CMP Profile Simulation Using An Elastic Model Based on Nonlinear Contact Analysis

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Abstract—**Recently, simulation of Chemical Mechanical Polishing (CMP) is becoming more important because planarity and unformity which are dependent on many dynamic factors are difficult to control. In this paper, a profile simulation environment based on the linear elastic material and nonlinear contact analysis that considers equipment parameters, such as pad hardness, thickness and down pressure is presented. In transient CMP simulation using the elastic model, the contact stress on the wafer surface is the dominent factor in polishing rate during the CMP process. The profiles of CMP simulation agree well with the measured data. This simulation can be used to optimize the CMP process and to generate design rules for filling dummy patterns which are used to improve planarity.**

I. Introduction

CMP has been widely used as a planarization technique for multilevel metalization in IC device manufacturing. CMP provides superb global and local planarization that meets the tight optical lithographic requirement for the depth of focus. Post-CMP layer thicknesses are critical to device performance and are difficult to control because CMP is very equipment and consummable dependent. Therefore, the simulation approach is getting more important because planarity depends on many dynamic factors, such as feature sizes, layout, equipment and process conditions. Another purpose of simulation is to understand the CMP mechanisms, such as the relationship between stress and polishing removal rate.

Much work has been done in process modeling of CMP [1]. Approaches, such as the phenomenological model[2], combined asperity contact and fluid flow model[3], chip level elastic model[4], feature-scale fluid-based erosion model[5], have been proposed.

In this paper, a transient profile simulation environment based on the linear elastic material and nonlinear contact analysis that takes in account the equipment parameters, such as pad hardness, thickness and down pressure[6].

II. Model

In CMP, the wafer-pad interface is a complex mixture of solid-liquid-solid and solid-solid contact. It can be shown that the hydrodynamic pressure of the fluid flow by slurry is small at low platen rotating speeds. In this case, the load is carried mainly by asperities of the pad surface and a polishing model that considers only the solid-solid contact is sufficient[3], [8]. This suggests that the stress-based process may contribute to the polishing rate. In addition, it is assumed that the surface of pad is smooth. Therefore, we ignore the effects of the slurry on the interface between the pad and wafer.

First, we consider the following set of governing equations for a elastic body. By considering the equilibrium of forces on a small differential element of the body, the equilibrium equations can be written as follows:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + f_i = 0 \tag{1}$$

where f is the body force and σ is stress. The planar solid (continuum) element of 4-node bilinear, reduced integration, and hourglass control type is used for mesh refinement. This reduced integration element type models bending accurately at the edge of the feature.

All materials are assumed to be linearly elastic because of simulation time and the difficulty for the nonlinear case. However, the nonlinearity could be incorporated if data were available. The simplest form of the linear elasticity is the isotropic case, and the stress-strain relationship (Hooke's law) is given by

$$\left\{ \begin{array}{c} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \gamma_{11} \\ \gamma_{22} \\ \gamma_{33} \end{array} \right\} =$$

$$\begin{bmatrix} 1/E & -\nu/E & -\nu/E & 0 & 0 & 0 \\ -\nu/E & 1/E & -\nu/E & 0 & 0 & 0 \\ -\nu/E & -\nu/E & 1/E & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G \end{bmatrix} \left\{ \begin{array}{c} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{array} \right\} \tag{2}$$

where E is Young's modulus and ν is Possion's ratio. The shear modulus G can be expressed in terms of E and ν as $G = E/2(1+\nu)$. These parameters may be given as functions of temperature and other predefined fields, if necessary. Table I shows the parameters of materials in this simulation and the pad parameters are measured values.

The stress on the wafer surface comes from two sources; the (*i*) down force from the carrier and (*ii*) shear force from friction on the wafer due to the relative motion of the pad and wafer. The contribution of the shear stress to the removal rate is uniform across the wafer because

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TABLE I
PROPERTIES OF MATERIALS

Material	Young's Modulus (MPa)	Poisson's ratio	Thickness (μm)
SUBA-IV[a]	115	0.2∼0.3	2032
IC-1000[a]	380	0.3∼0.4	1270
Silicon	110×10^3	0.28	675
Oxide	70×10^3	0.3	1.6

[a]The measurement system is from Roelig DIN53513.

