Beyond Periodic Pulse Reverse

Enrique Gutierrez, Jr., TecNu, Inc., Highlands Ranch, CO

Increasing demands are being placed on electrochemical plating processes, especially as related to the miniaturization trend of the electronics industry. Significant gains in electrochemical processes are now being realized from advances in non-DC power supply technology. The power supply plays a basic role in deposition rate, deposition distribution, crystal grain size, structure, surface morphology, and so forth. Recent advances have demonstrated increased capability while reducing cost and simplifying process complexity. This paper will discuss today's new power supply technology and capability, presenting benefits from advanced features, improved specifications, sequential wave and improved automation capabilities. Plating data on difficult geometries will be provided.

For more information, contact:
Enrique Gutierrez Jr.
TecNu, Inc.
66 W. Springer Dr., Suite 314
Highlands Ranch, CO 80129
303-471-0999
FAX 303-471-1104
enrique@tecnu.net

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1. INTRODUCTION

According to Michael Shernerof of Scientific American (Jan. 2002) technology has advanced more in the past one century than in the previous one hundred centuries. Yet it seems from a technical perspective that many of these advances yield distinct paths and isolationist positions, where each "technology island" meets only a part of our needs. Not until a technology is fully evolved, can we apply it to our entire spectrum of problems.

Some practical examples may help define "technology islands".

As the electronic typewriter evolved into a PC application such as MS Word, those who needed to utilize data adopted data base programs such as Excel, others who dealt primarily with presentations standardized on Power Point. Users were grouped or isolated into different applications based on their primary need. Yet each category of users did not have 100% of their needs met by their one primary application. Using two or three applications still limited them or at best reduced productivity. The evolution of this technology led to the Microsoft Office application allowing the seamless use of all three programs. This can be viewed as less choice; one program vs. three but yielding improved capability.

"The evolution of technology is not about increasing choices, but about it's ability to meet our spectrum of needs effectively".

Other examples include the DVD race. Currently there are 3 formats; one which is common and low cost, a second which is feature rich and a third which holds more data but is expensive. The evolution of this technology will be an affordable feature rich product that holds large amounts of video data.

Most of us have a home telephone number, a cellular telephone number, an e-mail address and some of us also have a personal pager number. Many choices, but not the most effective means of tracking a person down. This technology will eventually evolve to optimally meet our needs when a single personal identifier serves for all our voice and data communication, independent of our location.

Yet another technological advancement, which has led us into "technology islands" is the use of plating waveforms; Direct Current (DC), Periodic Pulse (PP) and Periodic Pulse Reverse (PR). Each provide unique capability but are exclusive and limit us to that specific benefit. This paper will deal with these waveforms and introduce a bridge between today's single waveform choice and tomorrow's evolved product, introducing a practical method (tool) for increasing quality, capability and profitability for electroplating advanced electronic parts.

How is it we evolved into "electroplating technology islands": DC, PP & PR? The short answer is that unique technologies evolve as a result of multiple companies independently advancing technology. The historic lack of cooperative effort between system integrators, chemical and power supply manufactures creates independent standards (plating methods), each driven by that individual company's desire and competency to generate revenue.

2. DC Power

Direct Current (DC) is the traditional and most widely used electroplating waveform. DC shown in figure 1, is characterized by a non-varying amplitude as a function of time.

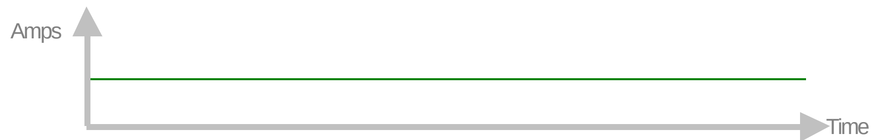


Fig. 1 *Direct Current Waveform (DC)*

DC power supplies and processes represent proven mature products that electroplaters and line operators are accustomed to using. Furthermore, most electroplating chemicals have been developed using DC.

DC represents minimal electrochemical control, the potential remains constant allowing chemical additives to control the process. Numerous limitations exist for DC, but as applicable to PWB's, wafers and other advanced electronic components, two are prevalent.

The first limitation is that while the output current density is constant, anode / cathode geometry and complex cathodic surfaces, force uneven current density across the cathodic surface forcing uneven material distribution. Figure 2 demonstrates high current density regions in the corners, leading to an uneven (dog-bone) deposit.

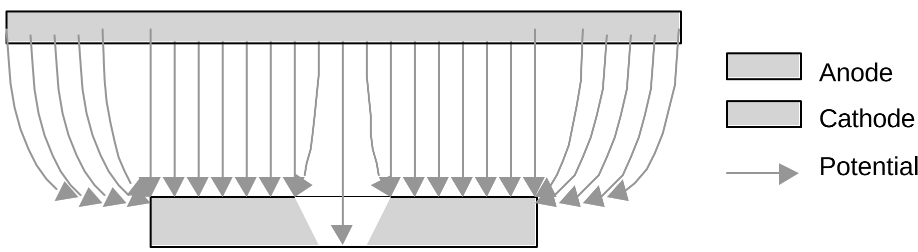


Fig. 2 *Uneven deposit is caused by anode / cathode geometry*

The second critical limitation, is that DC by virtue of it's constant potential creates a stationery diffusion layer at the cathode-solution interface. The theoretical diffusion layer is approximated at 75 microns. As a result features with openings near or below 150 micron (2X the diffusion layer thickness) become inaccessible to DC processes, without the use of complex chemical mediation. We can visualize this with the help of figure 3, it is reinforced by the fact that most successful Plated Through Holes plating (300-400 microns or 4-5 X the diffusion layer thickness) is done with pulse reverse[1], not DC.

