Modelling of Dishing for Metal Chemical Mechanical Polishing

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Abstract

In this paper, a physical model for the development of dishing during metal chemical mechanical polishing (CMP) is proposed. The main assumption of the model is that material removal occurs predominantly at the pad/wafer contacts. The distribution of pad/wafer contact size is studied first. This distribution is used as an input for a model of the dependence for the material removal rate on the line width. A relation that describes the development of dishing as a function of overpolish time will be presented. The model describes to a great accuracy the observed dishing effects, using one free parameter.

Introduction

Metal chemical mechanical polishing (CMP) has been recognized as the key technology for IC back-end processes. A major issue that remains is the dishing of metal lines. Dishing reduces the thickness of metal line causing an increase in line's resistance as well as in current density flowing through the line. Consequently, dishing reduces the speed of signal propagation through the circuit and threatens the reliability of metal line at high current density. In addition, dishing decreases the planarity of the wafer surface. This complicates the multi-level metallisation process [1]. Recently dishing has been categorized as a must-be-controlled parameter in the metal CMP process – see table 1 [2]. In this work, dishing during Copper CMP is studied and a physical model is proposed. The model accounts for the morphology and properties of the polishing pad and process parameters. One free parameter is needed to describe the experimental dishing data.

Experimental details

Copper CMP experiments were performed on a MirraTM polishing tool. An IC1400 pad was used. Structured wafers were polished with different pressures and overpolishing times. The overpolish time was controlled by a state-of-the-art end-point detector.

Experimental results

In figure 1 the blanket removal rate of Copper is plotted versus applied pressure. Preston's law [3] is followed. Further study showed that Preston's law is also valid at very low pressures. In figure 2 the time dependence of dishing is shown for various feature sizes. It appears that dishing occurs mainly during overpolishing. Small deviation may be due to chemical etching. In figure 10 dishing is plotted versus feature size for three overpolishing times. Clearly dishing increases strongly with feature size and saturates for larger line width. Furthermore a strong time dependence is observed for large line width.

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Model

To understand the origin of dishing during metal CMP, a model based on contacts mechanics is developed. Because of the large number of pad/wafer contacts, statistical technique is used. The following assumptions are made: 1) dishing occurs during overpolishing, 2) Preston's law is valid for all polish conditions, 3) material removal occurs at the mechanical contact between the pad asperities and wafer, 4) the distribution of pad asperity contact size is Gaussian, 5) a different removal rate (RR) occurs for asperities with contact size smaller (S) and larger (B) than the line width, 6) oxide erosion is neglected and 7) a homogeneous distribution of abrasive particles embedded into the pad surface. The model assumptions are reasonable for modern metal CMP processes and realistic overpolish time. In figure 3 a 3D surface plot of the polish pad is shown. The surface can be modelled well by assuming spherical asperities with a Gaussian size (R) and height (H) distribution $\Phi_R(R_a, \sigma_a)$ and $\Phi_H(H_a, \sigma_h)$. Here R_a , H_a , σ_a , σ_h are the median values and standard deviation of the asperity size and height distributions. Two other important parameters are the surface asperity density η and the pad Young modulus E. Experimentally determined values for R_a , σ_a , σ_h and η are 30 μm , 25 μm , 10 μm and $1.2 \cdot 10^5 \text{ cm}^{-2}$. E is equal to 29 Mpa [4]. H_a is the reference level and is set for convenience to 0 μm . Contact of the pad and a single asperity are schematically shown in figure 4a,b. Contact properties of a single asperity i.e. the contact radius r_c and load l carried by the asperity can be obtained from the theory of Hertz [5, 6].

$$r_c = \sqrt{R \cdot (H - G)} \quad (1)$$

$$l = 4/3 \cdot E \sqrt{R \cdot (H - G)^3} \quad (2)$$

Here G is the gap between the reference plane ($H_a = 0 \mu\text{m}$) and the wafer surface. At a certain separation distance G there will only be a few asperities, which have height H larger than G, and are touching the wafer. The number and size distribution of these contacts can be determined using equations 1 and 2.

In order to achieve a separation gap G between the reference plane of the polishing pad and the wafer surface, a pressure P must be applied to the wafer:

$$P = \frac{L}{A} = \eta \cdot \int_0^\infty \int_0^\infty l \cdot \Phi(R) \Phi(H) dR dH \quad (3)$$

where L is the total load carried by asperities within a pad area of A. Knowing the applied pressure P, morphology and properties of the polishing pad the separation gap G can be calculated using a numerical method. Consequently the number of contact and contact size distribution can be determined. Figure 5 shows the flow-chart of the numerical method used to determine the number of contacts and the contact size distribution for a certain polish pressure and pad

morphology. Using the IC1400 pad information the number of contacts is found to be a linear function of the applied pressure as shown in figure 6. Incorporation of this result in the Preston relation gives:

$$RR_{Bl} = K_p \cdot K_n \cdot N \cdot V \quad (4)$$

where RR_{Bl} is the blanket removal rate, K_p is the Preston constant, V is the linear velocity, N the total number of contacts and K_n is a proportionality constant linking the number of contacts with the applied pressure (determined from fig. 6). About 1 percent of the asperities is touching the surface, the average separation is larger than the largest line dimension (100 μm). At a pressure of 250 gr/cm^2 the average contact radius and standard deviation are 8.2 μm and 5.5 μm respectively. Figures 7 and 8 show the contact size distribution as function of pressure, height distribution, radius and its standard deviation and Young's modulus. Clearly the pad morphology has the largest impact on the contact size distribution.

