Validation of New Generation Tooling Concept for Electroplating of Copper on Printed Circuit Boards

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ABSTRACT

A dynamically software controlled electroplating tooling concept has been developed to compensate the pattern dependence of the deposited layer thickness on different substrates. In this paper a validation of this new tooling concept on industry relevant printed circuit boards is presented. Simulations are compared with experimental results as obtained in a prototype electroplating cell. A quantitative improvement of the plating thickness uniformity between a standard electroplating cell and the advanced tooling approach is given. The influence of the conductivity of the electrolyte on the deposit distribution is studied and indicates a way to obtain a significant improvement in uniformity.

Keywords: printed circuit boards, pattern plating, acid copper plating, computer simulation

Introduction

A dynamically software controlled electroplating tooling concept[**] has been developed where the pattern dependence of the deposited layer thickness on substrates (*e.g.*, printed circuit boards or semiconductor wafers) can be significantly reduced. The main change from a standard cell is the introduction of a controllable grid of anode segments, at a small distance of the substrate as shown in Fig. 1 on the right. In the implementation as presented here, the anode segments consist of rods covered with an inert anode material like platinum or IrOx depending on the application.

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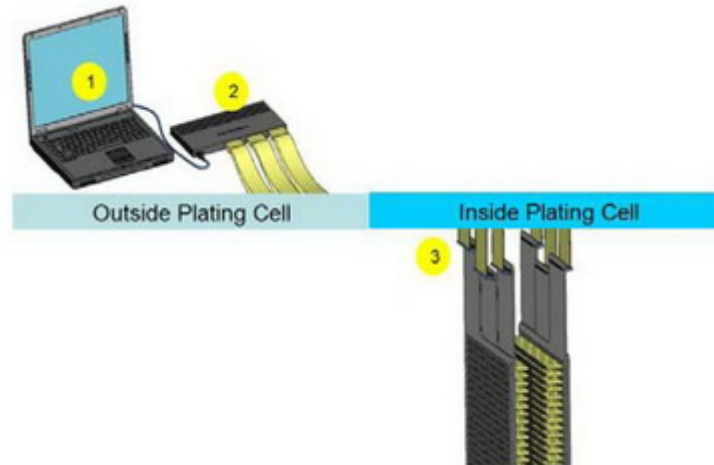
Figure 1 - Implementation of the new tooling concept.

As indicated in Fig. 1, the proposed solution consists of:

1. A simulation tool that optimizes the current on each anode segment in time to yield the desired (*e.g.*, uniform) deposition over the patterned substrate. These simulations take all relevant effects like cell design, pattern on the substrate and resistivity of the substrate into account. The results of the optimization are sent to the control unit and feeding network.

2. The feeding network contains a microprocessor that reads the calculated pattern of current, and then controls an array of DACs, which imposes the correct current on each anode segment. If needed, an amplification of the current can be implemented.

3. A holder (*e.g.*, printed circuit board with multiple layers, depending on the current and the number of anode segments) on which the anode rods are mounted, and which connects each rod individually to the feeding network through a series of connectors.

As the current on each of the anode segments can be individually controlled and changed in time, any desired pattern can be imposed. This means that based on simulations, the current on each of the anode segments can be determined upfront to yield a very uniform deposition, almost regardless of the pattern and/or resistivity of the substrate. As the current on each anode segment can also be varied over time, the plating process can be designed to take the change in resistivity of the conducting layer on the substrate as more metal is deposited into account. The optimization software can also take the effect of movement of the substrate into account and adapt the current pattern in time accordingly.