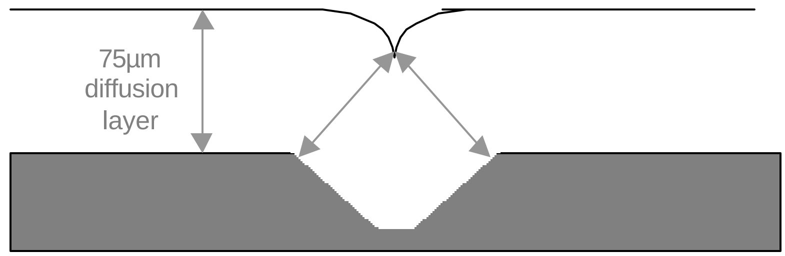


Fig. 3 *DC creates a stationary diffusion layer limiting accessibility to small features*

Today's technological advancement is marked by miniaturization, DC can help with many deposit properties but is limited in it's ability to process today's smaller features. It should be noted that DC has been successfully used to plate small features, but the plating rates are so low as to make this approach impractical. Table 1 summarizes DC benefits and disadvantages.

Table 1 DC Waveform

Pro's	Con's
Low cost equipment	Very slow plating to level small features
Considerable history and application material	Chemical cost & complexity increases with cathode surface complexity
Most chemicals developed with DC	Inability to access smaller features
Strong comfort level by operators	Inherently uneven deposition

3. PERIODIC PULSE POWER

Periodic Pulse (PP) has a long tradition in the electroplating of precious metals. PP shown in figure 4, is characterized by an interrupted current as a function of time.

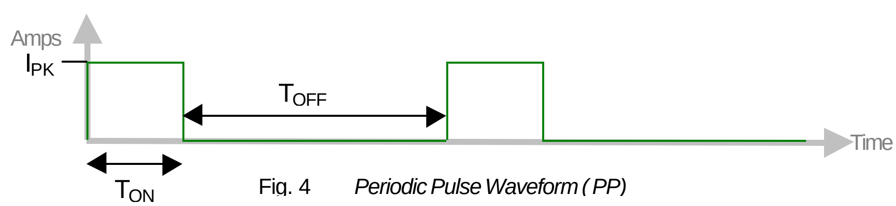


Fig. 4 *Periodic Pulse Waveform (PP)*

PP power supplies and processes represent a step up in complexity over DC. PP equipment has an increased number of adjustments over DC, but remains user friendly for electroplaters and line operators. It is important to note that because the PP waveform is uni-polar (positive only polarity), it has minimal negative interaction to most additives. PP can reduce the need for or dependency on such additives as grain refiners.

PP represents increased electrochemical control over DC. The changing potential created by T_{ON} and T_{OFF}, creates a second diffusion layer termed the *pulsating diffusion layer*, see figure 5.

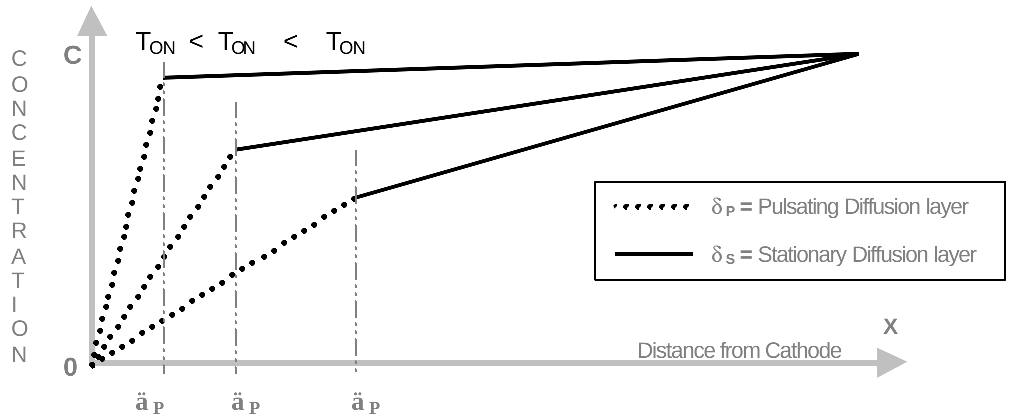


Fig. 5 *PP creates a 2nd "Pulsating Diffusion Layer"*

Common application of PP involves using the pulsating diffusion layer (not present in DC) to reduce grain size and increase nucleation sites. For PP waveforms it has been demonstrated that T_{ON} and I_{PK} are primary control parameters[2]. The T_{ON} is proportional to the pulsating diffusion layer thickness allowing for control over grain size. The nucleation sites are increased with increasing I_{PK}. The I_{PK} can be increased without exceeding the maximum DC current limit (plating rate limit), by reducing the duty cycle, where the duty cycle = $[T_{ON} / (T_{ON} + T_{OFF})]$. A low duty cycle pulse with increased peak current can decrease grain size and increase number of sites where crystals begin to grow to yield a flatter deposit, see figures 6 & 7. It is important to understand that increased output voltage may be required with increased I_{PK} in accordance to Ohm's law; V (volts) = I (amps) x R (ohms).

