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Modeling of chemical-mechanical polishing with soft pads

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Abstract. A new model is developed for chemical-mechanical polishing with soft pads. Contrary to prevalent views based on the existing polishing rate equation (i.e., the Preston's equation), the new model predicts a nonlinear pressure dependence of the polishing rate. It is shown that the fundamental mechanism of the pressure dependence for CMP with a soft pad is completely different from that with a hard pad. This new model, which is shown to be consistent with experimental evidence, resolves an apparent inconsistency between the Preston's equation and experimental observations concerning the pressure dependence of the polishing rate. The new model provides an important starting point for elucidating the other aspects of the CMP process including the pattern-density dependence of the planarization rate.

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The National Technology Roadmap for Semiconductors predicts the manufacturing of the 0.18-μm generation ULSI chips in 1999. A single logic chip of the 0.18-μm generation will consist of more than 20 million transistors and 6–7 interconnect metal layers. Development of planarization technologies that can be used for the manufacture of future-generation ULSI chips is one of the major challenges today [1]. Chemical-mechanical polishing (CMP) appears to be the only viable method for global planarization, though the CMP process is still not well understood at this moment. Understanding the fundamental mechanism involved in a CMP process is essential for meeting the strict planarization requirements in manufacturing the future-generation ULSI chips. Fundamental studies are expected to lead to a widening of the process window and a lowering of the manufacturing cost of CMP.

A CMP system (pad/slurry/wafer) involves many variables including tool process parameters (pressure or force applied to the wafer and pad, velocity of wafer and pad, polishing time, etc.), wafer variables (film type and pattern density), slurry variables (chemistry, particle size, and other properties), and pad variables (hardness, roughness, and other properties) [2]. A better control of a CMP process demands a detailed understanding of the role played by each of these CMP parameters and the subtle interactions between them. The most basic polishing rate equation that has been widely used is the so-called Preston's equation [3–9], although there are various models for different aspects of a CMP process [10–16]. The *Preston equation* which predicts that the removal rate (RR), i.e., the thickness decrease over time $(\Delta h/\Delta t)$, depends linearly on the downward wafer pressure P and the relative velocity between the pad and the wafer surface V, i.e., [4],

$$RR = \frac{\Delta h}{\Delta t} = K_\mathrm{p} PV \tag{1}$$

where K_p is Preston's coefficient, which is a strong function of the other CMP parameters. The wide use of Preston's equation for CMP is surprising since it was obtained for polishing with hard pads, whereas the conventional CMP pads used in IC manufacturing are soft compliant polymer ones. The difference in the pad hardness could be responsible for an inconsistency between the Preston equation and experimental observations concerning the pressure dependence of the polishing rate. The experimentally observed pressure dependence of the polishing rate could often be roughly fitted by some linear lines [18–20]. However, such linear fittings do not necessarily verify the Preston equation as people have often thought. This is because such linear fittings [18–20] do not satisfy the required physical limit of $RR \to 0$ as $P \to 0$ as predicted by the Preston equation.

It is the goal of this work to introduce a new model for CMP with soft pads. We have found that the softness and roughness of pads play a vital role in determining the pressure dependence of the removal rate. In contrast to the conventional Preston equation, the pressure dependence of the removal rate for CMP with soft pads is found to be nonlinear, i.e., $RR \propto P^{2/3}$. It is shown that the fundamental mechanism for the pressure dependence of the polishing rate in CMP process with a soft pad is completely different from the case of a hard pad. This new model is consistent with experimental evidence, and the apparent inconsistency between the Preston equation and experimental observations concerning the pressure dependence of the polishing rate is resolved.

