Material Removal Saturation in Chemical Mechanical Polishing with Abrasive Weight Concentration: Effects of Abrasive Size and Wafer-Pad Contact Area

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ABSTRACT

The material removal rate as a function of abrasive weight concentration has been proposed. With the increase of the concentration, three regions of material removal exist, first the chemical dominant region, where the abrasive weight concentration is quite small, second the mechanical dominant region, where the material removal increases linearly with the weight concentration, and third the mechanical dominant saturation region, where the material removal no longer increases with the weight concentration because the contact area is fully occupied by the abrasives. In the model, a fitting parameter is used to represent the effect of chemical dominant region. The slope of material removal increase in the linear region is a function of abrasive size distribution. The saturation removal rate in the saturation region is a function of abrasive size distribution too based on our model. The verification of the *MRR* formulation in these two regions clarifies the roles of contact area and abrasive size distribution in the developed material removal model.

I. INTRODUCTION

Usually the material removal rate in the solid-solid contact mode of CMP increases linearly with the abrasive weight concentration. It is observed that when the concentration of abrasives is larger than a special value, however, the material removal rate will stop increasing. We call this special value of concentration as saturation concentration C_S and this phenomenon as material removal saturation. A qualitative explanation of this phenomenon is that the total contact area between the wafer and pad surface has been occupied by the abrasives. The further increase of the concentration cannot increase the number of abrasives on the contact area any more, leading to the saturation of the material removal rate. This explanation is shown in Fig. 1 schematically. The material removal model developed by Luo and Dornfeld [1] supports this qualitative explanation. Moreover, it can explain this phenomenon in a quantitative way, pointing out that the saturation concentration is a function of abrasive size as well as the contact area. Based on the model, three regions exists with the increase of the weight concentration, one the chemical dominant region, second the mechanical dominant linear region and third the mechanical dominant saturation region. The slope in the linear region and the saturation material removal rate are functions of the abrasive size distribution. In this report, we discuss the material removal formulation from the viewpoint of the weight concentration and how the model predictions correlate with the experimental results.

II. MATERIAL REMOVAL MODEL AND MATERIAL REMOVAL RATE AS A FUNCTION OF WEIGHT CONCENTRATION AND ABRASIVE SIZE DISTRIBUTION

Before the saturation, the material removal formulation as a function of abrasive size distribution has been developed in [2] as follows:

$$MRR = \underbrace{\frac{C_5}{X_{avg}^3}}_{part1} \underbrace{\left(1-\Phi\left(3-C_6\left[\frac{X_{avg}+3\sigma}{\sigma}\right]\right)\right)}_{part2} \underbrace{\left(X_{avg}+\frac{\sigma p\left(3-C_6\left[\frac{X_{avg}+3\sigma}{\sigma}\right]\right)}{\Phi\left(3-C_6\left[\frac{X_{avg}+3\sigma}{\sigma}\right]\right)}\right)^2}_{part3=X_{avg-a}^2}, \qquad (1)$$

where C_5 is a function of the weight concentration C, relative velocity V, and other consumable parameters, and C_6 is a function of the pad hardness, pad topography, and down pressure [2]. According to our model, the C_5 is linearly related to the weight concentration, so we can write C_5 as $C_5 = h(C+b)$ where h is a parameter related with the pad topography, abrasive density, slurry dilution ratio, abrasive geometry and chemical enhancing effect [1]. Note here we assume that the chemical enhancing effect is independent of the weight concentration. A little difference between C_5 here and that in [1] is that we introduce a parameter b into C_5. This parameter is introduced into the model in consideration that when the weight concentration is very small, say, close to zero, the material removal is not mechanical dominant any more (it is possible for the chemical removal such as etching to be compatible to the mechanical removal even in solid-solid contact mode when the number of cutting tools is small.). Only when the concentration is larger than some value, say, C_1, which may be a function of the slurry chemicals, the material removal becomes mechanical dominant and increases linearly with the concentration. We don't know exactly what is the threshold concentration. The parameter b is simply introduced into the model as a function of the chemicals for considering this effect. We can take the b as independent of abrasive size considering the perfect correlation between the experimental results and model prediction in [2]. There the value of C_5 is considered as independent of abrasive size.