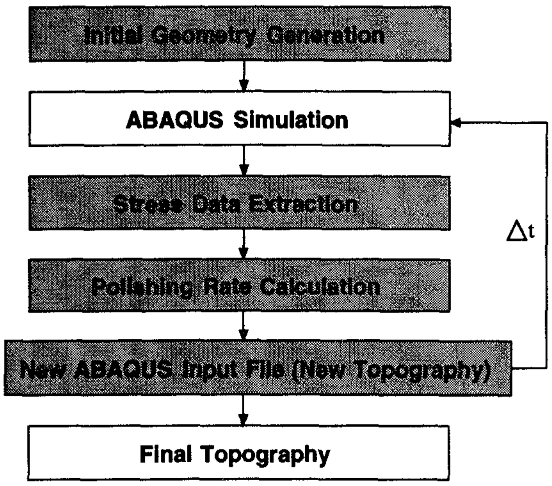


Fig. 1. The algorithm for transient profiles of CMP simulation.

the relative velocities of the pad and wafer are spatially uniform[8].

The boundary conditions are fixed at the bottom of the pad and the symmetric boundary conditions are imposed on the left and right side. Down pressure uniformly distributed on the top of the wafer surface is considered.

An infinitesimal sliding formulation is applied to modeling the interaction between the wafer and pad surface. In this problem, the contact surfaces undergo negligible siliding relative to each other. This is the approximation most commonly used in classical solutions of the contact problem, such as the Hertz contact problem.

The polishing rate PR_i at each node is calculated from the extracted stress as follows:

$$PR_i = PR_0 \cdot \sigma_i, \qquad 1 = \frac{1}{N} \sum_i \sigma_i \tag{3}$$

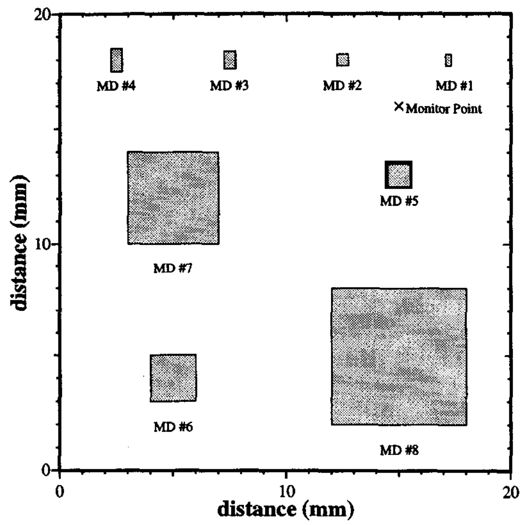
where PR_0 is the polishing rate of the blanket wafer, σ_i is the normalized stress enhancement factor, and N is the total number of node points on the wafer surface.

Then, the surface of the wafer as a function of the polishing time t after polishing for the time step Δt can be written as

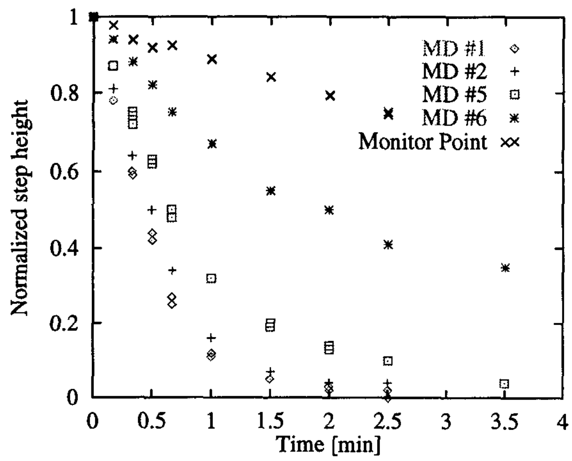
$$S_i(t + \Delta t) = S_i(t) - PR_i \cdot \Delta t \tag{4}$$

where S_i is the position of the wafer surface at each node. Iterations provide the time-dependent mechanical behavior of the wafer topography.

