

Study on Contact Forms in Wafer Chemical Mechanical Polishing in Nanomachining

¹Su Jianxiu, ¹Du Jiaxi, ¹Chen Xiqu and ²Kang Renke

¹Henan Institute of Science and Technology, Xinxiang, 453003, PR China

²Key Laboratory for Precision and Non-Traditional Machining Technology of Ministry of Education,
Dalian University of Technology, Dalian, 116024, PR China

Abstract: Chemical Mechanical Polishing (CMP) has become the most widely used planarization technology in the semiconductor manufacturing process. **Problem statement:** Studying the Contact Forms in Wafer Chemical Mechanical Polishing. **Approach:** A series test on the abrasion behavior and the lubricating behavior was conducted and then the test results were investigated by the abrasion and lubrication theory. **Results:** By the test results and analysis, it showed that the Material Removal Rate (MRR) was mainly due to the interaction between abrasives and polishing slurry and the main material removal of wafer surfaces was two bodies abrasive wear under chemical interaction. By the Stribeck curves obtained, the lubrication state in CMP interface is belong to the boundary lubrication and the material removal is the process of bringing and removed of the chemical reaction boundary lubricating film on wafer surface constantly. **Conclusion:** By the analysis results, it was concluded that the contact form between the Wafer and the polishing pad is the solid-solid contact. These results will provide theoretical guide to further understand the material removal mechanism of in wafer CMP.

Key words: Chemical Mechanical Polishing (CMP), material removal rate, abrasion behavior, lubricating behavior, contact form, boundary lubrication, planarization technology, semiconductor manufacturing process, CMP process, dry friction

INTRODUCTION

Chemical Mechanical Polishing (CMP) belong to the nanomachining in the semiconductor manufacturing process. Nowadays, it has become the most widely used planarization technology in the manufacturing process of Ultra Large Scale Integrated circuits (ULSI) (Abdullah *et al.*, 2009; Terrell *et al.*, 2010). However, the CMP mechanism has not been understood completely. The present CMP technology is incapable of meeting the needs of wafer surface quality in next generation IC. Studying on the material removal mechanism becomes an important fundamental research work to improve the CMP technology (Bais and Majlis, 2008). Then the material removal mechanism mainly depends on the contact relationships between the wafer and the pad. Because the models built for studying the material removal mechanism of wafer CMP have strong relationships to contact form. Before studying the material removal mechanism deeply, the contact mechanism between the wafer and the pad in wafer CMP process must be understood firstly (Ali *et al.*, 2010).

A schematic of CMP system sees literature (Krishnan *et al.*, 2010). In the CMP process, a rotating wafer is pressed face down onto a rotating polishing

pad at a proper pressure. The polishing slurry containing submicron or nanometer abrasives and chemical reagents flows between the wafer and the pad. The chemical reactant film is formed on wafer surface and then the reactant is removed from wafer surface by the mechanical action. The new surface will emerge and the next CMP cycle begins. What is the contact form between the wafer and the pad in wafer CMP process? Some researchers (Bozkaya and Muftu, 2009; Zhao and Chang, 2002; Liang, 2005) considered the contact form between the wafer and the pad is solid-solid contact and the lubrication forms between the wafer and the pad is the boundary lubrication. Some researchers considered that the wafer is not contact with the pad, the hydrodynamic of slurry between the wafer and the pad can float the wafer, the lubrication forms between the wafer and the pad is the hydrodynamic lubrication and the cutting action produced by slurry on wafer surface is the main power in material removal (Yeruva *et al.*, 2009). Some researchers considered that the wafer is semi-contact with the pad, the lubrication forms between the wafer and the pad is mixed lubrication and the polishing pressure on wafer is born by the mutual action of the pad and the slurry (Ng *et al.*, 2005).

Corresponding Author: Su Jianxiu, Henan Institute of Science and Technology, Xinxiang 453003, P.R. China
Fax: +86-373-3693192

In wafer CMP process, the movement relationship between the Wafer and the polishing pad exists and the slurry with abrasives can be brought into the polishing region between the wafer and the pad continuously. So the friction phenomena between the wafer and the slurry including abrasives, between the wafer and the pad and between the pad and the slurry can be produced in wafer CMP process (Qura'n, 2007).

