Effect of Mass Flow Induced by a Reciprocating Paddle on Electroplating

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Abstract: In this work, the mass flow induced by a reciprocating paddle in the electroplating cell is studied by the finite element analysis software-COMSOL Multiphysics®. The reciprocating movement of the paddle is simulated by using the moving mesh technique (Arbitrary Lagrangian-Eulerian: ALE method). The solution of fluid flows stirred by the paddle is coupled into the calculation of tertiary current distributions. The reciprocating frequencies are 0, 0.25, 0.5, 1 and 2 Hz. An acid copper sulfate electrolyte composed of 50 mM Cu_2SO_4 and 0.5 M Na_2SO_4 is taken into account. The results show that the reciprocating movement of the paddle can effectively increase the concentration of cupric ions at the cathode and improve the current density distribution.

Keywords: Electroplating, Reciprocating Paddle, Moving Mesh Technique, Mass Transfer, Current Distribution.

1. Introduction

The reciprocating paddle electrochemical plating cells have been widely applied in the microelectronics industry [1-3]. Recently, the investigation of the mass transfer boundary layer within an industrial wafer plating cell based on a shear-plate fluid agitation mechanism was also reported [4].

The reciprocating paddle is often driven over a cathode aspect horizontally by oscillation set outside a plating cell. The paddle reciprocating parallel to a plating side stirs the electrolyte around the plating aspect to improve electric current distribution at the cathode. The uniformity of plated film will be improved. However, the theoretical analysis is considerably complicated. The fluid flow induced by the reciprocating movement of the paddle, mass transfer and current density distribution have to be fully coupled [5], which was termed as a tertiary current problem by Averill and Mahmood [6]. The investigation of the tertiary current distributions in a plating cell using a reciprocating paddle driven over a cathode aspect horizontally [7] has been reported in our previous work. In this work, we coupled the calculations of fluid flows and current distributions in an electroplating cell. The distributions of tertiary current density at the cathode and plated film thickness were obtained. The effect of the fluid agitation by paddle reciprocating parallel to a plating side on the current distributions at the cathode was presented and discussed.

2. Numerical Model

The model geometry used in this work is shown in Fig. 1. It is known that Reynolds number for the geometry can be defined by $Re = UL/\nu$ [1], where U is the paddle reciprocating velocity, L is the paddle length, ν is the kinematic viscosity of the fluid. In the present research, the Reynolds number is ≤ ~5000. The previous research [1] on the reciprocating paddle has indicated that the wake dynamics of a blunt body in this Reynolds number regime are controlled more by pressure fields than by viscous diffusion. A two-dimensional laminar model may reasonably predict the dominant flow features for the purpose of estimating the mass transfer [1]. Therefore, in this work the laminar flow is taken into account by [8].

Continuity equation

$$\nabla \cdot (\rho \mathbf{u}) = 0 \qquad (1)$$

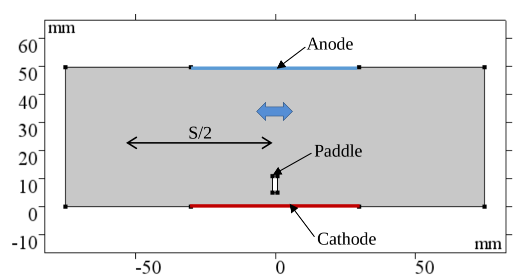


Figure 1. Schematic of a reciprocating paddle electroplating cell.

Momentum equation

$$\rho\frac{\partial \boldsymbol{u}}{\partial t}+\rho\mathbf{u}\cdot\nabla\mathbf{u}=-\nabla p+\nabla\cdot\left(\mu(\nabla\mathbf{u}+(\nabla\mathbf{u})^T)-\frac{2}{3}\mu(\nabla\cdot\mathbf{u})\mathbf{I}\right)+\mathbf{F} \tag{2}$$

where ρ is the density, $\mathbf{u}$ is the velocity vector, p is the pressure, $\mathbf{F}$ is the volume force vector, $\mathbf{I}$ is the identity matrix.

The material balance equation for the species i, in the electrolyte is calculated [8]

$$\frac{\partial c_i}{\partial t}+\nabla\cdot\left(-D_i\nabla c_i-z_i u_{m,i}Fc_i\nabla\phi_l+c_i\mathbf{u}\right)=R \tag{3}$$

where c_i is the concentration of species i, D_i is the diffusion coefficient of species i, z_i is the charge number of species i, $u_{m,i}$ is the mobility of species i, F is the Faraday's constant, and ϕ_l is the electrolyte potential.