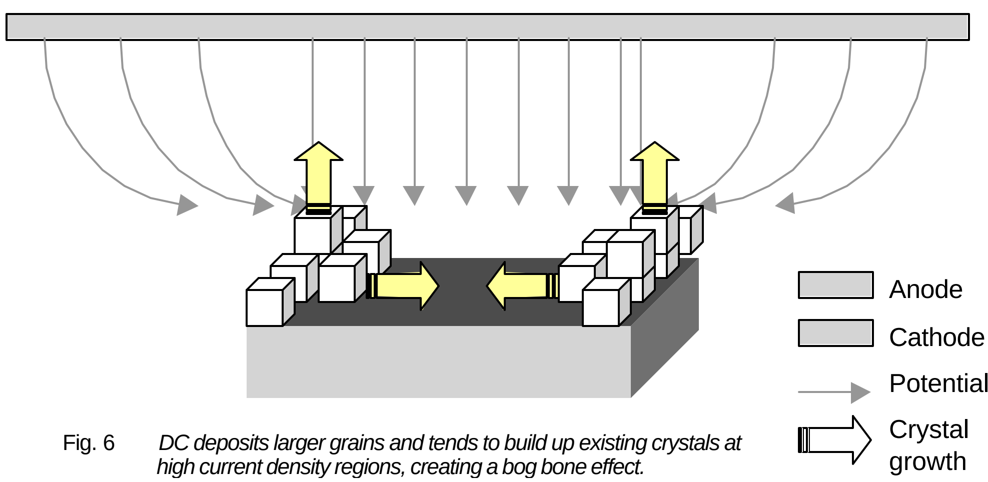


Fig. 6 *DC deposits larger grains and tends to build up existing crystals at high current density regions, creating a bog bone effect.*

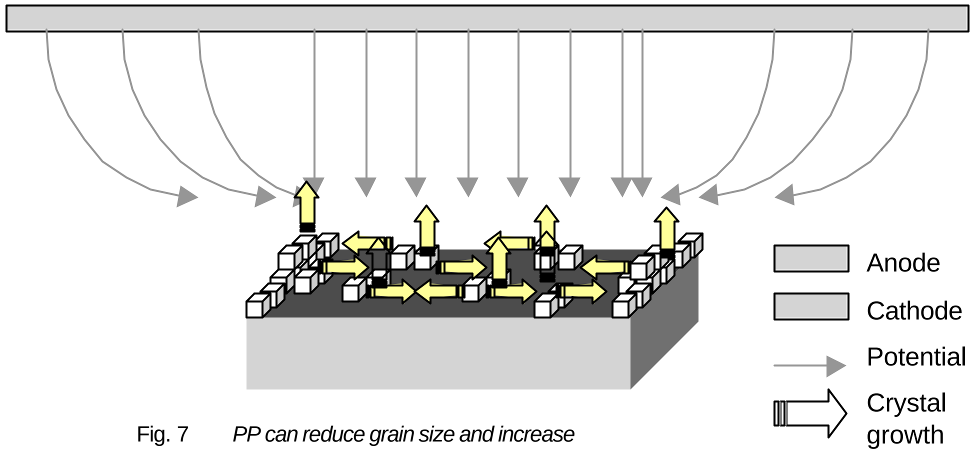


Fig. 7 *PP can reduce grain size and increase nucleation sites, yielding a flatter deposit.*

PP waveform parameters (T_{ON}, T_{OFF}, I_{PK}) are determined based on cathodic geometry, desired deposit characteristics, cell design, chemistry and additives.

The most prevalent limitations to PP is the inability to redistribute material along the cathodic surface. Although PP allows for the reduction of the diffusion layer thickness, some dog-boneing will inevitably occur. Over time small features such as PCB via's will become blocked before they can be properly filled. PP produces a flatter deposit over larger surfaces (as compared to the diffusion layer) but has limited throwing power into small features.

As with DC, PP can help with many surface properties but is limited in it's ability to process today's smaller PWB and wafer features. Table 2 summarizes PP benefits and disadvantages.

Table 2 PP Waveform

Pro's	Con's
Mid cost equipment	Increased complexity over DC
Application material available	Empirical data may be required to implement
Yields flat deposits & reduced grain size	Inability to access small features
Compatible with most DC chemicals	Produces an inherently matte finish

4. PERIODIC PULSE REVERSE POWER

Periodic Pulse Reverse (PR) is a relatively recent successful means of electroplating such difficult geometries as plated through holes (PTH). PR is characterized by a bipolar current as a function of time, shown in figure 8.