1 Model

The Preston equation as an empirical relation for optical glass polishing was substantiated by Cook [4, 5] who considered that the removal of atomic clusters involves the bond breakage as a result of elastic interaction between abrasive particles and the wafer. Consider the cross section of the worn groove caused by a spherical abrasive particle of radius R as shown in Fig. 1. Its cross-section area is $S \approx h \times r$. Here, r is the radius of the contact area, and h is the indentation depth of the abrasive particle. Since typically $h \ll R$, then $h \approx r^2/2R$ and $S \propto r^3/R$ [17]. Consequently the removal rate RR is

$$RR = N\frac{SL}{At}\,, \tag{2}$$

where N is the total number of abrasive particles in contact with the polishing surface whose surface area is A, L is the sliding distance of the particle during a time of t and $L/t \propto V$. Hence,

$$RR \propto r^3 V\,. \tag{3}$$

Note that the pressure dependence of N for the case of a hard pad is much weaker than that of S. Since $r \propto P^{1/3}$ for an elastic interaction between an abrasive particle and the polishing surface [17], then $RR \propto PV$. Note that $RR \propto P^{1.5}V$ for a fully plastic interaction since in such a case $r \propto P^{1/2}$ [17].

The above consideration can be applied to a CMP process with a hard pad, but is evidently not applicable for a CMP process with a pad which is much softer than that of the wafer and abrasive particles. As shown schematically in Figs. 1 and 2, there is a fundamental difference between the soft- and hard-pad CMPs in how the abrasive particles are held against the wafer surface and in how the force is applied to the abrasive particles. For a CMP process with a hard pad, a change in the applied force causes a change in the indentation depth of abrasive particles into the wafer. On the other hand, for a CMP process with a soft pad, an increase in the force applied to the wafer causes abrasive particles to embed into the asperities of the pad surface, which act like an elastically soft spring because the contact pressure is usually low [11–13, 16]. With the increase in the applied force, the asperities of the pad surface go into the pad, and the contact area between the wafer and pad is increased. Consequently, an increase in the applied force to the wafer can increase the number of particles in contact with the wafer but not markedly increase the force applied to each particle and its indentation depth into the wafer. Thus, the pressure dependence of the polishing rate for a soft pad is mainly determined by the pressure dependence of the total number of particles in contact with the wafer, i.e., $RR = N(P) \times RR_1$, where RR_1 is the polishing rate for a single particle in the case of a soft pad,

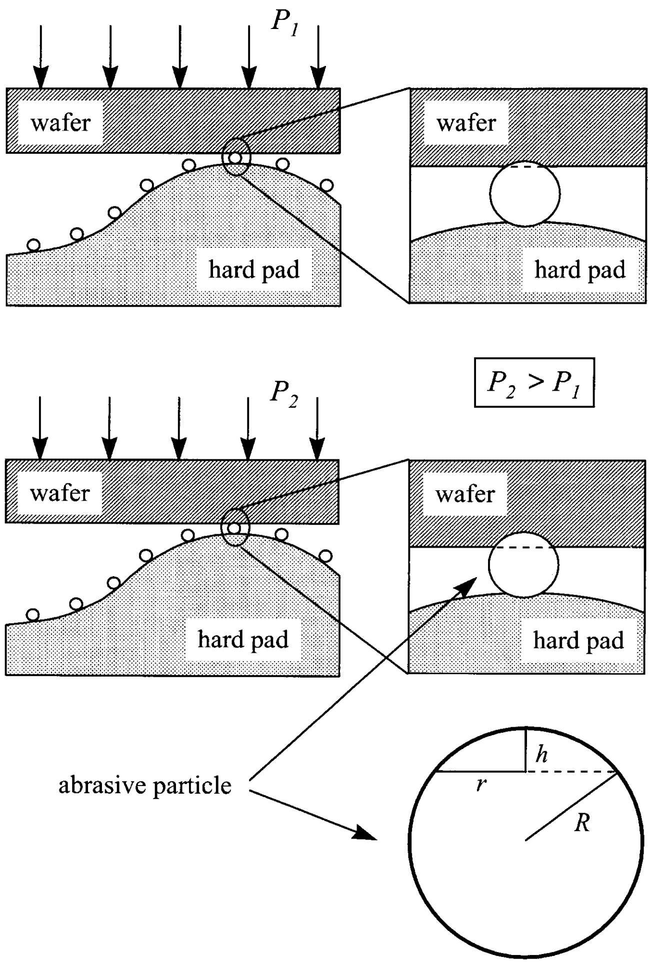

Fig. 1. Schematic of the contact between a wafer, an abrasive particle, and a hard pad. Here h and R are the indentation distance and the radius of an abrasive particle; r is the radius of the contact area between the particle and the wafer surface