The current density $\mathbf{i}_l$ in the electrolyte is

$$\mathbf{i}_l=F\sum_{i=1}^{n}z_i\left(-D_i\nabla c_i-z_i u_{m,i}Fc_i\nabla\phi_l\right) \tag{4}$$

and then the charge balance in the electrolyte becomes

$$\nabla\cdot\mathbf{i}_l=Q_l \tag{5}$$

where Q_l can here be any source or sink. Also, the equation for the electroneutrality condition is considered by

$$\sum z_i c_i=0 \tag{6}$$

It is known that the local current density at the electrode is related to the local overcharge, η at the electrode, which is the potential difference between the electrode, V, and the solution adjacent to the electrode, ϕ_0, *i.e.*, $\eta=V-\phi_0$. The overcharge can be adequately related to the magnitude of the local current density at the cathode through the Tafel approximation

$$i_{\mathrm{loc}}=-i_0\left(\frac{c_s}{c_b}\right)\exp(-\eta/b_c) \tag{7}$$

where i_0 is the exchange current density, c_s is the surface concentration at the cathode, c_b is the bulk concentration, and b_c is the Tafel slope.

Equations (1)-(7) are solved using the finite element simulation software COMSOL Multiphysics® 5.3. The calculation of flow is coupled into the Electrodeposition module [8]. The reciprocation of paddle is simulated by the moving mesh (ale) technique provided in COMSOL Multiphysics®. The computational mesh of original condition is presented in Fig.2. The mesh is composed of 2884 triangular and 1416 rectangle elements. The computational parameters considered are shown in Table 1.

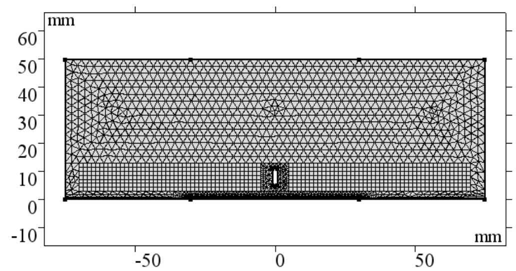


Figure 2. Computational mesh of an assembly geometry based on a reciprocating paddle of original condition (Thickness, a=2.0 mm and distance between cathode and paddle, δ=5 mm).

Table 1: Parameters used in this work

Paddle
Thickness, a : 2.0 mm and height : 6 mm
Stroke length, S : 110 mm
Reciprocating frequency, f : 0, 0.25, 0.5, 1, 2 Hz
Distance between cathode and paddle, δ : 5 mm
Electrolyte properties
Density: 1000 kg/m^3
Kinematic viscosity: 1×10^{-6} m^2/s
Bulk concentration of cupric ions c_b: 50 mol/m^3
Diffusion coefficient of cupric ions: 4.2×10^{-10} m^2/s
Electrode characteristics
Exchange current density: i_0: 5.37×10^{-5} A/m^2
Tafel slope, b_c: 0.0525 V
Average current density at the cathode: 10, 20, 50,100 A/m^2