So the CMP system composed of the wafer, the slurry and the pad is not only a mechanical system of the mutual movement, is also a tribological system with the friction between the various element. There are the friction, the abrasion and the lubrication phenomena. Therefore, the contact mechanism between the wafer and the polishing pad can be judged from the tribological (lubricating) behavior of the wafer surface materials and the material removal (or abrasion) behavior on the wafer surface. In studying the wafer CMP Theory and Technology, The major goals are how to improve and control Material Removal Rate (MRR) of the wafer surface, that is, the wear rate of wafer surface. The contact state are closely related to the abrasion form and the lubrication form, therefore, so long as the abrasion form of the wafer surface materials and the lubrication form between the wafer and the pad have been found out, then, the contact form between the wafer and the pad can be further obtained.

Analysis of the lubrication behavior in the wafer CMP process:

The discrimination of the lubrication form in wafer CMP process: According to lubrication theory, the lubrication form can be divided into 5 types. One is the hydrodynamic lubrication and the thickness of the typical lubrication film is 1-100 μm . Two is the static pressure lubrication and the thickness of the typical lubrication film is 1-100 μm . Three is the flexibility hydrodynamic lubrication and the thickness of the typical lubrication film is 0.1-1 μm . Four is the thin film lubrication and the thickness of the typical lubrication film is 10-100 nm. Five is the boundary lubrication and the thickness of the typical lubrication film is 1-50 nm. The last one is the dry friction and the thickness of the typical lubrication film is 1-10 nm. Figure 1 shows the friction coefficient at the various lubrication conditions. Figure 2 is a typical lubrication curve of the lubrication state transformation, this is the well-known Stribeck curve. It can very clearly reflect the variation relationship of the lubrication state and the motion parameters.

According to above mentioned, in the wafer CMP process, as long as the friction coefficient between the wafer and the pad can be known, the lubrication state can be determined. The friction coefficient is very easy to measure on-line in the wafer CMP process. Many companies have already produced experimental or

commercial CMP machine with detecting the friction coefficient on-line, such as the CP-4 experimental polishing machine produced by the CETR company USA. It is capable of meeting the on-line testing of friction coefficient in wafer CMP process.

MATERIALS AND METHODS

Experimental equipment and experimental conditions: The CMP tests were conducted on CP-4 CMP machine made by CETR Inc. All the experiments are done in clean room with 1000 grade at the constant temperature of 22°C. The silicon wafers of 2 inches in diameter, lapped before CMP, are used in polishing experiments. The surface roughness Ra of the silicon wafer, measured in ZYGO5022 surface profiler, is about 40 nm. DI (deionized) water with the resistance 18.24M Ω -cm is used in CMP test. The Rodel IC1000/Sub IV pad is applied and conditioned with the diamond conditioner online during CMP. It is also conditioned for 15 min using DI water before every polishing. The slurry SS12, made by Cabot Microelectronics Corporation, is used in CMP test.

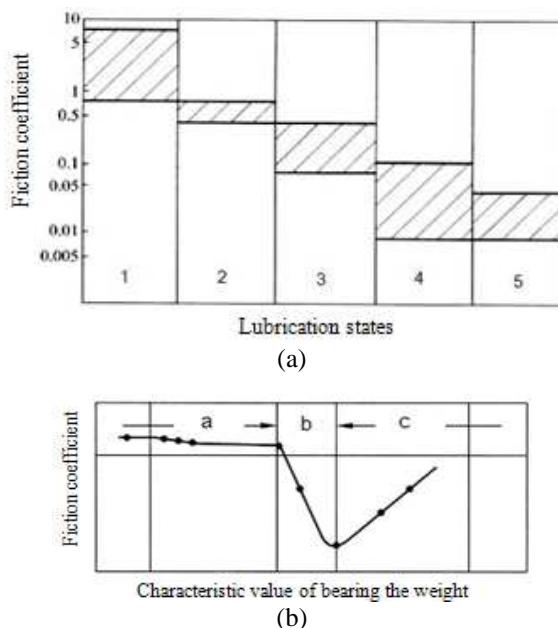


Fig. 1: The relationship between the lubrication states and friction coefficient and Curve of Stribeck (a) The relationship between the lubrication states and friction coefficient, (b) Curve of Stribeck; (1) The dry friction (metal); (2) The dry friction (oxidation film), (3) the boundary lubrication; (4) The mixed lubrication; (5) The hydrodynamic lubrication; (a) The boundary lubrication; (b) The mixed lubrication, c- The hydrodynamic lubrication

