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# Copper chemical mechanical polishing using a slurry-free technique

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**Abstract**

A study of the chemical mechanical polishing (CMP) of thin copper films using fixed-abrasive pads is presented. The composition of the polishing solution is optimized by investigating the impact of both the oxidizer concentration and the pH of the solution on the polishing characteristics of copper. The resulting optimum polishing solution gives a high removal rate (> 300 nm/min), good uniformity (standard deviation 3%) and a very high selectivity for the oxide removal rate (> 100:1). The dependence of the removal rate of copper on the geometry is studied for different feature sizes and various pattern densities. The geometry dependency is considerably less in the slurry-free process than in the conventional slurry CMP. This is crucial for copper CMP because it helps to minimize the overpolishing time and consequently the amount of dishing. Damascene copper structures have been successfully made by polishing patterned test wafers. The amount of dishing of the copper lines is smaller than that for the conventional polishing technique. The polished wafers were easily cleaned; a standard rinsing step seemed to be sufficient. 

*Keywords:* Slurry-free; Fixed-abrasive; Copper CMP; Chemical mechanical polishing

## 1. Introduction

The requirement for improved speed without sacrificing circuit reliability has made copper the interconnect metal of choice for integrated circuits (ICs) for 0.13-μm technology and smaller [1,2]. However, copper patterning cannot be carried out in the conventional way since dry etching of copper is difficult due to the lack of volatile halogen compounds at low temperature. To pattern copper for sub-micron technologies with a large process window, chemical mechanical polishing and the Damascene technology scheme are the only choices. The conventional CMP process uses a slurry, which consists of fine abrasive particles suspended in an aqueous solution containing chemical reagents. The process has limitations for deep sub-micron geometry. The use of a slurry reduces the cleanliness of the wafer after the CMP process and consequently lowers the yield. The conventional

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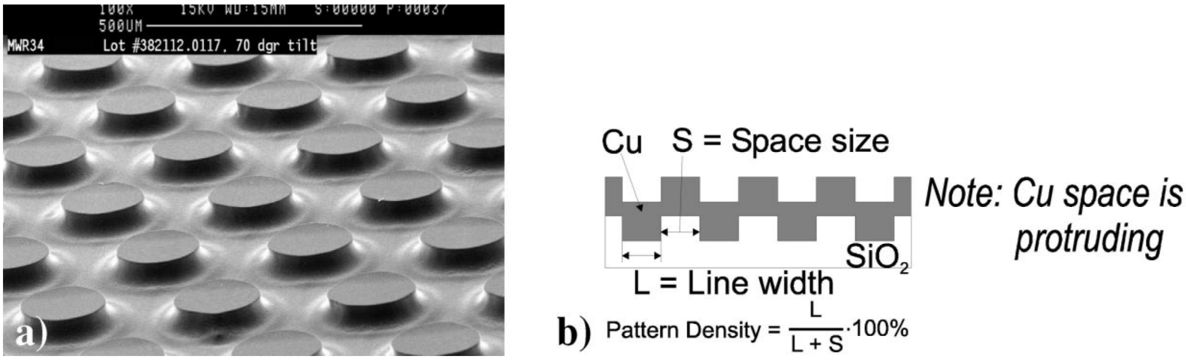


Fig. 1. (a) SEM image of the surface of the fixed-abrasive pad; (b) schematic of a test structure.

CMP process is handicapped by complexity in slurry handling and polishing pad maintenance. In addition, a strong dependence of copper removal rate on feature size and pattern density has been reported [3]. This leads to an uneven removal rate within a die, the so-called within-die-non-uniformity (WIDNU), which prolongs the overpolishing time, and increases the amount of dishing [4].

An alternative slurry-free polishing technique is being developed to overcome the drawbacks of the conventional CMP process. In this technique, the abrasive particles are embedded in a matrix, i.e. the polishing pad, instead of being suspended in a slurry. A scanning electron microscope (SEM) image of the new pad is shown in Fig. 1a. The lack of loose abrasive particles increases the expectation of a simple, clean and improved process. Good results for both oxide and copper CMP processes using a slurry-free technique have recently been reported [5–7].

