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Effect of Anode Shape on Uniformity of Electrodeposition onto Resistive Substrates

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ABSTRACT

This work is devoted to the theoretical study of the effect of anode shape, insulating shields, the exchange current density and operating conditions on the uniformity of metal layer deposited onto the resistive cathode. Laplace's equation for the potential in the electrolyte solution, Poisson's equation for the potential in the resistive cathode, and the equation of metal thickness evolution were used as the mathematical model. The numerical solution was performed using the boundary element and finite element methods. The possibilities for controlling the distribution of deposit thickness over the cathode surface are demonstrated by the example of metal deposition onto an annulus workpiece. The use of the anode of the calculated shape enabled us to obtain a deposit of uniform thickness over almost the entire workpiece surface except for the very edges, where the deposit was thicker. The application of shields designed in the work enabled us to eliminate this drawback.

1. Introduction

The problem of the effect of electrode resistance on the distribution of current density and, consequently, the uniformity of metal deposition over the electrode surface has long been known [1,2]. By now, the effect of electrode resistance on the distribution of current density has been well studied for the electrodes of simple shape (plane long electrodes, rectangular electrodes, cylindrical electrodes, disk electrodes, etc.) [3–9]. Only in a small number of works, the electrodes of more complex shapes or the electrodes of rather simple shape, but with different types of boundary conditions on different surface areas (for example, in the case of partial insulation of electrode surface) were considered [10–12]. In contrast to the earlier works devoted to the electrochemical systems with the resistive electrodes, where only the distribution of current density was estimated, in more recent works [13–16], the dynamics of the metal deposit growth on the surface of resistive electrode of simple shape has been considered.

The uniformity of the deposit thickness is one of the most basic factors that should be taken into consideration during the design of the electroplating reactor [17]. A more uniform distribution of current density can be obtained by various means: the dielectric shields [17], auxiliary electrodes (current thieves) [17], segmented anodes [18,19], highly resistive membrane in close proximity to the wafers [20], moving anodes [21], the jet supply of electrolyte solution [22,23], etc. The uniformity of the distribution of current density and, consequently, the uniformity of deposit layer over the substrate can be enhanced by using shaped anodes. This method is rather simple and could be widely used; however, the methods for determining the shape and dimensions of anode, which provide the most uniform coating over the substrate, have not been developed adequately. The known methods of determining optimal geometry of curved anodes are applicable only to the two-dimensional problems; the potential drop in the resistive electrode and the variation of deposit thickness in the course of machining are ignored [24].

In our previous work [16], the effect of anode shape on the uniformity of thickness of a layer deposited onto the annulus substrate was studied; a particular case of metal deposition on one side of substrate was considered.

This work is devoted to the study of the regularities of distribution of electrodeposit thickness over one or two sides of annulus cathode. This electrochemical system offers several advantages. When the inner radius of the substrate is equal to zero, we obtain a disk substrate; at a large inner radius, we obtain a

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plate substrate. Thus, one can pass from the axisymmetric problem to 2D problem by varying one of the substrate parameters. A possibility of using two current collectors (on the outer and inner parts of annulus substrate) is another merit of this approach. The electrochemical system under consideration is characterized, in particular, by the presence of two cathode areas adjacent to the solution with different edge effects due to different distances from the axis of symmetry. The theoretical analysis of the system enables us to show the means for controlling the current density and deposit thickness distribution by shaping the anode, using the shields, choosing the number of current collectors and operating conditions.

The use of the shaped anode enabled us to obtain a deposit of uniform thickness over almost the entire workpiece surface except for the very edges, where the deposit was thicker. The application of shields designed in the work enabled us to eliminate this drawback.

2. Mathematical model

Fig. 1 gives a scheme of electrochemical cell with a resistive cathode. An insulating annulus substrate *1* of inner radius r_I and outer radius $(r_I + L)$ coated with a thin conductive metal film *2*, of thickness s_0 and conductivity χ_m acts as the resistive electrode. Anode *3* is located at a distance *d*, and the region between two electrodes enclosed by concentric insulating walls (shown with dashed lines) is filled with the electrolyte of conductivity χ_s. Outer current collector *4* and inner current collector *5* are attached to the resistive cathode.

