CURRENT DISTRIBUTION ON A RESISTIVE WAFER UNDER COPPER DEPOSITION KINETICS

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Abstract

The deposit thickness uniformity in copper metallized semiconductor wafers is adversely affected by the limited conductivity of the thin copper seed layer. The resistive substrate tends to cause the copper to plate primarily near the terminal contact at the wafer rim. Models for this 'terminal-effect' have been presented in the literature for simpler electrode configurations, or for a disk electrode, using unrealistically simplified, linear electrode polarization.

We present here an analytically derived model for the current distribution on a resistive disk electrode subject to Butler-Volmer kinetics, with parameters typical to copper plating. The disk is assumed suspended in a semi-infinite large pool of electrolyte and the current is fed from its circumference. The predicted current distributions are compared to numerical simulations using electrochemical computer aided design software ("Cell-Design"). It is noted that, as expected, the current distribution is more uniform when a less conductive electrolyte is used and when the electrode kinetics are inhibited.

Introduction

The copper layer that is electroplated on semiconductor silicon wafers in order to provide high-conductivity interconnects, cannot be electrodeposited directly onto the silicon. A thin barrier layer, consisting of Ta, Ti, or their nitrides is applied first. Since electroplated copper does not adhere to the barrier materials, a thin copper seed is deposited first on top of the barrier layer, typically, by PVD. Economic and engineering considerations require that the thickness of this seed layer be as thin as possible, of the order of 500-2000 Å over the flat surface of the wafer. However, since the current for electroplating the copper layer must be fed from electrical contacts on the wafer circumference, the plating current must pass radially through the thin seed and barrier layers. Because of the high electrical resistance of these thin layers, the plating current tends to concentrate near the wafer circumference, leading to a thicker deposit near the edge than at the center. As the deposition proceeds, the resistive substrate effect diminishes due to the build-up of a thicker copper conductive layer. The final deposit profile exhibits, however, the effects of the initial non-uniform deposition, as shown below. This 'terminal effect' is a major cause for non-uniformity in the plated copper layer, and its quantification and minimization is of practical importance.

The effects of resistive substrates on the current distribution ('terminal effect') have been analyzed in the literature [1-3]. Tobias and Wiejsman [1] presented an analytical solution for parallel plate electrodes under linear polarization. Lanzi and Landau [2] developed a solution to the more practical Tafel range, extending it also to a larger variety of electrodes including cylindrical electrodes and fibers. Recently, Takahashi [3] analyzed the wafer (circular electrode) configuration, however, rather than developing a general solution, he has made the assumption that the current distribution is essentially uniform, deriving then the range of parameters that support this uniform distribution. We present here the results of an analytical solution that considers linear, Tafel and linearized Tafel polarizations for the plated wafer configurations and compare those with numerical distributions simulated using a commercial CAD software, "Cell-Design", that has been developed specifically for modeling electrochemical systems [4].

