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On the Relationship between Material Removal and Interfacial Properties at Particulate Abrasive Machining Process

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연마가공에서의 접촉계면 특성과 재료제거율간의 관계에 대한 연구

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Abstract – 본 연구에서는 마이크로/나노입자를 이용한 연마가공 공정에서의 입자-표면간 접촉상황에서 접촉계면의 기계적 성질과 재료제거율간의 관계를 실험적으로 고찰하였다. 연마가공 공정에서의 입자-평면간 접촉을 모사하기 위하여 팁 대신 실리카 입자를 부착한 콜로이드 프로브를 이용한 원자현미경 실험을 통하여 마찰력과 강성을 실험적으로 측정하였다. 실험결과와 이론적 접촉해석으로부터, 마찰계수는 횡방향 접촉강성에 따라 대체적으로 증가하고 재료제거율은 실리카 입자와 Cu, PolySi, Ni과 같은 다양한 재료표면간 접촉에서의 마찰계수들과 지수함수적인 비례관계를 가지고 있음을 규명하였다.

In this paper, the relationship between the material removal rate and the interfacial mechanical properties at particle-surface contact situation, which can be seen in an abrasive machining process using micro/nano-sized particles, was discussed. Friction and stiffnesses were measured experimentally on an atomic force microscope (AFM) by using colloidal probes which have a silica colloid particle in place of tip to simulate a particle-flat surface contact in an abrasive machining process. From the experimental investigation and theoretical contact analysis, the interfacial contact properties such as lateral stiffness of contact, friction, the material removal rate were presented with respect to some of material surfaces and the relationship between the properties as well.

Keywords – abrasive particle(연마입자), chemical mechan ical polishing(CMP, 기계-화학적 연마가공), contact stiffness(접촉강성), material removal rate(MRR, 재료제거율), tribology(트라이볼로지)

1. Introduction

Studies of abrasive machining and surface finishing processes using ultrasmall particles have long been a part of tribology. In an abrasive machining process using micro/nano-sized particles, two- or three-body contact takes place. For example, in the case of the chemical-mechanical polishing (CMP), a wafer surface is pressed and forced against a polishing pad. The pad is covered with liquid slurry that contains abrasive particles with average diameter of hundreds of nanometers. The wafer is moved relative to the pad, and the rate at which material is removed from the wafer surface is often described by the heuristic equation called Preston's law[1]. Several parameters such as pressure and velocities of carrier and

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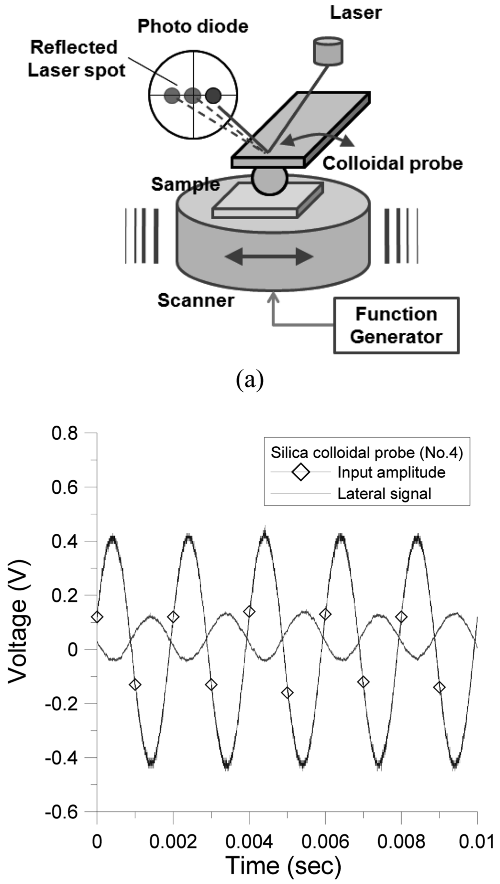
pad control the CMP removal and finish of the material on the wafer. The wide array of parameters and the competing interaction of their effects makes CMP a difficult process to model and predict.

Nevertheless, great efforts have been made to improve and solve the immediate problems of the CMP process such as surface defects, relatively low efficiency, post-process contamination, and high machining cost. Many previous studies, however, have approached mainly the process characteristics at a large-scale based whole machining system rather than a small-scale based particle-surface contact[1-6]. The polishing process for microelectronics is very complex because it exists on multiple scales, from the wafer-scale (hundreds of millimeter) to the damascene feature-scale (less than a micron), a distance scale factor of more than five orders of magnitude. Although the process is widely applied in integrated circuit (IC) fabrication, it is still a process of trial and error. As the pattern width of an IC structure is reduced rapidly, more precise and stringent control of the process are needed. In addition, in order to get the machined surface with high quailty by using such particle abrasion processes, the mechanical and tribological characteristics at particle-surface contact interface are very important and the fundamental understandings of them are essential.

Based on these backgrounds, this work was focused on finding the relationship between friction, material removal rate, and the system stiffness at a particle-surface contact, using both theoretical models and experiments on an atomic force microscope (AFM). The dependency of the load and contact material on the tribological behavior at the contact interface will be discussed. Contact stiffness were considered to observe the stiffness difference induced by various surface materials on a wafer used in semiconductor fabrication.