Lab scale validation

Set-up

A schematic view of the prototype cell used for the experiments is shown in Fig. 2. The segmented anode is positioned in the middle of the cell, the cathode substrate on the left hand

side. The distance between the tip of the anode pens and the substrate can be adapted by adding or removing one or more one-millimeter thick PVC spacers.
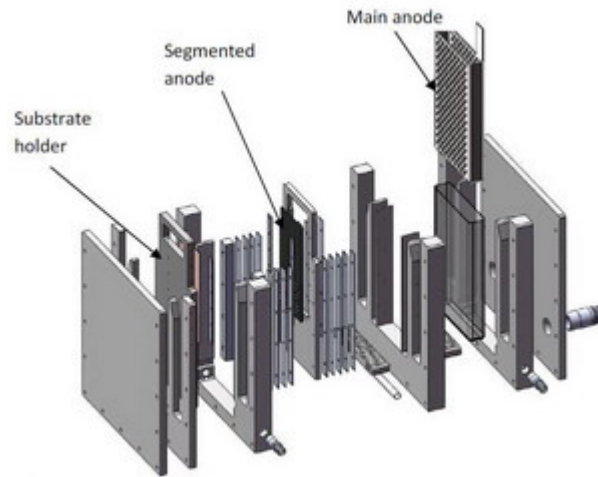
Figure 2 - Schematic view of the test cell.

A lab set-up as shown in Fig. 3 is constructed to validate the new tooling concept. The segmented anode consisting of 8×8 segments, as shown in Fig. 4, is inserted into the plating cell opposite the substrate. The current on each of the anode rods can be controlled individually. Each anode is 3 mm in diameter and the distance between two anode segments is 14 mm.

Figure 3 - Lab scale set-up.

**Figure 4** - Segmented anode with platinum-coated rods.

A proprietary acid copper electrolyte[***] is used in these tests, one that is widely used in the semiconductor industry. It needs to be noted that this electrolyte has been tuned to yield uniform distributions even when the anode or cathode is not uniform or patterned. This of course means that a significant part of the advantage of the segmented anode is counteracted by the electrolyte.

Additionally different "simple" electrolytes with different conductivities were tested to study the influence of the conductivity and throwing power on the performance of the segmented anode. The basic electrolyte is copper sulfate with polyethylene glycol (PEG) and Cl⁻, with different amounts of sulfuric acid to change the conductivity from 25 up to 50 S/m.

Polarization measurements were performed on the different electrolytes in order to obtain all the necessary input data for the simulations. Experiments at different rotations speeds (100, 400 and 800 RPM) were performed in order to assess the influence of the mass transport on the plating behavior. The polarization curve for the proprietary electrolyte, corrected for the ohmic drop, obtained for 800 RPM is shown in Fig. 5. The corresponding electrolyte conductivity is 53.3 S/m. As no sample of anode material in a usable size for the RDE was available it was not possible to perform the polarization measurements for the anodic part of the curve. As the main reaction on the anode is the production of O_2 for which the reaction rate is almost independent of the overpotential, a linear, quasi-primary distribution is assumed. It is not expected that this has any influence on the accuracy of the simulations and optimizations.


[***] Rohm&Haas Coppergleam 125 T-2 A, Rohm & Haas, Subsidiary of the Dow Chemical Co., Midland, MI, USA.
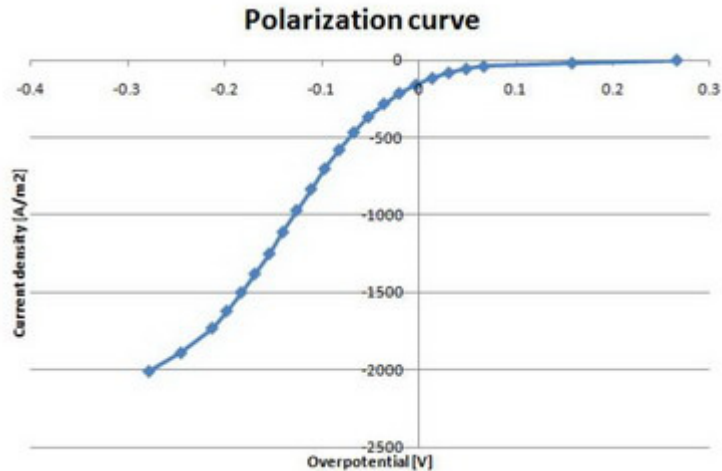
Figure 5 - Measured polarization curve of the proprietary copper electrolyte at 800 RPM.