Model of the resistive electrode

We model the resistive electrode as a thin disk with radius R and thickness h<<R, as shown schematically in Fig. 1. The current density i_c from the electrolyte into the disk electrode corresponds to a current density i within the seed layer or the pre-deposited copper layer on the wafer. We assume a homogeneous distribution of current across the thin conductive layer, i.e., no current density variations exist in the z-axis direction within the electrode.
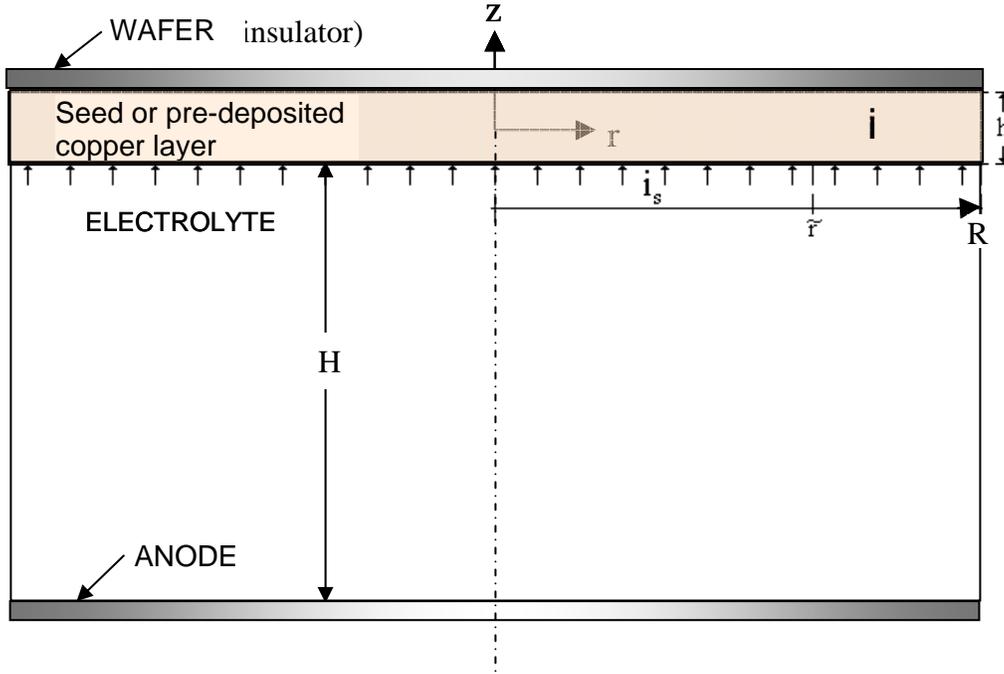

Fig.1: Schematic of the model configuration for the resistive disk electrode. *Not to scale.*

A current conservation in combination with Ohm's law provide the potential distribution along the electrode:

$$V_C(r) = V_R + \int_0^R G_V(r,r') i_C(r') r' dr' \tag{1}$$

Here, V_R is the voltage at the edge of the electrode and

$$G_V(r,r') = \begin{cases} \dfrac{1}{kh} \ln\left(\dfrac{R}{r}\right), & r' \le r \\ \dfrac{1}{kh} \ln\left(\dfrac{R}{r'}\right), & r < r' \le R \end{cases} \tag{2}$$

is the appropriate Green function.

Models of electrode kinetics

We apply and compare three simplified models for the deposition kinetics on the resistive electrode:

1) Linear kinetics

$$i_C = -\gamma \eta_C,$$ (3)

2) Linearized kinetics about the point (i_s^*, η^*)

$$i_C = i_C^* - \gamma^*(\eta_C - \eta^*),$$ (4)

3) Tafel kinetics

$$i_C = i_0 \exp\left(-\frac{\alpha_c F}{R_g T} \eta_C\right),$$ (5)

η_c the overpotential on the resistive electrode (the cathode):

$$\eta_C = V_C - E_C - \varphi_C.$$ (6)

On the anode we assume the primary electrode kinetics, i.e., we neglect any polarization effects:

$$V_A - E_A - \varphi_A = 0.$$ (7)

When the anode is relatively far away from the cathode, this is a good approximation.

Modeling the electric field within the electrolyte

We assume a cylindrical plating cell with radius R and height H as shown schematically in Fig. 2.
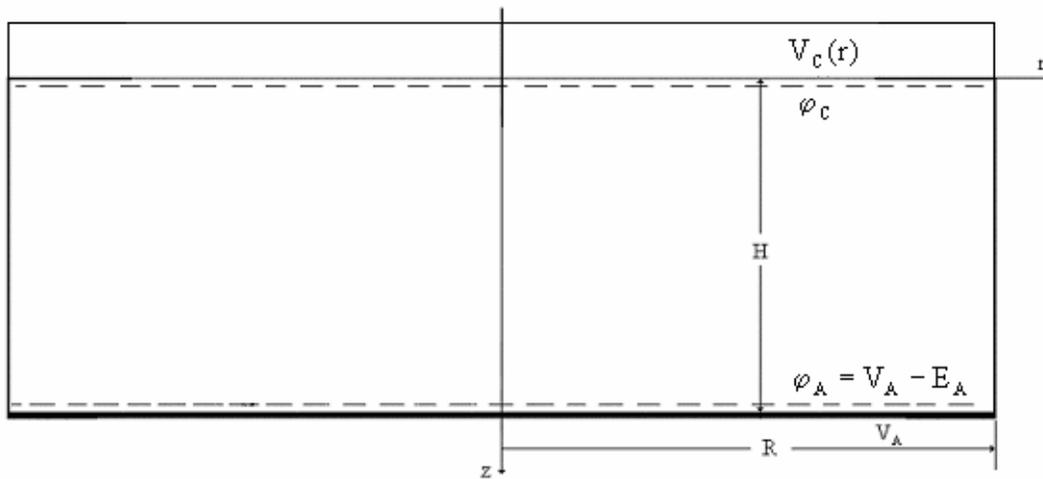

