Optimization of Film Uniformity by Electrochemical Copper Deposition Chamber Design

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The impact of chamber design parameters on the non-uniformity of Cu film deposited by electrochemical method were investigated quantitatively by simulating the film growth process. These parameters include chamber geometry, electrolyte flow path, electrode configuration, and electrical field division and isolation. Further studies were conducted to optimize basic process parameters such as deposition current and current distributions on electrodes.

Introduction

Copper metallization by electrochemical deposition has been replacing aluminum metallization in ULSI circuit fabrication to form interconnection (1). It has become increasingly difficult to electroplate uniform Cu film onto a thin resistive seed layer on a larger substrate, owning to a phenomenon known as “terminal effect” (2-5). In our work presented previously, the effects of electrodeposition process conditions, such as deposition current, current distribution, and electrolyte conductivity, on non-uniformity of the final films were investigated by simulating Cu film growth in a multiple electrodes deposition system. It was shown that additional electrodes, under optimized process conditions, greatly reduced the non-uniformity of the final films. In the present work, the same simulation method was employed to understand how the geometry aspects of a deposition chamber impact the non-uniformity of final films. These parameters include chamber size, flow circulation path, electrode configuration, and electrical field division and isolation. Non-uniformity of films of 3000 Å thickness deposited on 350 Å seed layers were quantitatively analyzed for different geometries, and optimized process conditions were further applied to the best chamber design.

Theory and Model Formulation

In our previous work, the numerical calculation of current densitiy distribution on the growing Cu film was employed to simulate the Cu film profile over time on wafer surface in an electrochemical deposition chamber. Under chamber electroneutrality condition, the total current density is expressed as (6):

$$i = -F\sum z_i D_i \nabla c_i - \nabla\Phi \sum \frac{F^2 D_i z_i^2 c_i}{RT} \qquad [1]$$

where F is Faraday constant, z is valence, D is diffusion coifficient, c is concentration, R is gas constant, T is absolute temperature, and $\nabla\Phi$ is ohmic drop. i can be estimated by solving Nernst-Planck equation for ion concentration and potential fields, together with

Navier-Stokes equation that describes the flow field. The calculation was based on two types of boundary conditions:

on insulators:

$$\nabla \Phi = 0, \quad [2]$$

and on electrodes:

$$\Phi = V - E_0 - \eta_a - \eta_C, \quad [3]$$

where V is electrode voltage, E_0 is standard electrode potential, η_a is activation overpotential, and η_C is concentration overpotential. Tertiary distribution was used in equation [3] to include influence of ionic concentration gradient, electric potential gradient and bulk flow convection in the deposition chamber (7-9). The calculation was carried out by a computer simulation package developed by L-Chem. Inc.

The geometry set up to simulate the multiple electrodes chamber in this study was illustrated in Figure 1. The electrical contact on the wafer was assumed to be continuous along its perimeter. A set of insulation shields inside the chamber dividing individual electrode and flow circulation path were used to control local electrical and flow fields.

