APPENDIX A EARLY MODELS OF OXIDE CMP

Over the past decade and a half several process models have been proposed to elucidate the mechanism and material removal rate in CMP. Each model addresses a specific aspect of the process. Some of these are briefly described below to focus on the mechanisms of the planarization process and to identify the research tasks. It is not the objective of this review to be exhaustive; only a few important process models are reviewed.

Brown, N.J., et al. [1981] These authors present a model for optical polishing and derive the Preston equation from the elastic model. The Preston equation may be written as

$$\frac{d\xi}{dt} = k_p p v_R \tag{A.1}$$

where ξ is the thickness of the layer removed, t the polishing time, p the nominal pressure, v_R the relative velocity, and k_p a constant known as the Preston constant. They assume that the volume of the material removed by each abrasive particle is equal to the product of the area of the side view projection of the penetration and the distance traveled. For the closest particle packing, the polishing rate, $d\xi/dt$ or R_i, is given by

$$R_i = \frac{1}{2E} p v_R \tag{A.2}$$

where E is the Young's modulus of the material being polished. Comparing with the Preston equation, the Preston coefficient, k_p, is $1/2E$.

Cook, L.M. [1990] Chemical processes during the glass polishing are reviewed. (Silicon oxides used for IC are a form of silicate glass.) The author points out that the primary chemical process during polishing is the interaction of both the glass surface and of the polishing particle with water. In order to explain the lower polishing rates observed in experiments than that predicted by the Hertzian indentation wear model [Brown, et al., 1981)],

he proposes that the material removal during glass polishing is a chemical process, such as dissolution, rather than mechanically produced particle generation. The presence of water is critical to glass polishing. The reactions between siloxane bonds (Si-O-Si) and water primarily determine the behavior of silicate glass surfaces during polishing, as attacking the siloxane network will control the rate of surface removal. The mass transport is determined by the relative rates of the following processes: (a) the rate of molecular dissolution and water diffusion into the glass surface, (b) subsequent glass dissolution under the load imposed by the polishing particle, (c) the adsorption rate of dissolution products onto the surface of the polishing grain, (d) the rate of silica re-deposition back onto the glass surface, and (e) the aqueous corrosion rate between particle impacts.

It is suggested that both elastic and plastic indentation wear cannot occur unless the net material transport off the worn surface is positive. Otherwise, the material behind the traveling indenter will simply spring back to its original position (elastic effects) or change it topography (plastic effects). In this model, the relative polishing activity of compounds as well as the requisite chemical environment at the glass surface for optimal polishing rate are predicted. However, a great deal of experimental work remains to characterize the effects of particle size distribution, surface area and surface activity of the polishing compounds on the polishing rate. In any case, even if this model can be applied to glass polishing, its applicability to metals and polymers is questionable.

Warnock, J. [1991] This paper presents a phenomenological model for the CMP process. This model allows quantitative predictions to be made on both relative and absolute polishing rate of arrays of features with different sizes and pattern density.

For each surface point i, the polishing rate, R_i, is defined as

$$R_i \sim \frac{K_i A_i}{S_i} \tag{A.3}$$

where K_i is a kinetic factor, A_i the accelerating factor associated with point i which protrudes above their neighbors, and S_i the shading factor which describes the decrease of

polishing rate by the effect of neighboring points protruding point i. In general, K_i, A_i ,and S_i are defined such that they are greater than or equal to 1. This model assumes that the polishing rate decrease at point i will be compensated for by a corresponding polishing rate increase at point j, i.e.

$$\sum_{i=1}^{n} \frac{A_i}{S_i} = n \tag{A.4}$$

The mathematical forms for S_i and K_i are chosen by considering the expected changes in features associated with the "spring-like" properties of the rough pad. Once the set of S_i is chosen, the set of A_i can be determined by the reciprocal relation, Equation (A.4). The polishing rates from experimental measurements supposedly show good agreement with those predicted by this model. But the tribological mechanisms of planarization and polishing are left unanwered.

Yu, T.K., et al. [1993] A physical CMP model that includes the effects of polishing pad roughness and dynamic interaction between pad and wafer is presented by these authors. Two assumptions have been made: (i) the pad asperity is spherical at its summit, and (ii) the variations in asperity height, z, and radius, β, are Gaussian distribution $\Phi_z(\mu_z, \sigma_z)$ and $\Phi_\beta(\mu_\beta, \sigma_\beta)$, where μ_x and σ_x are the mean and standard deviation of x. The asperity is defined such that μ_z=0.

