CIRP Annals - Manufacturing Technology xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Modeling and mitigation of pad scratching in chemical–mechanical polishing

S. Kim [a,*], N. Saka [a], J.-H. Chun (1)[a], S.-H. Shin [b]

[a] Laboratory for Manufacturing and Productivity, Massachusetts Institute of Technology, Cambridge, MA, USA
[b] Manufacturing Technology Center, Samsung Electronics Co., Ltd, Suwon, Republic of Korea

ARTICLE INFO

Keywords:
Defect
Polishing
Semiconductor

ABSTRACT

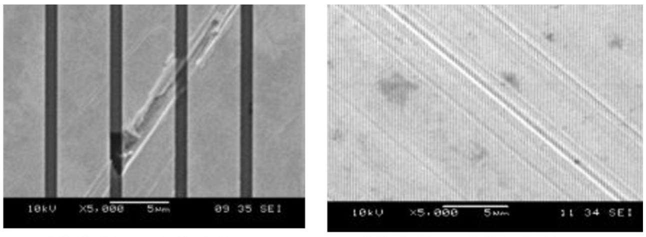
In the chemical–mechanical polishing (CMP) of semiconductor structures, such defects as micro- and nano-scale scratches are frequently produced on the surfaces being polished. Recent research shows that not only agglomerated abrasives but the softer pad asperities in frictional contact also scratch the relatively hard surfaces. Accordingly, pad scratching is modeled based on the topography and mechanical properties of pad asperities. Asperity radius, R_a, and the standard deviation of asperity heights, σ_z, are identified as the key topographical parameters. The theoretical models and experimental results show that pad scratching in CMP can be mitigated by increasing R_a/σ_z.

1. Introduction

The introduction of the dual damascene technique in the semiconductor industry over a decade ago has made possible the incorporation of copper interconnects in ultra-large-scale integrated (ULSI) circuits. To achieve both global planarization and local polishing of the Cu interconnects and dielectric layers, the chemical–mechanical polishing (CMP) process is widely used [1–3]. A continuing problem in CMP, however, is the generation of the so-called "killer" scratches on the wafer surface. Such scratches are several hundred nanometers or even several micrometers wide. Moreover, in recent years as the size of the device features continued to shrink, and the usage of low-*k*, low-strength dielectrics increase, scratching has emerged as the main defect-generation mechanism in CMP [4,5].

It is commonly believed that agglomerated hard, abrasive particles are the agents of scratching in CMP [6–8]. However, it has recently been found that under certain conditions even the pad, though soft, can scratch the relatively hard top layers being polished [9]. The width of the scratches produced by the pad is an order of magnitude greater than that of the particle-generated scratches [10]. Fig. 1 shows the scratches generated on Cu interconnects and low-*k* dielectric lines. The "polishing" experiments were conducted on Cu/low-*k* layers using a CMP pad but only with deionized water, i.e., without any abrasive particles. It is apparent that scratches produced by the pad asperities are far more critical than those produced by the agglomerated particles.

In this paper, accordingly, pad scratching models are developed in terms of the topography and the mechanical properties of pad asperities. The key topographical parameters that promote pad scratching are identified. Based on the contact mechanics models, control of the topographical parameters of the polishing pads is found to be an effective method of scratch mitigation. Results of sliding experiments validate the theoretical prediction that scratching by the CMP pads can be mitigated by modifying their topography. It has been observed, additionally, that material removal rate is enhanced by topography modification.



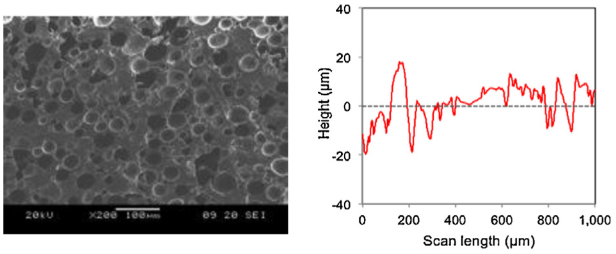
(a) Cu linewidth: 4.5 μm
low-*k* linewidth: 1.0 μm

(b) Cu linewidth: 0.05 μm
low-*k* linewidth: 0.05 μm

Fig. 1. Scratches produced by pad asperities on damascened Cu/low-*k* layers. Only deionized water was used in the experiments.