This paper presents an investigation of copper CMP using a fixed-abrasive pad and a newly developed polishing solution. Optimization of the chemistry of the polishing solution is discussed first. Then the polishing behavior of the fixed-abrasive polishing pad, using the optimized polishing solution on patterned copper wafers, is presented.

## 2. Experimental

The test structures, shown schematically in Fig. 1b, were fabricated as follows. Firstly, the trenches were etched in thermally grown silicon dioxide by reactive ion etching (RIE) to a depth of 600 nm. The size of the spaces (S) varied from 2 to 400 μm and the pattern density (PD) varied from 20 to 83%. Secondly, sputtering was used to deposit a 50-nm Ti layer for adhesion promotion and a 1200-nm film of Cu. These two layers were sputtered without breaking the vacuum between depositions. The starting step height of all the copper spaces is 600 nm, see Fig. 1b. For polishing solution optimization, blanket copper wafers were used. A 3M fixed-abrasive pad was applied together with the newly developed polishing solution. The new solution contains an amino acid as a complexing agent. The oxidizer, hydrogen peroxide, was added to the polishing solution in amounts

Table 1
Design of experiments and polishing results on blanket copper wafers

| Exp. No. | pH | $H_2O_2$ (vol%) | Material | Removal rate (nm/min) | WIWNU (%) |
|---|---|---|---|---|---|
| 1 | 4 | 10 | Cu | 156 | 11 |
| 2 | 4 | 10 | $SiO_2$ | No removal | |
| 3 | 3.5 | 12.5 | Cu | 188 | 5.5 |
| 4 | 3.5 | 12.5 | $SiO_2$ | No removal | |
| 5 | 4 | 15 | Cu | 88 | 9.5 |
| 6 | 4 | 15 | $SiO_2$ | No removal | |
| 7 | 3 | 10 | Cu | 503 | 9 |
| 8 | 3 | 10 | $SiO_2$ | No removal | |
| 9 | 3 | 15 | Cu | 346 | 3 |
| 10 | 3 | 15 | $SiO_2$ | No removal | |

ranging from 10 to 15 vol%. For optimization purposes, the pH of the polishing solution was varied from 3.0 to 4.0. Polishing runs were carried out using a PRESI MECAPOL E460 polishing tool. The polishing pressure was 250 $g/cm^2$. The rotation speed of the platen/pad and that of the wafer carrier was set at 50 rpm. The supply speed of the polishing solution was 250 ml/min. The copper surface profile and morphology were investigated using a profilometer (DEKTAK 3030) and an atomic force microscope (AFM) (Digital Instruments Nanoscope III).

A timed polish process was used for end-point detection. The nominal polish time was determined when all structures were cleared of excessive metals. Table 1 presents the experimental design for the polishing solution optimization. The purpose was to determine at which pH value and hydrogen peroxide concentration the solution gives the best polishing results, as regards the removal rate of copper, its uniformity across a complete wafer (the so-called within-wafer-non-uniformity WIWNU) and the selectivity for oxide removal rate.

## 3. Results and discussion

### *3.1. Polishing solution optimization*

The polishing results for blanket copper wafers using polishing solutions with different pH values and hydrogen peroxide concentrations are shown in Table 1. It can be seen that the pH value and the hydrogen peroxide concentration each have a strong impact on both the removal rate of copper and the WIWNU. The higher the pH value, the lower the copper removal rate. Similarly, an increase in hydrogen peroxide concentration results in a decrease in copper removal rate. The WIWNU is improved with an increase in concentration of hydrogen peroxide and a decrease in pH of the polishing solution. Overall, the polishing solution with pH 3 and a hydrogen peroxide concentration of 15 vol% gives the best result in terms of both copper removal rate and WIWNU (346 nm-min/3% — $1\sigma$).