Fig.2. Schematic of the electrolyte region (not to scale) considered in the model

The anode is assumed to be a disc with a radius R (equal to the cell), positioned at the bottom of the cylindrical cell. The cathode is a disc with radius R, positioned on top of the cylindrical cell, as shown schematically in Fig. 2. If the distance, H, between the cathode and the anode is small compared the radius of the resistive electrode, R (Fig. 2), we may assume that electric field in the electrolyte is homogeneous.

The solution of Laplace's equation for the potential within the cell gives the relationship between the potential and the current density on the resistive electrode

$$\varphi_C(r) = V_A - E_A - \int_0^R G_\varphi(r,r') i_C(r') r' dr' \tag{8}$$

where

$$G_\varphi(r,r') = \frac{2}{k_s R} \left(\frac{H}{R} + \sum_{n=1}^{\infty} \frac{th\left(\omega_n \frac{H}{R}\right) J_0\left(\omega_n \frac{r}{R}\right) J_0\left(\omega_n \frac{r'}{R}\right)}{\omega_n J_0^2(\omega_n)} \right) \tag{9}$$

is the Green function of Laplace's problem. ω_n represents the roots of the equation: $J_1(\omega_n) = 0$, $J_0(x)$ and $J_1(x)$ are the Bessel functions of orders 0 and 1, respectively.

If $H \ll R$, the potential is distributed linearly in the cell:

$$\varphi_C(r) = V_A - E_A - \frac{H}{k_s} i_C(r). \tag{10}$$

Current distribution on the resistive electrode

Combining equations (1), (6) and (8), provide a nonlinear integral equation for the currant density i_C on the resistive electrode:

$$\eta_C(i_C) = V_R - V_A + E_A - E_C + \int_0^R \left(G_C(r,r') + G_V(r,r') \right) i_C(r') r' dr' \tag{11}$$

where the overpotential on the resistive electrode is represented as:

$$\eta_C(i_C) = \begin{cases} -\dfrac{1}{\gamma} i_C & \text{linear kinetics,} \\[2mm] \eta^* - \dfrac{1}{\gamma^*}\left(i_C - i_C^*\right) & \text{linearized kinetics,} \\[2mm] -\dfrac{R_g T}{\alpha_C F} \ln\left(\dfrac{i_C}{i_0}\right) & \text{Tafel kinetics.} \end{cases} \tag{12}$$

According to Eqn. (9), the nonuniformity associated with the solution of Eqn. (11) depends on H (the distance between cathode and anode) within the region

$$H < \frac{R}{\omega_1}, \qquad (13)$$

where $\omega_1 \approx 3.85$ is the first nonzero root of the equation $J_1(\omega_n) = 0$.