2. Topography and properties of a typical CMP pad

Surfaces of the CMP pads are porous, Fig. 2a, and relatively rough, Fig. 2b. The average pore size is about 50 μm and the average roughness is about 5 μm. To facilitate slurry flow and eliminate hydroplaning during CMP, the pad roughness is maintained by an in situ diamond conditioner. The profile of an



(a) SEM image

(b) Surface profile

Fig. 2. SEM image and profile of the pad surface.

---

* Corresponding author.

0007-8506/$ – see front matter © 2013 CIRP.
http://dx.doi.org/10.1016/j.cirp.2013.03.069

Please cite this article in press as: Kim S, et al. Modeling and mitigation of pad scratching in chemical–mechanical polishing. CIRP Annals - Manufacturing Technology (2013), http://dx.doi.org/10.1016/j.cirp.2013.03.069

Table 1
Topographical parameters and mechanical properties of an IC1000 CMP pad, and of a monolithic Cu layer.

Material	Property	Avg.	Std. Dev.	C.V.[a]
CMP Pad	z_a (μm)	5.20	3.96	0.76
	R_a (μm)	23.48	10.69	0.46
	λ_a (μm)	102.38	70.09	0.69
	E_p (GPa)	2.21	1.49	0.67
	H_p (MPa)	290	220	0.76
Cu	E_l (GPa)	126.50	12.51	0.10
	H_l (MPa)	1560	260	0.17

[a] Coefficient of variation (C.V.) = Std. Dev./Avg.

IC1000 CMP pad manufactured by the Dow Chemical Co. is shown in Fig. 2b. Such topographical parameters, as the asperity height, z_a, radius, R_a, and the spacing, λ_a, were determined by a Tencor P16 stylus profilometer and are summarized in Table 1. Additionally, the Young's modulus and hardness, determined by a Hysitron TI900 nano-indenter, are also listed in the table.

3. Theory of scratching hard layers by soft pad asperities

At the typical polishing pressures employed in CMP, about 7 kPa, the real area of contact is about a percent of the nominal area [11,12]. Thus, only the tallest asperities of the pad surface contact the layer being polished, and thus the geometry and the mechanical properties of these asperities play a dominant role in pad scratching. Scratching is primarily by the plastically deformed asperities in the contact. The proportion of plastic asperities among those in contact, therefore, essentially determines the number of scratches. For a soft asperity to scratch the relatively hard layers, however, certain criteria must be satisfied. Such criteria for the limiting modes of asperity deformation, elastic and fully-plastic, have been developed [9].

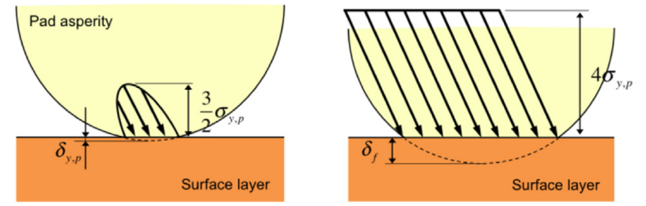
3.1. Single-asperity scratching

When a pad asperity is loaded against a hard layer and slid, in addition to the normal pressure tangential tractions due to friction are also developed. But if friction is small and the deformation is elastic the far-field displacement, δ_p, of the asperity would be less than that at the elastic limit, $\delta_{y,p}$, [13]:

$$\delta_{y,p} = \frac{\pi^2}{16}\left(\frac{H_p}{E_p}\right)^2 R_a \tag{1}$$

where H_p and E_p, respectively, are the hardness and Young's modulus of the asperities. In elastic deforamtion due to normal loading only, the contact pressure distribution is elliptical or Hertzian. But with friction it will be as shown in Fig. 3a. In the limiting case of elastic deformation, i.e., when the asperity is about to yield, the maximum contact pressure is about 1.5 times the yield strength. Then the condition for an elastically deformed asperity to scratch the top layer can be written as a function of the ratio of pad-to-layer hardness and the friction coefficient [9]:

$$\frac{H_p}{H_l} > 1, (0 \leq \mu \leq 0.3) \tag{2-a}$$



(a) elastically deformed asperity, at the onset of yielding (b) fully-plastically deformed asperity