The selectivity between copper and silicon dioxide in all experiments was more than 100:1. This important result leads to a minimal amount of oxide erosion during overpolishing and results in a larger process window for the copper CMP process.

### 3.2. Pattern dependency of the removal rate of copper

As reported for the conventional copper CMP process [3,4], there is a strong dependence of the copper removal rate on the feature size and pattern density. This leads to a poor WIDNU, which prolongs the overpolishing time and increases the amount of copper dishing. Expansion of the polishing pad into recessed areas and different local pressures are believed to be the main reasons for the strong geometry dependence. The fixed-abrasive pads are expected to exhibit a smaller dependence of the copper removal rate on the feature size and pattern density and therefore give a better WIDNU.

Using the optimized polishing solution, the dependence of the step-height reduction of the copper features on the polishing time was investigated. The results are presented in Fig. 2a. For comparison, the geometry dependence of the step-height reduction in a conventional copper CMP process is shown in Fig. 2b [3]. As expected, there is a considerable reduction in the dependence of the copper removal

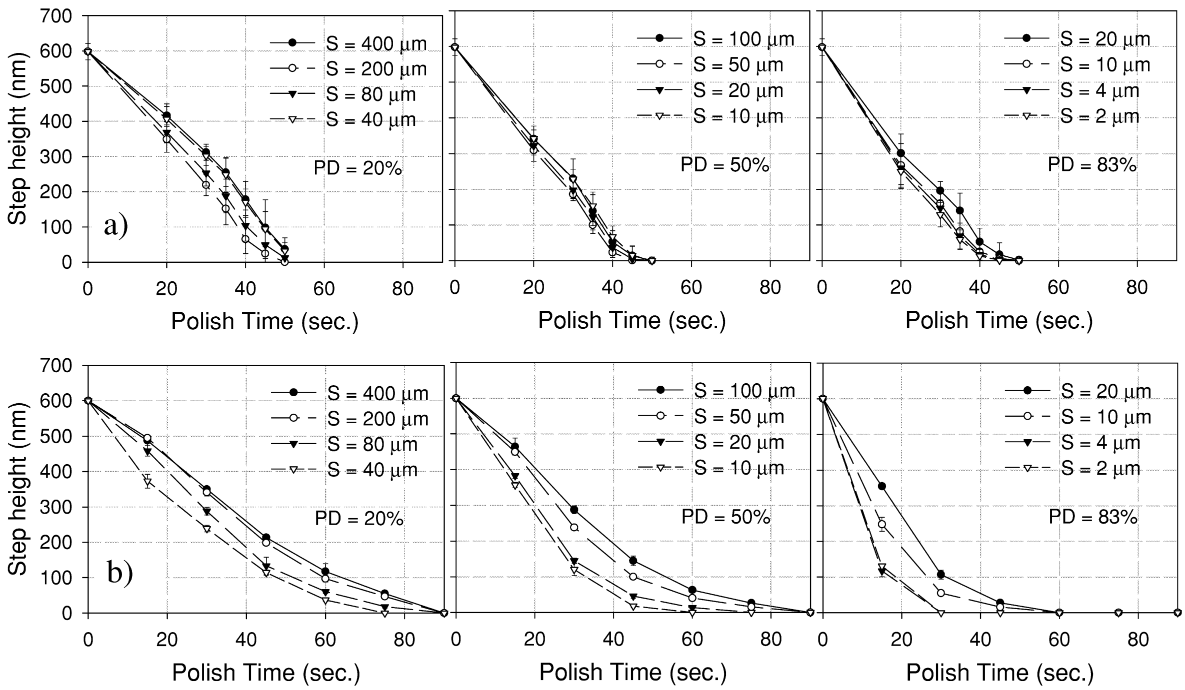


Fig. 2. Step-height reduction of different copper features: S at PD 20%, PD 50% and PD 83% of (a) fixed-abrasive CMP and (b) conventional CMP.

rate on the pattern density and feature size for the slurry-free CMP process when compared to the conventional process. The overpolishing time needed to planarize all features within a die is thereby reduced and the amount of dishing is smaller. In the slurry-free process, there is also a notable reduction in the polishing time required for planarization. This enables the use of thinner, as-deposited copper films.