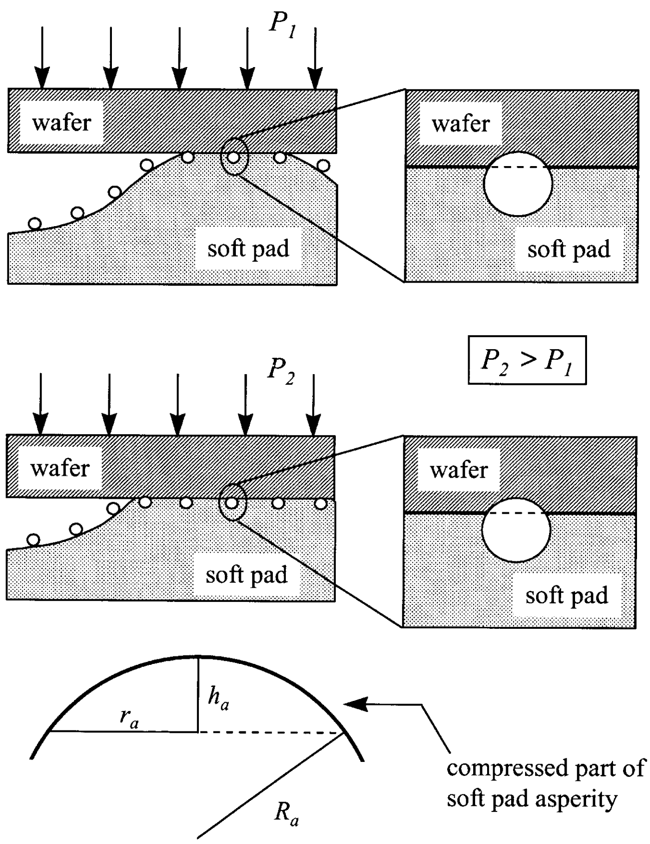

Fig. 2. Schematic of the contact between a wafer, an abrasive particle, and a soft pad which is much softer than both the wafer and particle. Here h_a and R_a are the indentation distance and the radius of an asperity of the soft pad; r_a is the radius of the contact area between the asperity and the wafer surface

which is again proportional to V, but the pressure dependence of RR_1 is negligible in comparison with $N(P)$. Hence, for the reasons discussed above, the polishing rate for a CMP process with a soft pad can be given by

$$RR \propto N(P)V\,. \quad (4)$$

The contact between the soft pad and the wafer surface can be considered to be elastic. The concentration of slurry particles on the pad surface is usually low. Hence, almost all the contact load is undertaken by the pad–wafer contact [11–13,16]. Consequently, the applied force (F) dependence of the contact area A_a between an asperity and the wafer is given by [17],

$$A_a \propto F^{2/3} \propto P^{2/3}\,. \quad (5)$$

The abrasive particles on the pad surface can simply be taken as evenly distributed. Thus, $N(P) \propto A_a \propto P^{2/3}$, and (4) becomes

$$RR = K_{sz}P^{2/3}V\,, \quad (6)$$

where K_{sz} is the coefficient which is a function of other CMP variables. Our new result given by (6) indicates that the polishing rate for a CMP process with a soft pad depends nonlinearly on pressure, and contains the physically correct limit of $RR \to 0$ as $P \to 0$.

This result is consistent with available experimental evidence as demonstrated in Fig. 3, which presents a comparison between the predicted $P^{2/3}$ dependence and the experimentally observed pressure dependence of polishing rates for thermal SiO_2, PETEOS SiO_2, and fluorine-doped silicon oxides [18–20]. It should be emphasized again that although the experimentally observed pressure dependence of the polishing rate could be roughly fitted by some linear lines, such linear fittings cannot satisfy the required limit of $RR \to 0$ as $P \to 0$, and thus do not validate the Preston equation.