Fig. 3. Surface tractions at a pad asperity/hard layer contact.

$$\frac{H_p}{H_l} > \frac{2}{3}\left[2.38\mu^2 + 0.45\mu + 0.04\right]^{-1/2}, (\mu \leq 0.3) \tag{2-b}$$

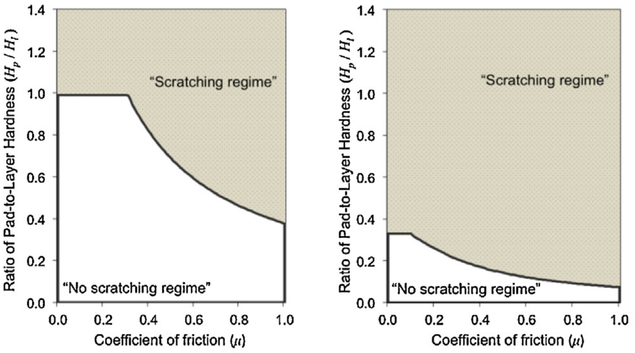
where H_p is the hardness of the pad asperities, H_l is the hardness of the layer being polished and μ is the coefficient of friction.

As the asperity deformation exceeds the elastic limit, the mean pressure applied by the asperity will be greater than its yield strength. In the extreme case of fully-plastic deformation of the asperity, the traction distribution will be uniform and the contact pressure will be three or four times the yield strength, as shown in Fig. 3b. Then the corresponding scratch criteria are [9]:

$$\frac{H_p}{H_l} > 0.34, (0 \leq \mu \leq 0.1) \tag{3-a}$$

$$\frac{H_p}{H_l} > \frac{1}{4}\left[7.76\mu^2 + 0.76\mu + 0.41\right]^{-1/2}, (\mu \leq 0.1) \tag{3-b}$$

Based on Eqs. (2) and (3), scratch-regime maps for elastically and plastically deformed asperities can be constructed as in Fig. 4a and b, respectively. A pad asperity can scratch the surface layer if the combination of hardness ratio and the friction coefficient falls in the "scratch regime" of the map. For the IC1000 pad and a Cu layer, and a friction coefficient (between the two surfaces in water) of 0.4, elastically deformed asperities of IC1000 pad do not scratch the Cu layer, whereas plastically deformed asperities will.



(a) elastically deformed asperity (b) fully-plastically deformed asperity

Fig. 4. Scratch-regime maps for elastic and fully-plastic pad asperities.

3.2. Multi-asperity scratching

Generally, asperity heights of CMP pads are normally or exponentially distributed. Though normal distribution may possibly give a better description of the topography, the exponential distribution has analytical advantages and gives similar results [13]. Thus, if the asperity heights are exponentially distributed, the probability-density function, $\phi(z_a)$, of the asperity height may be written as

$$\phi(z_a) = \frac{1}{\sigma_z}\exp\left(-\frac{Z_a}{\sigma_z}\right) \tag{4}$$

where σ_z is the standard deviation of asperity heights. As the pad is pressed against a hard, flat layer, only the tall asperities on the surface will be in contact, as shown in Fig. 5. If the distance of the layer surface from the centerline is d, the number of asperities in contact, N_c, is given by

$$N_c = N\int_d^\infty \phi(Z_a)dz_a = N\exp\left(-\frac{d}{\sigma_z}\right) \tag{5}$$

where N is the total number of asperities. In order for an asperity to deform plastically, $(z_a - d)$ should be greater than $\delta_{y,p}$, Eq. (1). Therefore, assuming that the radius of all the asperities is the same, the number of plastically deformed asperities, N_p, is

Please cite this article in press as: Kim S, et al. Modeling and mitigation of pad scratching in chemical–mechanical polishing. CIRP Annals - Manufacturing Technology (2013), http://dx.doi.org/10.1016/j.cirp.2013.03.069