### *3.3. Copper Damascene structures made by CMP using a fixed-abrasive matrix*

Several patterned test wafers were polished using the optimized polishing solution with the fixed-abrasive pad. After polishing, the sample was cleaned by rinsing in fresh de-ionized (DI) water. Fig. 3a shows a cross-sectional SEM image of a 2-μm wide copper line after polishing with a nominal polish time. More details are revealed by AFM of the same structure in Fig. 3b. The resulting height difference of the copper and oxide surface is measured by means of a line scan, shown in Fig. 4a. The step height after nominal polishing of a 2-μm copper line is only 20 nm, better than the 42-nm step height of a 2-μm copper line polished by the conventional method (Fig. 4b). The average roughness of the surface of the copper lines was 2.2 nm (Fig. 5a), comparable to that attained by the conventional method. The copper surface roughness depends strongly upon the chemistry of the polishing solution [3] as well as on the geometry. For a larger copper feature or for a blanket copper layer, the copper surface is usually very smooth after polishing, and its roughness can be as low as 0.5 nm (Fig. 5b). The rougher surface of the smaller lines is believed to have its origin in a larger etching (chemical) component of the CMP removal process, while wider trenches and blanket wafers experience contact with the pad which smoothens the surface.

Fig. 6 presents an AFM image of a test structure ($L = 2$ μm; PD 50%) polished by the conventional method. The sample was treated by a special step using ultrasonic cleaning in surfactant. When

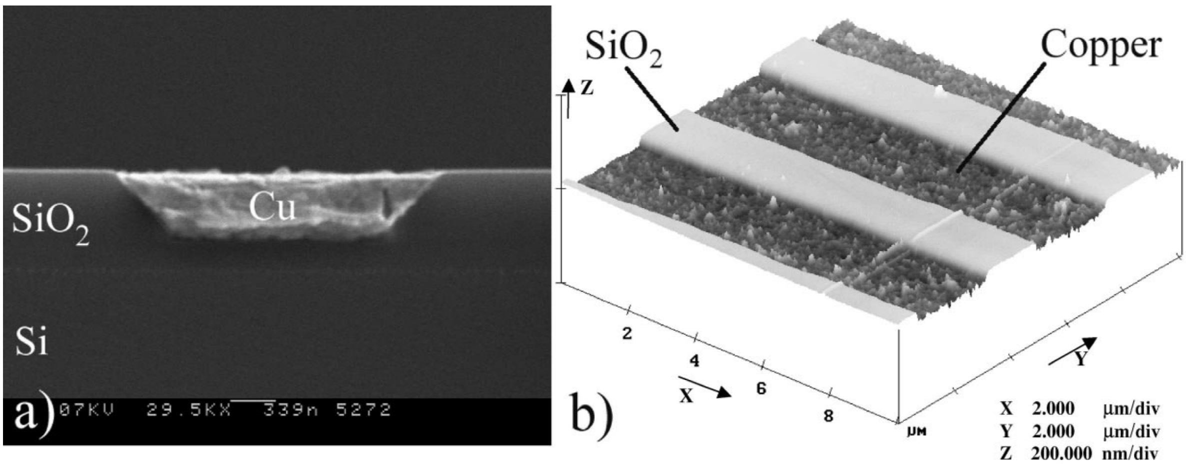


Fig. 3. (a) Cross-sectional SEM image and (b) AFM image (scan size 10×10 μm) of a test structure of 2-μm wide copper lines with a pattern density of 50% (slurry-free technique at nominal polish time).

