Methodology for High Aspect Ratio Pulse Plating

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Abstract
Two years ago when IBM Endicott, now Endicott Interconnect (EI), was preparing to install a new Acid Copper plating system, the Periodic Reverse Pulse (PRP) tanks installed at the end of the line were seen as a current density capacity enhancement for "standard thickness" boards. At the time, there was limited demand for thicker, higher aspect ratio boards which required plating in the pulse tanks. A lot has changed in the last two years!

In 2001, electroplated boards with a 15:1 aspect ratio were on EI's strategic road map; now they are on the manufacturing floor. The pulse tanks, empty two years ago, have evolved from merely being a productivity enhancement to becoming technology enablers - plating EI's highest aspect ratio boards.

This paper will discuss some of the methodologies of the plating system's design, the strategy deployed in evaluating and qualifying PRP and the migration to thicker boards. All of EI's PRP work on the production line has been done with Atotech's CUPRAPULSE S4 LEVELER system and PE PRP/DC rectifiers, capable of +1200A / -3600A; but the methodology and results should be applicable for most plating systems. The impact of process parameters and board features play a major role, but central to our findings is the need to migrate from a "one bath for all applications" mentality, which compromises results and capability. One simply cannot get optimal results by merely reducing the current density of their existing bath and just hoping for the best.

Introduction
Periodic Reversed Pulse (PRP) copper plating has been advertised as the greatest new development in copper plating in decades. Although the concept of applying a forward (plating) current and then switching to a reverse (stripping) current in the matter of fractional milliseconds was not new, the development of larger power supplies made it of practical use in manufacturing copper plating lines. Promises of faster plating rates, higher throw, and better line height uniformity all sounded intriguing enough to warrant investigation.

The potential of PRP couldn't be ignored in 1999, when IBM Endicott began its design of a new copper plating line for manufacturing. As with most new technology implementations, the starting point for consideration was to talk to a variety of suppliers and users. Several plating shops had PRP in production, others were in evaluation stages, but nobody seemed to have done much work on thicker boards at the time; some even suggested that thick boards and PRP would not work together. Several chemistry suppliers admitted to having issues with earlier formulations of their systems, but highlighted some of the fantastic results that they were able to achieve. Some fabricators were able to triple their operating current density, thus tripling their capacity. Others were able to improve their throw and plating distribution to be able to save thousands of dollars in yields and solder mask. In their minds, PRP was definitely the way of the future and for many applications, the way of the present.

Although there were positive results reported, many users still had reservations. Repeatedly we heard stories about severe bath life issues and process repeatability problems. In the some cases, fabricators would get great plating results for about a month, then be unable to produce product. Others would get good results in one tank but couldn't replicate them in another. There were issues relative to compromises in the tank designs of older equipment and concerns about the rectifier outputs. There was frustration, but also the hope of being able to harness and control the performance that had shown itself at one time.

It was decided that a new plating line SHOULD incorporate pulse plating into its design, but it was premature to commit all production to it. The ultimate design incorporated multiple smaller tanks, all which could readily be converted to pulse in the future, but that only a few tanks would be fitted upfront with the more expensive PRP rectifiers.

Tank Design
Field studies provided no clear view of the best tank design or the best source. Most of the data from suppliers had come from retrofitted DC tanks with whatever designs the customers had. Often the only changes that could be made were the cabling, rectifiers, and bath chemistry, without any clear understanding of what "best practice" or optimal design would be. Some of the recommendations received were in support of eductors; others air agitation.

Some promoted short anode-cathode distances; others suggested conventional spacing instead. Multiple inputs on cabling, rectifier suppliers, and debates on square vs. complex waveforms all had to be sorted out. In the absence of clear consensus, experience and best engineering assessments were the guides to design by. Adding some level of flexibility into the design to accommodate some of the options also provided some insurance. The final results are indicated in Table 1.

Table 1 - Tank Design Recommendations

AGITATION	Rack agitation (adjustable frequency) Flightbar vibration mounted on the flightbar Air and solution agitation within a "floating shield" assembly
CABLING	Twisted pairs, matched cable length, both ends of anodes Located as close to the plating cells as possible
RECTIFIERS	DC or PRP operable; Supplier: PE Square wave; 6 Volt; +1200 Amp / - 3600 Amp Forward-Pause-Reverse-Pause with programmable ramp
ANODE-CATHODE	Set at a maximum of 12" for thicker boards Adjustable up to a minimum of 6"

Chemistry

Supplier and customer visits along with sample board processing had not highlighted a clearly superior process, so out of project convenience, (our new plater was being built by Atotech) we opted to go with Atotech's Cuprapulse S4 Leveler system. Since this is a two-component system, Brightener (accelerator) and Leveler (suppresser), two separate dosing supports systems were required with traditional dosing based on amp-hrs.