In collaboration with ACB (Dendermonde, Belgium, www.acb.be), custom small printed circuit boards were designed and produced to ensure a maximum relevance of the lab scale tests. These printed circuit boards each contained an 8×8 cm portion of an industrial printed circuit board design. A typical example is shown in Fig. 6. The 8×8 patterns are positioned on panels that fit exactly in the prototype plating cell opposite-the segmented anodes, allowing an exact control of the position of the segmented anodes relative to the pattern. Figure 7 shows one of these panels mounted in the cathode holder. The copper strip at the top the panel is used to connect the panel with the multi-channel current source outside–the electrolyte. During the testing, two different patterns on the panels were used to verify that the improvement was not limited to a specific pattern design. They are labeled Pattern 1 and Pattern 2 in the subsequent sections.
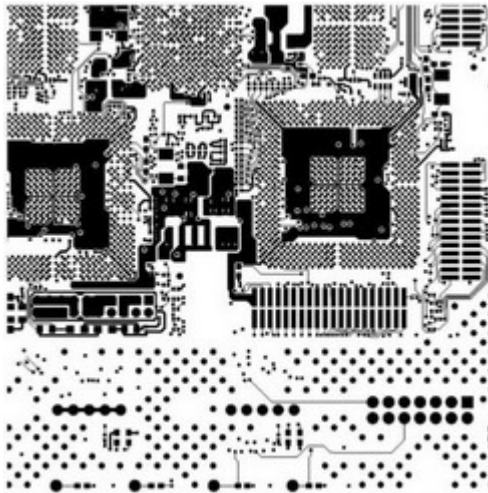

Figure 6 - Typical example of a small printed circuit board.

Figure 7 - Panel with Pattern 1 mounted in the cathode holder.

Using the optimization algorithm, the optimal current on each anode segment is calculated. The resulting deposit distribution and the position of each of the 8 × 8 anode pens relative to the pattern is shown in Fig. 8. The layout corresponds exactly to the configuration of the anode pens relative to the PCB as mounted in the prototype cell. It is evident that the resolution of the pattern is much finer than the resolution of the anode segments. It is not realistic to increase the number of anodes beyond a certain point. The minimum geometric distance at which a separate anode is still active is determined by the relative magnitude of the ohmic drop in the electrolyte and the resistance of the deposition reactions. From calculations the minimum distance for the copper electrolyte is about 5 mm. It does not make sense to position the anode sections closer than 5 mm apart as-the polarization will then be the dominant factor governing the local current density and deposit distribution. This then means that the segmented anode has lost all its compensating power. The polarization can only be changed by changing the chemistry (concentrations of the different species, additives, etc.) as is clearly demonstrated by the change in electrolyte as reported in the next sections of this paper.
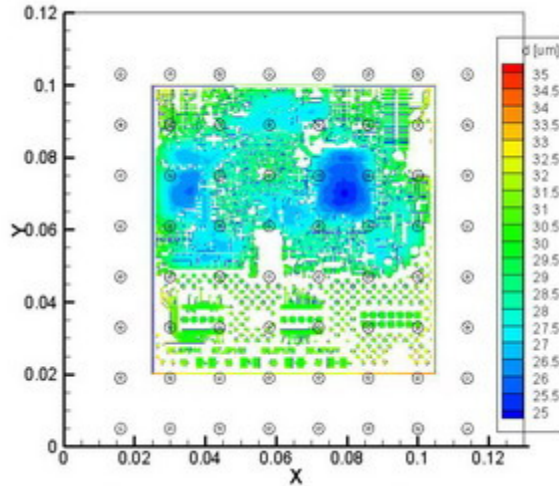
Figure 8 - Calculated copper thickness distribution over Pattern 1.

