

Effects of pattern characteristics on the copper electroplating process*

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Abstract: The non-planarity of a surface post electroplating process is usually dependent on variations of key layout characteristics including line width, line spacing and metal density. A test chip is designed and manufactured in a semiconductor foundry to test the layout dependency of the electroplating process. By checking test data such as field height, array height, step height and SEM photos, some conclusions are made. Line width is a critical factor of topographical shapes such as the step height and height difference. After the electroplating process, the fine line has a thicker copper thickness, while the wide line has the greatest step height. Three typical topographies, conformal-fill, supper-fill and over-fill, are observed. Moreover, quantified effects are found using the test data and explained by theory, which can be used to develop electroplating process modeling and design for manufacturability (DFM) research.

Key words: ULSI; electroplating; CEAC; pattern dependency; systematic variations; DFM

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1. Introduction

Electroplating (ECP) and chemical mechanical planarization (CMP) processes have gained broad applications in the back-end process of sub-130 nm technology nodes^[1, 2]. Moreover, continued aggressive scaling down of the ULSI feature size requires better planarization of chip surface topography in order to improve manufacturability, timing, reliability and yield. Hence, it is extremely important to reduce systematic topography variations during the fabrication process.

The post-ECP topography strongly depends on layout patterns. The following is a CMP process in which excess overflowing Cu is removed from the oxide surface^[3, 4]. The post-CMP topography will be influenced by the ECP process. To improve ECP performance, an understanding of the layout and process dependencies is required, and some research papers have been published about this. The curvature enhanced accelerator coverage (CEAC) mechanism was developed to describe the effect of area change on adsorbate coverage and explore the consequences on the rate of metal deposition and resulting shape evolution during growth on non-planar substrates^[5-7]. Park^[8] found that the post-ECP topography is strongly dependent on layout patterns and developed the first ECP empirical models to show this dependency. Luo^[2] put forward some problems of Park's model and proposed a physics-based layout dependent ECP topography model. In Luo's model, there are much fewer calibration parameters and it has the first metal filling algorithm to guide metal filling in order to improve the ECP process capability from a design angle^[9, 10]. The CEAC mechanism can explain supper fill very well, but it can not quantify pattern-dependent phenomena. Park and Luo's model can simulate pattern dependency with some precision, but the accuracy

is limited, especially for fine line and spacing with the continued aggressive scaling down of ULSI feature size. In order to accurately detect the pattern dependent characters, we design all kinds of line and spacing structures in our test chip and process it in a 65 nm process foundry. Finally, we explore the verified pattern dependency of the ECP process and draw some conclusions, which will be helpful for designers and process engineers.

2. Mechanisms of the electroplating process

In electroplating, as Figure 1 shows, a wafer coated with a thin electrically conductive layer of seed Cu is immersed in a solution containing dissolved salts of the metal to be deposited. The set up includes a cathode and an anode. When current is applied, the electrical energy carried is converted to chemical energy by decomposition, a reaction in which the elements are divided into positive and negative charged ions. The movement of positively charged ions towards the cathode surface results in metal deposition. This can be described by the following equation: $\text{Cu}^{2+} + 2\text{e}^- = \text{Cu}$. The Cu ions depleted from the

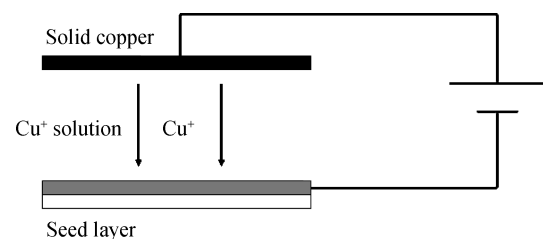


Fig. 1. An electroplating system.

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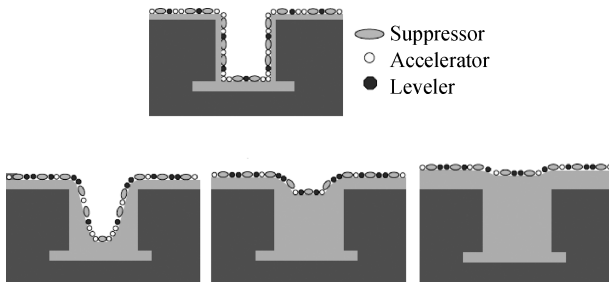


Fig. 2. Scheme of a bottom-up deposition.

chemical solution will be replenished from the solid Cu anode. This can be described by the following equation: $Cu - 2e^- = Cu^{2+}$.