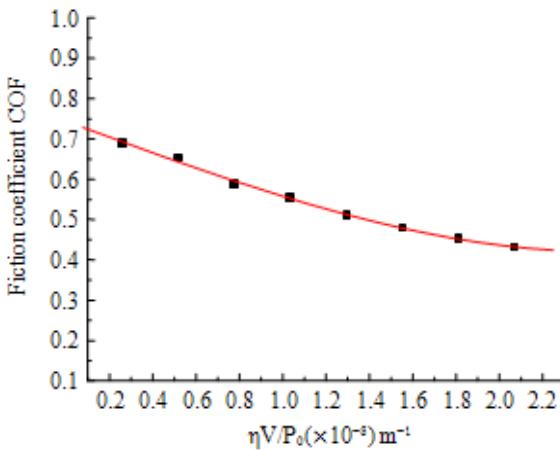


Fig. 2: The “Stribeck curve” of wafer CMP at $p_0 = 6\text{psi}$

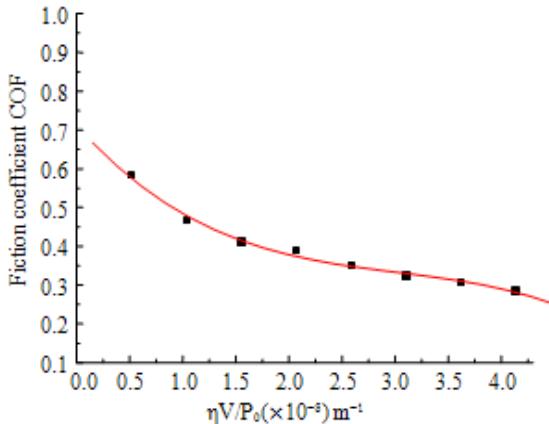


Fig. 3: The “Stribeck curve” of wafer CMP at $p_0 = 3\text{psi}$

Experimental parameters: In the experiments, the down force on the wafer are 3 psi and 6 psi, the carrier has a reciprocating motion with a stroke of 10 mm at speed of 2.5 mm sec^{-1} and the center distance between the platen and the wafer is set 60 mm. The slurry is supplied at the flow rate of 100 mL min^{-1} during the CMP. Each polishing time was 5 min. The rotational speed of polishing head n_w and the rotational speed of platen n_p are taken as $n_w = n_p = 50, 100, 150, 200, 250, 300, 350, 400 \text{ r min}^{-1}$ in experiments. The friction coefficients of each test are measured online. All the tests repeated three times and each test result took the average value of the three tests.

RESULTS

In order to evaluate the lubrication behavior in wafer CMP process, the friction coefficients were

obtained with the equal rotational speed n_w and n_p at the polishing pressure p_0 3 psi, 6 psi, respectively. The Stribeck curves are shown in Fig. 2-3.

Discrimination of the lubrication state in wafer CMP: In tribology, the friction coefficient is an important parameter to distinguish the lubrication state. By Fig. 2-3, when the $n_p = n_w = 400 \text{ r min}^{-1}$, the maximum line speed on the wafer surface is about 2.5 m sec^{-1} and the friction coefficient of polishing system is greater than 0.1. While in the actual CMP process, the polishing speed is about 1 m sec^{-1} or less. Comparing with Fig. 1a, the lubrication form in the wafer CMP should be the boundary lubrication, not mixed lubrication. Comparing the Stribeck curve shown in Fig. 2-3 with Fig. 1b, the lubrication state also is boundary lubrication. So, according to the friction characteristics of wafer CMP, it is can be considered that the lubrication is boundary lubrication in the wafer CMP process.