The interaction of chemistry concentrations, rectifier parameters, current density and board attributes cannot be over stressed at this point. The initial boards targeted for evaluations were 110 mils thick with 10 mil diameter drilled mod-sites, a standard line monitor Test Vehicle board used for process monitoring in Endicott. With a base assumption of operation around 20 asf for this type panel, Atotech's input for starting bath composition is given in Table 2.

Table 2 - Starting Bath Compositions

Copper	19.0 grams/liter
Sulfuric Acid	250 grams/liter
Chloride	65 ppm
Brightener	0.02 % by volume
Leveler	3.5% by volume

Experimentation

One of the most critical decisions made by the team at the onset was that bath aging, via dummy plating, would be deployed prior to running any test panels. The intent of this was to ensure that any results that were generated would be "real" and repeatable. This was a luxury that could be afforded due to the number of DC plating cells providing sufficient plating capacity on the new line. Testing an aged bath helped ensured no "one month fallout" scenarios and to provide reproducibility in results.

The testing of PRP has many variables for a new user! In DC trials, current density and additive concentrations tend to be the sole variables, with all other variables fairly well defined and set to preferred values. PRP, being a complete unknown, required a plan to assess an array of new variables, primarily forward pulse width (time), reverse pulse width, and forward-to-reverse current density ratio, while still having average current density and the additives to be concerned about. Even with these wide open ranges to choose from, it seemed that every supplier, user and paper on the subject of PRP recommended forward pulse widths of 10, 20 or 30 milliseconds with a fixed ratio of 20:1 for forward: reverse pulse widths. The typical current density ratios were reverse current densities of 1.5-3 times the amplitude of the forward.

At this point, a decision has to be made. One needs to either narrow the scope of the variables to attempt to define an operable range for manufacturing, or try to explore a more complete range of each component and include more different variables in more of a development effort. With the scope of this activity being so large, and the time already consumed by bath aging, opting to define a workable set of parameters first, then additional testing and optimization could occur later, was chosen. By accepting the limited ranges on pulse widths, staying with the fixed

20:1forward:reverse time ratio, and limiting the pulse waves to just the basic forward then reverse and repeat wave form, testing could be done quickly on a relatively small number of boards.

Results

Simple matrices were developed and run, looking at varied pulse widths, current densities, and current density ratios. The bath chemistry was controlled to the pre-defined set points so as to not be an additional variable. Multiple test boards were run across multiple days using cross sections and PTH copper thickness as the basic metric. These test runs resulted in 3 statistically significant "enhancers" to throwing power:

1) Increasing the pulse widths
2) Increasing the reverse current density ratio
3) Increasing the average current density

Enhanced performance with the wider pulse widths and increased reverse current density ratios were not surprising, but the improvement, although statistically less significant, with increased average current density was unexpected. The findings were welcome as they would enhance productivity. In retrospect, this result was most likely due to setting the initial target brightener concentration too high, thus favoring results at higher currents. Along with throw monitors from cross section boards, thermal cycling test vehicles were also processed through the various conditions. All runs showed very acceptable results, so it was concluded that process windows were fairly robust.

Using the best conditions as defined from the matrices, the ranges of the individual chemical concentrations were then tested and varied for production use. This helped to define proven conditions and specification ranges for the processing of customer acceptance product. It was obvious that these were not likely the most optimal parameters since the best conditions were found to be the extremes of what had been tested. But manufacturing conditions WERE identified and documented, allowing a path for production to begin. Other test vehicles panels and production boards were processed at these conditions and although they not have been fully optimized for PRP, the comparative results vs. DC plating of the same product given in Table 3was dramatic.

