

# Multigrid technique incorporated algorithm for CMP lubrication equations\*

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**Abstract** Chemical mechanical polishing (CMP) is a manufacturing process used to achieve required high levels of global and local planarity, which involves a combination of chemical erosion and mechanical action. The study on mechanical removal action of CMP with hydrodynamic lubrication involved will help us to get some insights into the mechanism of CMP and to solve the lubrication problem of CMP. In this paper, a full approach scheme of multigrid technique incorporated with line relaxation is introduced for accelerating the convergence. The effects of various parameters on load and moments are simulated and the results of computation are reported.

**Keywords:** chemical mechanical polishing, multigrid technique, line relaxation, full approach scheme.

Microelectronic industry has for a long time been on a burgeoning way. To develop an insulator with dielectric constant  $< 3$ , the gap filling at high aspect ratios, and a global planarisation is a challenge for dielectrics in conventional multilevel metallization schemes of modern integrated circuit (IC) technology<sup>[1]</sup>. IC is ballooning in complexity and its size is declining, which requires improvement in manufacturing. Electric circuit design and process demands a higher planarity. Chemical mechanical polishing (CMP) is a manufacture technique to obtain high levels of global and local planarity, which has drawn much concerns<sup>[2]</sup>.

CMP process involves complex tribological behaviors, including chemical reactions and mechanical effects. The critical interactions in CMP process are likely film formation/removal (oxidation of wafer metal coatings), transport of removed material away from the surface, adsorption of any additives in the slurry and local charges at particle surface, wafer surface and the corresponding double layers. In CMP process, the interactions among the pad, the polishing slurries, and the wafer take place simultaneously. Systematic tribological design is a scarcity up to now.

One key problem of CMP is to keep the slurries uniformly distributed between the pad and the wafer to be polished. Many approaches based on hydrodynamics have been developed. Runnels et al.<sup>[3]</sup> dis-

cussed the lubrication property and wear ratio after numerically solved the Navier-Stokes equation. Sundararajan et al.<sup>[4]</sup> gave the film thickness and the pressure of the slurries by solving the Reynolds equation. Park et al.<sup>[5]</sup>, through setting up the hydrodynamic model of CMP for silica wafers, analyzed the slurry thickness and pressure distribution, and contact stresses.

To date, researches on CMP have evolved into exploring the mechanism. It is conducive to accelerating this process to solve the fluid lubrication equation. In the present paper, the solvation technique is discussed and numerical simulation results are given accordingly.

## 1 CMP governing equations

Fig. 1 shows schematically a typical CMP system. The lubrication problem involves the following governing equations.

Dimensionless lubrication equation:

$$\begin{aligned} \bar{r}^2 \frac{\partial}{\partial \bar{r}} \left( \bar{h}^3 \frac{\partial \bar{p}}{\partial \bar{r}} \right) + \frac{\partial}{\partial \bar{\theta}} \left( \bar{h}^3 \frac{\partial \bar{p}}{\partial \bar{\theta}} \right) \\ = \chi \Delta \bar{r}^2 (\bar{r} + \xi \bar{r} + D \cos \theta) \\ * (\sin \alpha \sin \theta - \sin \beta \cos \theta) - \Delta \bar{r} D \sin \theta. \quad (1) \end{aligned}$$

Dimensionless film thickness equation:

$$\bar{h} = 1 - \chi \bar{r} \sin \alpha \cos \theta - \chi \bar{r} \sin \beta \sin \theta. \quad (2)$$

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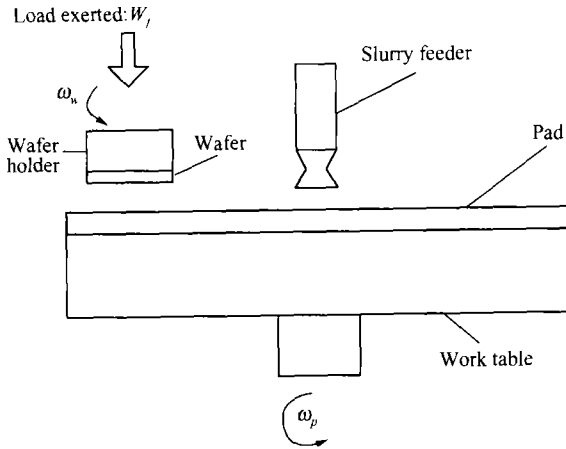


Fig. 1. Schematic view of CMP setup.

