Numerical Analysis of a Slurry Flow on a Rotating CMP Pad Using a Two-phase Flow Model

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Chemical mechanical polishing (CMP) is a very precise planarization technique where a wafer is polished by a slurry-coated pad. A slurry is dropped on the rotating pad surface and is supplied between the wafer and the pad. This research aims at reducing the slurry consumption and removing waste particles quickly from the wafer. To study the roles of grooves, slurry flows were simulated using the volume of fluid method (two-phase model for air and slurry) for pads with no grooves, and for pads with circular grooves.

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NOMENCLATURE

F = external force vector
m = mass transport
p = pressure
t = time
v = velocity components of each axis direction
α = volume fraction of slurry
μ = viscous coefficient
ρ = fluid density

1. Introduction

Chemical mechanical polishing (CMP) is an increasingly important planarization technique for producing multi-level interconnections.[1-4] In CMP, the wafer surface is polished by a slurry lowing on a polishing pad in contact with the wafer. There are various types of possible groove patterns on the polishing pad, including concentric circular, radial, lattice, and spiral forms. Grooves are intended to apply the slurry evenly, to improve the wafer surface flatness and removal rate efficiency, and to remove waste particles to prevent deep scratches and processing defects. Computational fluid dynamics (CFD) is a powerful tool for investigating the slurry flow on various grooved pads,[5-14] and to determine any relationship to the polishing performance.

More than a half the CMP cost is the price of the slurry consumed in the process. The objective of our research is to reduce the amount of slurry used while still supplying it evenly and effectively to the wafer and removing waste particles from the wafer quickly. We would like to optimize the groove pattern on the polishing pads. We can analyze the influence of the grooved pads on the slurry flow using CFD. We also wish to analyze flows with wafers, but before we can do that, we must create a two-phase flow simulation. The basic role of the grooves in controlling the slurry flow on the polishing pad must be studied without wafers. We modeled slurry flows using the volume of fluid (VOF) method with a two-phase model for the air and slurry. We used the model on pads without grooves and pads with circular grooves to study the effect of the grooves.

2. Simulation Method

2.1 Mathematical Model

For this analysis, we used FLUENT version 6.2 (Fluent Inc., Lehanon, NH) heated fluid analysis software. FLUENT has a pre-processor called Gambit, which creates a calculation lattice for the analysis. The governing equations consist of the continuity equation for mass conservation, Eq. (1), and Navier-Stokes equations for momentum, Eq. (2). Two-phase flow is modeled using the VOF method. Equation (3) is for the mass transport, and Eq. (4) indicates that the total volume fraction of the air and slurry is 1. These equations are discretised by the limited volume method.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \left[\mu\left(\nabla \vec{v} + \vec{v}^{T}\right)\right] + \vec{F} \tag{2}$$

$$\frac{\partial}{\partial t}(\alpha_q)+\nabla\cdot(\alpha_q\vec{v}_q)=-\frac{1}{\rho_q}\left(\sum_{p=1}^{n}\dot{m}_{pq}-\alpha_q\frac{d_q\rho_q}{dt}\right) \tag{3}$$

$$\sum_{q=1}^{n}\alpha_q=1 \tag{4}$$

2.2 Model Description and Simulation Conditions

Figure 1 shows a typical polishing pad with concentric circular grooves. The pad diameter is 455 mm. Slurry is supplied via the 2.5-mm diameter tube at the center of the pad at a flow rate of 150 cc/min. We studied the basic flow field without a wafer; the wafer will be included in our future work. The groove pitch was 2 mm, the groove width was 1 mm, the land width was 1 mm, and the groove depth was 1 mm. There were 108 concentric circular grooves.

The flow was treated as unsteady for both types of pad. We used a time step of 0.001 s and assumed that the slurry had the physical properties of water. For our simulations, we assumed a pad rotation speed of 60 rpm, a groove depth of 1 mm, and a pad diameter of 455 mm. We used 820,000 hexagonal elements for the non-grooved calculations and 1,500,000 hexagonal elements for the concentric-circular groove case.

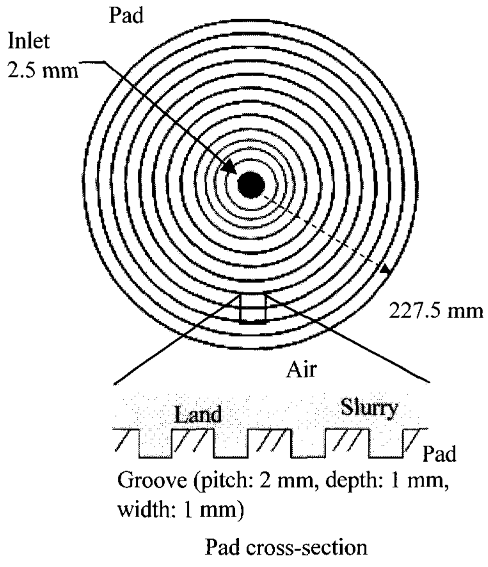


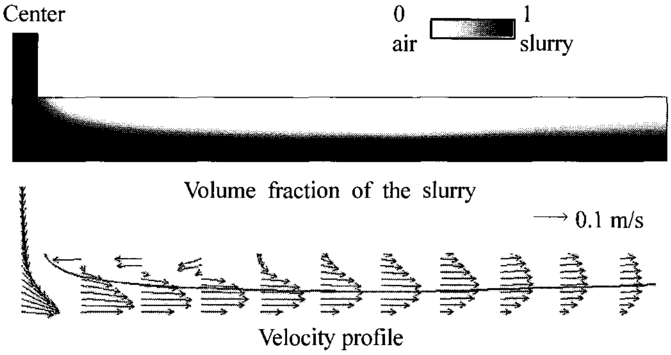
Fig. 1 Dimensions of the circular grooved pad