Fig. 1 shows the proposed algorithm for CMP transient simulation using ABAQUS, a general purpose finite element program[7]. Input variables are the initial wafer geometry, pad hardness and structure, polishing rate, etc. During the ABAQUS simulation, the small- and finite-sliding contact analysis and hourglass-controlled element type must be considered to extract a contact stress distribution at the surface of the wafer. The polishing rate PR at each surface node is calculated using the polishing rate for the blanket wafer and the enhancement factor from the normalized contact stress. A new topography is generated after a small time step Δt. Then the above procedure is repeated as in a real CMP process.



(a) Test layout for CMP experiments

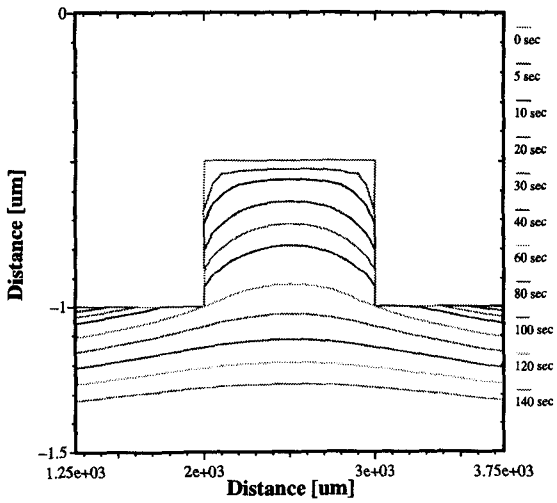


(b) Normalized step heights vs. time

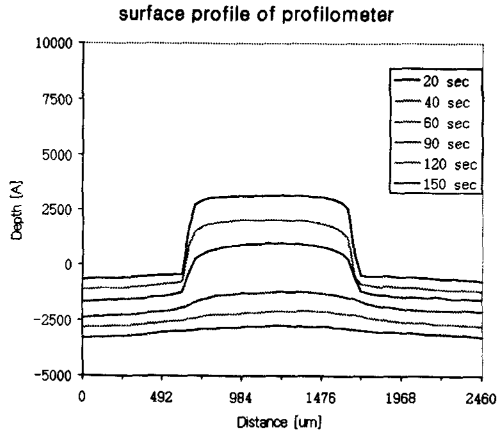
Fig. 2. (a) Test layout for CMP experiments and (b) Normalized step heights monitored during the CMP experiment.

III. EXPERIMENTS

Fig 2. shows the layout of the test CMP process and feature sizes are designed as square patterns from 0.25 to 6 mm. Test patterns are anisotropically etched down to a depth of 0.5 μm and deposited with the oxide film of 1.6 μm thickness. Wafers are polished using a double-



(a) Transient profiles of 2D simulation ($\Delta t = 5$ *sec*)



(b) Surface profiles of the wafer monitored by a profilometer

Fig. 3. The simulation and experimental results of test module MD #5. (a) Transient profiles of 2D simulation ($\Delta t = 5$ *sec*). (b) Surface profiles of the wafer monitored by a profilometer (process condition : up-feature size = 1 *mm*, step height = 5000 Å, down pressure = 8 *psi*).

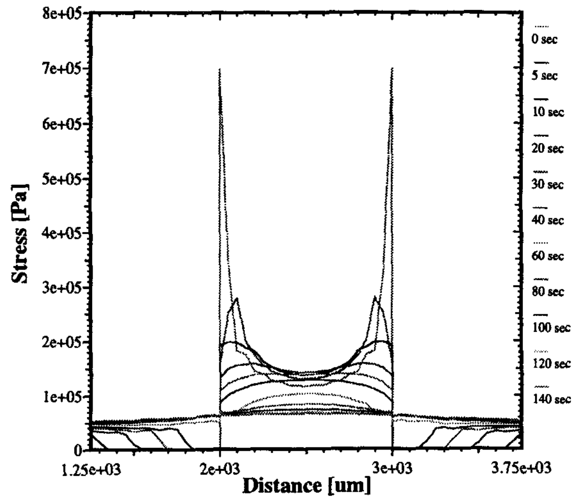


Fig. 4. Contact stress distributions during 2D transient CMP simulation ($\Delta t = 5$ *sec*).