The deposited copper thickness is measured by x-ray fluorescence (XRF) at 20 reference points of the pattern. A suitable calibration of the XRF, based on standard copper foils was performed to ensure maximum accuracy. Before deposition, the copper seed layer thickness was measured to be able to calculate the actual deposited value accurately. The reference points were selected to ensure that the x-ray beam was not wider than the structures to be measured to avoid errors in the measurements.

In order to assess the benefits of the new tooling approach, experiments with the main anode alone and with the segmented anode alone were performed. The measured deposit thickness was compared with simulations for both cases.

Figure 9 shows a comparison between the simulated and measured deposit thickness for Pattern 1, using the main anode configuration. An excellent agreement between the simulations and the experimental values is observed, again showing the validity of simulations in optimization the plating thickness distribution.
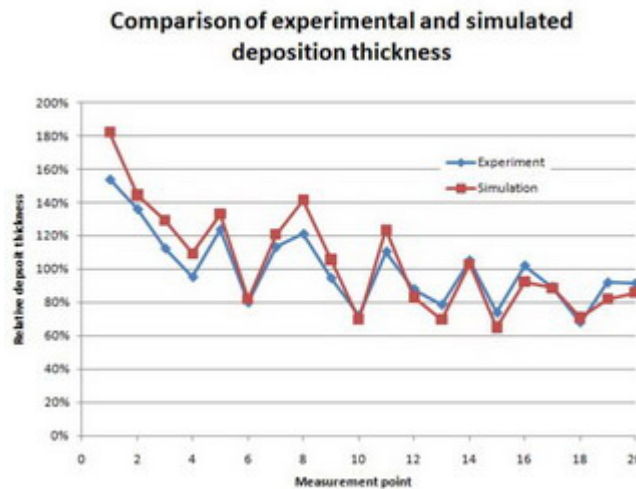
Figure 9 - Comparison of experimental and simulated deposition thickness for Pattern 1.

Figure 10 compares the measured deposit in the 20 predefined sample points for the two configurations of Pattern 2. The variation of the deposit thickness is clearly reduced by the segmented anode. The standard variation is reduced from 36% for the main anode configuration to 23% for the segmented anode configuration. Note that both the lowest and the highest deposition values are improved. If another target value for the optimization is selected, it is possible to focus the improvement more towards increasing the lowest values or decreasing the highest values. This choice depends on the requirements of the customer and is not investigated further here. From these measurements, the improvement of the deposition uniformity is evident. Different experiments on different patterns show a very similar behavior. Within the range examined in the experiments, no significant influence of the distance between the segmented anode and the substrate was detected. This is mainly due to the very high conductivity of the commercial copper plating electrolyte which ensures that the ohmic drop in the electrolyte is not the determining factor in the distribution of the current density on the patterned substrate.
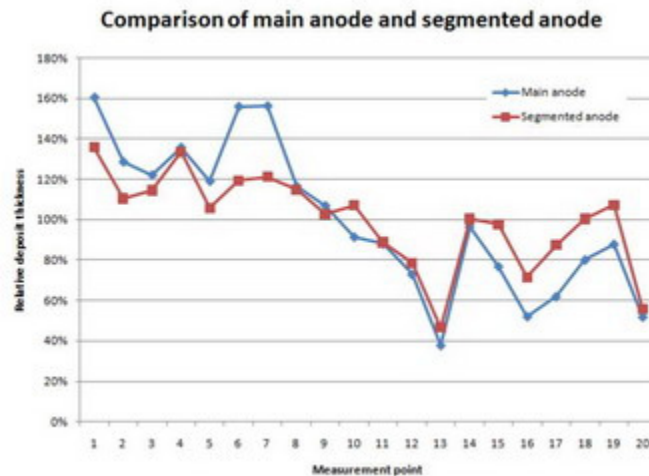
Figure 10 - Comparison of main anode and segmented anode for Pattern 2.

