# Highly Uniform Cu Film Deposition by Electrochemical Methods

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**Biography**

Xi Wang is a process engineer at ACM Research (Shanghai), Inc. Xi graduated with a M.S. degree in material science and engineering from Shanghai Jiaotong University in 2007 and a B.S. degree in materials science and engineering from Fuzhou University in 2004.

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**Abstract:**

Cu metallization by electrochemical deposition has been implemented in ULSI circuit fabrication for forming interconnects since 1998 [1]. As wafer size increases from 8- to 12-inch, and the Cu seed layer decreases in thickness for every technology node, ohmic resistance of Cu seed layer increases significantly, leading to severe non-uniform deposition of copper film due to a phenomenon called "terminal effect" [2-5]. A deposited Cu film that has within-film non-uniformity (WFNU, defined as the thickness standard deviation divided by the thickness mean) exceeding 2.5% fails to meet the requirement for subsequent CMP process [6]. In this report, impact on WFNU from chamber geometry factors and process parameters was quantitatively evaluated by simulating the growth process of Cu film. WFNU less than 1.0% was achieved for 3000Å Cu film deposited on 350Å Cu seed through optimization of chamber design and the deposition process.

**Data**

I. Theory： Cu film deposition profile can be calculated from current density distribution on the growing Cu film surface over deposition time. The total current density under chamber electroneutrality condition is expressed as [7]

$$i = -F\sum z_i D_i \nabla c_i - \nabla\Phi_S \sum \frac{F^2 D_i z_i^2 c_i}{RT}$$

To determine $i$, Nernst-Planck equation for ion concentration and potential fields, together with Navier-Stokes equation that describes the flow field, were solved numerically using a computer simulation package developed by L-Chem, Inc. The methods used for determining the boundary conditions on insulators and electrodes were adapted from work by Landau [8]. In most cases, tertiary distribution was applied to electrodes.

II. Optimization procedures:

(1) Run screening simulation experiments to evaluate the impact of chamber geometry factors on simulated WFNU with a simple 2-step process recipe.
(2) Use central composite design of experiments to establish quantitative correlations between simulated WFNU and the chamber geometry factors that are dominant.
(3) Finalize chamber design (optimal geometry).
(4) Run screening simulation experiments to evaluate the impact of process parameters on simulated WFNU based on the optimal chamber geometry.

(5) Use central composite design of experiments to establish quantitative correlations between simulated WFNU and the process parameters that are dominant.
(6) Use the process parameters that resulted in the smallest WFNU (predicted) in step (5) for simulation to obtain the optimal WFNU.

III. Simulation setup:

The right half of a deposition chamber cross-section is illustrated in Figure 1. Filled solid segments indicate electrodes and wafer; dashed segments indicate insulating shields. The electrical contact is assumed to be continuous along the perimeter of the wafer.

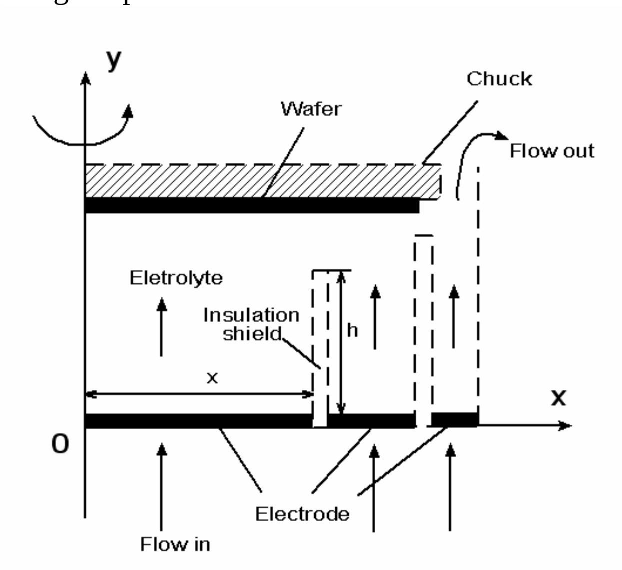


Figure 1. Illustration of deposition chamber

Parameters used in the simulations are listed in the table below.

| | |
|---|---|
| Seed layer thickness (Å) | 350 |
| Deposit thickness (Å) | 3000 |
| Wafer edge exclusion (mm) | 2.3 |
| Electrolyte flow rate (L/min) | Up to 18 |
| Wafer rotation (rpm) | 20-90 |
| x (cm) | 1-14.5 |
| h (cm) | 10-20 |
| # of electrodes | 1- 4 |
| Electrolyte conductivity (S/cm) | 0.064-0.264 |

Table 1. Parameters used in the simulation

Contributions to WFNU from chamber geometry factors and process parameters, such as chamber diameter, distance between wafer and electrode, wafer rotation speed, electrolyte flow rate, and flow exit gap size, were analyzed using similar methods by Malyshev, et. al. [9]; therefore, they are not discussed in this paper.