Figure 2 shows the scheme of a bottom-up deposition for micro-via metallization. To achieve such a fill behavior, additive chemicals known as accelerators, suppressors and levels are added to the plating solution. The bottom-up filling dynamic is seen to be a consequence of competitive adsorption between inhibiting and accelerating species on the local surface. The accelerators are the stronger surfactant; and can be displaced and adsorbed at a faster rate than suppressors. At the same time, up-growth on non-planar geometries leads to the enrichment of accelerators on advancing concave surfaces and dilution on convex areas. Because the metal deposition rate rises monotonically with the local accelerator surface coverage, it ensures that the deposition starts at the bottom of the trench and move upwards with no void formation. As the action of the accelerators can also be decreased by the addition of a cationic “leveling” surfactant (LEV), additive concentrations can be optimized to allow accelerator derived bottom-up superfilling followed by LEV induced accelerator deactivation^[11]. The LEV addition can thus be used to inhibit overshoot. Otherwise, it will result in undesirable bump formation above the features.

3. Effects of pattern characteristics on post ECP topography

The thickness variations of the chip surface post ECP and CMP processes are mainly dependent on variations of key layout characteristics, which include line width, line spacing and metal density (defined as the ratio of the line width to pitch, where pitch is the separation of the center of lines). The three output variables that represent the final topography are the array height H , the field height H_0 and the step height S . As shown in Fig. 3, the array height H is defined as the thickness of Cu above the oxide of the array area after deposition; the field height H_0 is defined as the thickness of Cu above the oxide of the field area; the step height S is defined as the difference of Cu height between the Cu above the oxide and the Cu above the trench in the oxide. When the height of Cu above the oxide is larger than the height of Cu above the trench, the step height S is a positive value. Otherwise, it is a negative value.

To capture the characterization of copper electroplating process pattern dependencies, a mask has been designed, as shown in Fig. 4(a). It is a single level mask with dimensions 5 mm by 3 mm, which contain 32 array structures. The size

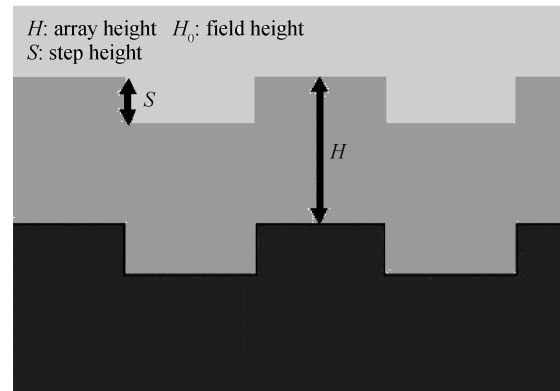
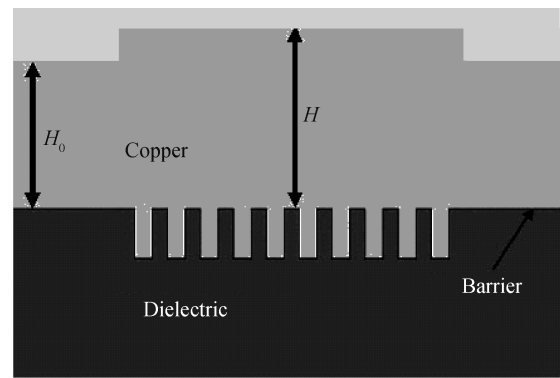


Fig. 3. Description of the array height, the field height and the step height.

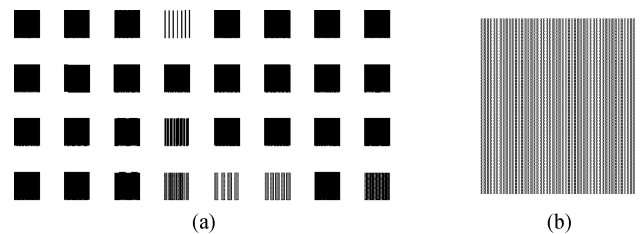


Fig. 4. (a) Single-level copper test mask. (b) Physical test structure.

of each array is about $300 \mu m$ by $300 \mu m$; the space between neighboring arrays is also $300 \mu m$, which is designed to decouple interactions among structures and also serve as measured surface profile reference points. To mimic interconnect, arrays of lines and spaces form the fundamental test structure for the study of pattern dependencies. Figure 4(b) is an array structure that incorporates two regions or elements. The “array” region gives information about array height and local step height within array lines in electroplating. As a whole, the range of the feature size is about $0.09 \mu m$ to $40 \mu m$ and the metal density coverage is from 10% to 91%. Unlike other test masks introduced in papers, the feature size is small enough for the coverage characterization of a 65 nm process, so the conclusion obtained from this paper will be more accurate and useful.