The non-uniformity of the current density on a 100 mm (radius) disk was computed as a function of the distance H, using the electrochemical CAD program "Cell-Design" [4]. Fig. 3 indicates, as expected, that the nonuniformity in the current density decreases when the gap is increased, because the electrolyte resistance increases. However, as H exceeds about 30 mm, an asymptotic value for the non-uniformity is reached and the current distribution is no longer affected by further increase in the anode to cathode gap. This numerically determined value of about 30 mm is in good agreement with the analytically indicated value of 26 mm (Eqn. 13).
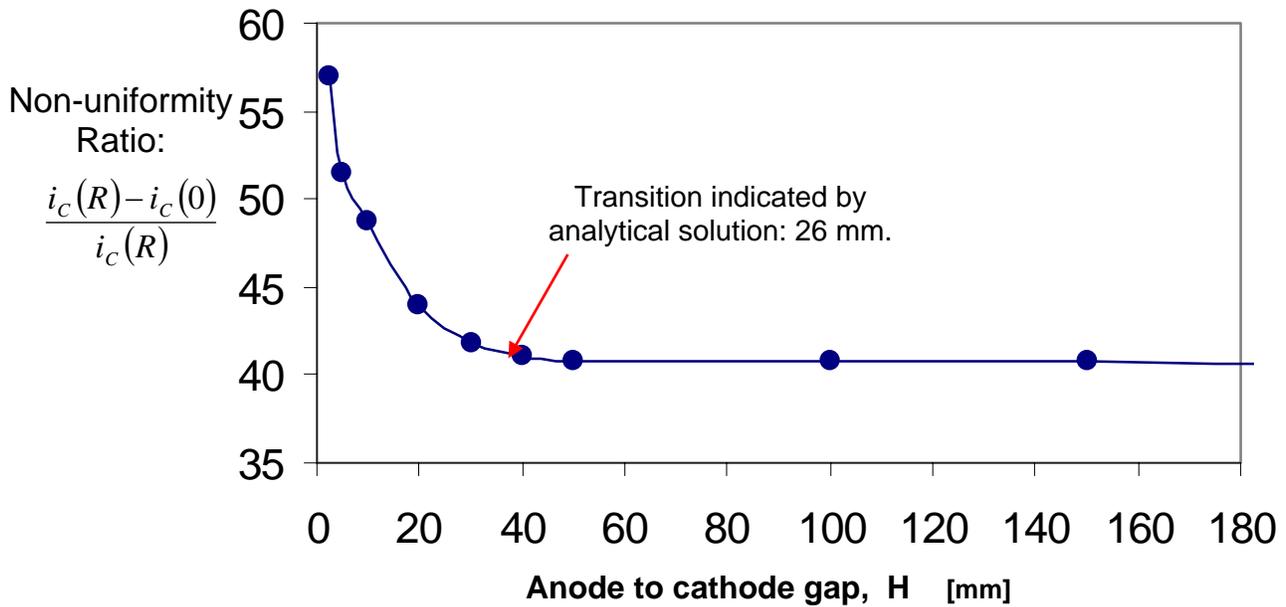

Fig.3. Non-uniformity of the current distribution on a resistive electrode (R= 100 mm) as a function of the anode to cathode distance. The data is based on numerical computations by "Cell-Design". As noted, for small anode to cathode gaps, the distribution improves with increasing gap (due to the increased electrolyte resistance). However, this improvement reaches an asymptotic value, and no further improvement in the current distribution is noted for gaps exceeding about 30 mm. This is in good agreement with the analytical solution indicating transition at about 26 mm. Parameters used in the numerical simulations: electrolyte conductivity, k_S = 0.55 S/cm; seed thickness = 1000 Å; seed conductivity, $k = 5.98 \cdot 10^5 \, S/cm$; Butler-Volmer kinetics for copper deposition with $\alpha_A = 1.5$; $\alpha_C = 0.5$; n=2; i_0 = 1 mA/cm^2; T = 300K.

In the opposite case, where $H \ll \dfrac{R}{\omega_1}$, the potential is linearly distributed in the cell and equation (11) takes the form

$$\eta_C(i_C) = V_R - V_A + E_A - E_C + \frac{H}{k_s} i_C(r) + \int_0^R G_C(r,r') \, i_C(r') r' dr' \tag{14}$$

In the case of linear kinetics, equation (14) has an analytical solution:

$$i_C = \frac{V_A - V_R + E - E_A}{\dfrac{H}{k_s} + \dfrac{1}{\gamma}} \frac{I_0\left(r \Big/ \sqrt{kh\left(\dfrac{H}{k_s} + \dfrac{1}{\gamma}\right)}\right)}{I_0\left(R \Big/ \sqrt{kh\left(\dfrac{H}{k_s} + \dfrac{1}{\gamma}\right)}\right)} \tag{15}$$

where $I_0(x)$ is the modified Bessel function of zero order.