To model the dishing of a line with width LW , the material removal by asperities with contact diameter smaller than LW (S) and larger than LW (B) has to be considered separately (see fig. 4c). For group S the removal rate RR_S is similar to the blanket removal, however Preston's law has to be corrected for the lower number of asperities N_s with contact radius $r_c < LW/2$.

$$RR_S = K_p \cdot K_n \cdot N_s \cdot V = K_p \cdot K_n \cdot N \cdot V \cdot \int_0^{LW/2} \Phi(r_c) \cdot dr_c \quad (5)$$

$$= K_p \cdot P \cdot V \cdot \int_0^{LW/2} \Phi(r_c) \cdot dr_c$$

where $\Phi(r_c)$ is the distribution of contact size; r_{Ca} and σ_C are the average contact radius and standard deviation.

For group B with r_c larger than $LW/2$ the pressure that is exerted on the metal in the trench is geometry and time dependent. As illustrated in figure 9, the more dishing develops, the less pressure can be exerted on the metal in the trench because of the elasticity of asperity. According to theory of elasticity [7], the maximum deflection amount $d_{\max}$ of an asperity into a trench of trench-width LW under a pressure of P_1 can be calculated as:

$$d_{\max} = \frac{m \cdot (1 - \nu^2) P_1 \cdot LW}{E} \quad (6)$$

where ν is Poisson ratio, E is Young modulus of the asperity i.e. of the pad material and m is a free numerical factor. Thus, the pressure P' exerted on the metal when a dishing amount $Dish$ has been developed is

$$P' = P - P_1 = P - \frac{E \cdot Dish}{m \cdot (1 - \nu^2) \cdot LW} \quad (7)$$

Obviously, at zero overpolish time when $Dish = 0$ (i.e. assumption 1) $P' = P$. The development of dishing amount by time is obtained using Preston law:

$$\frac{dDish}{dt} = K_p \cdot V \cdot P' \quad (8)$$

Solving equations 7 and 8 for the time dependent of the pressure P' gives

$$P' = P \cdot \exp\left(-\frac{K_p \cdot V \cdot E}{m \cdot (1 - \nu^2) \cdot LW} \cdot t\right) \quad (9)$$

Substituting equation 9 into Preston equation, we obtain equation 10 for the removal rate RR_B of asperities group B as function of the overpolish time t

$$RR_B(t) = K_p \cdot P \cdot V \cdot \exp\left(\frac{-t}{LW \cdot K}\right) \cdot \int_{LW/2}^{\infty} \Phi(r_c) \cdot dr_c \quad (10)$$

where

$$K = \frac{m \cdot (1 - \nu^2)}{K_p \cdot V \cdot E} \quad (11)$$

Adding the RR of group S and B (equations 5 and 10) we finally obtain equation 12 for the total time dependent of dishing amount for a line with a width LW .

$$Dish(LW, t) = RR_{Bl} \cdot \int_0^{LW/2} \int_0^{LW/2} \Phi(r_c) dr_c + \exp\left(\frac{-t}{LW \cdot K}\right) \cdot \int_{LW/2}^{\infty} \Phi(r_c) dr_c dt \quad (12)$$

The only adjustable parameter is K , other parameters can be obtained from the pad morphology, properties and the blanket removal rate RR_{Bl} .

Model verification and discussions

In figure 10a, b, c experimental dishing data and predicted dishing data are plotted for three overpolishing times. Excellent agreement between the model and experimental data is obtained for realistic overpolishing times. Both time dependence and feature size dependence are modelled well. It is noteworthy that in this model erosion effect is neglected and therefore it only valid for a limited overpolishing time or for the process that have high selectivity in removal rate between metal and barrier/oxide materials. This can be seen in figure 10c that for a long overpolishing time erosion starts and actual dishing values are slightly smaller than those predicted by the model.

Conclusions

A physical model based on contacts mechanics for the development of dishing in metal CMP is developed. The model describes to a great accuracy the observed dishing effects. It can be used to predict, understand and control the amount of dishing in metal CMP.

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Table 1. Microprocessor interconnect technology requirements from [2].

Year	1999	2002	2005	2008	2011	2014
Technology node (nm)	180	130	100	70	50	35
Cu local dishing (nm), 5%×height	18	14	11	9	7	5
Cu intermediate dishing (nm) 15 μ m wide wire, 10%×height	64	51	41	30	22	17
Cu global wiring dishing (nm) 15 μ m wide wire, 10%×height	116	95	76	55	38	29

Fig. 1 Blanket removal rates of copper at different polishing pressures. Slurry 1 = QC1010: H₂O₂ = 3:1 (vol.); Slurry 2 = QC1010: H₂O₂ = 2:1 (vol.).

Fig. 2 Development of dishing as function of the overpolishing time.

Fig. 3 Surface of an IC 1400 (Rodel) polishing pad after break-in procedure

Fig. 4 Schematic diagrams of the contact between polishing pad and wafer (a), contact between asperity and wafer (b) and contacts between asperities with relatively big and small trenches (c).

Fig. 5 Flow-chart diagram of the program that calculates the number of contacts and the distribution of the contact size.

Fig. 6 Calculated number of contact versus applied pressure.

Fig. 7 Calculated contact size distribution at different pressures.

Fig. 8 Dependency of the contact size distribution on (a) the height distribution, (b) the size distribution of the asperities and (c) the Young modulus of the pad.

Fig. 9 Deformation of an asperity into a trench.

Fig. 10 Experimental data versus calculated data using the proposed model.