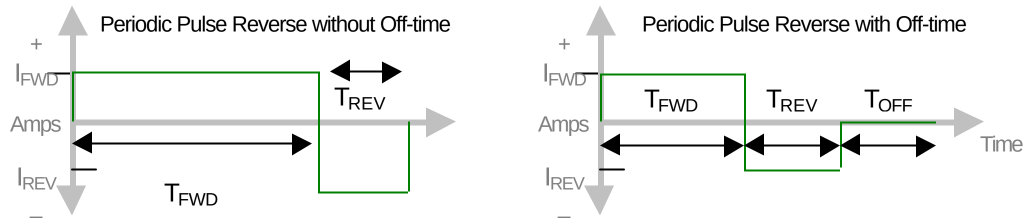


Fig. 8 Periodic Pulse Reverse *waveforms (PR) with and without off-time*

PR power supplies and processes represent a step up in complexity over PP plating. PR equipment has an increased number of adjustments over PP, and vary in level of user friendliness for electroplaters and line operators. It is important to note that because the waveform is bi-polar (positive & negative polarity), PR may be incompatible with certain additives. Some chemical vendors are now providing PR chemicals & additives.

PR represents increased electrochemical control over DC and PP. PR benefits include the ability to modulate the pulsating diffusion layer and redistribute material over a cathodic surface. The cathodic current (I_{FWD}) selectively deposits metal and the anodic current (I_{REV}) selectively removes metal, resulting in redistributing the deposit over the surface for proper leveling.

Common application of PR is to improved throwing power. The T_{FWD} & T_{REV} remain proportional to the pulsating diffusion layer thickness allowing for control over grain size. The nucleation sites continue to increase with increasing peak-amplitude. The forward / reverse polarities are used to redistribute metal over the cathodic surface, as shown in figure 9.

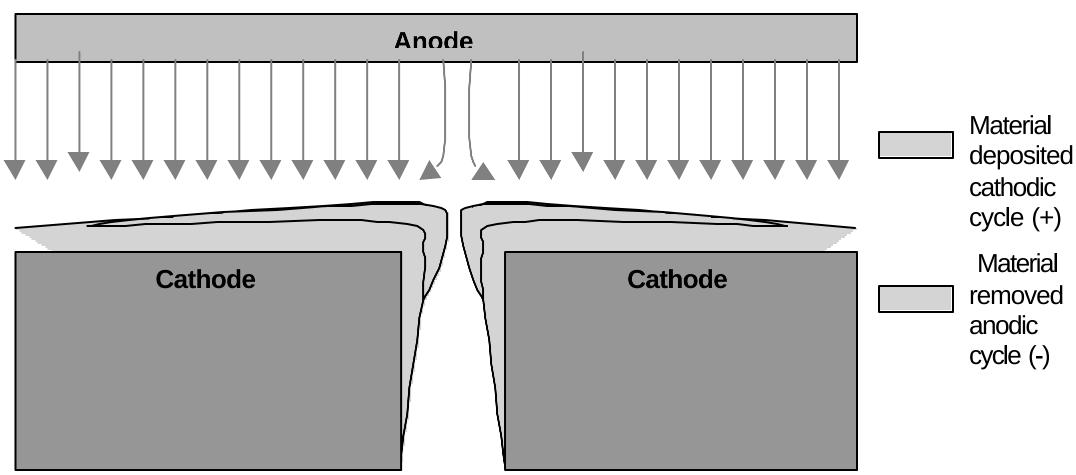


Fig. 9 *PR deposits during the forward cycle (+ cathodic) and removes material from high current density regions during the reverse cycle (- anodic).*

Pulse waveform parameters; T_{FWD}, T_{REV}, T_{OFF}, I_{FWD} & I_{REV}, are determined based on cathodic geometry, required throwing power, cell design and chemistry + additives. Prevalent PR limitations include; limited range of effectiveness and incompatibility with many common chemical additives.

The T_{FWD}, T_{REV}, T_{OFF}, I_{FWD} & I_{REV} settings demonstrated to properly level a 350ìM PTH will not properly level a blind 100 ìM via[3,4]. A specific set of waveform parameters, yield desired leveling for a given feature type +/- a limited range. As PR waveforms are periodic (continuous & repetitive), and can only address a single feature type or deposit requirement. This can be overcome by multiple baths and masking, but this approach is not practical as it reduces throughput, increases cost and opportunities for error.

Secondly, PR anodic current (I_{REV}) can interacts negatively with many common additives, such as brightners and levelers. These selectively attach themselves to high current density areas to inhibit growth, the I_{REV} then attempts to remove them. It's an electrochemical tug of war which complicates the plating process.

PR has excellent throwing power but is limited in it's ability to process multi-feature surfaces. Table 3 summarizes PR benefits and disadvantages.

Table 3 PR Waveform

Pro's	Con's
Excellent throwing power	Specific to a feature type +/- limited range)
Ability to selectively deposit metal	High cost equipment & increased complexity (including inductance)
Proven to work well on PTHs	Limited application information & considerable empirical analysis may be required
	Incompatible with many DC chemicals
	Inherently produces a matte finish

5. CHOOSING A WAVEFORM?

Understanding the general capability of each waveform; DC, PP and PR- the obvious question is, "Which waveform is right for my application?"

If we consider chemical additives important, the right choice may be DC.