The contact area , *a,* and load, *l*, on each asperity are known from Hertz's equations. Then the total contact area, A_{con}, and the load, L, over the nominal pad area, A, are obtained as:

$$A_{con} = \eta A \int_{d}^{\infty} \int_{0}^{\infty} a \Phi_\beta \Phi_z \, d\beta \, dz \tag{A.5}$$

$$L = \eta A \int_{d}^{\infty} \int_{0}^{\infty} l \Phi_\beta \Phi_z \, d\beta \, dz \tag{A.6}$$

where η is the asperity density. Measurements give η, μ_β, σ_z, and σ_β. The results show that the contact pressure p_{con} is independent of the nominal pressure p. This leads to the relation:

$$A_{con} / A = k_1 p \tag{A.7}$$

where k_1 is a constant solely determined by the pad roughness and elasticity. The authors try to connect the above result with the Preston equation. For an unpatterned wafer, if the material removal rate, R, is proportional to the area wiped by the pad per unit time:

$$R = k_2 A_{con} v \tag{A.8}$$

where k_2 is an experimental constant and v the pad velocity. By relating Eqns. (A.7) and (A.8), a form similar to the Preston equation can be obtained.

$$R = k_1 k_2 pv = k_p pv \tag{A.9}$$

Surface chemistry and abrasion effects are combined into constant, k_2, and may be de-coupled from the wafer-pad contact problem.

Runnels, S.R and Eyman, L.M. [1994] The authors give a wafer-scale model to demonstrate that hydroplaning is possible during the standard CMP process. A feature-scale erosion model is employed to calculate the stresses induced by the flowing slurry and the polishing rate on the feature surfaces. For the wafer-scale model, they assume that both the pad and the wafer are rigid. The pad surface is flat and the wafer surface is smooth with a given curvature. A Newtonian fluid assumption and the two-dimensional Navier-Stokes equations are used to describe the flow field and pressure at the wafer-pad interface. Three parameters are introduced to describe this fluid film: the minimum thickness of the film (t), the wafer angle of attack (θ), and the radius of curvature of the wafer (R_w). Once h is found for the given pad velocity and wafer curvature, it can be used in a feature-scale model with the

real feature shape as the flow boundary to calculate the stress distribution on the feature surface. To estimate the polishing rate, an erosion model of the following form is assumed:

$$R_n = f[\sigma_t(t), \sigma_n(t)] \tag{A.10}$$

where R_n is the erosion rate in the normal direction at a point on the surface, f the law empirically relating the chemistry and mechanics to erosion, and σ_t and σ_n are normal and shear stress on the feature surface. The authors estimate R_n in the form:

$$R_n = C\sigma_t^2 \tag{A.11}$$

They suggest this form because the approximation

$$\sigma_t \cong \frac{\mu v}{h} \tag{A.12}$$

is similar to the tribological behavior for slider bearings:

$$h \propto \sqrt{\frac{\mu v}{pA}} \tag{A.13}$$

(where A is the area of wafer, and p the average pressure). By using Eqns. (A.11), (A.12), and (A.13), R_n becomes

$$R_n \propto (\mu A) p v \tag{A.14}$$

which is identical to the Preston equation. Compared with the experimental results, the predicted profiles show good correlation with the shape of the eroding features. The authors claim that the discrepancy between the experimental data and the predicted curve is due to measurement inaccuracy, pad feature size, pad deformation and to two-dimensional modeling.

In addition, the experimental data were obtained for a poorly characterized pad-wafer interface, and thus the validation of the hydroplaning model is questionable.

Nomenclature

A = wafer area (m^2)
A_{con} = total contact area of the pad (m^2)
A_i = accelerating factor at point i
a = contact area of a pad asperity (m^2)
C = proportionality constant
E = Young's modulus (N/m^2)
h = slurry film thickness (m)
K_i = kinetic factor at point i
k_p = Preston constant (m^2/N)
L = load on the wafer (N)
l = load carried by a pad asperity (N)
n = number of point considered on the wafer surface
p = normal pressure on wafer (N/m^2)
t = polishing duration (s)
R = material removal rate (m/s)
S_i = shading factor at point i
v, v_R = magnitude of the relative velocity (m/s)
x, y = Cartesian coordinates
z = asperity height (m)
β = radius of the asperity (m)
Φ = normalized Gaussian distribution function
η = asperity density
μ = dynamic viscosity of the slurry (Pa·s)
σ_n, σ_t = normal and shear stresses on the feature surface (N/m^2)
ξ = thickness of the material removed on wafer surface (m)

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