Dimensionless load and dimensionless moments equations:

$$\bar{W}_f = \frac{1}{\pi} \int_0^{2\pi} \int_0^1 \bar{p} r dr d\theta, \quad (3)$$

$$\bar{M}_x = \frac{1}{\pi} \int_0^{2\pi} \int_0^1 \bar{p} r^2 \sin \theta dr d\theta, \quad (4)$$

$$\bar{M}_y = -\frac{1}{\pi} \int_0^{2\pi} \int_0^1 \bar{p} r^2 \cos \theta dr d\theta. \quad (5)$$

Dimensionless parameters indicated above are defined as follows.

$$\chi = \frac{r_0}{h_{piv}}, \quad \Lambda = \chi^2 \frac{6\eta\omega_p}{p_0}, \quad \bar{r} = \frac{r}{r_0},$$

$$\bar{h} = \frac{h}{h_{piv}}, \quad \bar{p} = \frac{p}{p_0}, \quad D = \frac{d}{r_0}, \quad \xi = \frac{\omega_w}{\omega_p},$$

where  $r_0$  is the wafer radius,  $h_{piv}$  the central height of the wafer,  $\eta$  the slurry viscosity,  $\omega_p$  and  $\omega_w$  are rolling angles of the pad and the wafer, respectively,  $p_0$  is the reference pressure (usually the atmosphere pressure),  $d$  the center distance between the wafer and pad,  $\alpha$  and  $\beta$  are roll angle and pitch angle respectively. A dash over any parameters means dimensionless variable.

## 2 Numerical technique

### 2.1 Discretization of lubrication equation

Applying the five-points central difference, which has a precision of order two, the discretization takes the following form:

$$\begin{aligned} \frac{\bar{r}^2}{h_r} & (\epsilon_{i-1/2,j} \bar{p}_{i-1,j} + (\epsilon_{i-1/2,j} + \epsilon_{i+1/2,j}) \bar{p}_{i,j} \\ & + \epsilon_{i+1/2,j} \bar{p}_{i+1,j}) + \frac{1}{h_\theta^2} (\epsilon_{i,j-1/2} \bar{p}_{i,j-1} \end{aligned}$$

$$\begin{aligned} & + (\epsilon_{i,j-1/2} + \epsilon_{i,j+1/2}) \bar{p}_{i,j} \\ & + \epsilon_{i,j+1/2} \bar{p}_{i,j+1}) = f_{i,j}, \end{aligned} \quad (6)$$

$$\epsilon = \bar{h}^3,$$

$$\begin{aligned} \epsilon_{i\pm 1/2,j} &= \frac{1}{2} (\epsilon_{i,j} + \epsilon_{i\pm 1,j}) \epsilon_{i,j\pm 1/2} \\ &= \frac{1}{2} (\epsilon_{i,j} + \epsilon_{i,j\pm 1}), \end{aligned}$$

$$\begin{aligned} f_{i,j} &= \chi \Lambda \bar{r}_i^2 (\bar{r}_i + \xi \bar{r}_i + D \cos \theta_j) \\ &\quad * (\sin \alpha \sin \theta_j - \sin \beta \cos \theta_j) - \Lambda \bar{r}_i D \sin \theta_j. \end{aligned}$$

### 2.2 Computation mesh structure

As shown in Fig. 2, equidistance grids in both circumferential and radial directions are used. The start point ( $j=0$ ) and the end point ( $j=jj$ ) are the same in circumferential direction. Center point pressure is given by the flux volume of the shaded area<sup>[5]</sup>.

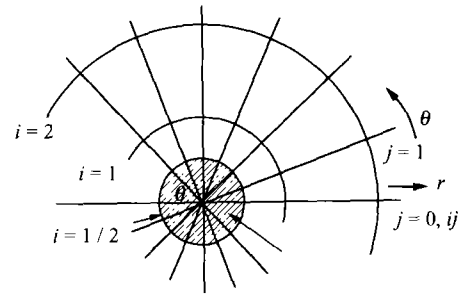


Fig. 2. Computation mesh structure.

### 2.3 Line relaxation

A key problem is to solve the discretized Eq. (6). Since the coefficient  $r_i$  of the first item on the left side varies between 0 and 1, a weak coupling in radial or circumferential direction will appear. Adoption of line relaxation will contribute largely to accelerating the convergence of the iteration process<sup>[6]</sup>.

Line relaxation in radial direction can be described simply as follows. The system of equations for each line  $j$  can be written as

$$\mathbf{A}^j \bar{\mathbf{p}}_j = \mathbf{f}_j, \quad (7)$$

where  $\bar{\mathbf{p}}_j = (\bar{p}_{1,j}, \dots, \bar{p}_{ii-1,j})^T$  is the vector of unknown variables at column  $j$ ,  $ii$  the node number in radial direction,  $\mathbf{f}_j = (f_{1,j}, \dots, f_{ii-1,j})^T$  the corresponding right-hand-side vector,  $\mathbf{A}^j = (a_{k,l})$  is a diagonal-dominated three diagonal matrix, and the non-zero items are given by

$$a_{k,k-1} = \frac{r_i^2}{h_r^2} \epsilon_{k-1/2,j},$$

$$a_{k,k} = -\frac{r_i^2}{h_r^2} (\epsilon_{k-1/2,j} + \epsilon_{k+1/2,j}),$$

$$a_{k,k+1} = \frac{r_i^2}{h_r^2} \epsilon_{k+1/2,j}.$$

Eq. [7] can be precisely and rapidly solved by means of Gaussian elimination with back-substitution<sup>[7]</sup>. Due to the variation character of  $r_i$ , one successful approach is obtained by carrying out line relaxations in circumferential and radial directions by turns.