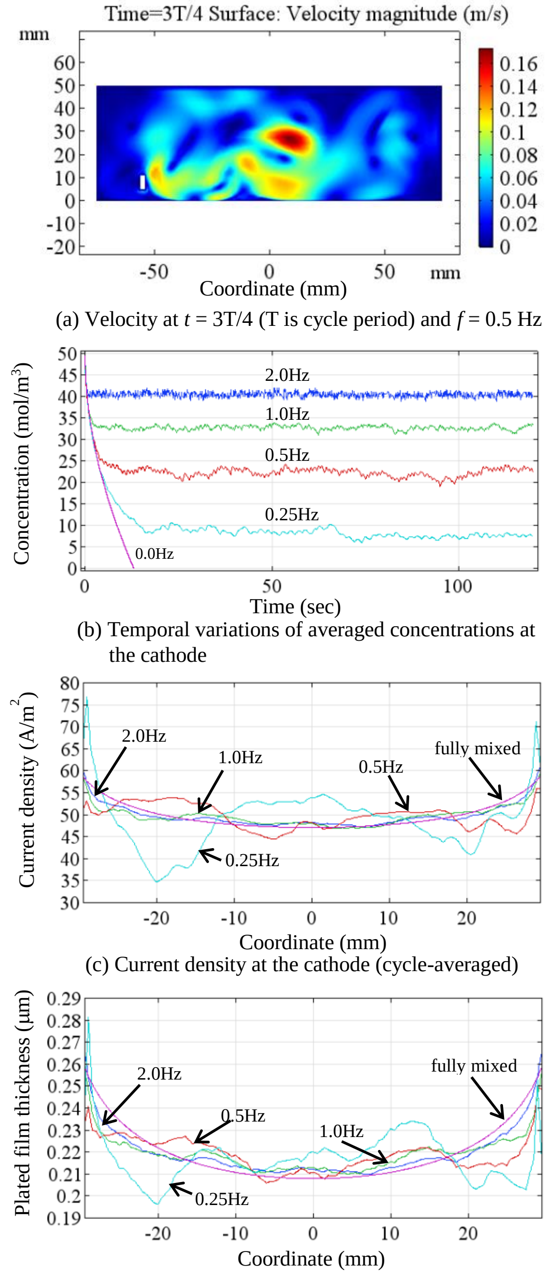
3. Results

The computations are performed for obtaining the distributions of fluid flows and tertiary current densities in a plating cell. The plating time is 2 minutes, for which the mass-transfer characteristics could be stabilized [1]. The surrounding boundaries as well as the surfaces of electrodes are stationary no-slip walls. The boundaries for paddle walls are defined as moving walls with the reciprocating velocity. The obtained results include the distributions of velocity of fluid flows, temporal variations of averaged concentrations at the cathode, current density at the cathode, and plated film thickness.

Figure 3 shows the computational results of fluid flows and tertiary current densities at the average current density of 50 A/m^2, in which T is the reciprocating period. The results show that a number of vortexes occur and the maximum value of flow velocity arrives 0.38 m/s. The ion concentration at the cathode surface falls to 0 in 81.7 s and the plating fails for the case without the reciprocating paddle. As the reciprocating frequency f increases, the ion concentration at the cathode surface is increased to improve current density distribution at the cathode and plated film thickness. At $f \geq 1$ Hz, the calculated results are consistent with that from the condition the electrolyte is fully mixed. It could be deduced to a fact that the flows with high reciprocating frequency causes more cupric ions to arrive at the cathode so that sufficient cupric ions are supplied to the chemical reactions at the cathode surface. Therefore, the controlling of reciprocating frequency of the paddle could govern the plated film distribution at the cathode.

Figure 4 shows the computational results at the average current density of 10, 20, and 100 A/m^2, in which the results of 50 A/m^2 are also included for comparison. As shown in Fig. 4 (a), the plated film thickness is increased in proportion to the average current density. At the average current density of 10 A/m^2, the ion concentration at the cathode surface does not fall to 0 even for the case without the reciprocating paddle and the plating of 2 minutes can be finished. However, at average current density of 100 A/m^2, the ion concentration on the cathode surface falls to 0 at $f \leq 0.5$ Hz and the plating fails, in contrast, at $f \geq 1$ Hz, the plating of 2 minutes can also be performed. It can be concluded that the reciprocating paddle is a necessary component for an electroplating cell configuration.

In this work, the effects of thickness of paddle, a, distance between cathode and paddle, δ, and bulk concentration of cupric ions c_b on the plating are also studied. The computational conditions considered are shown in Table 2, in which i_{avg} is the average current density at the cathode.



(a) Velocity at t = 3T/4 (T is cycle period) and f = 0.5 Hz

(b) Temporal variations of averaged concentrations at the cathode

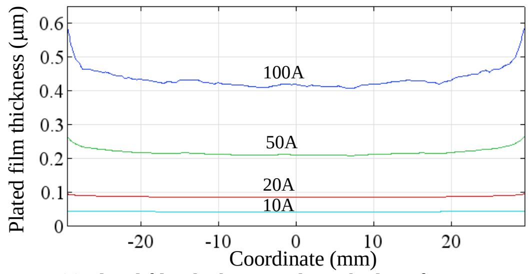
(c) Current density at the cathode (cycle-averaged)

(d) Plated film thickness

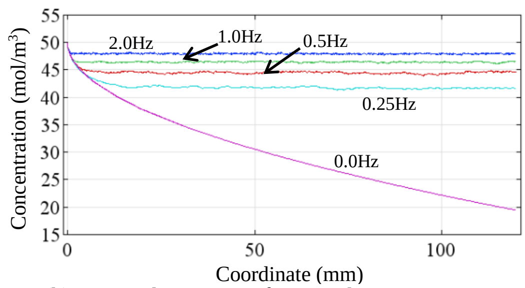
Figure 3. (a) Velocity at t = 3T/4 and f = 0.5 Hz, (b) Temporal variations of averaged concentrations at the cathode, (c) Current density at the cathode, and (d) Plated film thickness.