Analysis of the abrasion behavior in wafer CMP process (Su *et al.*, 2008a; 2008b):

The differentiating method of contact form between the wafer and the pad based on abrasion behavior: In wafer CMP process, the abrasion always occurs with friction. So, the contact form can be judged by abrasion kind obtained by the relating test. In wafer CMP process, the film of chemical reaction on wafer surface is removed by mechanical action, but the mechanical action on wafer surface are mainly produced by the abrasive in slurry, the pad and the slurry. Each mechanical action is corresponding to a certain contact state and brings different abrasion behavior. Which one of the mechanical actions plays the dominant role in material removal of wafer CMP process? If the mechanical action form is achieved, the contact form between the wafer and the pad can be obtained.

According to the literature (Lin *et al.*, 2004), the hydrodynamic of slurry between the wafer and the pad can be neglected in wafer CMP process. It is concluded that the higher MRR is obtained when the contact form between the wafer and the pad is solid-solid contact and the lower MRR happens when the wafer does not contact with the pad in wafer CMP process. So at the same condition, when the material removal related to abrasive abrasion is in domination, the contact form between the wafer and the pad can be thought as solid-solid contact.

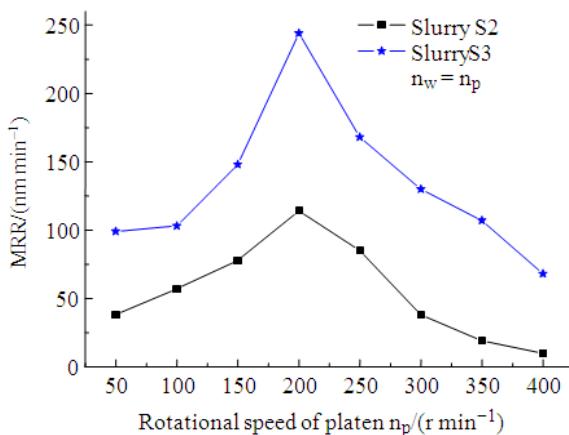


Fig. 4: MRR of CMP using slurry S2 and slurry S3

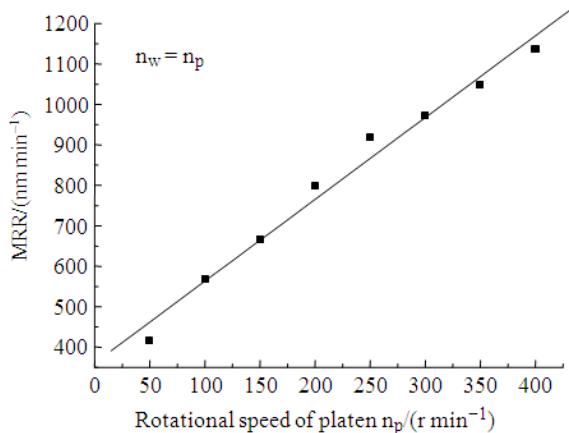


Fig. 5: MRR of CMP using slurry S1

MRR test of wafer CMP: There are 3 different slurries, made by Tianjing Jingling Electronic Material Technology Corporation, used in CMP test. One is number S1, the “FA/O” slurry used to polish silicon wafer. The second slurry is number S2 consisting of DI water and abrasives. The content of abrasives in slurry S2 is the same as slurry S1. The third slurry is number S3. The chemical ingredient and content of Slurry S3 is the same as slurry S1, but without abrasive in it. Test condition is the same as the section of Experimental parameters. In the choice of parameter, take the polishing pressure $P_0 = 6$ psi. Other parameters are the same as section of Experimental parameters too. The test results are shown in Fig. 4-5. Figure 4 shows the test results polishing with slurry S2 and S3 under different rotational speed. Figure 5 shows the test results polishing with slurry S1 under different rotational speed.