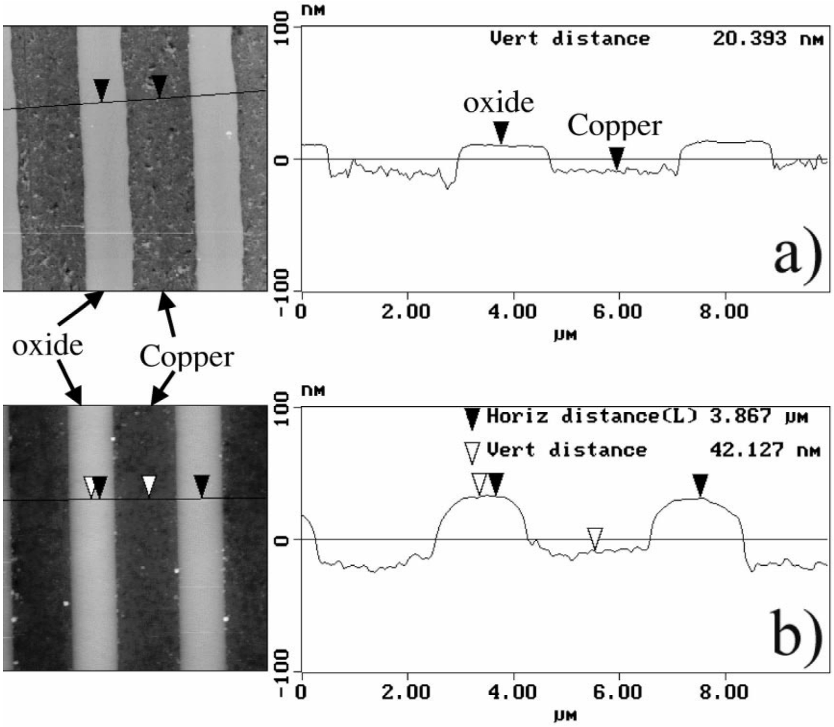


Fig. 4. Remaining step height at nominal polishing time by (a) the slurry-free technique and (b) the conventional CMP technique (IC1000/Suba IV pad and QCTT1010 slurry from Rodel were used in the latter).

compared with the fixed-abrasive process (Fig. 3b), where there was little trouble in post-polish cleaning, the number of observable particles in the AFM image shows that the post-CMP cleaning of conventional copper CMP is relatively difficult.

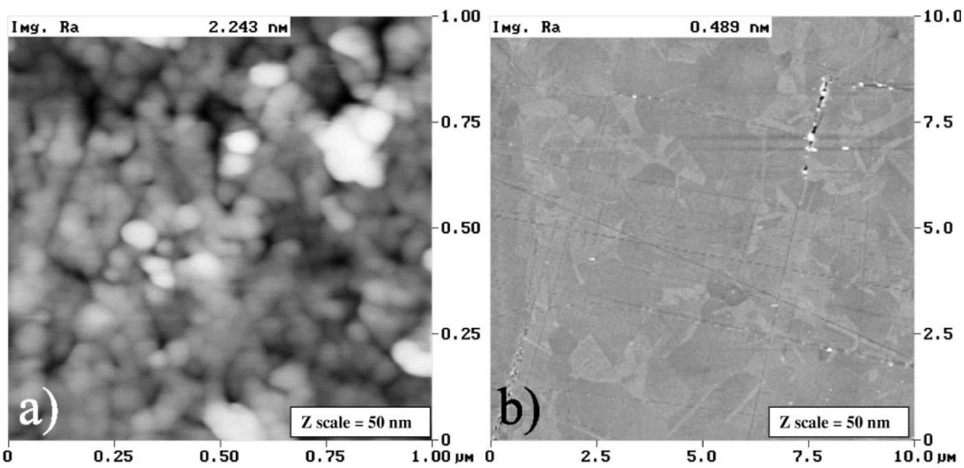


Fig. 5. Surface morphology of (a) a 2-µm copper line and (b) a blanket copper wafer polished by a fixed-abrasive pad.