Table 2: Original and modified conditions

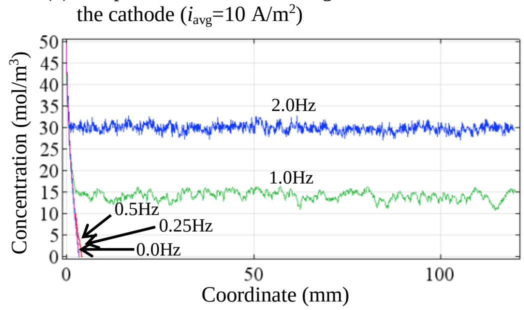
condition	a (mm)	δ(mm)	c_b (mol/m^3)	i_{ave} (A/m^2)	f (Hz)
original	2.0	5.0	50	10-50	0.25-2.0
modified 1	4.0	5.0	50	50	0.5
modified 2	2.0	3.0	50	50	0.5
modified 3	2.0	5.0	100	50	0.5



(a) Plated film thickness at the cathode at $f = 0.5$ Hz

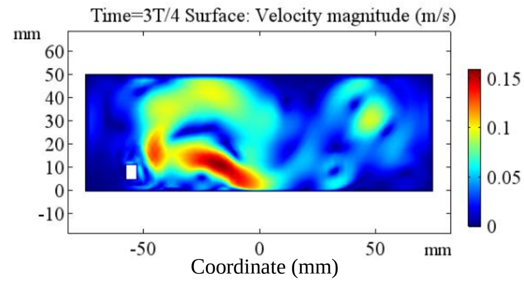


(b) Temporal variations of averaged concentrations at the cathode (i_{avg}=10 A/m^2)

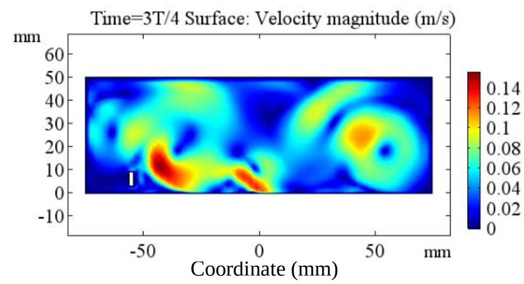


(c) Temporal variations of averaged concentrations at the cathode (i_{avg}=100 A/m^2)

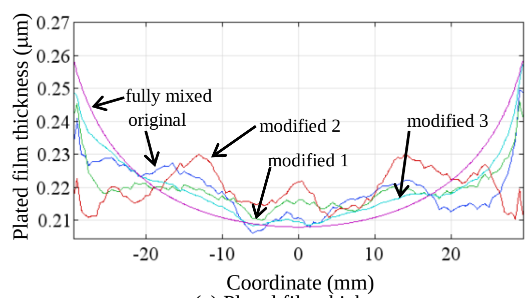
Figure 4. (a) Plated film thickness at $f = 0.5$ Hz, Temporal variations of averaged concentrations at the cathode at (b) $i_{avg} = 10$ A/m^2, and (c) $i_{avg} = 100$ A/m^2.



(a) Velocity at t = 3T/4 and $f = 0.5$ Hz (modified 1)



(b) Velocity at t = 3T/4 and $f = 0.5$ Hz (modified 2)



(c) Plated film thickness

Figure 5. (a) Velocity at t = 3T/4 for modified condition 1, (b) Velocity at t = 3T/4 of modified condition 2, (c) Plated film thickness at the cathode for original and modified conditions at $f = 0.5$ Hz.

Figure 5 shows the computational results for the modified paddle parameters. The plated film thickness does not appear a significant change at the modified conditions 1 and 2, but it is improved to be close to that from the condition that the electrolyte is fully mixed for the modified condition 3. The high bulk concentration of cupric ions markedly increases the supply of cupric ions to the cathode.

4. Conclusions

The effect of mass flow induced by a reciprocating paddle on the electroplating has been studied in this work by coupling the solution of fluid flows with the calculation of tertiary current distributions. The finite element analysis software-COMSOL Multiphysics® is used. The simulation results included the distributions of velocity of fluid flows, temporal variations of averaged concentrations at the cathode, current density at the cathode, and plated film thickness. The results show that the reciprocating movement of the paddle could effectively improve the concentration distribution of cupric ions and the current density distribution at the cathode.

The present research provides an efficient method to simulate the behavior of reciprocating paddle and the application of the method would be very beneficial in studying industrial reciprocating paddle electroplating systems.

5. References

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