Uniformity study of nickel thin-film microstructure deposited by electroplating

Jia-dong Li · Ping Zhang · Yi-hui Wu · Yong-shun Liu · Ming Xuan

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Abstract The thickness uniformity and the cross-sectional profiles of electroplated individual nickel microstructures were investigated in given electroplating conditions. The main factors influencing the thickness uniformity of microstructures were discussed. An effective method to overcome the burning problem by increasing the sacrifice seed layer structure is proposed. It is shown that the thickness uniformity and the cross-sectional profiles of the microstructures can be controlled by changing the process conditions. The current crowding observed in patterned specimens is responsible for the saddle shape profile of individual microstructures, while the combination of the current crowding and the cathodic polarizability are believed to be responsible for the abnormal cap-like profile of individual microstructures. A uniform thickness distribution and microstructures with flat profiles were obtained at optimal plating conditions of 8.05 mA/cm² and 20°C.

1 Introduction

Recently, metal electroplating has become into one of the most important technologies in micro electronics mechanics system (MEMS). By combining photolithography technology and electroplating it is possible to fabricate microstructure, and it is a simple and low-cost process (Yeh et al. 2005; Green et al. 2003; Judy et al. 1995). However, one of the problems associated with electroplating is the uniformity control of the electroplated films both in thickness and composition (Wei et al. 2000; Du et al. 2007; Qu et al. 1997). This affects the material properties and resulting performance of micro components.

The thickness uniformity of electroplated metal films was intensively investigated during 1990s; especially for the microelectronics industry as Cu became the standard for interconnects in integrated circuits and also for the MEMS society as plated metal microstructures became popular micro components for sensors and actuators. The copper film on a silicon wafer typically has a saddle shape. The thickness at the edge of the micro structure is larger than that in the center as shown in Fig. 1 (Takahashi 2000; Flake et al. 2003). The active-area density model was proposed to explain this phenomena, which it ascribes to current crowding at the edge of photoresist patterns (Mehdizadeh et al. 1992). In fact, for the patterned wafer plating, the cross-section of the microstructure not only has the saddle-shaped structure, but also has the cap-like structure. Clearly this model can not explain the cap-like microstructure profiles. In order to explain this phenomenon, Luo et al. (2005) proposed the fluidic friction and electrophoresis effects model to explain the thickness distribution of the specimen. The combination of fluidic friction and electrophoresis effects is believed to be responsible for this abnormal profile and thickness.
distribution. However, in related experiments described in this paper, we found that this model is also not enough to explain the cap-like microstructure profile.

In this paper we managed to improve electroplated microstructure profiles and thickness uniformity by optimizing the plating conditions. One effective method to improve thickness uniformity for low active-area density electroplating process was described. Several factors that affect the structure surface quality of electroplating were discussed. Furthermore, a more reasonable explanation was given to explain the cap-like profile of patterned microstructure plating.

2 Experimental conditions

2.1 Plating bath and solution

In the experiments, the bath solution was commercially purchased from Highnic Surface Technology Ltd and it is consisted of nickel sulfate 250 g/L, nickel chloride 55 g/L, and boric acid 45 g/L. The pH value of the plating solution was between 3.5 and 4.0. A Ni plate with an area of 35 cm² was used as the anode. A 2-L Pyrex glass beaker was used as an electroplating tank. A magnetic pellet was used to stir the solution to keep the concentration uniform and to prevent the formation of hydrogen bubbles on the sample surface. The electrolyte was heated by DF-101s hot stirrer placed beneath the beaker. A temperature sensor from the hot stirrer was placed in the electrolyte to control the bath temperature with the error of ±1°C.

2.2 Sample preparation

The analyzed structure is the micromirror nickel posts, as shown in Fig. 2. The marks on the cross section are the height detecting points.

The process flow to fabricate the photoresist micromolds was as follows: a silicon wafer was used as the substrate and was covered with a conductive sandwich layer comprising of 100 nm of evaporated Cr as adhesion layer to the flat silicon surface and 700 nm of evaporated Cu layer as the electroplating seed layer. The Cr/Cu layer served as the electroplating cathode. The seed layer was then coated with photoresist AZ4620 to obtain a thick photoresist micromold structure. Each coating was baked at 85°C for 30 min. This was followed by exposure using Karl SUSS MA6. Developing and rinsing steps followed. The final photoresist micromolds were soft baked at 110°C for 10 min to improve the adhesion between the photoresist and the seed layer. Micromold structures with width of 50 μm were used. The typical photoresist thickness of micromold was 10 μm.