Equation (15) indicates that the current distribution on the cathode is more uniform when a less conductive electrolyte is used and when the electrode kinetics are inhibited [5-8]. It can be seen that this holds for any anode to cathode gap and for nonlinear kinetics. Figs. 5 and 6 present the relative variation of the current density along the resistive electrode as a function of the electrolyte conductivity, k_s and the exchange current density, i_0, respectively. The linearized kinetics constant (in Eqn. 12), was taken as $\gamma = 0.077 \, \mathrm{Ohm^{-1} cm^{-1}}$. The disk radius, R, is 100 mm, the seed thickness, h, was assumed to be $1000 \, \overset{o}{\mathrm{A}}$, and the seed layer conductivity, $k = 5.98 \cdot 10^5 \, S/cm$.
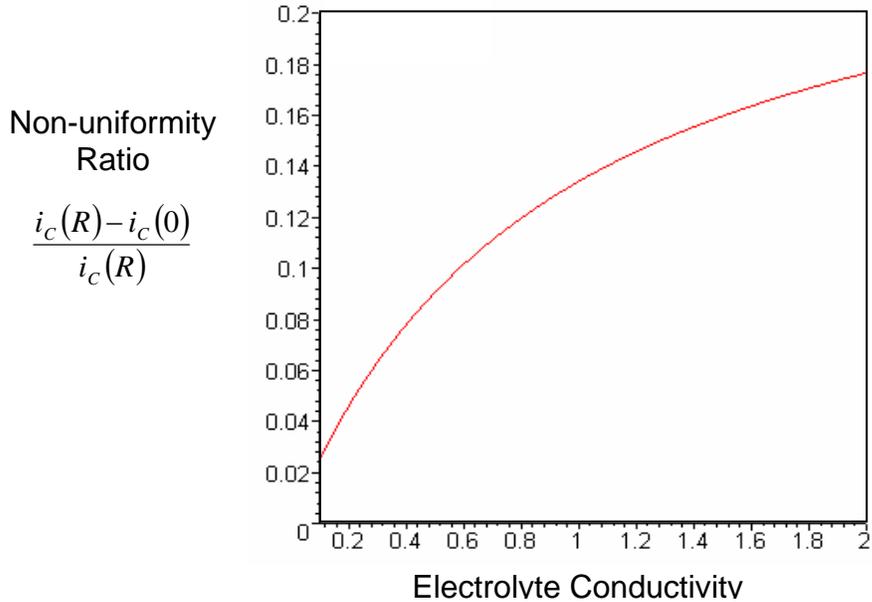

Fig.4. Nonuniformity of the current distribution on a resistive 100 mm electrode as a function of the electrolyte conductivity. Seed layer thickness = 1000 Å and its conductivity, $k = 5.98 \cdot 10^5 \, S/cm$. Linear kinetics with $\gamma = 0.077 \, \mathrm{Ohm^{-1} cm^{-1}}$ are assumed.

