ABSTRACT

Particle’s behavior in the slurry with power-law viscosity shows great effect on the wafer surface polishing process. Hydrodynamic pressure is periodically generated on the surface asperity when particles are passing through. Due to the periodic pressure, fatigue fracture occurs and begins from the top to the bottom of the asperity, then the material on the top is removed. Removal rate is calculated based on the energy-balance fracture theory, and the result shows good agreement with experiment data. The effects of the particle size and the slurry film thickness are also discussed.

1. INTRODUCTION

Polishing slurry contains nano abrasive particles and chemical reagents. Some experiment results have proved that the particle size and slurry properties take great effects on the polishing results\textsuperscript{[1\textendash}3]. In many researches, particle abrasive\textsuperscript{[3]} and hydrodynamic pressure\textsuperscript{[4]} are considered to cause the polishing effect, little work appears to have been done on the hydrodynamic pressure caused by nano particles near the wafer surface. This pressure is calculated in this paper and the effects of nano particles’ behavior and non-Newtonian properties of the slurry are analyzed.

2. MODELS AND METHODS

All particles are considered to be spherical with an average diameter of $D$\textsuperscript{[3]}. The wafer surface is a kind of Reynolds surface. The schematic of polishing process is shown in figure 1(a). The geometric model of SiO$_2$ particle and the wafer asperity is shown in figure 1(b). Parameter $x_0$ in figure 1(b) represents the particle’s relative position to asperity peak on direction $x$ at different moment. The dashed line represents the original position of the particle while the continuous line represents the current position of the particle.

When a nano particle is moving towards the asperity, the fluid film thickness $h(x)$ decreases gradually and hydrodynamic pressure is developed in the film. There are a lot of particles in the slurry and they are continuously passing through the asperity during the polishing process, so the hydrodynamic pressure is periodically generated on the asperity surface. One period is defined here as the time that is needed for a particle’s center passing the whole asperity wave length. The pressure at different moment in one periodic can be calculated by solving Reynolds equation (1).

$$
\frac{\partial}{\partial x}\left(\frac{1}{12}\frac{1}{h(x)}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{12}\frac{1}{h(y)}\frac{\partial p}{\partial y}\right) = \frac{U}{\gamma h}
$$

(1)

In equation (1), $p$ is the pressure, $h$ is the fluid film thickness, $x$ and $y$ are the directions of the coordinates shown in figure 1(a), and $\gamma$ is the viscosity. Usually, the polyoxyethylene (PEO) is added into the slurry. The PEO has a long chain and the slurry has some non-Newtonian properties. A rheological experiment has been made with Haake Rotovisco RS300, and result of the slurry viscosity variation is shown in figure 2. The viscosity can be specified by the power-law model shown as equation (2). $k$ is a measure of the average viscosity of the slurry, $n$ is the power-law index. $T_0$ is the reference temperature and the temperature effect is not considered here. According to the experiment data, the fitted value of $n$ is 0.366, $k$ is 4.3, the lower and upper limits of the viscosity are 0.08 Pa$\cdot$S and 0.001 Pa$\cdot$S, respectively. The fitted power-law model is shown as the dashed line in figure 2.

$$
\eta = k\gamma^{n-1}x^{n-11}
$$

(2)
Reynolds equation (1) is numerically solved with finite differential method. Super relaxation iteration is adopted, and the relaxation factor is 1.5. The calculated pressure is dimensionless and its expression is \( \bar{p} = \frac{pH}{6\eta U} \).

### 2. ASPERITY FATIGUE

Figure 3 shows the pressure on the asperity peak in one periodic and corresponding surface deformations. \( P \) represents the pressure and \( d \) represent the deformation.

It is well known that fatigue fracture will occur at the material surface under cyclic loading condition. Fatigue fracture will happen at the peak firstly, and the material of the asperity will be removed from the top to the bottom. It will lead to the roughness height reduction and it is a kind of important material removal mechanism.

Energy-balance fracture theory\(^{[5]}\) is adopted here to establish a material removal model for the polishing process under ideal conditions. The work done by the hydrodynamic pressure is to break down the bind energy of silicon. The input energy \( W_i \) produced by hydrodynamic pressure in one periodic is calculated according to equation (3). In the equation, \( m \) is the discreet point in one periodic.

\[
W_i = \sum_{j=1}^{m} P_i \cdot \Delta x \cdot (d_i - d_{i-1})
\]

The input energy at the asperity peak is \( 1.66 \times 10^{-17} \) (J). The bind energy of silicon is 99.8eV, which is about \( 10^{-7} \) (J). The stable structure of silicon will be destroyed under the periodical input energy and the micro crack will appear at the asperity peak. With the periodical input energy, the micro crack grows and the fatigue fracture happens.

### 3. REMOVAL RATE

When 1 nm height material of the asperity is removed, the time requested can be calculated as equation (4).

\[
t = R_s \cdot 2S \cdot f \cdot W_i.
\]

\( R_s \) is the silicon surface energy, and it is equal to 1400 mJ/m\(^2\). \( S \) is the area of new formed surface. \( f \) is the particles passing frequency. \( W_i \) is the work done by the hydrodynamic pressure in one periodic. \( \Delta h \) is the removed height of the asperity.

\[
S = \Delta h \cdot \tan(\frac{\pi}{2}).
\]

\[
W_i = \sum_{j=1}^{m} \sum_{i=1}^{n} p_{i,j} \cdot \Delta x \cdot (d_{i,j} - d_{i-1,j})
\]

\[
f = \frac{U}{\xi}
\]

\[
\xi = \sqrt{1 \times 10^6 \cdot m_s} \times 6.022 \times 10^{23}
\]

The removal rate is shown in figure 4. It shows good agreement with the experiment data of 24 nm/min given by Lei\(^{[2]}\), also it is agrees with the removal rate given by Zhao\(^{[3]}\). However, the removal rate decreases as the removed height increases. Because the area of the new formed surfaces increases when the height of asperity decreases.

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### REFERENCES