We know that $h(C+b)/X_{avg}^3$ is equal to the number n of abrasives on the contact area A. When the weight concentration is small, most part of contact between the wafer and pad is direct contact between the wafer and pad asperities, and the contact area A is dependent on the down pressure, pad material and pad topography but independent of the abrasive geometry and abrasive size [1], Fig. 2 (a). When the area is totally occupied by abrasives, however, abrasives behave as an interfacial layer between the wafer and pad asperities, Fig. 2 (b). In this case, we can consider the pad asperities having higher effective Young’s modulus.

When the abrasives are larger, the effective Young's modulus of the pad is larger, leading to smaller contact area A'. We consider that when saturation happens, the contact area has been totally occupied by *active* abrasives. (The abrasives smaller than these active abrasives are rolling down the asperities.) The area of each single abrasive on the contact area is equal to $0.25\pi X_{avg\text{-}a}^2$, where $X_{avg\text{-}a}$ is the size of the active abrasives. So when the contact area A' is totally occupied by the abrasives, there should approximately be

$$[h(C_S+b)/(VX_{avg}^3)]\times\left\{1-\Phi\left(3-C_6\left[\frac{X_{avg}+3\sigma}{\sigma}\right]\right)\right\}[0.25\pi X_{avg\text{-}a}^2]=A' \qquad (2)$$

$$\Rightarrow \quad C_S=\frac{A'V\underbrace{X_{avg}^3}_{part1}}{0.25\pi h\underbrace{X_{avg-a}^2}_{part3}\underbrace{\left[1-\Phi\left(3-C_6\left[\frac{X_{avg}+3\sigma}{\sigma}\right]\right)\right]}_{part2}}-b \qquad (3)$$

From Eq. 3, we can see that C_S is a function of abrasive size distribution. Part 2 in Eq. 3 is usually close to each other for different abrasive size distributions [2]. Part 3 is the size of active abrasives and it is usually close to kX_{avg} where k can be considered close to a constant independent of abrasive size [2]. A', the contact area at saturation, is dependent of the abrasive size, but does not change too much for different abrasive sizes, as to be shown later. Therefore, the C_s should be approximately linearly related to the abrasive size, indicating the material removal saturates earlier for smaller abrasive size. For abrasive concentration larger than C_S, the material removal will keep constant since the number of abrasive on the contact area cannot further increase.

Based on the above discussions, the material removal can be written as a function of abrasive size distribution and concentration as follows:

$$MRR=\underbrace{\frac{h(C+b)}{X_{avg}^3}}_{part1}\underbrace{\left(1-\Phi\left(3-C_6\left[\frac{X_{avg}+3\sigma}{\sigma}\right]\right)\right)}_{part2}\underbrace{\left(X_{avg}+\frac{\sigma p\left(3-C_6\left[\frac{X_{avg}+3\sigma}{\sigma}\right]\right)}{\Phi\left(3-C_6\left[\frac{X_{avg}+3\sigma}{\sigma}\right]\right)}\right)^2}_{part3}$$

when $C\leq C_S$

and

$$MRR = \underbrace{\frac{h(C_s + b)}{X_{avg}^{3}}}_{part1} \underbrace{\left(1 - \Phi\left(3 - C_6\left[\frac{X_{avg} + 3\sigma}{\sigma}\right]\right)\right)}_{part2} \underbrace{\left(X_{avg} + \frac{\sigma p\left(3 - C_6\left[\frac{X_{avg} + 3\sigma}{\sigma}\right]\right)}{\Phi\left(3 - C_6\left[\frac{X_{avg} + 3\sigma}{\sigma}\right]\right)}\right)^{2}}_{part3} \qquad (4)$$

when $C \geq C_S$

Substituting C_s into the material removal rate function, we obtain the saturation material removal rate as