If we consider flat deposit and small grains important, the right choice may be PP.

If we consider the ability to throw into small features and high aspect ratio holes important, the right choice may be PR.

We have a dilemma, similar to the WORD, EXCEL, POWER POINT scenario described in the introduction, these waveforms are inherently exclusive in the benefit they provide, see figure 10. Give serious thought to your PWB or wafer geometries, and it becomes clear that all three waveforms are required- i.e. MS OFFICE. If all three waveforms are not required, at least two of the three will be each time you plate, and we have no way to know which two therefore we need to count on all three.

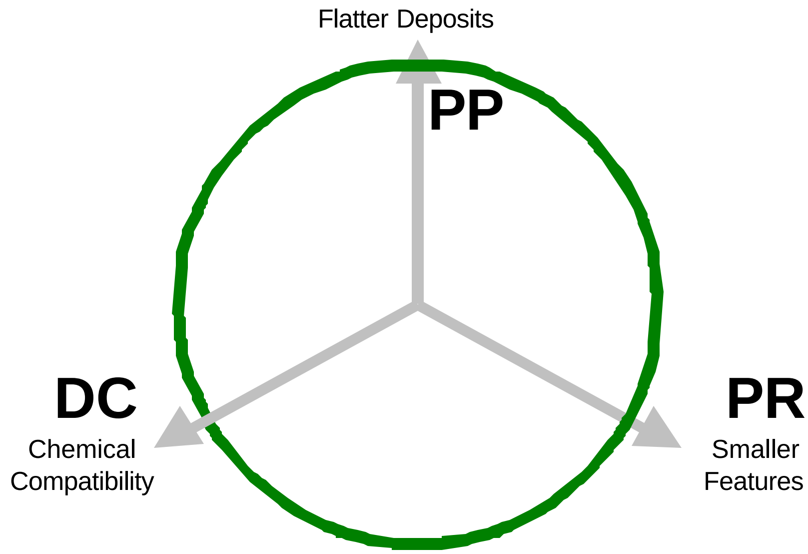


Fig. 10 *Individual waveforms provide a specific plating capability, today's electronic components require we combine all these capabilities for every job, shown in green circle.*

Technology, especially in the electronics arena, is advancing at an unprecedented pace. They continue not only to miniaturize but to increase in complexity by combining multiple feature types on a common surface.

As previously stated, waveform parameters yield optimal plating for a limited range surrounding a specific feature type. Periodic waveforms are therefore limited in their ability to properly level cathodic surfaces with widely varying features. Rehrig & Mandich suggest that "simple electronic manipulation of the pulse waveform" could be used to "tune" the electro-deposition process and replace chemical additives[7]. E.J. Taylor, J.J. Sun, M.E. Inman and L. Zhang have published numerous papers successfully achieving this result[3,4,5,6].

Which waveform? – In practice we cannot predict our next part geometry, therefore we need the ability to use any or all three waveforms for any given job. Additionally, in considering equipment needs, we need to go beyond the cathodic surface geometry and consider the manufacturing process, quality, cost and throughput.

Real world answers are rarely black and white. After a detailed review of numerous plating shops the list of requirements, looks something like this:

- DC for it's compatibility with chemical additives, such as brightners.
- PP for it's ability to provide flatter deposits over large surfaces.
- PR for throwing power and material redistribution ability.
- User friendly equipment for low skilled operators and to minimize scrap.

- Clear application data and the ability to break the process down into manageable size steps.
- Reliable equipment for reduced down time, critical in fast turn shops.
- Ability to plate at high current densities for increased throughput
- Reasonable equipment costs to justify investment.
- Advanced internal instrumentation to monitor quality metrics.
- Automation to reduce labor cost and operator error. Especially for shops that run 2 or 3 shifts, as key personal are not always available.

The above list may seem a bit overwhelming, perhaps even unrealistic. Common sense dictates that unless we purchase flexible systems, which meets or exceeds our needs, we will find ourselves re-investing in capitol equipment much sooner then anticipated.

The good news is, a few advanced technology equipment manufactures have products that comply with this list of requirements. These products are based on a Wave Sequencing approach, combining advanced power conversion electronics with embedded microprocessor control. Table 4 provides additional detail regarding these requirements.

Table 4 Equipment Requirements

MINIMAL REQUIREMENT	INCREASED TECHNICAL DETAIL
DC for compatibility with certain chemical additive such as brighters	Current control, low ripple DC, line & load regulation & increased operating range
PP for flatter deposits	Control of T_{ON}, T_{OFF} & I_{PK}
PR for throwing power	Control of T_{FWD}, T_{REV}, T_{OFF}, I_{FWD}, I_{FWD}
User friendly equipment for low skilled operators and to minimize scrap	Programmable by a friendly menu system including nonvolatile memory for storing job recipes
Clear application data & ability to break the process down into manageable steps	Wave Sequencing to combine individual waveforms and utilize available application data
Reliable equipment for reduced down time, critical in fast turn shops.	Small environmentally sealed enclosure to place near the tank reducing inductance
Ability to plate at high current densities	Ability to generate a wide variety of PR waveforms including non 1:1 forward to reverse ratios and .1 – 100ms pulse widths for anodic and cathodic pulses
Reasonable equipment costs	Pricing varies by supplier, but advanced technologies are more cost effective.
Advanced internal instrumentation to monitor quality metrics	Internal mirco-P and software provide advanced and accurate instrumentation
Advanced automation to reduce labor cost and decrease operator error	Bi-digital control interface & software compatible with PCs and PLCs