IV. Results and Discussions:

Chamber Geometry: Configurations of electrodes and insulating shields had a significant impact on WFNU, when applying a simple process recipe with a first step of lower current and a second step of higher current. With one electrode configured in parallel to wafer surface, a WFNU less than 2.5% was not achievable under the simulation conditions here. A WFNU less than 2.5% required the chamber design to have at least two electrodes in a low acid (LA) electrolyte and three electrodes in a high acid (HA) electrolyte. When more than one electrode was present in the chamber, both positions and heights of the insulating shields between the electrodes affected WFNU significantly, as shown in Figure 2. By changing only x and h of the insulating shield between electrodes in a three-electrode chamber geometry and keeping all other parameters the same, WFNU varied from 3.75% to 2.29%. The deposition profile changed from center-thick to edge-thick. The importance of the insulating shield to current density uniformity during metal electrochemical deposition on smaller substrates was reported in literature [10].

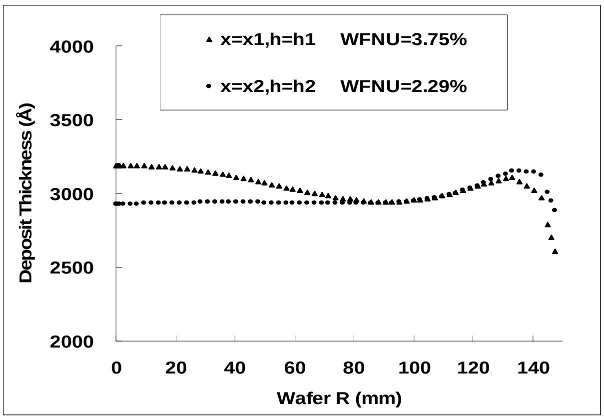


Figure 2. Insulating shield effect on WFNU

Current Distribution: Increasing the number of electrodes in the deposition chamber made process optimization far more complicated. The parameter that had the most profound impact on WFNU was found to be the ratio of currents distributed on individual electrodes. Such impact was analyzed over a large range of current ratios, as shown in Table 2, and the simulation was performance in both LA and HA electrolytes.

| | i1:i2 | i1:i3 | i1:i4 |
|---|---|---|---|
| **2E** | 1:1- 300:1 | - | - |
| **3E** | 1:1- 50:1 | 1:1 - 300:1 | - |
| **4E** | 0.5:1 -10:1 | 0.5:1- 50:1 | 1:1 - 300:1 |

Table 2. Ratios of current distribution for different numbers of electrodes

After a coarse study of current ratios was completed, simulations using central composite design of experiments were performed again over a finer range of current ratios. Predicted WFNU values from analyzing the design of experiments results fit those from actual simulations reasonably well. Figure 3 shows predicted WFNU values and the actual simulated results from 3-electrodes chamber in LA electrolyte.

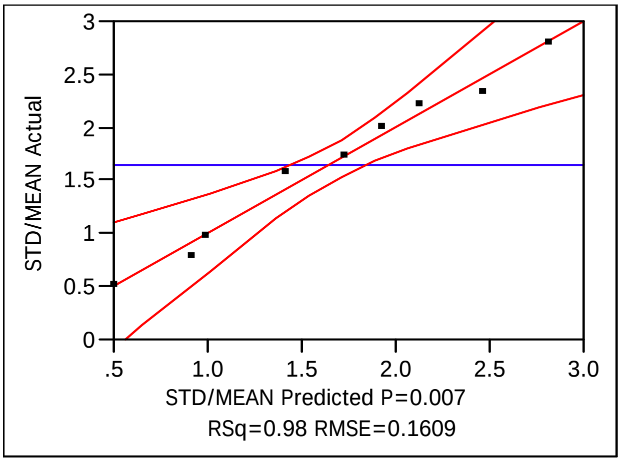


Figure 3. Predicted WFNU vs. simulated WFNU

Based on the results from the design of experiments, the current ratios that produced the optimal WFNU were used to simulate WFNU, and the final film profiles are shown in Figures 4 and 5. In a LA electrolyte (conductivity = 0.064S/cm), a WFNU value of 2.35% was obtained with optimized 2-electrode chamber configuration and current distribution. The WFNU was improved to 0.54% with optimized 3-electrode and 0.33% 4-electrode chamber configurations and current distributions, far less than that required by CMP process.