Static corrosive test: The sample was immersed into the slurry S1 for 60 min. During the static corrosive tests, the slurry was stirred continuously. Supposing MRR_C denotes the MRR brought by chemical action of slurry. There was $MRR_C = 0.05 \text{ nm min}^{-1}$.

Test of MRR produced by mechanical action of the pad: Supposing MRR_p denotes the MRR brought by mechanical action of the pad without chemical action. According to the test results of CMP with DI water, the MRR of mechanical action made by polishing pad is $MRR_p = 0.5 \text{ nm min}^{-1}$.

DISCUSSION

Analyzing of MRR produced by mechanical action of the abrasive: By Fig. 4, because there is no chemical ingredient in slurry S2, it can be concluded that the MRR polishing with Slurry S2 is brought by the mechanical action of the pad and the abrasive. By the analysis above-mentioned, the mechanical action of the pad is very small. So it can be considered that the MRR polishing with Slurry S2 is fully brought by the mechanical action of the abrasive. Supposing MRR_{am} , MRR_{S2} , MRR_{S3} denote the MRR produced by mechanical action of abrasive, the MRR polishing with slurry S2 and the MRR polishing with slurry S3, respectively. So, there is $MRR_{am} = MRR_{S2} - MRR_p \approx MRR_{S2}$.

Analyzing of MRR produced by the interaction between the mechanical action of the pad and the chemical action of slurry: By Fig. 4, because there is no abrasive in slurry S3, it can be concluded that the MRR polishing with Slurry S3 is brought by the mechanical action of the pad, the chemical action and the interaction between the mechanical action of the pad and the chemical action of slurry. According to the analysis above-mentioned, the $MRR_C = 0.05 \text{ nm min}^{-1}$ and the $MRR_p = 0.5 \text{ nm min}^{-1}$. So it can be considered that the MRR polishing with Slurry S3 is fully brought by the interaction between the mechanical action of the pad and the chemical action of slurry. So, there is $MRR_{PC} = MRR_{S3} - MRR_C - MRR_p \approx MRR_{S3}$. Where MRR_{PC} is the MRR of the interaction between the mechanical action of the pad and the chemical action of slurry.

Analyzing of MRR produced by the interaction between the mechanical action of the abrasive and the chemical action of slurry: Supposing MRR_{aC} is the MRR of the interaction between the mechanical action of the abrasive and the chemical action of slurry.

According to the analysis above-mentioned, there is $MRR_{ac} \approx MRR_{S1} - MRR_{S2} - MRR_{S3}$. Then, the MRR_{ac} under different rotational speed can be calculated expediently. supposing that CR is the contribution rate for the MRR, $CR = MRR_i/MRR_{S1}$, MRR_i is the material removal rate produced by the i factor, MRR_a is the material removal rate produced by the abrasive, $MRR_a = MRR_{am} + MRR_{ac}$. So, the interaction between the mechanical action of the abrasive and the chemical action of slurry was in dominant and had a very important influence in MRR in wafer CMP.

According to the analysis results above-mentioned, the mechanical action produced by abrasive on wafer surface is the main mechanical action in material removal of wafer. By abrasion theory, it is concluded that the material removal behavior is two-body abrasive wear under chemical action of slurry mainly in traditional CMP process. However, the two-body abrasive wear can be realized only when the abrasive is embedded the asperity of the pad under the pressure of the wafer and removes the chemical reaction layer on wafer surface. So it is concluded that the contact form between the wafer and the pad is solid-solid contact in wafer CMP process and the polishing pressure is born by the pad fully.

CONCLUSION

- In wafer CMP process, the contact form between the wafer and the pad can be deduced by the abrasion behavior on wafer surface and the lubrication behavior between the wafer and the pad
- According to the tribological behavior of the wafer CMP system, it can be drawn that the lubrication state of wafer CMP should be in the boundary lubrication, not mixed lubrication, say nothing of hydrodynamic lubrication. The material removal of the wafer surface is the process with the growing and destructing of the boundary film produced by chemical reaction on wafer surface
- The material removal behavior is two-body abrasive wear under chemical action of slurry mainly , the contact form between the wafer and the pad is solid-solid contact in wafer CMP process and the polishing pressure is born by the pad fully

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