Dr. E. Jennings Taylor • Faraday Technology, Inc.
315 Huls Drive • Clayton, OH 45315-8983
E-Mail: FARATECH/FARATECH 5/ejtaylor@mailcore1.oh.voyager.net

Not All Electric Fields are Created Equal For Emerging Electronic Applications

As evident by the upcoming Fifth International Pulse Plating Symposium (June 29-30, Chicago, Navy Pier), a renewel of interest in non-DC processes, including plating, anodizing and machining, has developed over the last several years. One driver for the interest of non-DC processes is the success reported for high-rate copper plating of plated through-holes (PTHs) for z-axis interconnects for printed wiring boards (PWBs). In fact, approximately seven of the 20 papers scheduled for the symposium deal with copper deposition for PWB applications. The successful high-rate plating of PTHs has led to non-DC processes being considered for other electronic interconnect applications. These electronic interconnects include submicron trenches for semiconductor applications and 25- to 125-micron microvias for high density interconnect applications.

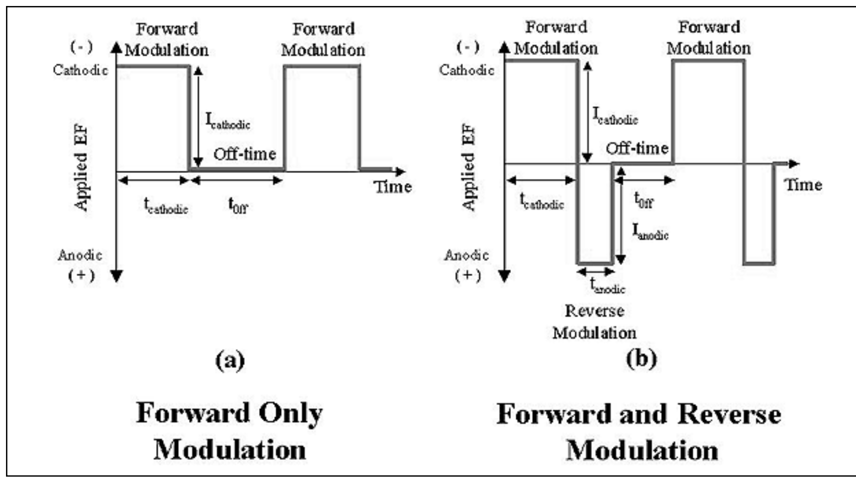

Fig. 1—Square wave modulated electric field for (a) forward only modulation and (b) forward and reverse modulation.

"I Tried Pulse Plating And It Didn't Work!"

What I have found to be extremely curious is the number of researchers who have reported, during their presentation or in response to questions or in their conclusions, that pulse reverse plating of trenches and microvias did not work! However, just as there is an infinite combination of length, width and height to obtain a given cubic volume, there is an infinite combination of electric field parameters to obtain a given plating rate. Clearly, the researchers did not intend to imply that they investigated an infinite combination of electric field parameters and found that all of them failed.

As depicted in Fig. 1, the basic parameters of the "square wave" modulated electric field (a subset of non-DC processes) are: 1) cathodic and anodic on-times ($t_{cathodic}$ or t_{anodic}), 2) cathodic and anodic currents ($I_{cathodic}$ or I_{anodic}); and 3) off-time (t_{off}). The period, frequency, cathodic and anodic duty cycles, and average current or plating rate are derived from the basic parameters. The average current is given by:

$$I_{average} = I_{cathodic}(t_{cathodic} /(t_{cathodic} + t_{anodic} + t_{off})) - I_{anodic}(t_{anodic} /(t_{cathodic} + t_{anodic} + t_{off}))$$

The result of my query of a number of researchers, presenters and authors, is that the more accurate description of their encounter with modulated electric fields would be: "I tried the pulse reverse current parameters reported for high-rate deposition of PTHs, and found that these parameters did not work for submicron trenches or 25- to 125-micron microvias."

In addition, these researchers all conducted their experiments in plating baths with a particular brew of proprietary additives, *i.e.* brighteners, levelers and suppressors. Several recent articles from *P&SF* illustrate the point that there are specific electric field parameters for specific plating bath chemistries and for specific applications.

In studying leveling in pulse plating with brighteners, Aroyo reported on the synergistic effect of frequency and hydrodynamically active additives (Aroyo, 1995). Aroyo studied the leveling power in the presence of a hydrodynamically active additive as a function of frequency for acid copper, bright nickel and gold-cobalt plating. At the same average current density, a leveling power maximum was observed at an optimum frequency. Compared to the DC baseline, the leveling power for acid copper, bright nickel, and gold-cobalt increased five, two, and 10 times, respectively. Aroyo rationalized the presence of a frequency optimum as being caused by the competing tendencies of increasing nuclei formation with increasing frequency, and decreasing brightener surface concentration with increasing frequency.

