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A Reynolds equation modelling Coriolis force effects on chemical mechanical polishing

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ABSTRACT

A Reynolds equation modelling chemical mechanical polishing in cylindrical polar coordinates is derived. Coriolis force effects are included in the derivation of the model equation. The main effect of the Coriolis force is to increase the magnitude of the peak pressure. A model for the peak pressure is given by $\max|p/p_{\text{atm}}| \approx \kappa/\epsilon$ where p is the pressure, p_{atm} is atmospheric pressure, $\kappa = 5 \times 10^{-8}$ is a constant and $\epsilon$is a ratio of the thin film height to the height of the Ekman boundary layer. The value of $\epsilon$is obtained through numerical experimentation. Using the physical experimental parameters we show that for Newtonian fluids $\epsilon = O(10^{-5})$.

1. Introduction

In this paper we derive a Reynolds equation modelling the effects of Coriolis force on chemical mechanical polishing (CMP). CMP is a process that uses an abrasive-corrosive chemical slurry with a polishing pad to smooth down the surface of a wafer and reduce any irregularities on the wafer surface. The diameter of the polishing pad is greater than the diameter of the wafer. CMP is used to remove unwanted conductive or dielectric materials from a silicon wafer in order to achieve a flat and smooth surface upon which an integrated circuit can be etched. The pad and wafer are pressed together by a dynamic polishing head and held in place by a retaining ring (see Fig. 1). The dynamic polishing head is rotated about a different axes of rotation. CMP removes material from the wafer in the process of making the wafer flat. Coriolis force effects are included in the Reynolds equation by investigating an inertial frame rotating about a vertical axis on the rotating disk. The mass lost from the wafer is neglected in our model. A schematic of the problem is shown in Fig. 2.

Beschorner et al. [1] derive a Reynolds equation in cylindrical polar coordinates to model a pin-on-disk and CMP system without entrainment velocity assumptions. Beschorner et al. [1] find that using a Reynolds equation in cylindrical polars is not useful when modelling physical phenomena where the radial velocity $u = u(r)$ and the angular velocity $v = v(\theta)$ because a big discrepancy between experimental data and physical phenomena occur. Beschorner et al. [2] show that the Reynolds equation in cylindrical polar coordinates that they derive should be used when entrainment velocities are known to vary with radial and/or angular velocity, i.e. $u = u(r, \theta)$ and $v = v(r, \theta)$ to determine the pressure. This Reynolds equation yields results that compare well with experimental data and physical phenomena.

Momoniat and Mason [3] and Myers and Charpin [4] have introduced two alternate models for the Coriolis force acting on a thin film on a rotating disk. The major difference between the two models arises in the formulation of the azimuthal velocity scale. Momoniat and Mason [3] assume that the azimuthal velocity scale is the same order as the radial velocity scale. This implies that the angular velocity of the fluid is similar to the velocity at which the fluid is sliding horizontally. Myers and Charpin [4] assume the Coriolis force drives the flow in the azimuthal direction. In this paper we follow the formulation of Myers and Charpin [4] where we assume the fluid is Newtonian.

The paper is divided up as follows: in Section 2 we derive and solve a Reynolds equation modelling CMP in cylindrical polar coordinates that includes Coriolis force effects. Concluding remarks are made in Section 3.

2. Chemical-mechanical polishing

From Fig. 2 we observe that the disk has angular velocity $\mathbf{\Omega}_D^A = (0, 0, \omega_D)$ relative to frame A centered on the disk and the wafer has angular velocity $\mathbf{\Omega}_W^B = (0, 0, \omega_W)$ relative to frame B centered on the wafer. Since $\mathbf{v} = \mathbf{\Omega} \times \mathbf{r}$ we have $\mathbf{v}_A = (-\omega_D\theta_D, \omega_D r_D, 0)$ for any point on the disk. For any point on the wafer we have $\mathbf{v}_B = (u, v, w)$ where (u, v, w) are the radial, angular and azimuthal velocities respectively.

We consider a point Q on the wafer with coordinates $\mathbf{r}_B = (r_B, \theta_B, 0)$ relative to frame B. The position of Q relative to an observer at the centre of the disk is given by

$$\mathbf{r}_A = \mathbf{r}_{AB} + \mathbf{r}_B, \tag{2.1}$$

where $\mathbf{r}_A$ is the position of the point relative to frame A, $\mathbf{r}_{AB}$ is the is the relative position of the origin of frame B from frame A and $\mathbf{r}_B$ is the position of the point on the film relative to frame B. In CMP the wafer remains a fixed distance, d, away from the centre of the rotating disk.