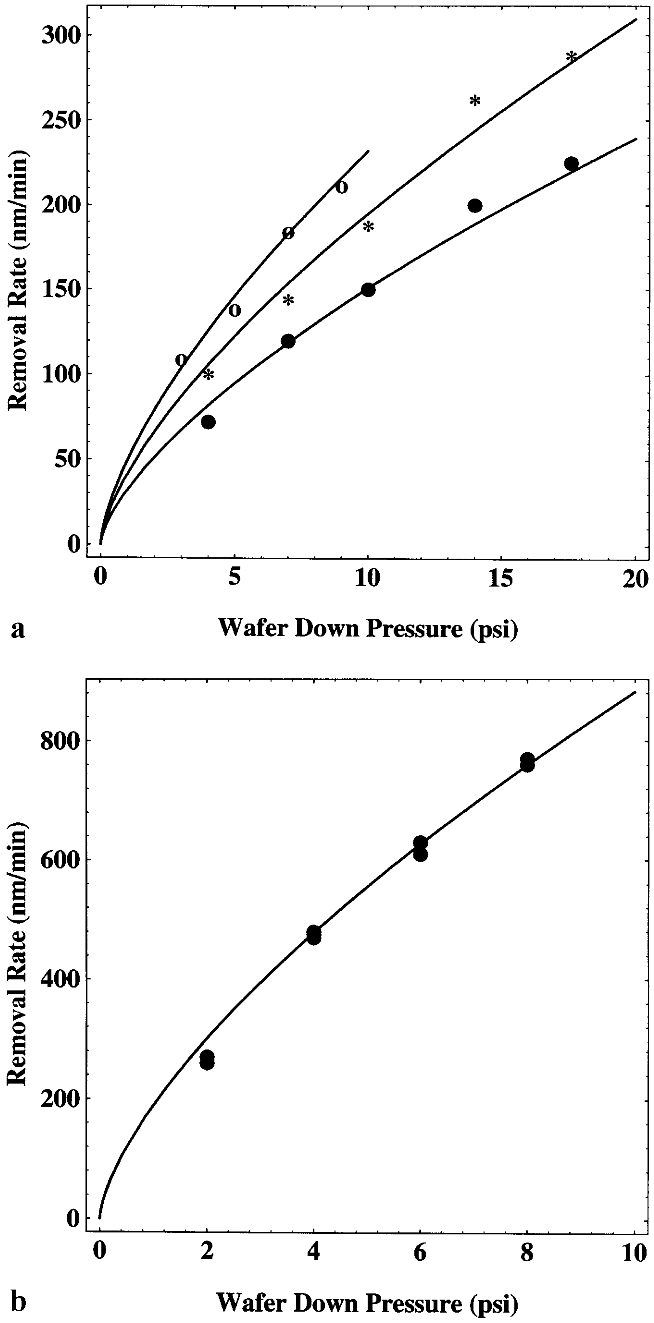

Fig. 3a,b. A comparison between predicted (curves) and measured data for polishing rates of undoped TEOS and fluorine-doped silicon oxides versus applied down pressure. **a** polishing data (○) of Morimoto et al. for TEOS films [18], polishing data (∗) of Tseng et al. for SiOF [19], and the data of Tseng et al. for TEOS oxide films [17] are represented by solid dots; **b** polishing data of Pak et al. [20] for PETEOS oxide films

2 Concluding remarks

A new polishing rate equation, (6), has been established for the chemical-mechanical polishing with soft pads. The model has been developed on the basic of the physical observation that for CMP process using a soft pad (whose hardness is much less than that of both the abrasive particles and wafer), an increase in the overall force applied to the wafer leads to an increase in the number of abrasive particles in contact with the wafer. However, this does not markedly increase the local force applied to each particle and the indentation depth of a particle. The pressure dependence of the total number of particles in contact with the wafer is much stronger than that of the indentation depth of a particle (and thus the removal rate caused by a single particle). The pressure dependence of the polishing rate with a soft pad is nonlinear and is determined by the pressure dependence of the number of particles in contact with the wafer. This result is in contrast to the existing polishing rate equation, i.e., the Preston equation. This new model is in full agreement with experimental evidence and will provide an important starting point for elucidating the other aspects of CMP process including the pattern-density dependence of the planarization rate.

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