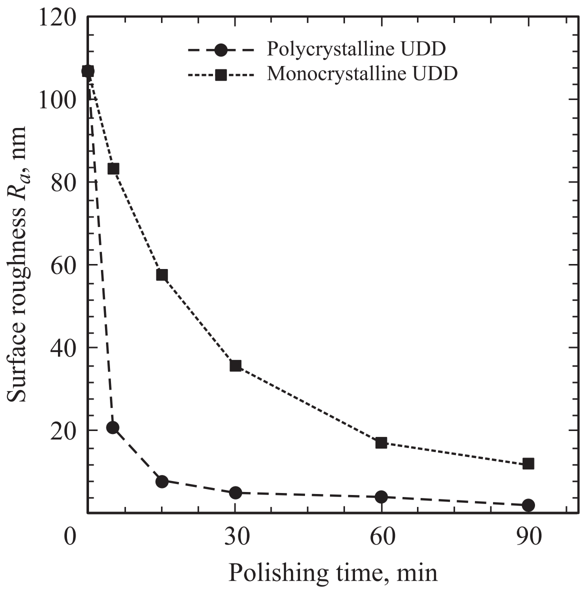

Figure 3. Surface roughness obtained using new polishing pad with self-generating porosity.

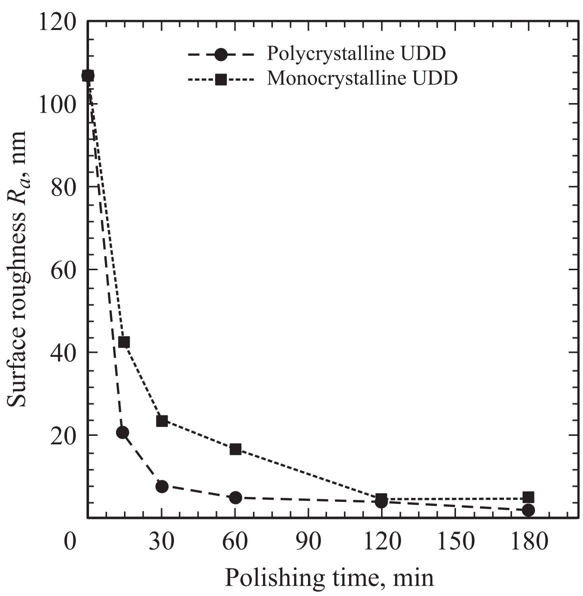

Figure 4. Surface roughness obtained using foamed polyurethane pad.

In this series of experiments, we used the silicon wafer samples with initial surface roughness of $R_a = 107$ nm. The following combinations of polishing materials were tested:

1) the new pad with self-generating porosity and the slurry of the monocrystalline UDD in water suspension;

2) the new pad with self-generating porosity and the slurry of the polycrystalline IDD in water suspension;

3) the foamed polyurethane pad and the slurry of the monocrystalline UDD in water suspension;

4) the foamed polyurethane pad and the slurry of the polycrystalline UDD in water suspension.

4.2. Experimental results and discussions. The polishing tests showed that in the case of using the UDD in water suspensions with the new self-generating porosity pad, the surface roughness of the silicon wafer was rapidly decreased at the beginning and slowly decreased in the rest of the polishing process.

The test results for the pad with self-generated porosity are plotted in Fig.3 and the results for the foamed polyurethane pad are shown in Fig.4. After polishing for 90 min using the new polishing pad with the polycrystalline UDD in water suspension, the surface roughness of the silicon wafer reduced from $R_a = 107$ to 2 nm (Fig.3). Twice longer polishing time, about 180 min has been required to achieve the same surface roughness using the foamed polyurethane pad with the polycrystalline UDD in water suspension. Moreover, the surface was more scratched in this case than it was obtained in the case of the polycrystalline UDD in water suspension and the pad with self-generating porosity. The optical micrographs of the finally polished surfaces and the surface profiles are presented in Fig. 5 for the case of the pad with self-generated porosity.

Fast decrease of the surface roughness by polishing using the polycrystalline UDD in water suspension may be explained by a peculiar polishing mechanism when many new cutting edges can be created after cleaving of the polycrystalline UDD grains during polishing process.

Thus, using the polycrystalline UDD suspensions in conbination with the new polishing pad it is possible to achieve the specified surface roughness of the silicon wafer rather faster than using the foamed polyurethane pad.

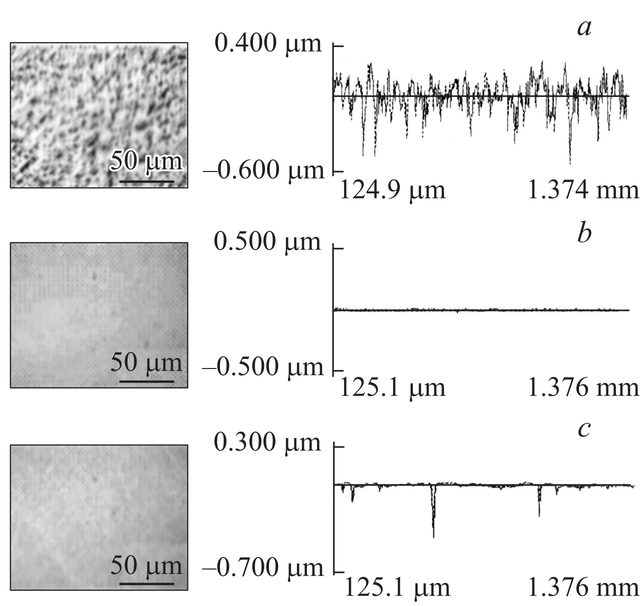

Figure 5. Optical micrographs of surfaces polished by new polishing pad with self-generating porosity. a — prior to polishing, $R_a = 107$ nm; b — polycrystalline UDD, $t = 90$ min, $R_a = 2$ nm; c — monocrystalline UDD, $t = 90$ min, $R_a = 12$ nm.

5. Conclusions

In this study, we proposed two methods for precise polishing of silicon wafers and investigated the efficiencies of the methods using the UDD in water suspensions for the abrasives.

The fist polishing method uses ultra-fine abrasive grinding wheels manufactured with the monocrystalline UDD. The surface roughness of the silicon wafer has been reduced from $R_a = 107$ to 4 nm after 30 min of dry polishing by the ultra-fine abrasive grinding wheels. The method showed satisfactory results for dry polishing of silicon wafers, but the overall performance of the method was poor. We concluded that this method still needs improvements and it cannot be recommended at the current stage of the research.

The second method uses a new-type polishing pad with self-generating porosity. Polishing was done with monocrystalline and polycrystalline UDD in water suspensions. In addition, we used a conventional foamed polyurethane pad for comparison of the polishing performances. The tests showed that the surface roughness of the silicon wafer has been reduced from $R_a = 107$ to 2 nm after polishing by the new-type polishing pad and the polycrystalline UDD for 90 min. Comparing with polishing by the conventional foamed polyurethane pad, we showed that the same surface roughness of the silicon wafer could be achieved after twice shorter polishing time using the pad with self-generating porosity. Although cutting ability per one UDD grain is very small, we considered that many UDD grains per unit of polishing area are responsible for high polishing performance.

The results of silicon wafer polishing showed that the pad with self-generating porosity could be effectively used in combination with the polycrystalline UDD in water suspensions.

References

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[2] J. Ikeno, Y. Tani, H. Sato. Ann. CIRP **39**, *1*, 341 (1990).