Table 3 - Comparative Results of DC and PRP Plating
0.140" Thick Production Board with 0.014" Diameter Drilled PTHS (10:1 Aspect Ratio)

	DC Plating	PRP Plating
Current Density	19 asf	27 asf
Plating Time	115 minutes	75 minutes
Average Surface Cu Thickness	45 microns	40 microns
Minimum PTH Cu Thickness	20 microns	22 microns
Average Thermal Cycles	25 cycles	43 cycles

This allowed production of 10:1 aspect ratio boards to begin. This also provided the benefit of more regular loading and use of the plating bath to occur, and additional testing of more challenging boards and aggressive pulse parameters to commence as well. The trend of better throw with increased pulse widths continued beyond 30 ms pulse widths. Due to program limitations, forward pulse widths were only allowed to be two digits, so nothing greater than 99 ms forward could be explored. Even at the most extreme, 99 ms forward and 5 ms reverse, the increased throw performance was observed, but the grain structure of the resulting deposit was not very ascetically pleasing. Visually comparable large-grained structures plated from DC baths in the past had been very susceptible to solder shock failures and very poor physical properties. But all solder shocks and other thermal cycling tests showed acceptable results. Still, even though all product test results were positive, we had exceeded our "comfort level" and settled on narrower pulse widths for production use.

Thick Boards

To begin evaluation of thicker boards quickly, existing test boards with small clusters of thermal cycling PTH test sites were tested next. The boards were 0.220" thick with 0.014" diameter drilled PTHs and were run with only 90 minutes plating time, yielding over a mil of plating in the PTHs! It was noted on these and several other panel designs that the plating thickness in the smallest signal vias was the same as larger connector holes. This made parameter selection just based on specified aspect ratio impossible. Hole quantity and the resulting plateable areas were already accounted for in the definition of each part number, but not the variation in hole density or their affect on plating distribution and/or throw. Parameters used to plate test parts with a sparse number of small PTHs could not necessarily be used to plate the same aspect ratio boards with mod-sites. Often, maintaining the same parameters except for adding some additional plating time could compensate this for. The impact of this affect finally couldn't be simply overcome by plating "a little more copper" when attempting to plate a board 0.174" thick with approximately a 3.5" square mod-site of 0.012" drilled PTHs.

Mod-sites create distribution challenges on the same order as dense lines versus isolated features in pattern plating. The thicker the board, the more tightly packed the holes, and the larger the mod-site, the greater the impact. At a thickness of 0.174", full grid 0.012" PTHs increase the plateable area 3X - that's 3 square inches of plateable area for every square inch of board per side. With small mod-sites, this increase in plateable area can be overcome. Large mod-sites, such as the 3.5" one, allow no recovery to the system and act as a big blackhole. The surface copper thickness within the mod-site dropped off instantly, typically around 1 mil. It was clear that it was time for new parameters.

Using the big mod-site boards as the test vehicle, dramatic improvement was gained by moving to wider pulse widths. Reduction in current density showed initial improvements, but below 20 asf, PTH roughness appeared, getting more severe as the current density was further decreased, as shown in Figure 1. The general roughness continued to degrade to "spiky" plating at lower current densities or when brightener concentrations drifted higher. Roughness would first be seen in the center of the small PTHs, but as the severity increased, the roughness would extend further up the barrel of the hole and begin to affect the larger hole sizes too.

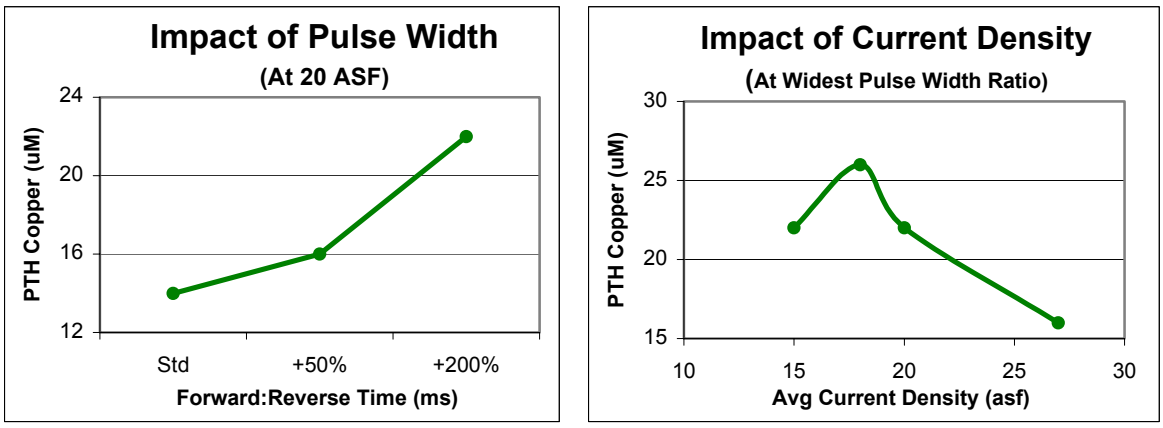

Figure 1 - Impact of Wider Pulse Widths and Reductions in Current Density

To continue exploring lower current densities, it was clear that a separate bath with lower brightener concentration would be required. The existing production process would be negatively impacted if the brightener concentration of the bath was significantly reduced. To complement these current density and brightener reductions, it seemed appropriate to adjust the copper and other bath constituents at the same time.