2.3 Measurements

The thickness was measured using a Non-contact depth measurement, with the resolution of 0.1 μm on thickness. A digital instruments electrochemical workstation CHI660 was used to measure the cathodic polarizability as shown in Fig. 3.

3 Results and discussions

3.1 Active-area effects

Active-area accounts for the presence of patterning features on the electrode surface. When the active-area of the
cathode is smaller than the anode, current tends to be greater at the edges of the active-area. This makes more current flow than the nickel ions can carry, forcing the nickel ion to deposit as tiny black smut instead of building a proper crystal structure. This black smut is called ‘burning’.

According to the electric field distribution, the same size anode and cathode should have a uniform distribution of plating current. An attempt was made to improve the thickness uniformity by changing the anode geometry. However, it is difficult and expensive to get an anode shaped liked the cathode. Auxiliary cathodes are frequently used in industrial electrodeposition to obtain uniform thickness distribution (Flake et al. 2003). In this situation, the experimental apparatus needs two power supplies. The equipment becomes complex. In order to overcome this problem, a sacrifice seed layer structure on the same substrate with microstructures was applied to reduce burning problem as shown in Fig. 4. The object of the sacrifice seed layer was to reduce local ion concentration in the microstructure plating area, then to reduce the growth rate on the edges of the nickel deposit. By using the sacrifice seed layer structure, No burning was found in Fig. 5 even it was overplated.

3.2 Current density effect with sacrifice structure

The profiles corresponding to different current density were shown in Fig. 6a–c. In the experiment, when the plating current density was 1.03 mA/cm², the nickel post has a cap-like shape. The thickness of the plated nickel post at the middle is thicker than that at the edge. When the specimen was plated at a current density of 8.05 mA/cm², the nickel post becomes flatter with a uniform thickness from the edge to the center of the nickel post. Further increasing the plating current density to 15.5 mA/cm², it leads to a change in the cross-sectional profile. The profile of the nickel post becomes saddle shape. It is shown that the uniformity of microstructure profiles and the thickness can be improved by varying changing the plating current density.

So far, only the saddle profile structure and thickness distribution have been noticed and studied. The cap profiles of individual microstructures have actually been shown in many publications but without comment. For example, the cap-like profiles and cap-like pillars in electroplated microstructures were shown in (Green et al. 2003) and (Zappe et al. 1997). In order to explain the cap-like profiles, Luo et al. developed the fluidic friction and electrophoresis effects model to explain the thickness distribution of the specimen. The fluidic friction between the solution and the solid surface produces a thin boundary layer, which does not move freely. Ions in the boundary
layer have a very small mobility. The mobility of ions near the solid surface is almost zero and gradually increases as they move away from the interface. As a consequence, there is insufficient supply of ions for plating in the boundary-layer regions. However, ions outside the boundary layer can move toward the surface of the cathode under an electrical field (electrophoresis effect), providing a continuous source of ions for plating. The thickness of the boundary layer can be varied by applying an external potential and varying the ion concentration. At a low current density (a low electrical field), the friction effect is dominant and a lightly crowded current density is not sufficient to compete with the friction effect, and so the plating rate on the edge is still small. As the current density increases (the field increases), the thickness of the boundary layer reduces. But the electrophoresis effect becomes stronger even for those ions in the boundary layer. A highly crowded current density leads to much faster plating at the edge; hence, a thicker film is formed on the edge. These two effects are superimposed and eventually form a saddle shape on the microstructure.

Close examination reveals that when the micromold does not have a 90° sidewall, it has a slope (as shown in Fig. 7) that may waken the fluidic friction effect. The cap-like shape profile on the microstructure (as shown in Fig. 8) is still obtained. Clearly this model is unable to explain the cap-like microstructure profile and the thickness distribution in this situation. So there must be other mechanisms accounting for the slower plating at the edge of microstructures.

Cathodic polarizability is one of the most important factors that influence the profiles and the uniformity of microstructures (Ren 2001). Current crowding should always exist for patterned wafer plating (Luo et al. 2005).