$$MRR_s = \frac{A^{'}V}{0.25\pi}, \qquad (5)$$

which is a function of contact area at saturation and relative velocity. If the slope of the linear region is S, which is a function of abrasive size distribution as shown above, then Cs can be written as

$$C_s = MRR_s/S - b \qquad (6)$$

The contact area $A^{'}$ at saturation is a function of abrasive size, or exactly the *active* abrasive size, down pressure and pad topography. For smaller abrasive size, the contact area A' is larger. Based on contact mechanics, an approximate relationship between the abrasive size X_{avg-a} and the contact area $A^{'}$ can be obtained as

$$A^{'} \propto (1+m_1 X_{avg-a})^{-2}, \qquad (7)$$

where m_1 is a constant related to the pad topography [2] [4]. Details about how to obtain this formulation will not be discussed here.

Figure 3 shows schematically the plot of material removal as a function of abrasive weight concentration based on above discussions. In summary, there are three regions of material removal. When $C < C_1$, the material removal is chemical dominant. When the weight concentration is zero, the material removal is totally chemical removal and it is very small in comparison with mechanical removal. Material removal increases rapidly with the increase of the weight concentration. A parameter b; see $-b$ in the figure, has been used to represent the effect of this region on the material removal formulation. When $C_1 < C < C_S$, the material removal is mainly mechanical removal, the chemical enhancing the two body abrasion in this area and the direct chemical removal can be neglected. A linear relationship between the concentration and the material removal rate exists in this region. The contact mode in this region is described in Fig. 2 (a) schematically. When $C > C_S$, the material removal rate is saturated since the contact area has been totally occupied by the abrasives. The contact mode in this region is shown in Fig. 2 (b). The contact area in saturation region is smaller than that in the linear region.

III. EXPERIMENTAL VERIFICATION

The experimental results from Bielmann et. al. are used to verify the material removal formulations [3]. Bielmann et. al. did Tungsten CMP experiment using five different distributions of abrasives. The size distribution is measured using dynamical light scattering technology. Table 1 lists the average size and the standard deviation for the five kinds of distributions [3]. Bielmann et. al. changed the weight concentrations of abrasives from 2% to 15% and obtained the material removal rate as a function of abrasive concentration for the five different abrasive size distribution, as shown in Figure 4. It is observed that the material removal saturation happens when the concentration is larger than 10% for abrasive sizes 0.29μm, 0.38μm and 0.60μm, while the linear relationship still holds for the abrasive sizes 0.88μm and 2μm. This agrees with Eq. 3, which indicates that the saturation concentration is smaller for smaller abrasive sizes. It can also be observed that the slopes of the material removal vs. concentration in the linear regions change with the abrasive size. The slope S is the smallest for abrasive size X_{avg}= 2μm, increasing to larger value with the decrease of the abrasive size. The slope is a function of abrasive size distributions based on equation 4. Figure 5 shows the good correlations between the slopes S from experimental results and those from model predictions. Table 2 lists the experimental slope values and the model predictions. The value of b, which reflecting the effect of the chemical dominant region, is also fitted using the experimental data in the linear region. A value of 10 is obtained.

Based on Eq. 5, the saturation *MRR* for abrasive size 0.29μm should be larger than that for abrasive size 0.6 μm. This is shown in Fig. 4. According to our model, the ratio of saturation *MRR* for abrasive sizes 0.29μm and 0.6μm should be equal to the ratio of the contact areas A' for these two abrasive sizes and it is 758/622= 1.22, Fig. 4. Using equation 7, we can obtain m_1 as 0.1553. The X_{avg-a} for X_{avg}=0.29 and 0.6μm can be found in [2] to be approximately 0.495 and 1.22µm. Then substituting the calculated m_1 into formulation 7, we can predict the ratio of the saturation MRR_s for X_{avg}= 0.29 and 0.38µm as 1.069, indicating that they are close to each other. This correlates with the experimental results, Fig. 4.

