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# Nanoscale friction and wear properties of silicon wafer under different lubrication conditions

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ABSTRACT

The nanoscale friction and wear properties of single crystal silicon wafer under different lubrication conditions are studied in this paper. The experiments were performed with $Si_3N_4$ ball sliding on the surface of silicon wafer under four different lubrication conditions: dry friction, water lubrication, hydrogen peroxide lubrication and the static hydrogen peroxide dry friction. The results from the experiments have been analyzed showing the different friction and wear properties of the silicon wafer in different lubrication conditions. It is concluded that the wear rates under the water lubrication and under the hydrogen peroxide lubrication are both small, the chemical reactions are facilitated by the mechanical processes when the load and the sliding speed reach certain levels. This is mainly resulted by the enhanced lubricant performance with the formed silicon hydroxide $Si(OH)_4$ film. Under the water lubrication, the wear is found in a way of material removed in molecule scale. Under the hydrogen peroxide lubrication, the wear is mainly caused by the spalling of micro-cracks. Under the dry friction condition, the wear is found being adhesive wear. And under the static peroxide dry friction, the wear is prevailing adhesive wear. These results are essential and valuable to the development of the efficient and environmental-friendly slurry for the chemical mechanical polishing (CMP) process.



## 1. Introduction

Single crystal silicon is an important material for semiconductor industry. Silicon wafer is widely used in the integrated circuit (IC) devices, high-density information storage devices, and micro-electric-mechanical systems (MEMS) [1,2]. The fabrication and application of these delicate devices require high surface quality of IC chips. This has become one of the major concerns [3]. Up to now, CMP has been proven the best global planarization technique which can satisfy the requirements on surface quality of silicon wafer and chips in the semiconductor industry [4]. With the scientific progress in nanotechnology in recent years, CMP has been developed rapidly. However, the material removal mechanism of the CMP process is not yet clearly understood [5]. Many scientists are extensively working from different aspects to reveal the insights of the CMP technology in order to gain the effective method to remove the material with minimized damage to the polished surface quality, and minimized damage to the environment [3,6].

In a typical CMP process in the semiconductor industry, the silicon wafer is carried by the polishing head and pushed onto the polishing pad. The polishing head and the polishing pad rotate, oppositely to each other at a relative speed. Meantime the polishing slurry is fed onto the pad and flows into the polishing interface between the wafer and the pad. The material removal in the CMP process is a synthetic function of chemical and mechanical actions [7]. The friction and wear property of the polished material in a given lubrication condition is an essential factor as well to the quality of the polishing surface and the material removal rate. Therefore, to study on the friction and wear properties of the silicon wafer is an important part of silicon wafer CMP research.

By using a servo-hydraulic reciprocating sliding apparatus, Wang et al. [8] studied the effects of water and oxygen on the tribochemical wear of single crystal silicon (1 0 0) against $SiO_2$ ball. The wear tests were performed under four different atmosphere conditions, those were, pure nitrogen, dry air, humid air and pure oxygen. The results from the experiments indicate that the increase in hydrophilicity of silicon (1 0 0) surface will induce an obvious increase of the friction coefficient and the wear depth of silicon surface. Moreover, the oxygen plays a very important role in the wear behavior. The wear depth on silicon surface was highest due to the strong oxidation reaction under the condition of pure oxygen atmosphere. Varenberg et al. [9] studied nano fretting wear on the silicon surface by using scanning probe microscopy. Partial and gross slip fretting with displacement amplitudes from 5 to 500 nm

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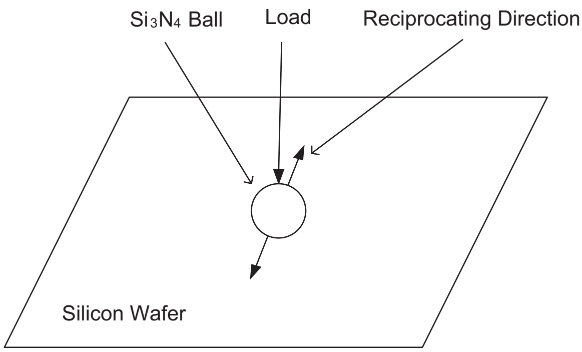


**Fig. 1.** Schematic of ball-on-flat sliding.

were used for the study, and the results from their study show a substantial increase of the friction at the transition from partial to gross slip and a significant difference between damage surfaces in the two fretting regimes. Although the study was concentrating on the nano fretting wear of the silicon surface which was not chemical modified, the results from the study are good reference for the study of this paper to understand the friction and wear behavior of the modified silicon surface. Singh and Yoon [10] studied the micro- and nano-frictional properties of chemically and topographically modified Si (1 0 0) surfaces. The results indicate that at the micro- and nano-scales, the modified Si (1 0 0) surfaces show enhanced friction behavior when compared to the bare Si (1 0 0) surfaces. The modified Si (1 0 0) surfaces exhibit lower friction values. Singh and Yoon found that at the nano-scale, the lower friction values of modified surfaces were due to the lower intrinsic adhesion and contact areas. And with the chemically modified surfaces, the reduction of the contact area was because of the lower interfacial energies.