6. WAVE SEQUENCING™- BEYOND PULSE REVERSE

Wave Sequencing[8] (WS) is a device / process, capable of sequentially combining two or more waveforms as a function of time, into a single electrochemical process. Wave Sequencing goes beyond Periodic Pulse Reverse allowing the operator to generate multiple waveforms (DC, PP, PR) and combine these waveforms in a common process, see figure 11. This includes the ability to combine multiple PR waveforms to address multiple feature sizes on a common cathodic surface. The duration of each waveform is variable and their need be no relationship from one waveform and the next.

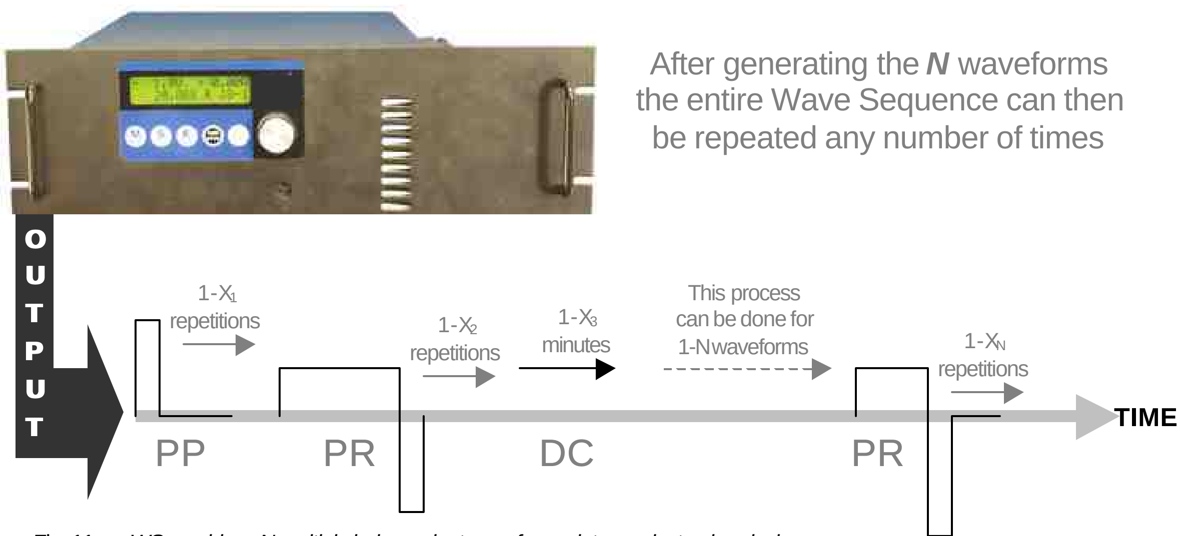


Fig. 11 *WS combines N multiple independent waveforms, into an electrochemical process*.

Wave Sequencing, the sequential combination of multiple waveforms effects the cathodic surface as a multi-step electrochemical process. Each waveform is selected or specified for a specific deposit characteristic or leveling capability by feature sizes. The WS net result, after completion of it's ***N*** individual process steps, is the desired surface deposit characteristics and proper leveling of the entire cathodic surface.

WS is a relatively new area of power conversion, developed to over come the limitations of today's electronics plating industry. It can be viewed as a bridge between the "*Plating Waveform Islands*" of today (DC, PP & PR) and tomorrows more advanced electrochemical process solutions. WS simply segments a plating job into a number of manageable steps. Each step can be programmed with the best waveform to achieve a partial deposit result. The sum of the partial results, or process steps, yields a finished part.

WS power supplies typically consist of an input stage, power stage, rectification, output stage, control system and user interface, illustrated in figure 12. WS Equipment has greater sophistication in the User Control section than DC, PP or PR units. This additional capability enables the unit to generate numerous waveforms and provides improved user ergonomics to reduce process errors.