Using Eq. 6, we can calculate the saturation concentration C_s for X_{avg}= 0.29, 0.38 and 0.6µm respectively. The predicted slopes in the linear region are 41.573, 39.035 and 28.614 for the above three abrasive sizes. The value of b is equal to 10. The MRR_s= 758, 758/1.069=709 and 622nm/min. So the values of C_s are 8.23%, 8.16% and 11.73%, respectively.

Based on the above discussion, we can predict the saturation material removal rate and saturation concentration for X_{avg}= 0.88 and 2µm approximately. Using Eq. 7, we obtain the ratio of saturation material removal rate/ contact area for abrasive size X_{avg}=0.6 and 0.88µm is 0.774. Similarly, the ratio for abrasive size X_{avg}=0.6 and 2µm is approximately 0.582. Therefore, the saturation *MRR*s for X_{avg}= 0.88 and 2µm are predicted as 481nm/min and 362nm/min, respectively. Using Eq. 6 and the slope data, we can predict the saturation concentration for X_{avg}= 0.88 and 2µm are 17.43% and 19.16%, respectively.

In summary, using the material removal curve at X_{avg}= 0.6µm as reference, we can predict the material removal as a function of concentration for other abrasive sizes and they are plotted in Fig. 6 schematically. The slopes in the linear region and the saturation material removal rates can be predicted based on the two contact modes shown in Figure 2.

IV. CONCLUSION

The material removal rate as a function of abrasive weight concentration has been proposed. With the increase of the concentration, three regions of material removal exist. The verification of the *MRR* formulation clarifies the roles of contact area and abrasive size distribution in the developed material removal model.

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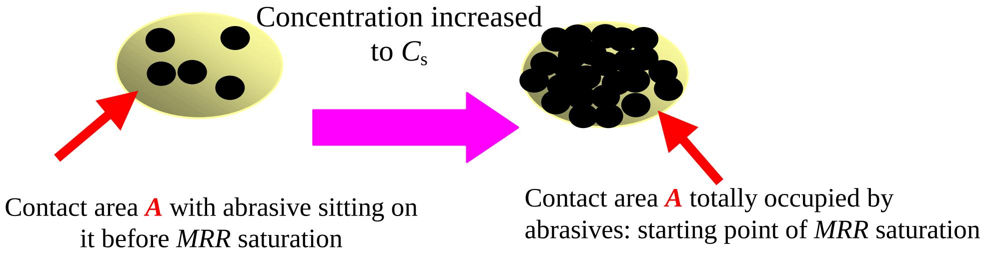
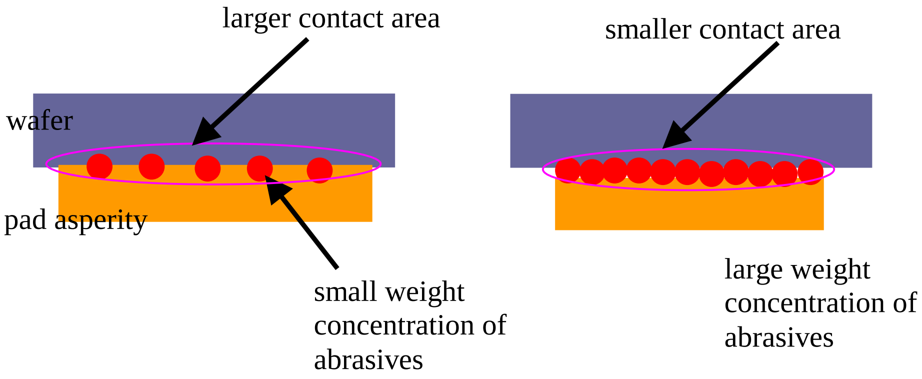


Figure 1. Material removal saturation due to the limitation of contact area



(a) Linear Region (b) Saturation Region

Figure 2. Schematic of two contact modes with different abrasive weight concentrations