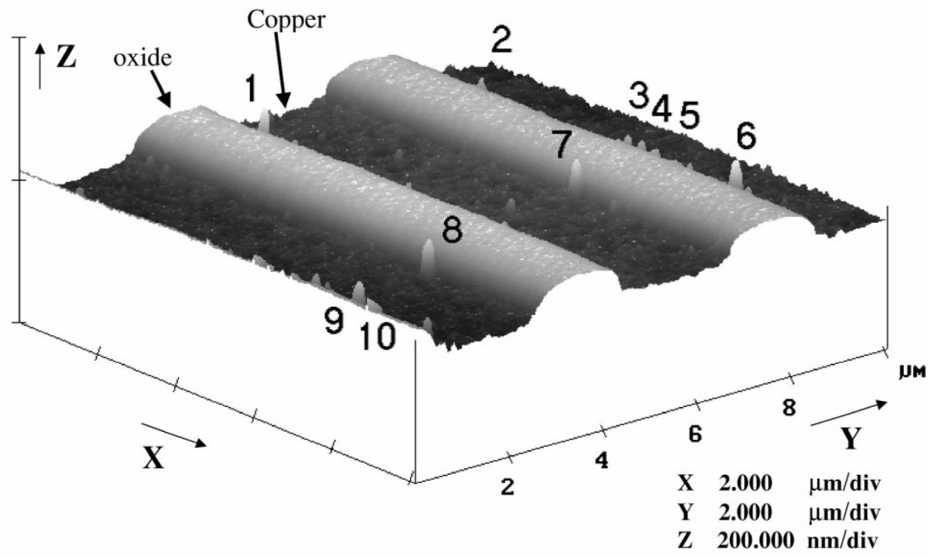


Fig. 6. AFM image of a test structure of 2-μm wide lines with a pattern density of 50% (scan size 10×10 μm) at a nominal polishing time. The sample was polished by an IC1000/SubaIV pad and QCTT1010 slurry from Rodel. After polishing, the sample was treated by ultrasonic cleaning.

## 4. Conclusions

Copper CMP using fixed-abrasive pads was investigated. The polishing solution, which consists of hydrogen peroxide as oxidizer and complexing and buffering agents, was optimized. Experimental results show that the optimized polishing solution has a pH of 3 and a hydrogen peroxide concentration of 15 vol%. Investigations of patterned copper wafers using the optimized polishing solution showed a considerably reduced dependence of the copper removal rate on the pattern density and feature size for the slurry-free CMP when compared with the conventional copper CMP. This helps to minimize the overpolishing time and consequently the amount of dishing. The good polishing results for patterned wafers include a small amount of dishing, a smooth copper surface, a fast planarization and relatively easy post-CMP cleaning. The fixed-abrasives technique is therefore a very promising alternative for copper CMP.

## References

[1] D. Edelstein et al., Full copper wiring in a sub-0.25 μm CMOS ULSI technology, in: Proceedings of an IEEE International Electronic Device Meeting, 1997, CD-ROM.

[2] S. Venkatesan et al., A high performance 1.8 V, 0.20 μm CMOS technology with copper metallization, in: Proceedings of an IEEE International Electronic Device Meeting, 1997, CD-ROM.

[3] V.H. Nguyen, B. Timmer, H. van Kranenburg, P.H. Woerlee, Time dependency of the planarization process in copper chemical-mechanical polishing, in: Proc. ESSDERC'99, 1999, pp. 260–263.

[4] V.H. Nguyen, H. van Kranenburg, P.H. Woerlee, Dependency of dishing on polish time and slurry chemistry in Cu-CMP, Microelectron. Eng. 50 (2000) 403–410.

[5] P. van Velden, F. Weimar, Chemical mechanical polishing using fixed abrasives, in: CMP Proc. Semicon Europa 98, 1998.
[6] P. van Velden, Chemical mechanical polishing with fixed abrasives using different sub-pads to optimize wafer uniformity, Microelectron. Eng. 50 (2000) 41–46.
[7] M. Matsumoto, K. Suzuli, T. Sakamoto, A. Kamisawa, Evaluation of Cu CMP for interconnects using a new slurry-free process, in: Proc. CMP-MIC '99, 1999, pp. 176–183.