Non-uniformity Ratio

$$\frac{i_C(R) - i_C(0)}{i_C(R)}$$

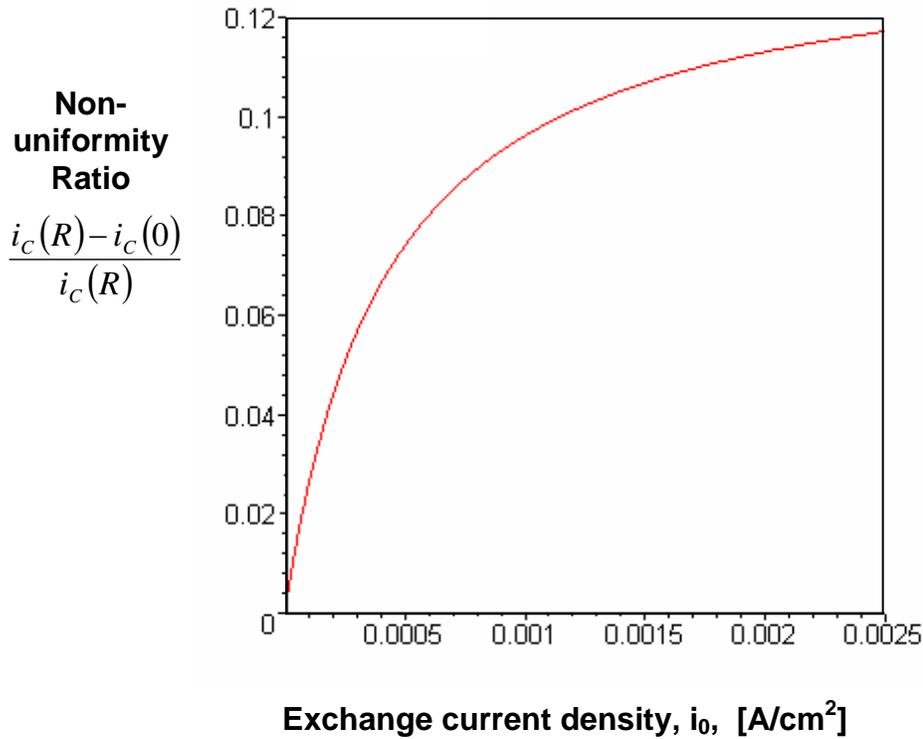**Exchange current density, i$_0$, [A/cm^2]**

Fig.5. Nonuniformity of the current distribution on the resistive electrode (R=100 mm) as a function of the exchange current density. The electrolyte conductivity is 0.55 S/cm. Seed thickness = 1000 Å and its conductivity, $k = 5.98 \cdot 10^5 \text{ S/cm}$.