3. Results and Discussion

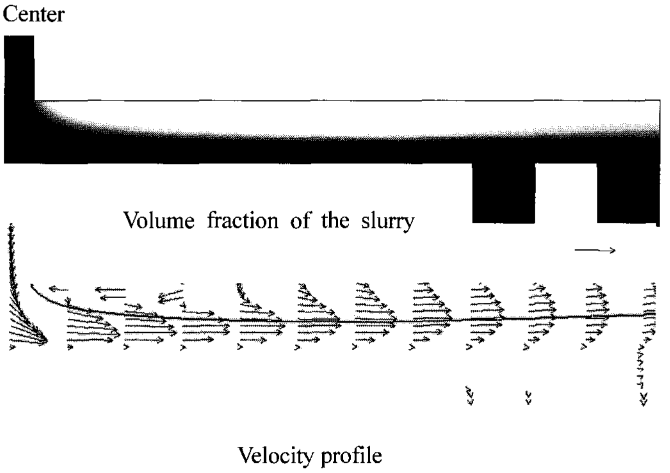
Figure 2 shows a comparison of the volume fraction of the slurry and velocity profiles for the grooved and non-grooved pads. A volume fraction of 1 (black) indicates 100% slurry (0% air) while a volume fraction of 0 (white) indicates 0% slurry (100% air). The fluid layer thickness was estimated for a 50% slurry volume fraction. Wafer surface damage that occurs during CMP was modeled by Ring *et al.*[15] In our simulation, slurry was dropped on the pad center and spread over the pad surface by the centrifugal force. The velocity profiles show that the flow was fast at the slurry surface and slow close to the pad surface due to the wall resistance. Although the flow inside the groove was almost stagnant, vortices with very small velocities were observed. The grooves were small and the viscous effect was dominant, so the flow field was laminar and no turbulent flow was observed.

Figure 3 shows the results of particle tracking. Here, two phases represent the air and the slurry (modeled by water). The effect of particles on the flow field was negligible but was important in the polishing process. Water and particles less than 1 μm in diameter and 2.2g/cm^3 in density move in a similar manner. After simulating the flow field, particles with same density as the slurry were selected and their movements followed. On the non-grooved pad, particles close to the slurry surface (initial height of 0.5 mm) were carried away quickly, while particles close to the pad surface (initial height of 0.07 mm) flowed slowly. On the pad with circular grooves, particles spread more slowly and particles close to the pad surface did not spread at all. The inset to Fig. 3 shows they were trapped inside the groove. We analyzed their motion and found they moved in a spiral.

These results indicate that circular grooves tend to keep the slurry on the pad and are effective for reducing slurry consumption. The circular grooves also keep the particles inside. Particles that are kept at the bottom of the grooves by gravity do not matter, but if the particles do flow out of the pad, they could cause the deep scratches on the wafer.

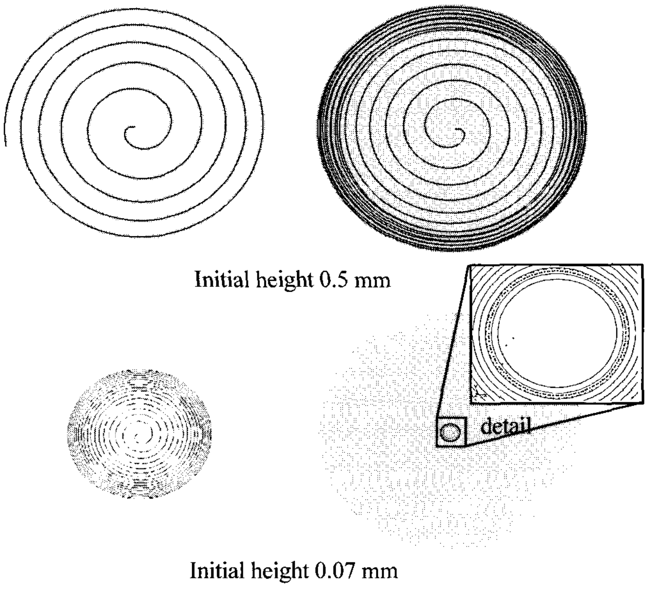


(a) Non-grooved pad



(b) Circular-grooved pad

Fig. 2 Flow profiles at vertical cross-sections



(i)Non-grooved pad (ii) Circular-grooved pad

Fig. 3 Particle tracking on the pads

4. Conclusions

We conducted numerical simulations of slurry flows on polishing pads using the VOF method (two-phase model for the air and slurry). The aim of our research was to reduce the slurry consumption and remove particles quickly. We compared non-grooved and circular-grooved pads and studied the role of the grooves. Slurry was dropped on the pad center and spread over the surface by the centrifugal force. The velocity profiles show that the flow was fast at the slurry surface and slow close to the pad surface due to the wall resistance. We observed stagnant flow in the circular grooves.

Particles on the slurry surface were carried away quickly while particles close to the pad surface flowed slowly. Particles close to the surface of the pad with circular grooves did not spread and were trapped inside the grooves. This indicates that the circular grooves tend to keep the slurry on the pad and are effective for saving slurry. However, the circular grooves also keep particles inside. Too many circular grooves could hold the polish waste particles, resulting in deep scratches on the wafer.

Future studies will consider the effect of other factors on the slurry flow pattern, such as the motion of the conditioner and wafer, the temperature, the pad surface roughness, and the fluid drop-off location.

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