A MATERIAL REMOVAL RATE MODEL CONSIDERING INTERFACIAL MICRO-CONTACT WEAR BEHAVIOR FOR CHEMICAL MECHANICAL POLISHING

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ABSTRACT
Chemical Mechanical Polishing (CMP) is a highly effective technique for planarizing wafer surfaces. Consequently, considerable research has been conducted into its associated material removal mechanisms. The present study proposes a CMP material removal rate model based upon a micro-contact model which considers the effects of the abrasive particles located between the polishing interfaces, thereby the down force applied on the wafer is carried both by the deformation of the polishing pad asperities and by the penetration of the abrasive particles. It is shown that the current theoretical results are in good agreement with the experimental data published previously. In addition to such operational parameters as the applied down force, the present study also considers consumable parameters rarely investigated by previous models based on the Preston equation, including wafer surface hardness, slurry particle size, and slurry concentration. This study also provides physical insights into the interfacial phenomena not discussed by previous models, which ignored the effects of abrasive particles between the polishing interfaces during force balancing.

Keywords: CMP, material removal rate, micro-contact wear, interfacial phenomena

1. INTRODUCTION
Chemical Mechanical Polishing (CMP) is the method of choice in the semiconductor industry to planarize inter-level dielectrics and damascene metal wiring for on-chip multi-level interconnects. During the CMP process, the surface of the wafer is polished both by mechanical abrasion and by chemical erosion to achieve a global planarization.

Due to the complexity of the operational parameters, process control of the CMP process remains at an empirical stage. The current study employs a micro-contact model for pad asperity deformation and abrasive wear to develop a CMP material removal model in which the effects of these particles are considered. In contrast to the periodic surface profile proposed by Luo et al. [1], the current model assumes the heights of the pad surface asperities to be normally distributed. Meanwhile, the pad asperities/wafer contact pressure acting on the polishing interface is calculated from the micro-contact model for pad asperities. Furthermore, it is assumed that the deformations at the wafer/abrasive and pad/abrasive contact surfaces are plastic and elastic in nature, respectively. Since the particle effect is taken into consideration during force balancing, the down force applied on the wafer is carried both by the deformation of the polishing pad asperities and by the penetration of the abrasive particles. Having developed a suitable material removal rate model, this study then investigates the surface parameters and examines the influences of the significant consumable material parameters.

2. MODELING
The current paper presents the incorporation of a force balancing model, which considers the particle effects acting between the polishing interface, into a material removal rate model which is derived from micro-contact theory.

Basing on the phenomena of wear, the material removal rate model can be expressed in the following form [1]:

\[
MRR = n \cdot \text{Vol}_{\text{removed}}
\]  

The current material removal rate model employs the micro-contact theory proposed by Jeng et al. [2] to calculate the real contact area and the asperity contact force between the polishing interface.

2.1 Contact force and contact area of single effective abrasive particle

During the CMP process, the abrasives embedded in the real contact area of the polishing interface penetrate into both the polishing pad asperities and the wafer surface causing the wafer surface to deform plastically.

The bulk of the abrasive particle becomes embedded in the polishing pad asperity surface rather than within the wafer surface and it is clear that:

\[
x = \delta_{ap} + \delta_{av}
\]  

Meanwhile, the wafer/abrasive contact interface is assumed to deform plastically and the pad/abrasive contact interface is assumed to deform elastically. Consequently, the force equilibrium on a single particle can be shown that:

\[
\frac{4}{3} \cdot E_{ap} \cdot \left( \frac{x}{2} \right)^{0.5} \cdot \delta_{ap}^{1.5} = H_k \cdot \pi \cdot x \cdot \delta_{av}
\]
Substitution of Equation (2) into Equation (3) enables the indentation depth of the wafer/abrasive interface to be solved. And the contact area and the contact force for a single effective abrasive at the wafer/pad asperity interface can be determined respectively.

2.2 Number of effective abrasives

This study assumes that wafer surface wear occurs only as the result of the abrasive particles embedded in the wafer/polishing pad asperity contact area. In the initial stages of the CMP process, the abrasive particles are distributed uniformly throughout the slurry and are spread over the polishing pad surface. The effective particle number can be evaluated by multiplying the number of abrasive particles in a unit volume with the total space of the polishing pad asperity that be compressed after contact. The number of effective abrasive particles can be determined from:

\[ n = G \cdot A_{aw} \cdot (3 \cdot \sigma_{aspery} - d) \]  
(4)

where \( G \) represents the number of particles in the selected slurry per m³.

2.3 Force balancing

Having determined the contact area and the contact force for a single effective abrasive at the wafer/pad asperity interface, and having established the number of effective abrasive particles at the polishing interface, the total contact force and the total contact area of the abrasive/wafer contact can be derived respectively from:

\[ A_{aw\_total} = n \cdot A_{aw} \]  
(5)

\[ F_{aw\_total} = n \cdot F_{aw} \]  
(6)

From above equations, it can be determined that the direct contact area of the polishing pad asperities and the wafer surface is given by:

\[ A_{pw\_total} = A_r - A_{aw\_total} \]  
(7)

Additionally, the contact force produced at the direct contact area of the polishing pad asperities and the wafer surface can be determined from:

\[ F_{pw\_total} = F_r \cdot \frac{A_{pw\_total}}{A_r} \]  
(8)

When the applied down force on the wafer balances the force at the polishing interface provided by the abrasive/wafer contact force and the pad asperity/wafer contact force. Under these conditions, the separation distance of the polishing interface can then be determined.

2.4 Material removal rate

Having established the separation distance between the polishing pad and the wafer surface, the real contact area between the polishing interfaces can be derived. Subsequently, it is possible to calculate the penetration depth of a single abrasive particle into the wafer/abrasive interface and to determine the total number of effective abrasive particles. Finally, the material removal rate of the wafer can be expressed as:

\[ MRR = G \cdot A_r \cdot (3 \cdot \sigma_{aspery} - d) \cdot \delta_{aw} \cdot R_{aw} \cdot V \]  
(9)

Figure 1: Comparison of normalized predicted material removal rate with experimental results of Bielmann et al.

3. RESULTS

In a previous study, Bielmann et al. performed an experimental investigation into the effects of particle size in the tungsten chemical mechanical polishing process. Their study includes a wide range of particle size and provides the detail operation parameters used in their experiments.

Figure 1 presents a comparison of the removal rate data measured by Bielmann et al. with the current removal rates predicted theoretically. It is observed that good agreement exists between the two sets of results. Furthermore, it is noted that the material removal rate of the tungsten CMP process decreases as the average alumina particle diameter increases. This trend corresponds to that noted previously by Xu et al. [3] and Izumitani [4]. In addition, the theoretical models for the CMP process proposed by Luo et al. [1], and Fu et al. [5] for spherical abrasive particle support this material removal rate trend.