2. Experimental details

To observe and analyze various interfacial phenomena at particle-surface sliding contacts, a commercial AFM (Nanoscope III, Digital Instruments Co.) was used. For various probe-surface contacts, frictional force and contact stiffness according to the normal load were measured. Sliding velocity was set to 10 μm/s. All of the experiments were carried out at room temperature and the humidity level of 35~50% RH.



(a)

(b)

Fig. 1. Lateral contact stiffness measurement; (a) a schematic illustration of the experimental setup, (b) an example of the measured data.

As for the sample surface, various materials such as copper, nickel, polysilicon were coated on a silicon wafer. The coating thicknesses of the materials were about 1 μm.

To simulate the contact between a particle and a workpiece or wafer surface in abrasive machining process, colloidal probes attached with a silica microsphere on each cantilever in place of tip were used. In order to make the probes with various normal and lateral stiffnesses for the experiment, cantilevers with

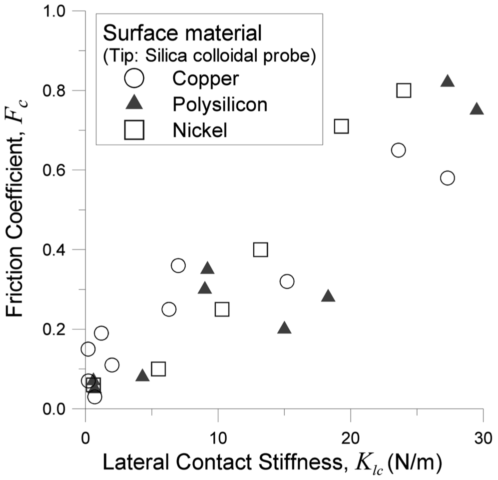


Fig. 2. A plot of the relationship between friction and lateral stiffness of the contact between a silica colloidal probe and various material surfaces.

various dimensions were selected. The average size of a particle was the range of 5~10 μm diameter. A custom-built micro-manipulator setup was used for the colloidal probe fabrication.

The normal and lateral stiffnesses of the colloidal probes and frictional force calibration were measured on the basis of the established methods[7-10]. Especially, the changes in the lateral contact stiffness according to various materials and loads were measured by using AFM. In the measurement, as shown in Fig. 1, the piezo scanner moves back and forth laterally by applying the well-defined sinusoidal wave within the range that no slipping at the particle-surface contact occurs and then the consequent lateral deflection signal of the probe is detected. The signals shown in Fig. 1(b) are the ones that are obtained in the case of no slip at the probe-surface contact interface.

3. Results and Discussion

Fig. 2 shows variation in the friction coefficients of various material surfaces with respect to the lateral stiffness of contact. The data were obtained experimentally by using the colloidal probes with various lateral and normal stiffnesses. The data indicates that friction coefficient generally tends to increase with lateral contact stiffness regardless of material. Theoretically, the lateral contact stiffness for a sphere-plane contact geometry can be given as the following equation[11]:

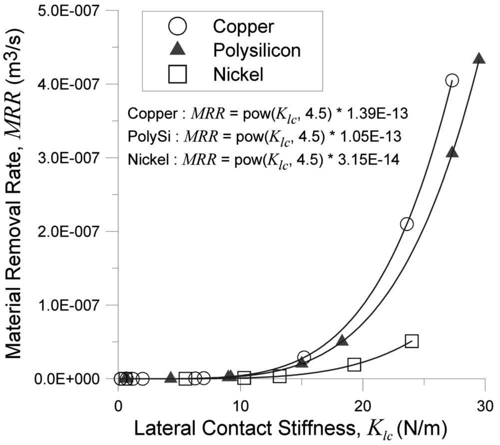


Fig. 3. Material removal rate (MRR) with respect to the lateral stiffness of contact of some materials.

$$K_{lc} = 8aG^* = 8G^* \sqrt[3]{\frac{3RF_N}{4E^*}} \tag{1}$$

where, a, R, F_N, G^*, E^* are the contact radius, the radius of an abrasive particle, the load applied to the particle, the effective modulus of shear and elasticity, respectively. From the equation, it can be found that the lateral stiffness of contact increases with the normal load. Increase in the normal load will become the contact interface stiffer and consequently friction will rise up. This corresponds well to the experimental result.

The amount of material removal generated by one time abrasion using a single abrasive particle is extremely small and hardly detected reliably even with an AFM. Therefore, the material removal rate was estimated by a theoretical contact model. Considering a sphere-plane contact geometry and mechanics, the material removal rate(MRR) obtained by a single abrasive particle can be expressed as the following Eq.(2) [12]:

$$MRR = \frac{2V}{3R}\sqrt{\left(\frac{F_N}{\pi H}\right)^3} \tag{2}$$

where V, H are the sliding velocity and the hardness of the material in contact, respectively.