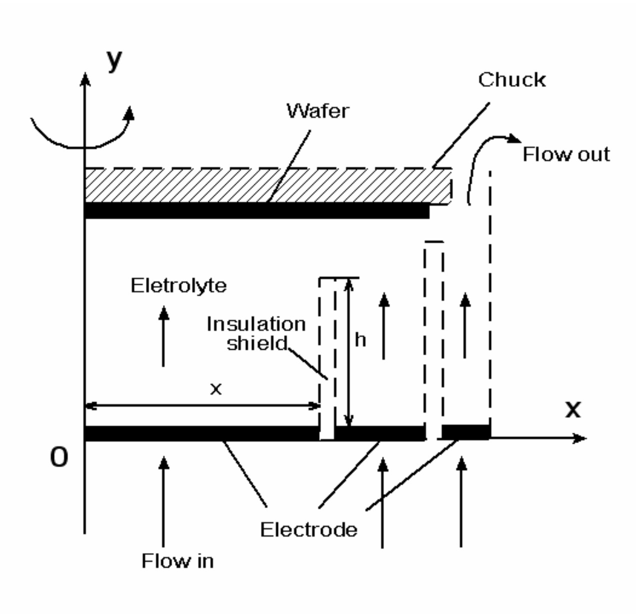

Figure 1. Illustration of deposition chamber for 300 mm wafer

Two-step deposition sequence was used to simulate the deposition process, including a low current deposition to fill the vias and trenches on the wafer surface and a high current deposition to continue to plate the bulk film to the targeted thickness. Time-stepping method was employed to simulate real time growth of Cu film by continuously updating the ohmic resistance distribution across wafer surface. Average deposition thickness was 3000 Å, and the substrate was a 300 mm wafer bearing a 350 Å Cu seed. In the final calculation of non-uniformity, the outer-most 2.3 mm film near wafer edge was excluded. The non-uniformity within the wafer was defined as the ratio of the standard deviation of film thickness over the average film thickness.

Simulations and discussions

Chamber geometry

The influence of chamber geometry on the non-uniformity of the deposited Cu film is important. The main parameters of the chamber geometry were chamber radius *R*, width of electrolyte flow path *w*, and gap between chuck and chamber wall *g*, as illustrated in Figure 2. Simulation was done in a conventional single-electrode deposition chamber with three different geometries, listed in Table 1. Figure 3 showed the influence of these three parameters on the non-uniformity of deposited Cu film.

TABLE 1. Chamber geometry and electrolyte flow path parameters

Simulation Condition	Chamber size	Flow path width	Gap between chuck and chamber wall
Geometry 1	1.0*R*	1.0*w*	1.0*g*
Geometry 2	0.8*R*	1.0*w*	1.0*g*
Geometry 3	0.8*R*	0.5*w*	0.5*g*

Electrolyte deposition chamber with small chamber radius, short flow path and narrow gap between chuck and chamber wall resulted in the least non-uniformity at 3.72%. The radius of deposition chamber has the most significant impact to deposited film non-uniformity. The non-uniformity was reduced from 27.77% to 4.49% by changing chamber radius from 1.0*R* to 0.8*R*. The non-uniformity could be further lower down from 4.49% to 3.72% by reducing the width of flow path and gap between chuck and chamber wall. However, the terminal effect existed in all three conditions with a single electrode deposition chamber. Further work was done on chamber geometry 3 in table 1, with revised electrode configuration to reduce the non-uniformity down to target value of less than 2.5%, which was required by the subsequent CMP process (10).