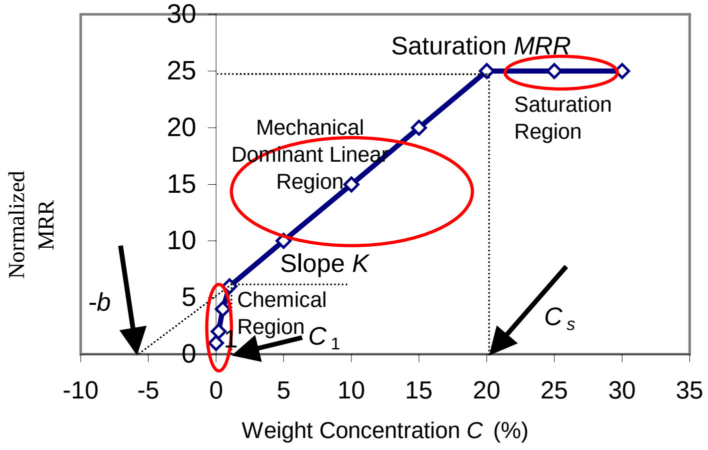
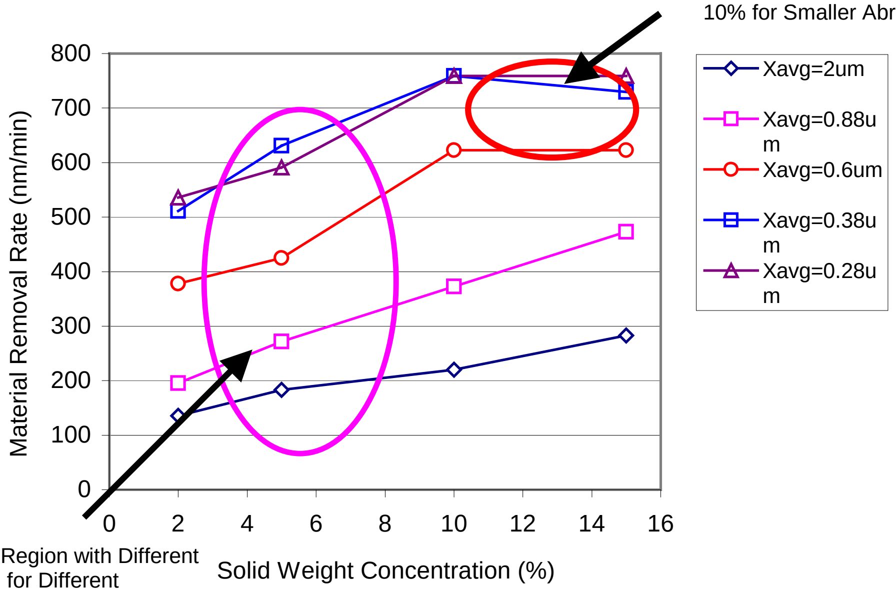


Figure 3. Three regions with the increase of weight concentration

	Mean Size (µm)	Standard Deviation (µm)
AKP50	0.29	0.070222
AKP30	0.38	0.118959
AKP15	0.60	0.210633
AA07	0.88	0.288768
AA2	2.00	1.056197

Table 1. The mean size and standard deviation of the abrasive size distributions



MRR Saturation at
Concentration
10% for Smaller Abrasives

Linear Region with Different
Slopes for Different
Abrasive Size

Figure 4. Material removal rate as function of weight concentrations under five different abrasive size distributions