Experiments performed with an in-house standard copper plating electrolyte consisting of copper sulfate and sulfuric acid show the influence of the electrolyte conductivity on the deposition distribution. A limited amount of PEG + Cl⁻ was added to ensure the adhesion and improve the quality of the electrodeposited copper layer. The conductivity of this electrolyte was 25 S/m, half of the value of the commercial electrolyte. From the experiments, as shown in Fig. 11, it is clear that the reduced conductivity of the electrolyte yields a significant improvement in deposition uniformity. The standard deviation is reduced from above 17% for the commercial electrolyte to below 11%. This means that for this electrolyte, the copper thickness in at all measured points is within 20% of the average value. Note also the very significant improvement when comparing the distribution using the segmented anode and the optimized electrolyte (Fig. 11) with the distribution from only the main anode and the standard electrolyte (Fig. 9). Based on these results, it can be concluded that it would be very beneficial to tune the electrolyte and the segmented anode approach together to achieve maximum uniformity in the plating distribution.
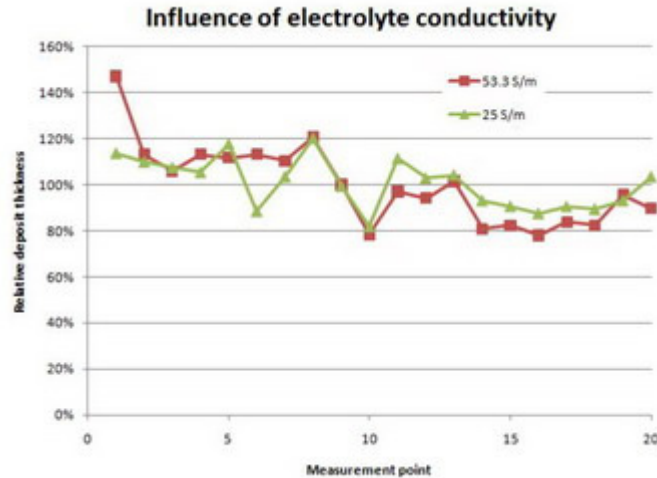
Figure 11 - Influence of the conductivity of the electrolyte on the deposition distribution on Pattern 1 using the segmented anode.

Additional experiments using the Pattern 2 design show that the improvement of the uniformity achievable with new tooling depends strongly on the electrolyte conductivity. Table 1 shows the standard deviation as measured over the 20 sample points for the two electrolytes, each time with the main anode and with the segmented anodes. It is clear that the best results are achieved with a less conductive electrolyte combined with the segmented anodes.

Table 1 - Standard deviation of the distribution for the different configurations.

	Electrolyte 53.3 S/m	Electrolyte 25 S/m
Main anode	22.4 %	39 %
Segmented anode	17.1 %	11 %

Conclusions

From the results as presented above it can be concluded that the validity of the new tooling approach has been clearly demonstrated for industrially relevant printed circuit boards. The gain in uniformity of the deposition as achieved in the experiments is significant.

The proposed tooling concept yields a significant increase in the overall control of the deposit distribution. The electroplating cell actively compensates the non-uniformity in the deposit based on upfront simulations and optimization.

Different targets and specification for the optimizations are possible depending on the user requirements:
- More uniformity with the same current density
- Higher plating speed/throughput with same uniformity
- Increasing the minimum deposit or decreasing the maximum deposit with limited influence on the rest of the distribution

- Combinations of the above

It was established that the control of the deposit distribution can be further improved when the electrolyte is tuned together with the hardware.

The resulting increase in plating control is important to a production plant for PCBs for several reasons:
- It allows plating at higher speed, thus improving throughput.
- It reduces the consumption of copper.
- It relaxes the design rules (*e.g.*, the width and distance between single tracks, isolated vias, etc.), so more complex designs can be produced reliably.

Acknowledgements