For the given process, the trench depth is about 2600 \AA and the copper thickness filled is about 7700 \AA in theory. To measure step height, a surface profile measurement is taken with a Veeco profiler, which is a two dimensional measurement device that gives the relative heights of the different regions of the surface in question. To investigate the evolution of copper

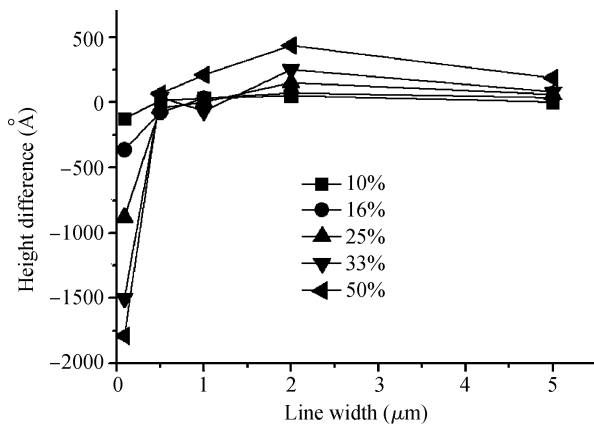


Fig. 5. Height difference dependent on line width and density.

thickness, its measurement is necessary. However, it is not easy to do this. As the smallest line width is about 0.09 μm and the trench depth is about 0.26 μm, it is very difficult to use common tools such as the Metapulse 300 from Rudolph measure it directly. Therefore, we cut the test structures, obtain cross-section images and then measure them by SEM photo.

In the following, the paper will analyze key layout characteristics' effects on chip topographies after deposition.

3.1. Height difference between the field height and the array height after the ECP process

The height difference is defined as the difference between the field height and the array height. If the height difference is a positive value, it means the field height is more than the array height. Otherwise, it is a negative value, as shown in Fig. 4. By reviewing the curve of the height difference shown in Fig. 5, we can draw some conclusions. When the line width is less than 0.5 μm, the height difference is less than zero and evidently decreases with the density augment, and the greatest difference is about -1800 Å. However, when the line width is more than 0.5 μm, the height difference slowly increases with the density augment, and the largest difference is less than 500 Å. In addition, the height difference increases quickly as the line width is enhanced from 0.09 to 0.5 μm, and then increases slowly when the line width is more than 0.5 μm. In other words, the array height of the 0.09 μm line width is far bigger than other structures. From the SEM pictures of the wafer cross section, such as Fig. 6, we can draw the same conclusion: that fine lines have the largest array height. When the density is 50% and the line widths are 0.09, 0.3, 0.75, 1.5, 3 and 10 μm, the array heights are 9910, 8080, 7723, 8038, 7123 and 7213 Å, respectively.

From the testing data, we can see that the feature size of the line width has a critical impact on array height. When the size scales down to 0.09 μm and below, there is more copper deposition. Based on the CEAC mechanism, as Equation (1) shows, the local curvature k_c of the interface has momentous influence on the non-planar geometries^[7]. In the equation, θ is the local coverage of the accelerator, v the local growth velocity, κ^* the rate constant, C_a^i the accelerator concentration and t the time.

$$\frac{d\theta}{dt} = vk_c\theta + \kappa^* C_a^i(1 - \theta). \quad (1)$$

The curvature k_c of the convex surface is positive while it is negative for the concave surface. Therefore, the curvature k_c dependence leads to increasing local coverage on concave surfaces and a decrease on convex surfaces during growth.

Since the deposition rate rises monotonically with accelerator coverage, this naturally gives rise to bottom-up filling of features and, more generally, super-conformal film growth. The area change effect becomes increasingly important as the dimensions of the surface profile shrink into the sub-micrometer regime. As Figure 2 shows, the accelerator accumulates easily at the corner of the bottom where the curvature k_c is great. If the depth of the trench is definite, the finer the line width is, the greater the curvature is. When the line width is 0.09 μm, more accelerator coverage leads to more deposition thickness. Nevertheless, the shape effect has little influence on the deposition rate for the wide line width.

3.2. Step height after the ECP process

The step height S is defined as the difference of Cu height between the Cu above the oxide and the Cu above the trench in the oxide. From Fig. 7, we can see that the value of step height is predominantly determined by the line width. If the line width is less than 0.5 μm, there is no obvious concave. When the line width increases from 2 to 5 μm, the step height increases from 1100 to 2300 Å. When the line width is bigger than 5 μm, the step height is about 2400–2600 Å which approaches the trench depth. Therefore, we can come to a conclusion that the step height reaches saturation when the line width is more than 5 μm. At the same time, Figure 7 also shows that copper density has a small influence on the step height.

From the above discussion about the array height, it is easy to conclude that there is a low average curvature k_c for wide lines. In some papers, this is called conformal fill. When the line width is bigger than some critical dimension, the deposition rate in the trench is close to the growth rate on the surrounding dielectric surface and the step height is approximately equal to the trench depth. For the fine line, the shape is a dominant factor for deposition rate. There is little step height in the local area.