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Nomenclature

p_{atm}	the atmospheric pressure
ρ	the density
Bo	the Bond number
B	the pin curvature parameter
h_M	the mean film thickness
α	the roll angle
β	the pitch angle
ω_D	the angular velocity of the pad/disk
$\overline{\omega}_D$	the dimensionless angular velocity of the pad/disk
ω_w	the angular velocity of the wafer
$\overline{\omega}_w$	the dimensionless angular velocity of the wafer
R	the wafer radius
d	the distance of the wafer centre from the centre of the pad
$\overline{d}$	the dimensionless distance of the wafer centre from the centre of the pad
r	the radial coordinate
$\overline{r}$	the dimensionless radial coordinate
θ	the angular coordinate
z	the azimuthal coordinate
$\overline{z}$	the dimensionless azimuthal coordinate
u	the radial velocity
$\overline{u}$	the dimensionless radial velocity
v	the angular velocity
$\overline{v}$	the dimensionless angular velocity
w	the azimuthal coordinate
$\overline{w}$	the dimensionless azimuthal coordinate
h_0	the characteristic height of the film
L	the characteristic length of the fluid
U	the characteristic horizontal velocity
t	the time
$\overline{t}$	the dimensionless time
p	the pressure
$\overline{p}$	the dimensionless pressure
μ	the dynamic viscosity
$\underline{b}$	the body force
$\overline{\underline{b}}$	the dimensionless body force
Ω	the angular velocity
ν	the kinematic viscosity
W	the characteristic azimuthal velocity
g	the gravitational constant of acceleration
κ	constant
ϵ	a ratio of the thin film height to the height of the Ekman boundary layer
Ek	height of the Ekman boundary layer on the wafer
Ek^D	height of the Ekman boundary layer on the disk
$\mathbf{\Omega}_D^A$	angular velocity of the disk relative to frame A centered on the disk
$\mathbf{\Omega}_W^B$	angular velocity of the wafer relative to frame B centered on the wafer
$\mathbf{v}_A$	velocity of a point on the disk
$\mathbf{v}_B$	velocity of a point on the wafer
Q	point on the wafer
$\mathbf{r}_A$	position of Q relative to frame A
$\mathbf{r}_{AB}$	relative position of the origin of frame B from frame A
$\mathbf{r}_B$	position of Q on the film relative to frame B
Re	the Reynolds number
Ro	the Rossby number
ρ_m	the density of the slurry mixture
ρ_s	the density of solid in the mixture
ρ_L	the density of liquid in mixture
c_W	the concentration of solids by weight as a percentage
c_v	the concentration of solids by volume as a percentage
ϕ	the volume fraction
μ_m	the viscosity of the slurry mixture
μ_L	the viscosity of the liquid in the mixture

The velocity of the centre of frame B relative to the centre of frame A is given by $\mathbf{v}_A = (-\omega_D\theta_D, d\omega_D, 0)$.

For the angle in radians we have the arc-length $S = r\theta$ where $S = \omega t$ for the angular velocity ω. For the disk we therefore have $\theta_D = r_D/(\omega_D t)$ and for the wafer $\theta_W = r_W/(\omega_W t)$. The dimensions of the angle $[\theta] = [S]$ when using this formulation. This is important later on when we apply the thin-film approximations to the Navier-Stokes equations in a rotating frame. From the arc-length formulation for the angle we get $\mathbf{r}_{AB} = (d, d/(\omega_D t), 0)$ where t is the duration of the motion. The position of Q relative to frame B is given by $\mathbf{r}_B = (r, r/(\omega_W t), 0)$. We find that

$$\mathbf{\Omega}_B \times \mathbf{\Omega}_B \times \mathbf{r}_B = (-r\omega_W^2, -r\omega_W/t, 0), \quad \mathbf{\Omega}_W^B \times \mathbf{v}_B = (-v\omega_W, u\omega_W, 0). \tag{2.2}$$

When comparing velocities from frame A to frame B we have

$$\frac{\partial \mathbf{v}_A}{\partial t} = \frac{\partial \mathbf{v}_{AB}}{\partial t} + \frac{\partial \mathbf{v}_B}{\partial t} + 2\mathbf{\Omega} \times \mathbf{v}_B + \frac{\partial \mathbf{\Omega}}{\partial t} \times \mathbf{r}_B + \mathbf{\Omega} \times \mathbf{\Omega} \times \mathbf{r}_B, \tag{2.3}$$

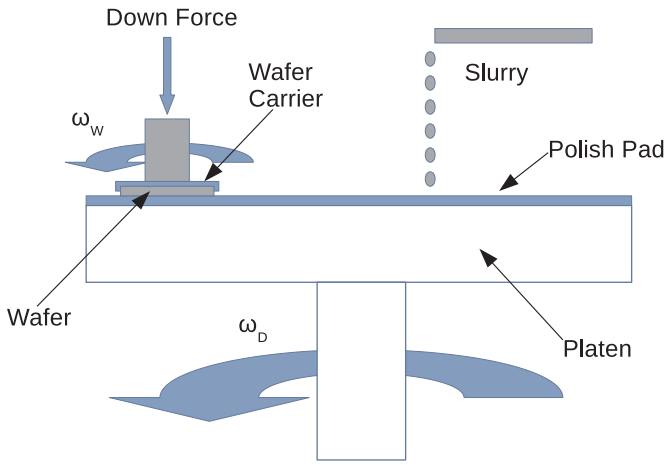

Fig. 1. Chemical mechanical polishing system.

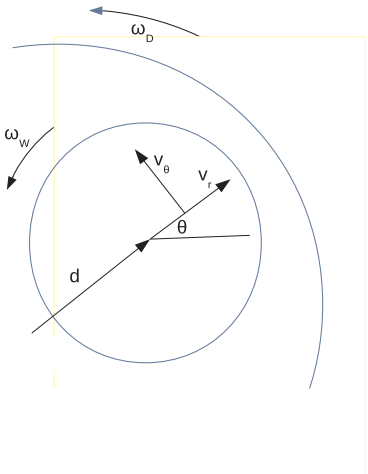

Fig. 2. Diagram showing chemical mechanical polishing coordinate system centered on wafer.