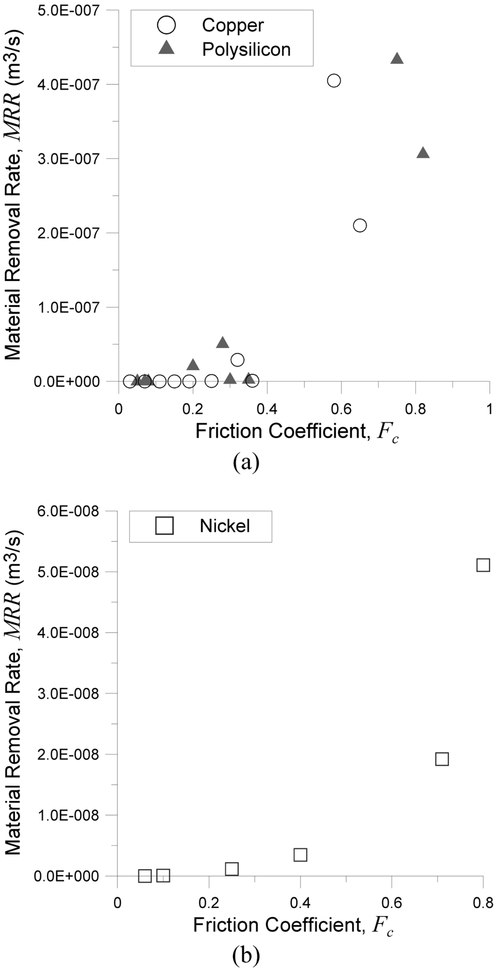


Fig. 4. Material removal rate (MRR) with respect to friction coefficient; (a) copper, polysilicon, and (b) nickel.

From Eq.(1), the following equation can be drawn :

$$F_N = \frac{4E^*}{3R}\left(\frac{K_{Ic}}{8G^*}\right)^3 \qquad (3)$$

Also, from Eq.(2),

$$F_N = \pi H\sqrt[3]{\left(\frac{3R}{2V}MRR\right)^2} \qquad (4)$$

By combining Eqs. (3) and (4), the relationship between MRR and the lateral stiffness of the contact can be obtained as following:

$$MRR = \frac{2V}{3R}\sqrt{\left(\frac{4E^*}{3\pi RH}\right)^3\left(\frac{K_{Ic}}{8G^*}\right)^9} \qquad (5)$$

Eq.(5) indicates that the material removal rate is proportional to square root of the 9th power of the lateral stiffness of contact under a sphere-plane contact condition. Fig. 3 gives the relationship according to the materials in contact with a silica colloidal probe.

From the observations so far, the relationship between MRR and friction coefficient can be obtained. Fig. 4 shows the material removal rates and friction coefficients of copper, polysilicon and nickel surfaces that were slid against a silica colloidal probe. From the result, it can be found that the material removal rate seems to jump up above certain friction coefficient in the case of all materials considered. The friction coefficients at the boundary where the material removal rate jumped up were around 0.4~0.5 in the case of the materials used in this experimental study.

By considering nanoscale scratch situation, the validity of such a jump in the material removal rate may be verified. Eq.(6) gives the relationship between load and penetration depth h in a nano-scratch situation [13-15]:

$$F_N = \frac{4}{3}E^*\sqrt{R}h^{\frac{3}{2}} \qquad (6)$$

Also, a general exponential relation between the lateral force F_L and the normal load is experimentally found as shown in Eq.(7) and the relation is secured for virtually all types of solid materials [14] :

$$F_L = KF_N^{\frac{3}{2}} \qquad (7)$$

where K is the scratching coefficient which reflects the effects of scratching direction on a material and the indenter (particle) geometry.

Combination of Eqs. (6) and (7) with the definition of the friction coefficient gives the following:

$$h = \frac{3}{4E^*\sqrt{R}}\left(\frac{F_c}{K}\right)^{\frac{4}{3}} \qquad (8)$$

The material removal rate at a constant scratch length and a constant speed will correspond to the penetration depth. Therefore, the relationship between the material removal rate and the friction coefficient can be deduced from Eq.(8) and this exponential relation can also be found in Fig. 4. The relation shown in the experimental data, however, is quite different from the relation shown in the equation. This may be due to the fact that the friction coefficient is also largely varied with the lateral stiffness of the indenter (particle) as well as the lateral contact stiffness, as reported elsewhere [16].

4. Conclusions

In this paper, the relationship between the material removal rate and the interfacial mechanical properties at particle-surface contact situation, which can be seen in an abrasive machining process using micro/nano-sized particles like chemical mechanical polishing (CMP), was discussed. Friction and stiffnesses were measured experimentally on an atomic force microscope (AFM) by using colloidal probes with a silica colloid particle in place of tip to simulate the particle-flat surface contact in an abrasive machining process.

From the experiment and theoretical contact analysis, the interfacial contact properties such as lateral stiffness of contact, frictional force, the material removal rate were presented with respect to some of material surfaces and the relationship between the properties as well. The results showed that the friction coefficient increased with the lateral stiffness of the contact and the material removal rate had an exponential relation with the friction coefficient at the contact interface of a silica particle and various material surfaces.

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