3.3. Surface topography after the ECP process

Luo *et al.* think that there are three kinds of fill: conformal-fill, super-fill and over-fill. In our test, we see the continuous transformation of the topographies from fine line to wide line obviously, as Figure 6 shows. Nevertheless, it also has three kinds of typical characteristics, shown in Fig. 8. For simplicity, we use the same names as Luo to describe the topographies. In our test, when the line width is less than 0.3 μm, the topography is over fill; from 0.5 to 1.5 μm, it is a super fill; when the line width is more than 2 μm, it is a conformal fill.

For the great fine line, its deposition conforms to CEAC mechanisms. The local curvature of the trench dominates bottom-up filling. After the trench is filled, the overflowing copper above the trench expands to both sides as silver sand accumulates, which is called over fill. When the line width increases to 0.5 μm, the local curvature in the trench has an effect on the bottom-up fill and the overfill copper above the trench also expands to both sides. However, the effect is not enough to cover all the spacing area, so the copper thickness above the

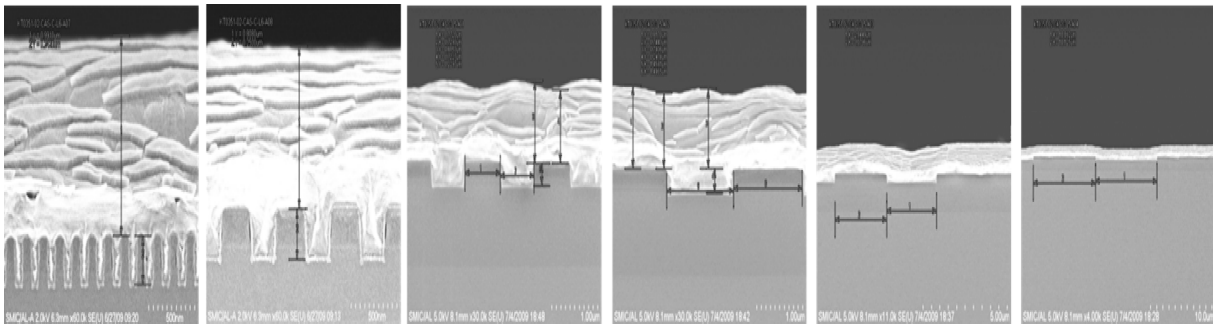


Fig. 6. SEM images of trenches with line width: 0.09, 0.3, 0.75, 1.5, 3 and 10 μm .

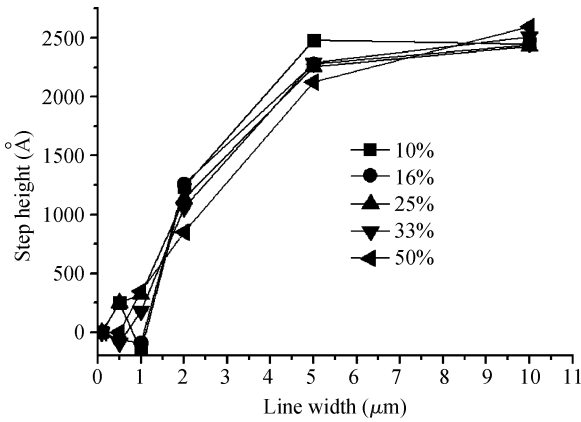


Fig. 7. Step height dependent on line width and density.

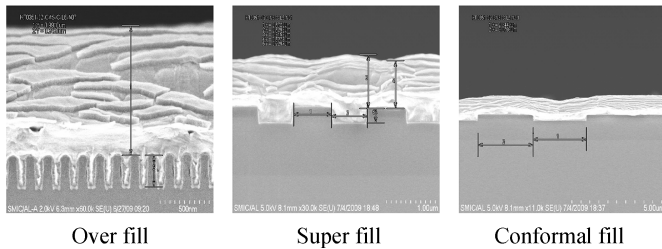


Fig. 8. Three typical topographies.

trench is slightly higher than on the spacing dielectric, which is called a super fill. If the line width is more than 2 μm , the local curvature in the trench is small and has little effect on the fill, so both the trench and spacing area have the same deposition rate and the step height is equal to the trench depth, which is called conformal fill.

4. Conclusions

In this paper, we consider the effects of pattern on ECP deposition. Under the same ECP process, some conclusions are made and explained using CEAC mechanisms. Fine lines, such as one with a 0.09 μm line width, have thicker copper. Line width is a dominant factor affecting step height; when its size is more than 2 μm , the step height can be observed and increase rapidly until it reaches saturation close to the trench depth. There are three kinds of typical topographies, which are

mainly decided by line width; when the size is less than 0.3 μm , it causes over fill; when the size is between 0.5 μm and 1.5 μm , it causes super fill; when the size is more than 2 μm , it causes conformal fill. To sum up: line width is a critical factor of the ECP process.

Next steps are to optimize ECP models which consider the effects of layout on the ECP process and, then use the test data to calibrate the ECP model and develop DFM research.

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