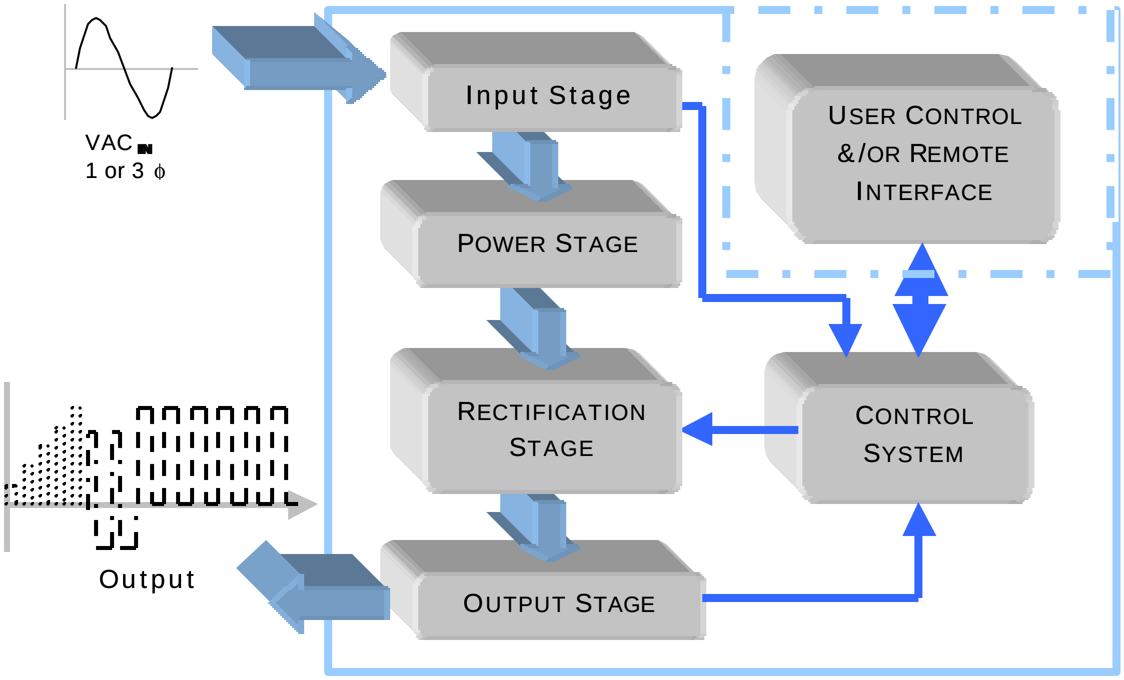


Fig. 12 *Block diagram of a basic WS Power Supply*

Critical in today's fast paced fabrication shops is it's simple equipment operation and advanced features. DVD players today are more powerful and simpler to operate then the early VCR's. This is due to the incorporation of On-Screen Menu Driven Control. Similarly WS equipment incorporate Menu Driven Controls and non-volatile memory to simplify data entry, store vital setting, reducing task duplication and insure user friendly operation.

Much of the user ergonomics is accomplished through the introduction of a *JOB LIBRARY*. The Job Library is a menu driven software tool within the unit that allows the operator to store and recall "job recipes". Data entry is done in multiple steps making programming very manageable. Menu Driven systems are used in storing/recalling numbers in cellular phones. Numerous other advanced features can be combined with the WS equipment to yield further process capability, these will be discussed in section 9.

Figure 13 is an example of the data entry of a four process-step wave sequence. Note that the defining waveform parameters, for each sequential waveform, are independent. This is critical in order to insure the ability to generate the exact waveform required to process a specific cathodic surface geometry. As an example, some WS systems require a forward to reverse ratio of 1:1, thereby severely limiting the waveform capability and compatibility to many chemistries. Other systems require a longer T_{FWD} than T_{REV}, limiting the ability to generate waveforms which process sub-diffusion layer thickness features like micro-vias and semiconductor trenches.