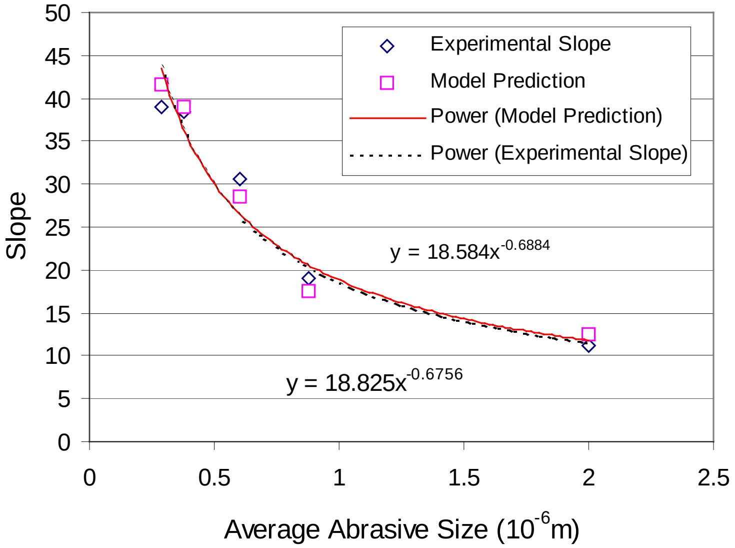


Figure 5. Experimental slope values vs. predictions

	Mean Size (µm)	Experimental Slope (*b*= 10)	Model Prediction
AKP50	0.29	38.929	41.573
AKP30	0.38	38.355	39.035
AKP15	0.60	30.516	28.614
AA07	0.88	19.025	17.537
AA2	2.00	11.243	12.416

Table 2. Experimental slope values vs. predictions

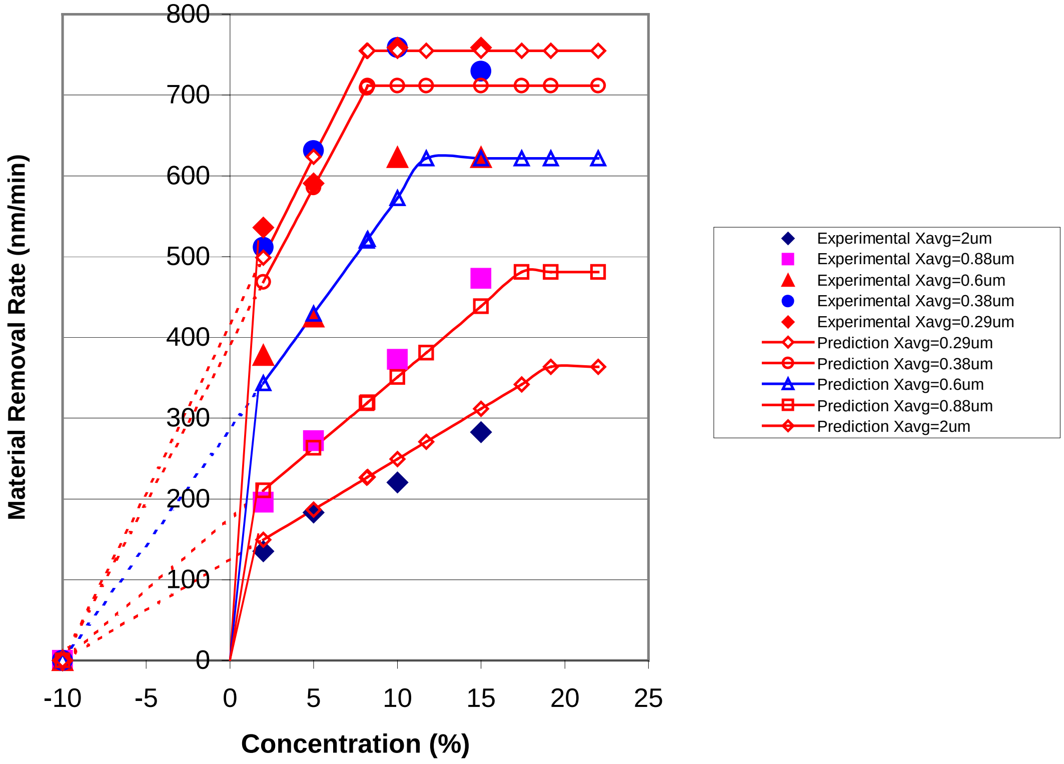


Figure 6. Prediction of material removal as a function of weight concentration for five different abrasive size distributions (using X_{avg}= 0.6μm as reference)