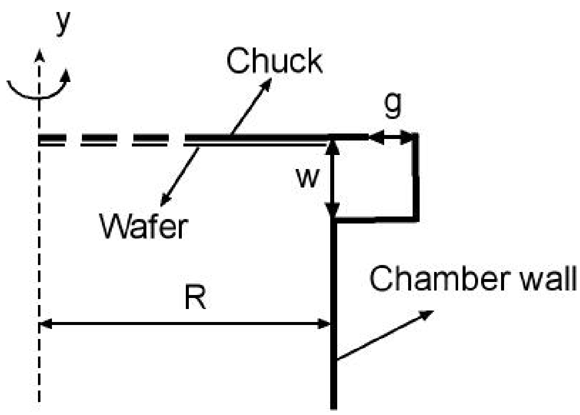

Figure 2. Local geometry configuration

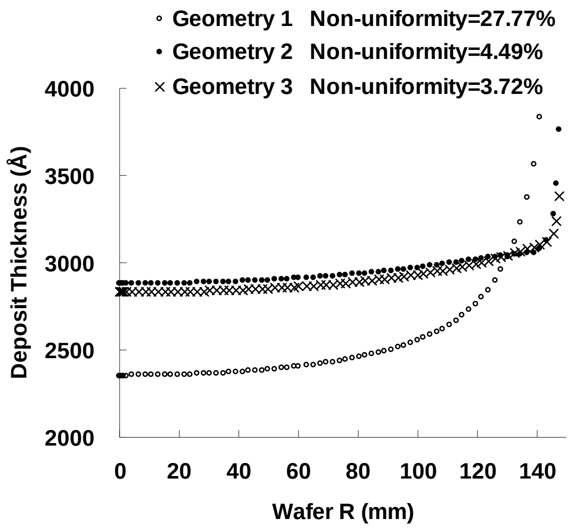

Figure 3. Deposition profile with different chamber geometry

<u>Electrode configuration</u>

The deposition performance of chamber with two electrodes was compared with that with only one, as shown in Figure 4. The non-uniformity of the deposited Cu film was improved from 3.72% to 2.19% by applying a 2-electrode deposition system. This simulation was done with a low conductivity electrolyte to reduce the terminal effect. If a high conductivity electrolyte was used, the terminal effect would become more significant. The deposition chamber with 2-electrode configuration was difficult to control the non-uniformity below the target value, and chamber with more than two electrodes was required in a high conductivity electrolyte. For multiple-electrode system to work in a controllable fashion, the electrical field generated by each electrode must be effectively isolated. Thus the insulation shields were presented in the following studies.

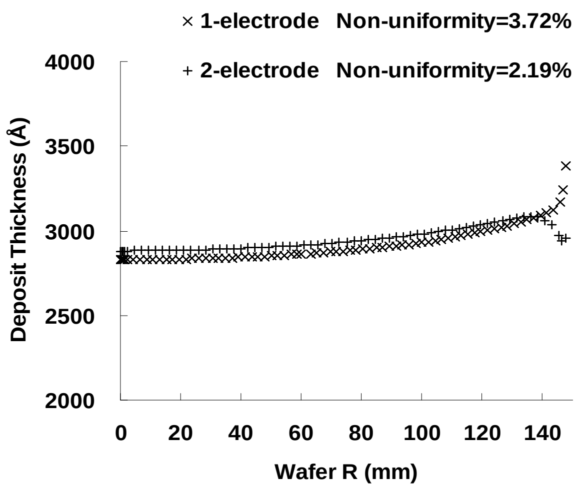

Figure 4. Deposition profile with different electrode configuration

Electrical Field Division and Isolation

Insulation shields were required to eliminate electron transfer from one electrode to another, and also to control the local potential field near wafer surface so as to control the current density distribution across wafer surface. The importance of the insulator to current density uniformity during metal electrochemical deposition on smaller substrates was reported (11).

However, the insulation shield also introduced the nonuniform geometry boundary in the chamber, leading to equipotential lines bending and concentrating at the insulator. Thus the design of the insulation shield is important.

The design parameters were position and height of the insulation shield, which were shown as x and h in Figure 1, respectively. Simulation was done with different positions and heights of insulation shield in a 2-electrode chamber, shown in Figure 5. Two different geometries of the insulation shield were applied in the simulation to explore the influence of insulation shield, position x and height h, on the non-uniformity of deposited Cu film. The relative values of x and h were listed in Table 2.

TABLE 2. Insulation shield geometry

Simulation Condition	Shield position	Shield height
Geometry 1	1.0x	1.0h
Geometry 2	1.2x	1.2h

By varying the position and height of the insulation shield, the profiles of deposited Cu films can be tuned, and a uniform deposited Cu film was obtained. Through a series of CCD (Central composite designs of experiment) methods, the preferred relation of position and height of the insulation shield for the 2-electrode chamber was established, shown in Figure 6. The height of the insulation shield was linear to the position of the shield, and this simulation result was further applied in the design of multiple electrodes chamber with more than two electrodes.