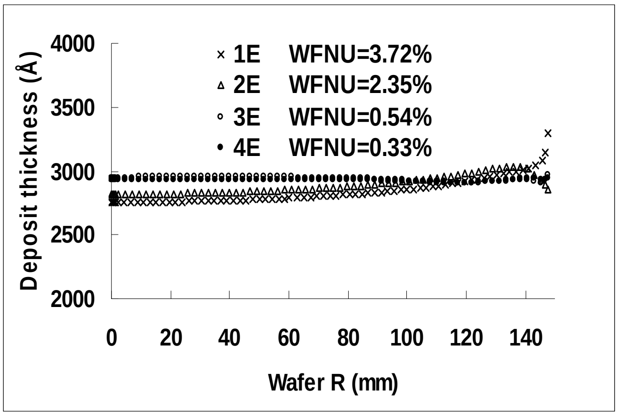


Figure 4. Optimal deposition profiles in LA electrolyte

In a HA electrolyte (conductivity = 0.264S/cm), a WFNU value of 1.52% was obtained with optimized 3-electrode chamber configuration and current distribution. The WFNU was improved to 0.66% with optimized 4-electrode chamber configuration and current distribution. Note that with 1- or 2-electrode chamber configurations, the best WFNU values obtained failed to meet CMP process requirements by large margins.

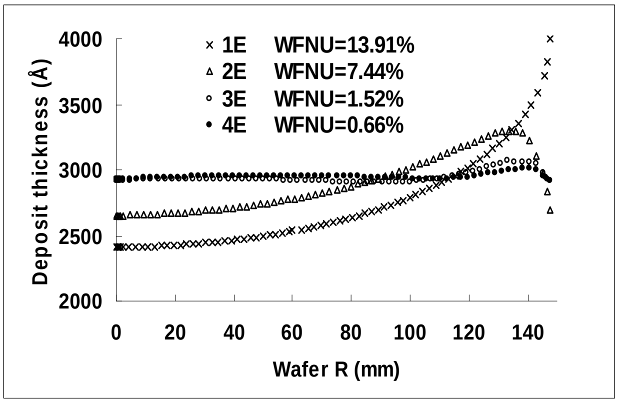


Figure 5. Optimal deposition profiles in HA electrolyte

Deposition in a LA electrolyte generally reduces terminal effect, thereby improving WFNU. However, multiple electrodes must be used under the simulation conditions in this paper (3000Å Cu film on 350Å Cu seed) to produce a film profile whose WFNU is less than 2.5%.

Profile Tuning: The deposition profiles can be adjusted to suit a particular CMP process. For example, higher or lower Cu polish rate at the center or the edge of the wafer. By varying process parameters, the profiles of deposited Cu films can be drastically different. Figure 6 shows the deposition profiles obtained under three sets of processing conditions.

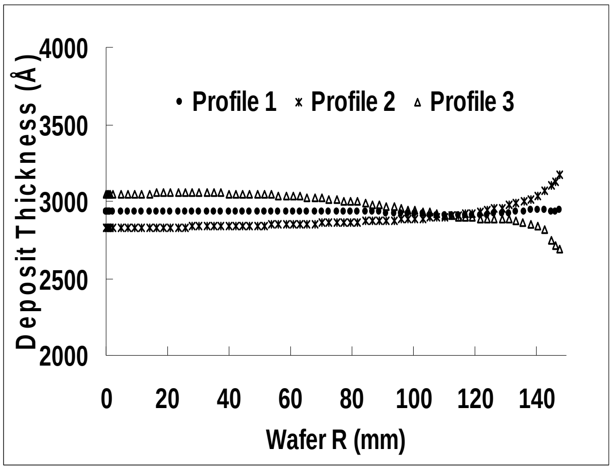


Figure 6. Profiles tuned using different deposition conditions

Profile 1 is suitable for a center-fast CMP process, profile 2 is suitable for a CMP process with uniform polishing rate, and profile 3 is suitable for an edge-fast CMP process.

## Conclusion

Multiple electrodes chamber design coupled with insulating shields are needed for highly uniform copper deposition on ultra-thin seed (350Å) in both LA and HA electrolytes. Simulation results show that under optimized deposition process conditions, WFNU less than 1.0% is achievable with 3-electrode chamber configuration in LA electrolyte and with 4-electrode chamber configuration in HA electrolyte, respectively. Deposition profiles of Cu films are highly tunable with multiple electrodes chamber configurations.

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