To minimize any "new bath" affect, the existing bath was cut in half, half for the new bath chemistry and half for the existing process. New bath parameters were somewhat arbitrarily selected, focusing on the brightener reduction as the most significant change. Just as in DC plating applications, when reducing operating current density significantly, it is best to reduce the copper concentration and brightener, while increasing the suppressor additive content.

Now, with the inorganic and organic bath constituents set for lower current density plating, the most aggressive pulse parameters were retested with the average current density cut in half, to 10 asf. Instantly, enhanced throwing power was observed. The results were so good that little additional optimization work was needed. The only additional adjustments required were to reduce the dwell time to minimize the amount of PTH over-plating that was occurring.

These same parameters have also been successfully tested on other high aspect ratio boards with varied sized mod-sites, with no other optimization work done, as indicated in Table 4.

Table 4 - Throwing Power for High Aspect Ratio Boards

Board Thickness	Drill Diameter	Aspect Ratio	Board Diff Factor	Throw *
147	10	14.7	2161	90%
174	12	14.5	2523	75%
250	16	15.6	3906	70%
365	26	14.0	5124	59%

* Throw was determined by dividing the average of the center PTH reading over the total average surface plating

This is not to say that these results are optimal either. Additional testing is still required to evaluate several individual and interactive variables. Required as well are boards or test vehicles that are sufficiently difficult to evaluate the parameters. Using boards that are 0.196" thick with the same 3.5" mod-site of 0.012" PTHs, the next round of tests will investigate:

- Larger current density ratios
- Forward:Reverse pulse width ratios less than 20:1
- Wider pulse widths
- Alternate pulse wave forms
- Alternate bath chemistry
- Combined variables

Reoptimization

Insights gained from the new bath with reducing current densities and widening the pulse widths merited revisiting the "high copper bath". The investigation of these variables in the old bath chemistry provided new capabilities and opportunities. Although reducing the current density did impact productivity, the resulting performance gains given in Table 5 were obvious.

Table 5 - Performance and Productivity Comparison Among Plating Processes
0.140" Thick Production Board with 0.014" Diameter Drilled PTHS (10:1 Aspect Ratio)

	DC Plating	"OLD" PRP	"NEW" PRP
Current Density	19 asf	27 asf	22 asf
Plating Time	115 minutes	75 minutes	87 minutes
Average Surface Cu Thickness	45 microns	40 microns	38 microns
Minimum PTH Cu Thickness	20 microns	22 microns	27 microns
Average Thermal Cycles	25 cycles	43 cycles	56 cycles

Conclusion

Periodic Reverse Pulse plating has evolved significantly over the last few years. Chemistry suppliers have continued to upgrade their additive systems, addressing previous deficiencies. Rectifier suppliers have, in addition to larger amperages, continued to grow the capability and options of their product offerings. The number of options or process combinations that present themselves to a copper plate today is nearly overwhelming! With so many things possible, it is hard to ever say that one is "fully" optimized. The good news is that although not "fully" optimized, one can still achieve significantly better results than what were previously available in DC plating.

Some of the most basic lessons learned about PRP in the last two years at EI would be:

- Clearly define the goals and product types being targeted
  - Highest Throw
  - Highest Productivity
  - Surface Finish
- Understand that significantly different product types or goals will require different bath configurations
- Lab bath or new bath results will not be attainable long-term in manufacturing
- Bath stability and performance is degraded with intermittent usage
- Don't under estimate the capability of the process

Part of learning is also realizing what you don't know. As previously stated, there are many tank design and process variables that have yet to have been altered or evaluated. Therefore, their relative importance or impact on results is still unknown. It is important to try and keep track of these base conditions so that if the process is re-deployed in another area, any differences are accounted for, even if their relative impact is unknown at the time.

Another significant unknown at this time is whether or not the process parameters deemed best from full panel plating will be useable in a pattern plate mode. The addition of microvias to a high aspect ratio has already been seen to disallow use of some of the more aggressive rectifier conditions. Pattern plating need only be treated as another board type and have new "optimal" parameters defined for it.

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