Fig. 6 compares the current density at the center of the resistive disk as computed by "Cell-Design" software and by the analytically derived equation (11), for linear, linearized, and Tafel kinetics as a function of the applied voltage between the anode and the rim of the resistive electrode (cathode). The latter is also referred to as the 'terminal' voltage or the 'contact' voltage. The kinetics model applied to the numerical simulations by "Cell-Design" is the complete Butler-Volmer model, with parameters typical to copper deposition. It is noted that all simulations are in good agreement with the different analytical models, indicating the validity of the theoretical approach. The differences between the models become noticeable only at fairly high applied voltages corresponding to unrealistically high current densities. In the range of practical current densities used in copper metallization, i.e., current densities below ~ 40 mA/cm^2, the difference between all assumed models is negligible. As expected, the linear kinetics indicate somewhat lower current densities at higher applied voltages; a region where deviations from the Butler-Volmer kinetics are appreciable.
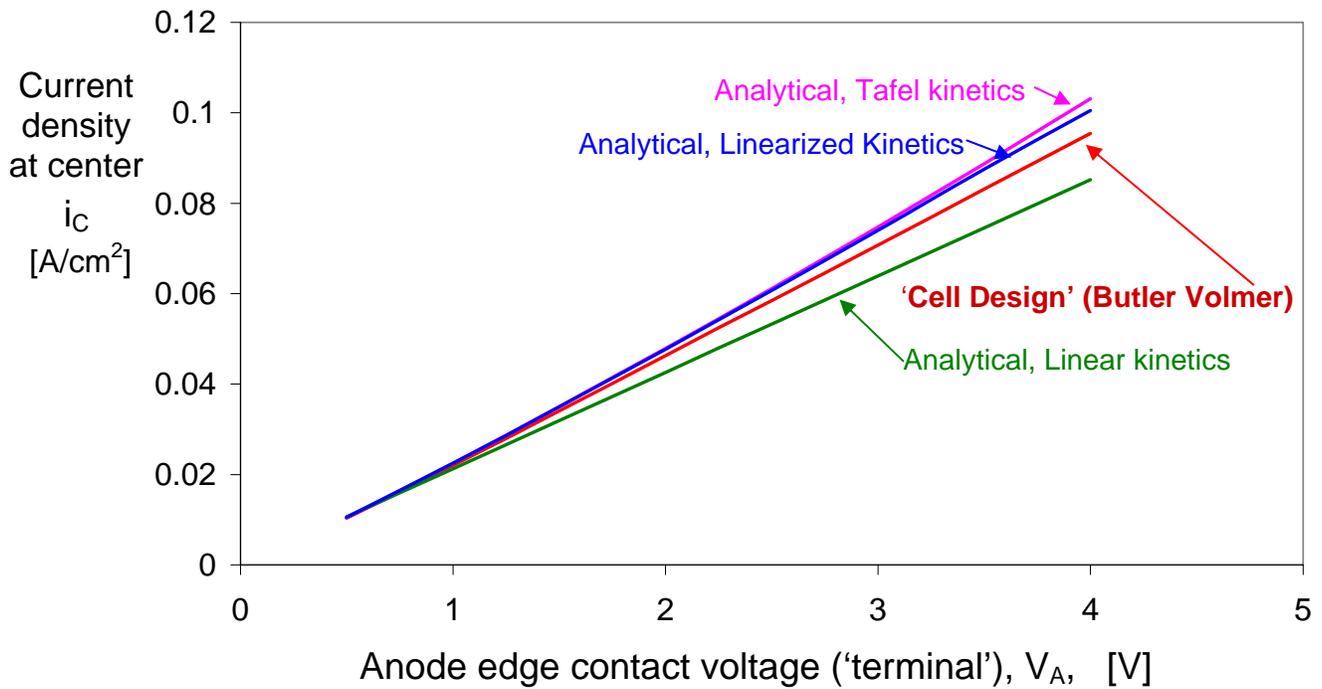
Fig.6. Current density in the center of the resistive disk electrode (R=100 mm) as computed by 'Cell-Design' software and by using equation (11) for linear, linearized and Tafel kinetics as a function of the voltage applied between the disk edge ('terminal' or 'contact' point) and the anode. The electrolyte conductivity was 0.55 S/cm. Seed layer thickness = 1000 Å and its conductivity, $k = 5.98 \cdot 10^5 \, \mathrm{S/cm}$. Butler-Volmer parameters typical to copper deposition were assumed: $\alpha_A = 1.5$; $\alpha_C = 0.5$; n=2; $i_0 = 1$ mA/cm^2; T = 300K; Cell height, H, was taken as 150 mm and the electrolyte conductivity, $k_s = 0.55$ S/cm.