Fig. 6 Height of the microstructure plated at $i = 1.03$ (a), 8.05 (b), 15.5 mA/cm$^2$ (c) at a fixed plating solution and a fixed temperature of $20 \pm 1^\circ$C

Fig. 7 Cross section of the micromold

Fig. 8 SEM image of the nickel post
Both current crowding and cathodic polarizability are believed to be responsible for the thickness distribution. The cathodic polarizability \( \delta \) is given by

\[
\delta = \frac{\Delta \varphi}{\Delta I}.
\]

Here \( \Delta \varphi \) is voltage-difference, \( \Delta I \) is current difference. As shown in Fig. 9, cathodic polarizability decreases with the current density increases. At a low current density, according to the primary current distribution, the current density is lower in the center and becomes higher toward the edge, so the edge polarization resistance is higher than the center polarization resistance, according to the Ohm’s law

\[
I = \frac{U}{R_1 + R_2 + R_3},
\]

where \( R_1 \) is polarization resistance, \( R_2 \) and \( R_3 \) are electrolyte resistance and seed layer resistance, respectively. We know that the current density on the edge is lower than the current density in the center after the second current distribution. The cathodic polarizability effect is dominant and a lightly crowded current density is not sufficient to compete with the cathodic polarizability effect, and so the plating rate on the edge is small. As the current density increasing, the cathodic polarizability effect reduces, but the current crowding effect becomes stronger. Under these two influences, the coating surface tends to smoothly with a uniform thickness from the edge to the center of the microstructure. Further increasing the plating current density, the cathodic polarizability tends to zero, and the impact on the uniformity of the coating can be ignored. The current crowding effect is dominant; a highly crowded current density leads to much faster plating at the edge; hence, a thicker film is formed on the edge.

3.3 Temperature effect

In order to quantify the variation of the nonuniformity \( \eta \) on the process conditions, we define the nonuniformity of a microstructure as follows:

\[
\eta = \frac{h_e - h_{mid}}{h_{mid}} \times 100\%
\]

where \( h_{mid} \) is the thickness of a wide structure in the center, and \( h_e \) is the thickness at the edge of the microstructure.

The nonuniformity variation corresponding to different temperature and current densities (20, 25 and 40°C) are shown in Fig. 10. Although the nonuniformity follows the same trend with the current density at different temperatures, it changes from a negative to a positive nonuniformity, non-uniformity becomes stronger when plated at a higher temperature. The thickness uniformity and the profile of a microstructure plated at 20°C is generally better than those plated at 25 and 40°C over the whole range of current densities used here. A higher temperature corresponds to a higher diffusion rate of Ni ions in the solution. This enhances the current crowding effect in patterned microstructure plating, thus the nonuniformity of plated microstructures as was observed.

3.4 Stirring effects

It was found that there was a visible difference in the microstructure profiles for plating with or without magnetic pellet stirring was introduced. In solution with magnetic pellet stirring, the profile of the microstructure was typically asymmetrical. As shown in Fig. 11, the film on the microstructure array 1 was typically thicker than microstructure array 2. Since stirring the solution increase the
diffusion of Ni ions near the cathode and leads to a higher plating rate on the on-coming side. Further increasing the stirring speed, the seed layer will be shed from the silicon substrates. Therefore, stirring is unnecessary, in order to obtain uniform layer.

The effects created by other process parameters such as PH value, the spacing between anode and cathode, and aging of solution on the uniformity of plated microstructures have also been investigated. It was found that the effects from these process parameters are not as significant compared with plating current density and temperature when the pH value is lower than 5.

4 Conclusions

The thickness uniformity of electroplated nickel post has been investigated as a function of plating conditions. The following conclusions can be drawn:

1. The technique of applying the sacrifice seed layer structure to overcome burning problems has been proved the effect in nickel electroplating process.
2. The uniformity and profiles of electroplated nickel posts are controlled mainly by plating current density and temperature. Optimal conditions of 8.05 mA/cm² and 20°C were obtained to fabricate flat cross-sectional profile microstructures and a uniform thickness distribution across a specimen.
3. The current crowding observed in patterned specimens can be used to explain the saddle shape profile, while a combination of current crowding and cathodic polarizability is believed to be responsible for the cap-like profile of microstructure.

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References


Fig. 11 Scheme of microstructure location and flow direction


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