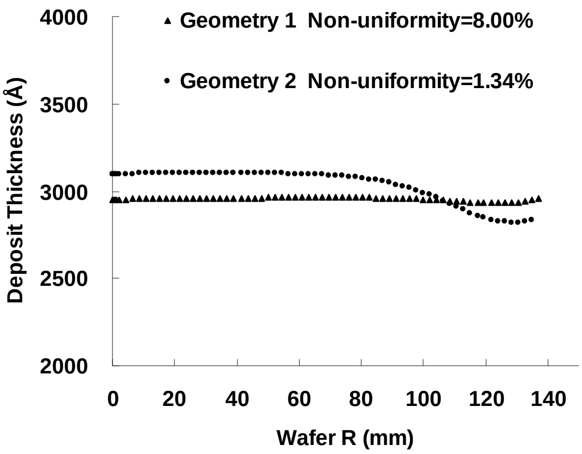

Figure 5. Deposition profile with different insulation shield configuration

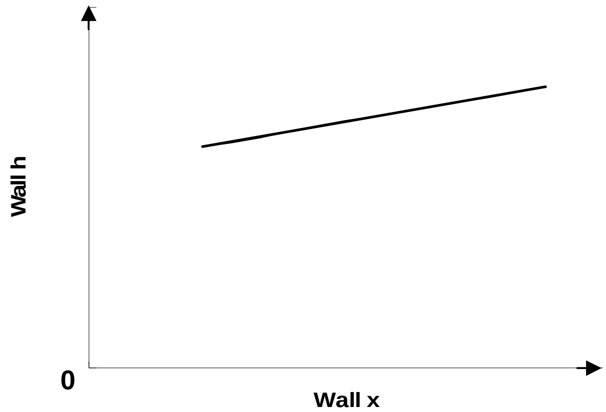

Figure 6. Relation of insulation shield position and height

Optimization of basic process parameters

The method of optimizing process parameters was the same as that was applied in previous work. DOEs of process parameters, such as deposition current and current density distribution were carried out with the optimized chamber geometry of multiple electrode systems to obtain the least deposited film non-uniformity.

Figure 7 and 8 showed the simulation results of 3000Å Cu film deposited on 350Å Cu seed layer with optimized multiple-electrode chamber geometry and process parameters in low and high conductivity electrolyte, respectively. With a 4-electrode deposition system, the non-uniformity of the deposited film could be controlled within 1% even with high conductivity electrolyte.

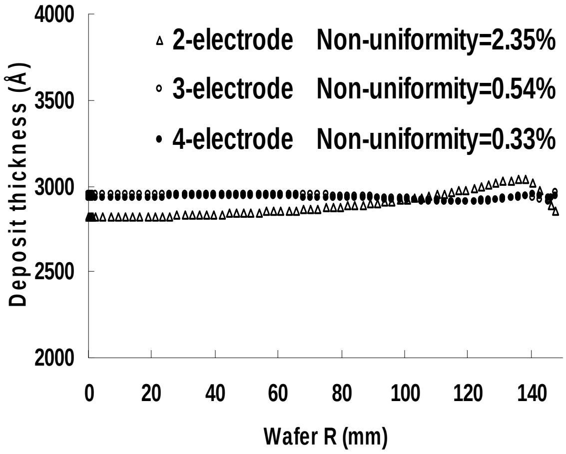

Figure 7. Deposition profile of optimized chamber for low conductivity electrolyte system

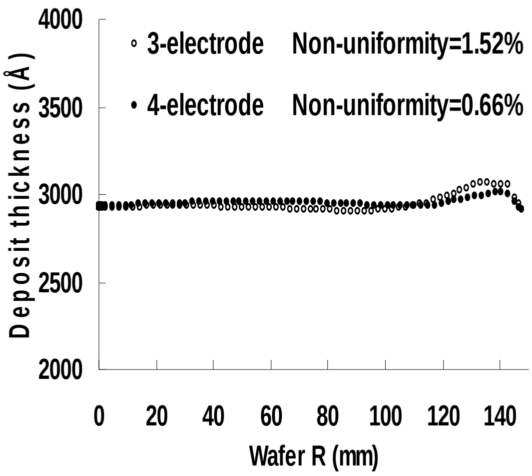

Figure 8. Deposition profile of optimized chamber for high conductivity electrolyte system

Conclusion

Key parameters of chamber geometry, such as chamber dimension, electrolyte flow path, gap between chuck and chamber wall, electrode configuration and insulation shield, were studied by simulating a film growth process during deposition. Chamber geometry was optimized based on non-uniformity value of Cu film. With optimized chamber geometry, non-uniformity could be further improved by varying process parameters to meet technology requirement.

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