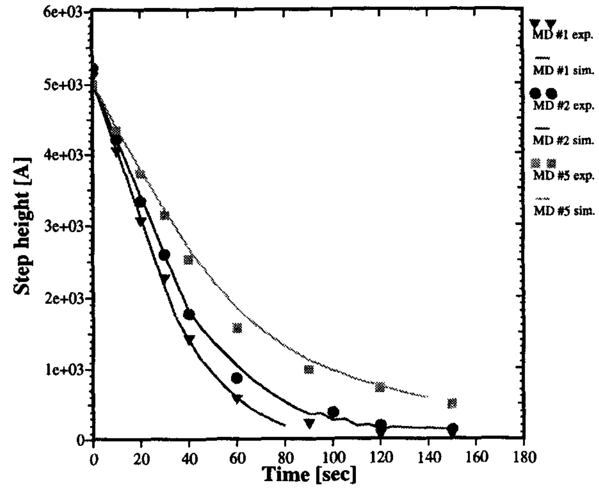


Fig. 5. The variation of the step height during the CMP process and simulation.

stacked pad at the down pressure of 8 *psi* for 4 *min*. Measurements are performed according to a time interval. An optical film thickness analyzer is used for the oxide thickness measurement at the down-feature site (the monitoring point as shown in Fig. 2.). From the results of the oxide thickness monitoring, it is shown that the polishing rate PR_0 of a blanket wafer is 1600 Å/*min*. The distribution of the step heights is monitored by a profilometer.

IV. Results and Discussions

A simulation is perfomed on a SUN Ultra SPARC workstation. The initial node number is around 3400 and the time interval for the transient simulation is 5 *sec*. It takes about 10 *min* for one iteration, and the total iteration number is 36. Therefore, the simulation time of about 360 *min* is needed for a simulation condition.

The simulation and experimental results of a test pattern structure are illustrated in Fig. 3. Fig. 3 (a) shows transient profiles using simulation. The shape of the feature qualitatively depicts the general behavior as expected during polishing. Especially, the corners become more rounded and overall heights decrease with time. Also, the down-features are polished with a slower polishing rate than the up-feature. The experimental results of the wafer surface profiles during the CMP process for the up-feature size of 1 *mm* are shown in Fig. 3 (b).

Fig 4. depicts the transient distribution of the contact stress at the wafer-pad interface. At the initial time stage, it is found that the maximum stress arises on the edge of the up-feature, and at the same time the minimum stress arises on the down-feature region near the edge. Then, the distribution at the corners are rounded due to stress concentration of locally deformed polishing pad. As the wafer gets planarized, the location of the maximum stress moves into the center region and the magnitude decreases. In addition, the stress increases at the down-feature region. These distributions are related with the wafer-pad contact due to the pad deformation.

The variation of the simulated step height is nearly consistent with the experiment as shown in Fig. 5. As the size of up-feature is small, the polishing rate is high and the step height is reduced quickly.

V. Conclusions

Transient CMP simulation using the elastic model based on nonlinear contact analysis is applied to a test structure. The profiles of CMP simulation agree well with the measured data. Mechnical behaviors during simulation are investigated. The contact stress on the wafer surface is the dominent factor in the polishing rate during the CMP process. This simulation which includes equipment parameters, such as the pad hardness and down pressure, can be applied to optimize the CMP process and to generate design rules for filling dummy patterns which are used to improve planarity. The modeling of the contact stress does not include the effects of (*i*) the wafer carrier and carrier film, (*ii*) the shear stress, and (*iii*) the nonlinear properties of materials. These effects are to be studied in the future.

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