The scheme presented on Fig. 1a corresponds to the metal deposition on one side of substrate. In the case of simultaneous metal deposition onto both sides of substrate (Fig. 1b), assume that initially two conducting layers on the resistive cathode are equal in thicknesses $(s_0/2)$ and the upper and lower anodes are arranged symmetrically about the resistive electrode at a distance *d*.

Due to the resistance of thin conducting layer, a potential drop develops along the electrode surface, causing the current lines to be more concentrated near the current collector. The resulting variation in the local current density leads to a variation in the deposit thickness 6. To provide more uniform distribution of current density, curved anode 7 and/or insulating shields 9 and 10 can be used. For the sake of simplicity, let us consider the curved anodes of rather simple shape, which can be prescribed by three parameters: the average distance (*d*), the deviations from the average distance at the inner (Δd_I) and outer (Δd_O) boundaries of the anode (Fig. 1c).

In addition, assume that the cross-section of insulating shield is a rectangular of length l_O (l_I) and height h_O (h_I) and its lower boundary is separated from the resistive cathode by a distance z_O (z_I). Here, the subscripts O and I denote the outer and inner insulating shields, respectively.

The analysis is restricted to the deposition of a single metal at a current efficiency of 100 percent:

$$M \Leftrightarrow M^{+n} + ne^{-}. \quad (1)$$

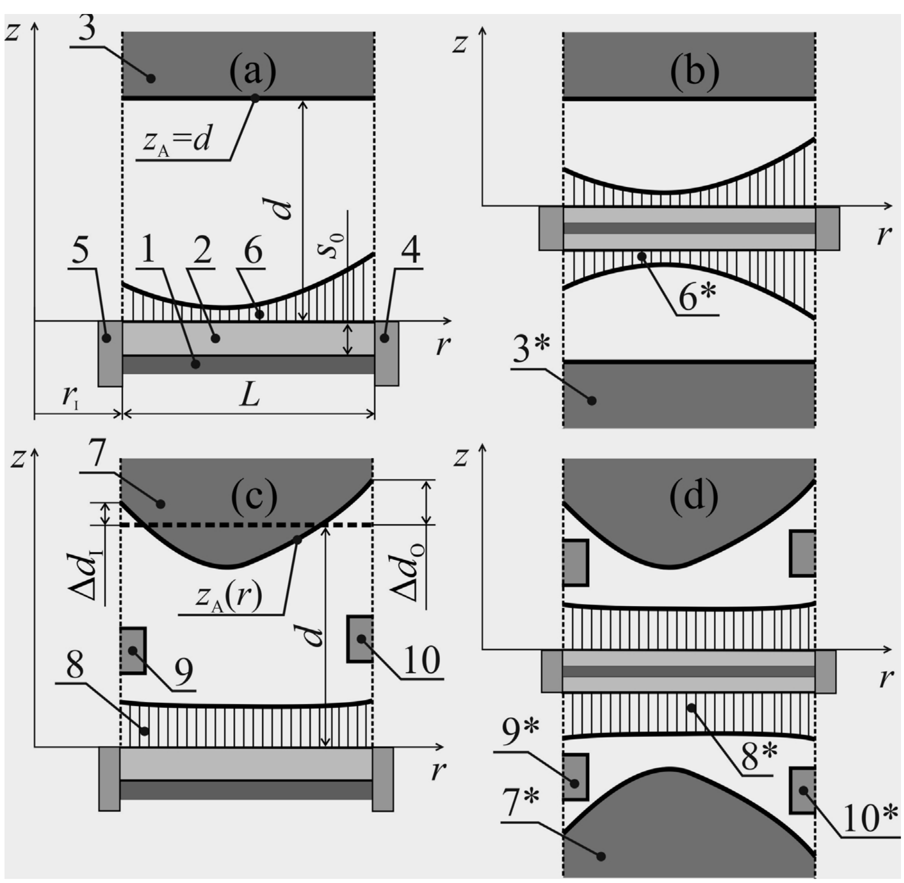

Fig. 1. Scheme (not drawn to scale) of cathodic deposition for the resistive electrodes: (a, b) straight anode; (c, d) curved anode; (a, c) one-side deposition; (b, d) two-side deposition; (1) insulating substrate, (2) initial metal layer on the electrode with thickness s_0, (3) straight anode, (4) and (5) current collectors, (6) and (8) cathodic deposit, (7) curved anode, (9) and (10) ring insulating shields. The asterisked numbers correspond to the electrodeposition onto the lower surface of substrate.