Silicon wafers are thin and brittle slices, which are formed of highly pure and nearly defect-free single crystal silicon. For the application in the IC and MEMS, silicon wafers must have the super surface quality, and be free of defects after fabrication [11–13]. CMP is now the only ideal process to achieve global planarization of silicon wafers [4]. However, it is still lack of fundamental understanding of this process although many researchers have studied it intensively in the past decades [14–16]. Meanwhile traditional CMP slurry contains a large number of chemical substances, such as oxidants, corrosion inhibitors and chelating agents. All these chemicals generate great deal of wastewater and cause heavy environmental pollution. With the strengthening of environmental protection, safety and health consciousness, green polishing slurry is desired in order to replace traditional slurry. It has been becoming research's hotspot in the world in recent years [6]. In this paper, nanoscale friction and wear properties of single crystal silicon wafer under different lubrication conditions are studied. At the same time, the results from this study are supporting to use deionized water and $H_2O_2$ as possible less harmful green slurry for the CMP process.

## 2. Experimental

The p- Si (1 0 0) single crystal silicon wafers were selected as the test material. The samples were cut from the wafers with a rectangle size of 20 mm × 20 mm. The nanoscale friction and wear tests were performed on a reciprocating UMT-2 micro-tribotester at standard room temperature of 20 ± 1 °C with a relative humidity of 45–55%. The type of frictional contact was ball-on-plate contact, as illustrated in the Fig. 1, a $Si_3N_4$ ceramic ball with the diameter of 4 mm slides on the 20 mm × 20 mm sized sample of p- Si (1 0 0) rectangle silicon wafer. During the experiment, a new $Si_3N_4$ ball is used only one time for each single test in order to minimize the effect of the wear of the ball on the wear of the wafer silicon surface. Before the sliding experiment, both the $Si_3N_4$ ball and the silicon wafer were dipped into acetone and cleansed with an ultrasonic cleaner for 10 min. The test load was 30–110 mN, the sliding speed was 5.33–10.66 mm/s, the time of friction and wear test was 2 min, the amplitude of the reciprocation sliding is 2 mm. A group of friction and wear experiments were conducted under different lubricating conditions namely dry friction, water lubrication, $H_2O_2$ lubrication and static $H_2O_2$ dry friction. Deionized water was used as lubrication medium in water lubrication experiments. 30% $H_2O_2$ was used as lubrication medium in $H_2O_2$ lubrication experiments. In the static $H_2O_2$ dry friction experiments, the wafer samples were immersed in the 30% $H_2O_2$ liquid for 30 min before the experiments, then taken out and got it dried afterward. During the sliding tests in so-called static $H_2O_2$ dry friction experiments no lubrication medium was used. The UMT-2 micro-tribotester collected and recorded the friction coefficients from the sliding experiments automatically. The surface morphology was characterized with Phase Shift MicroXAM-3D, by measuring the length, the width and the depth of the wear marks. The wear rate and the wear depth of single scratch are therefore able to be computed for further analyses. Furthermore, it was pointed out a mathematical modeling for the contact pressure between the ball and surface would be benefit for the understanding of the sliding wear mechanism, which would be addressed in future.

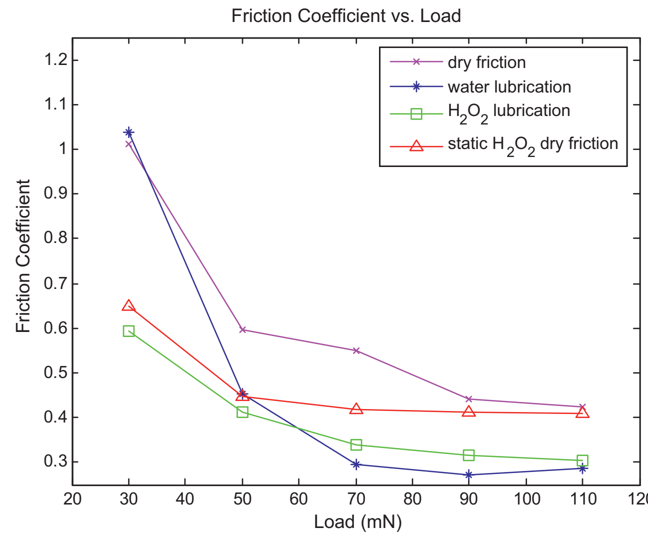


**Fig. 2.** Results from experiments about relation between friction coefficient and load.

## 3. Results and discussion

### 3.1. The effects of load on friction coefficient and wear rate

A series of experiments have been conducted to investigate the relationship between the friction coefficient and the applied load. The friction coefficients between the $Si_3N_4$ balls and the single crystal silicon wafers were collected and recorded by the Micro-tribotester from the sliding experiments under four different lubrication conditions. The sliding speed was 8.00 mm/s, the applied loads were 30 mN, 50 mN, 70 mN, 90 mN, 110 mN. The coefficients obtained from the experiments are shown in the Fig. 2.

From the Fig. 2, it can be seen that the friction coefficient is becoming smaller with the increasing of the load from 30 mN to 70 mN under all four different lubrication conditions, and there is no big difference with friction coefficient when the load increases above 70 mN.