Fig. 7 depicts the radial distribution of the local current density across the resistive disk electrode. The distributions were derived using two approaches: simulations by 'Cell Design' software (shown as open points) and by applying the analytical solution (solid lines). Excellent agreement is noted between the two methods. As expected the distribution becomes significantly less uniform at higher voltages and correspondingly, at higher average current densities.
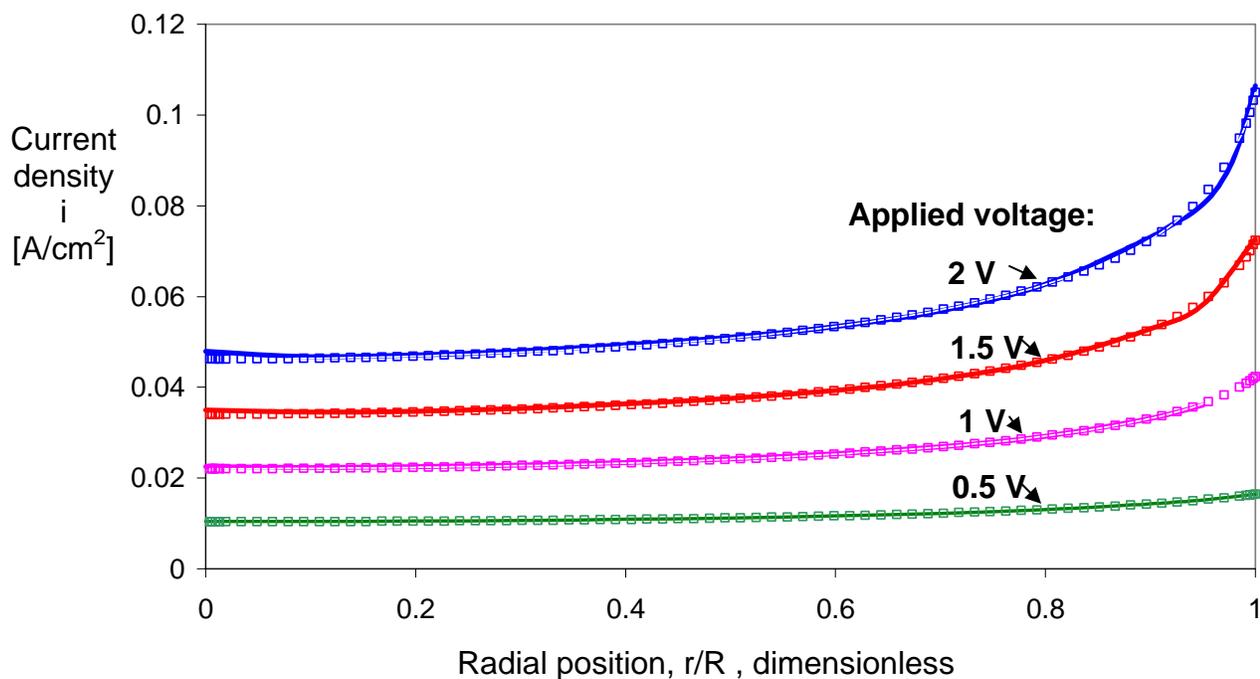
Fig.7. Current density across a resistive disk electrode (R=100 mm) as computed by 'Cell-Design' software (open squares) and by using equation 11 (solid lines) at different applied voltages. The indicated voltages are between the anode and the edge of the resistive disk ('terminal' voltage). The electrolyte conductivity was 0.55 S/cm. Seed layer thickness = 1000 Å and its conductivity, $k = 5.98 \cdot 10^5 \ S/cm$. Butler-Volmer parameters typical to copper deposition were applied: $\alpha_A = 1.5$; $\alpha_C = 0.5$; n=2; i_0 = 1 mA/cm²; T = 300K; Cell height, H, was taken as 150 mm and the electrolyte conductivity, $k_s = 0.55$ S/cm.

Summary and conclusions

An analytical model has been derived for the current distribution on a resistive disk, where the current is fed from a ring contact along the rim of the disk. Different models for the deposition kinetics were compared: Tafel, linearized Butler-Volmer equation about a point, and linear kinetics. The analytical results were also compared to an electrochemical CAD software ('Cell-Design') that employs the complete Butler-Volmer Kinetics. Excellent agreement was noted between the analytical model and the software simulations, with the linear kinetics model exhibiting a slightly larger deviation at the higher current densities. The solutions indicates, as expected, an increased current distribution non-uniformity at higher electrolyte conductivity (less resistance in the electrolyte) and at a higher exchange current density (more reversible kinetics). At small gaps between the anode and the cathode (H < 30 mm), a larger gap corresponds, as expected, to a more uniform distribution due to the increased resistance of the electrolyte phase. However, according to both the theoretical analysis and the computer simulations, there is no further improvement in the current distribution when the gap is increased beyond about 30 mm.

It should be noted that all the current distributions discussed herein are based on an initial, or a non-varying seed layer thickness ('h'). In typical plating applications, a conductive deposit builds up on top of the substrate, thereby reducing its resistance, leading to a more uniform current and deposit thickness distributions. It is difficult to model analytically this time-dependent effect, however, CAD software, such as 'Cell-Design' can model this build-up by iteratively time stepping through the simulations. This is discussed elsewhere in this Symposium [9].

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