## 2.4 Multigrid technique

Multigrid, a. k. a. multilevel method, is a promising numerical technique, and has been widely used in solving lubrication problems<sup>[6,8]</sup>. Advances are continuing, for instance, minimal residual smoothing<sup>[9]</sup> and FULL-FAS<sup>[10]</sup> algorithms have been put forward in succession.

For discretized equation

$$Lp = f, \quad (8)$$

where  $L$  is a differential operator,  $p$  the unknown variable vector,  $f$  the right-hand-side function vector, the multigrid algorithm can be ascribed to solving the residual difference equation on a coarse grid.

$$L_c v = I_f^c (f - L_f p), \quad (9)$$

where,  $L_c$  is a differential operator on coarse grid level,  $I_f^c$  the restriction operator from a fine grid level to a coarse grid level, and  $L_f$  the right-hand-side function vector on the fine grid level. Corrections will be performed on fine grid level after interpolating the corrections obtained on coarse grid level.

## 3 Numerical computing results

The parameters used in the computing process take the following values unless specified.  $\omega_w = 50$  r/min,  $\omega_p = 100$  r/min,  $h_{piv} = 50$   $\mu$ m,  $\alpha = 0.02^\circ$ ,  $\beta = 0.018^\circ$ ,  $\eta = 0.00214$  Pa·s,  $d = 150$  mm,  $r_0 = 50$  mm,  $p_0 = 101$  kPa.

Fig. 3 depicts the variation of the dimensionless load and the dimensionless angular momentum with respect to the pitch clearance. As shown in Fig. 3, the load and moments (absolute value) decrease with the clearance between the wafer and the pad. This shows that, to maintain the feasible polishing character, clearance should be carefully chosen (overlarge clearance value leads to load capacity declining and subsequently deterioration of CMP; too low clearance will hamper the delivering of particles in slurry and consequently deteriorate the CMP performance).

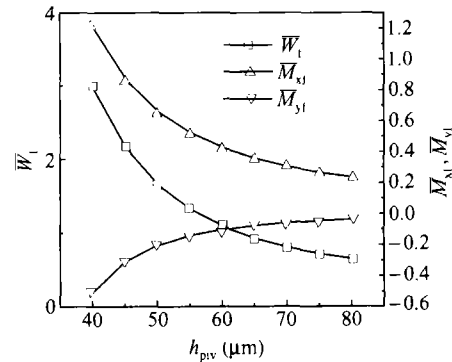


Fig. 3. The relationship of dimensionless load, moments with pitch height.

Figs. 4 and 5 show the varying of the dimensionless load, dimensionless angular moments versus the roll angle and the pitch angle. It can be seen from Fig. 4 that the minimum load capacity appears while the roll angle approaches zero. The angular moment related to y-axis is symmetric. The increase of pitch angle will give rise to increase of load and angular moments. This means that the choice of the attitude angle is very important in CMP.

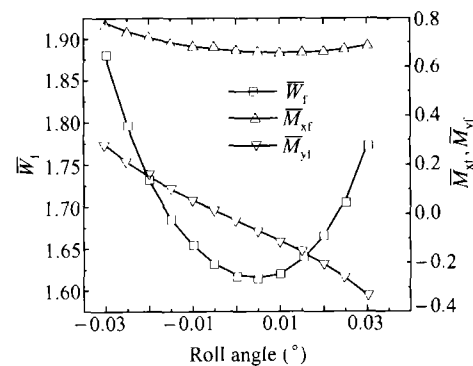


Fig. 4. Dimensionless load and moments vs. roll angle.

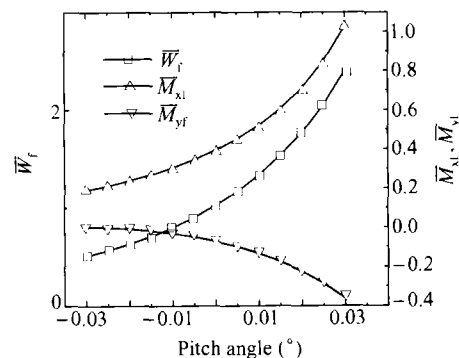


Fig. 5. Dimensionless load and moments vs. pitch angle.

## 4 Conclusions

CMP is of vital importance to attaining a high

level global and local planarity. To date, the research on CMP has been developed into the stage of exploring the mechanisms. The behavior of slurries involves hydrodynamic effects. Therefore, it is of key interest to explore the lubrication characteristics.

Numerical solution method for Reynolds equation accounting for CMP lubrication is proposed in the present paper, i. e. by coupling the line relaxation technique and the multigrid method in an effort to provide a fast and stabilized convergence solution.

This paper gives, through numerical simulation, the variation relations between dimensionless load, dimensionless moments and gap size, roll angle, and pitch angle. This will give insight into the understanding of CMP mechanism.

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