A Recent Study

In a paper submitted for publication, my colleagues and I have investigated copper plating of PTHs, trenches, and microvias (Taylor, Sun and Inman, 2000). In this study, we employed a simple plating bath containing copper sulfate/sulfuric acid and polyethylene glycol/chloride. We found that the copper distribution in the three electronic interconnects features was governed by the cathodic peak current and cathodic on-time and the anodic peak current and anodic on-time.

Consequently, we termed this modulated electric field process as charge (*i.e.* current X time = charge) modulated electrochemical deposition (CM-ECD). The dramatic size differences of the three interconnect features necessitated very different CM-ECD parameters, specifically for the 325-micron PTH compared to the sub-micron trench and 100-micron microvia. The shape of the electric field for the PTH consisted of a relatively long cathodic on-time/low peak current, followed by a relatively short anodic on-time/high peak current (see Fig. 2a).

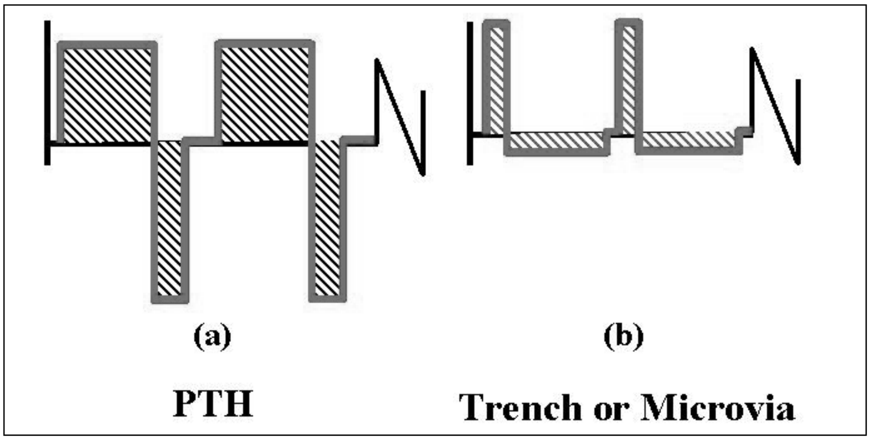

Fig. 2—Electric field shape for (a) PTH and (b) trench or microvia.

In contrast, the shape of the electric fields for the trench and microvia consisted of a relatively short cathodic on-time/high peak current, followed by a relatively long anodic on-time/low peak current (see Fig. 2b). In addition to the shape, all three CM-ECD process parameters operated at very different frequencies. Furthermore, not only were the optimum process parameters very different, using the PTH parameters to plate the trench or microvia resulted in an absence of copper in the interconnect. This fact explains the lack of success in applying a set of parameters for high-rate PTH deposition to trenches and microvias.

Another Example

A final illustrative example is from the recent work of Rehrig and Mandich (1999). They considered the effect of pulse plating on gold plating in a Haring-Blum cell. Rehrig and Mandich analyzed throwing power (TP) and current efficiency (CE) data in terms of cathodic on-time. From their study of 30 "pulse waveform conditions" (their term), these researchers observed a dramatic effect of waveform parameters on TP and CE. Some waveform parameters yielded higher TP and CE compared to DC and some yielded lower TP and CE than DC. Rehrig and Mandich speculated that a potential benefit of pulse plating is the ability to alter the deposit properties by electronic manipulation rather than by using the traditional chemical additive formulation approach. (I will pick up this point in the next column.)

Not All are Equal

So, for a specific application or for a specific problem with specific attributes, not all electric field parameters are created equal. In DC processes, there are optimum current densities, *e.g.* the highest plating rate without burning the deposit or the highest plating rate with acceptable throwing power and current efficiency.

In DC plating, there are optimum bath chemistries, *e.g.* for high-rate panel plating or for high aspect ratio through-hole plating. So, it is indeed curious that many technology developers would expect to apply specific electric field modulation parameters from one application, such as high-rate PTH plating, to another, such as submicron trench or microvia plating.

If the metal finishing industry is going to fully utilize the potential of this emerging technology or tool for electronic applications, we must recognize the need to identify sets of parameters relevant to a specific application, based on understanding or on statistical optimization techniques guided by understanding, such as Taguchi.

In the next column, I will present a vision for the metal finishing industry for the new millennium—electric field process control. P&SF

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About the Author

Dr. E. Jennings Taylor is the chief technical officer at Faraday Technology, Inc. He founded the company in 1992 to develop and commercialize innovative electrochemical technology using sophisticated charge-modulated electric fields.

Dr. Taylor holds a BA in chemistry from Wittenberg University, an MA in technology strategy and policy from Boston University, and MS and PhD Degrees in Materials Science from the University of Virginia. He has published more than 70 technical papers and articles and holds 11 patents. He serves on the AESF Pulsed Electrodeposition Processes Committee and the Research Committee.