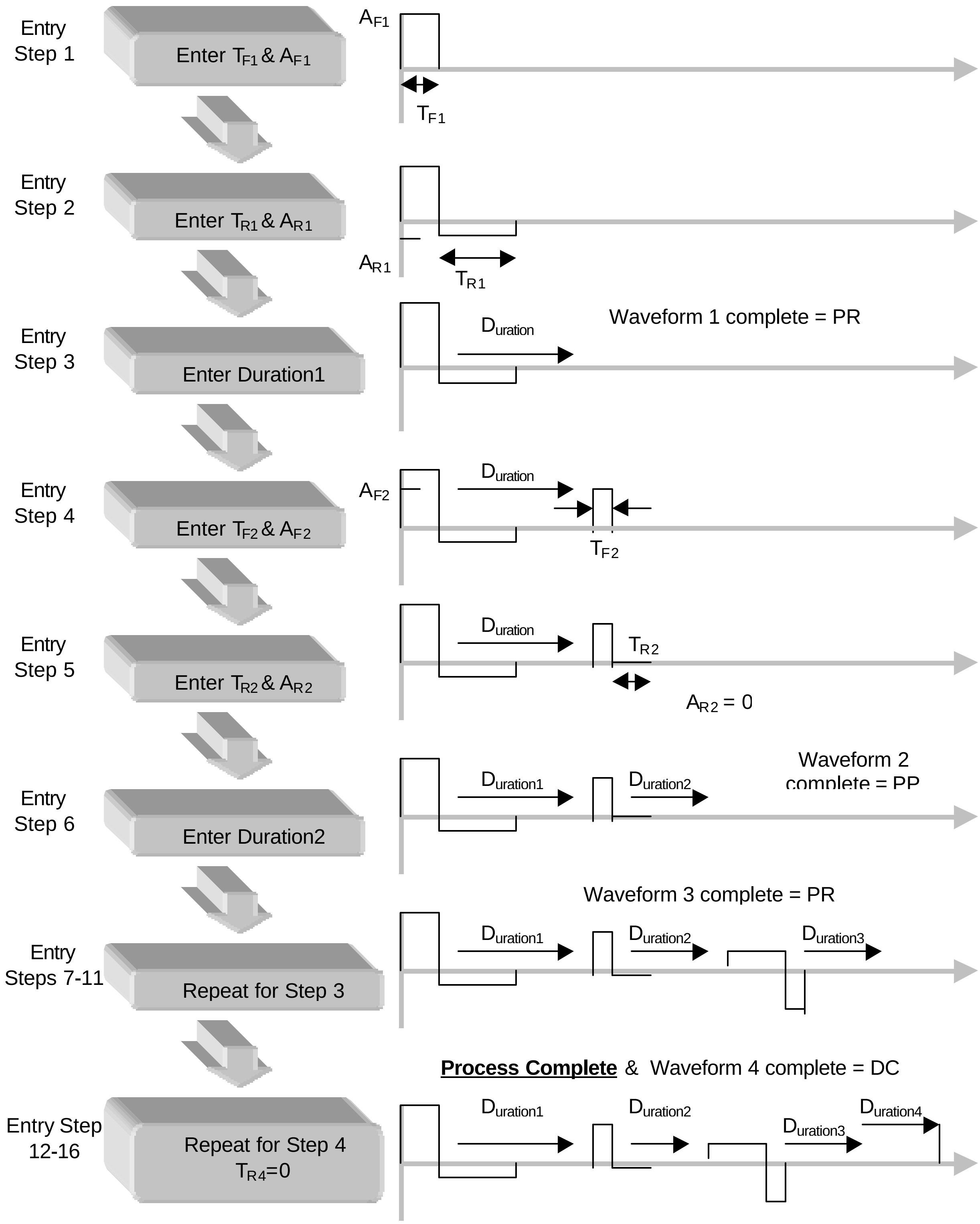


Fig. 13 Example of data entry for a four step Wave Sequence Electroplating Process

The benefit of Wave Sequencing over traditional periodic waveforms is it's ability to process geometries with multiple feature types. These complex geometries are basic to the electronics industry and describe a wide range of parts and processes.

One of the concepts basic to WS is accessibility. Accessibility to sub diffusion layer thickness features and to multiple feature types on a single surface. The prior governs the waveform parameters and the later governs the order or progression of the waveforms.

Waveforms for small features (require less material) must necessarily precede those of larger features (require large material). Reversing the order would cause the small features to be plated over and become inaccessible to remaining waveforms, as show in figure 14.

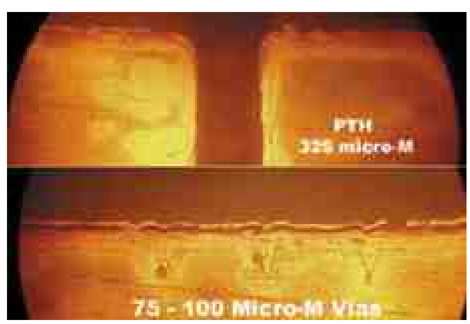
Case study examples may help further the understanding of WS technology.

Fig. 14 *Incorrect waveform parameters or the incorrect sequence of waveforms can block access to smaller features*

7. PCB CASE STUDY EXAMPLE

Cathodic Surface – Two sided PCB with PTHs & blind micro-vias

Fig. 15 *Two sided PCB with PTh and blind via features*



PCB feature details – 325 µM Plated Through Holes

75 –100 µM blind vias

Requirement – Leveling of surface including bright finish

Brief Feature Analysis –

Blind via - Smallest feature and therefore requires the least amount of material. This feature is well below the diffusion layer thickness and is inaccessible using traditional DC at production current densities.

PTH - Next smallest feature and material requirement. This feature is about 4X the diffusion layer thickness.

Traces - Require even deposit across the entire panel area.

Bright Finish - Customers appreciate the aesthetics a bright finish.

Waveforms Analysis –

Blind via - First waveform in sequence to access the smallest features before they are rendered inaccessible by the other waveforms.

Will require a short T_{FWD} of high I_{FWD} to reduce the diffusion layer thickness and to increase nucleation sites in this low current density region.

Will require a long T_{REV} low amplitude I_{REV} pulse to remove material in a "*DC like*" fashion

PTH - Second waveform in sequence to access the next smallest features before they are rendered inaccessible by the other waveforms.

Will require a long T_{FWD} of low to mid-amplitude as the feature openings are over four times the diffusion layer thickness and open on both sides.

Will require a short T_{REV} high amplitude I_{REV} to remove material in a from the opening to this feature.

Traces - Based on the traces and surface, a PP waveform will be required to uniformly coat the entire surface, especially if multiple panels are placed in the same bath.

Bright Finish - If additives are present a DC signal may be applied for a short time to over come the inherent matte finish associated with many pulse plating processes.

Duo Sided PCB – Typical PCB's have different trace patterns on each side requiring different current densities based on the surface area. This means two power supply outputs with independent amplitudes are required.

Additionally, in order to minimize negative interaction between the two power supply outputs in the common bath, both signals are required to be synchronized in time. Both will need to have the same waveform envelope (although amplitude may vary) and have similar polarity as a function of time.

Assumptions – Plating system is optimized for DC plating including; cell geometry, agitation, anode spacing and other critical factors that affect mass transport.

Wave Sequence –

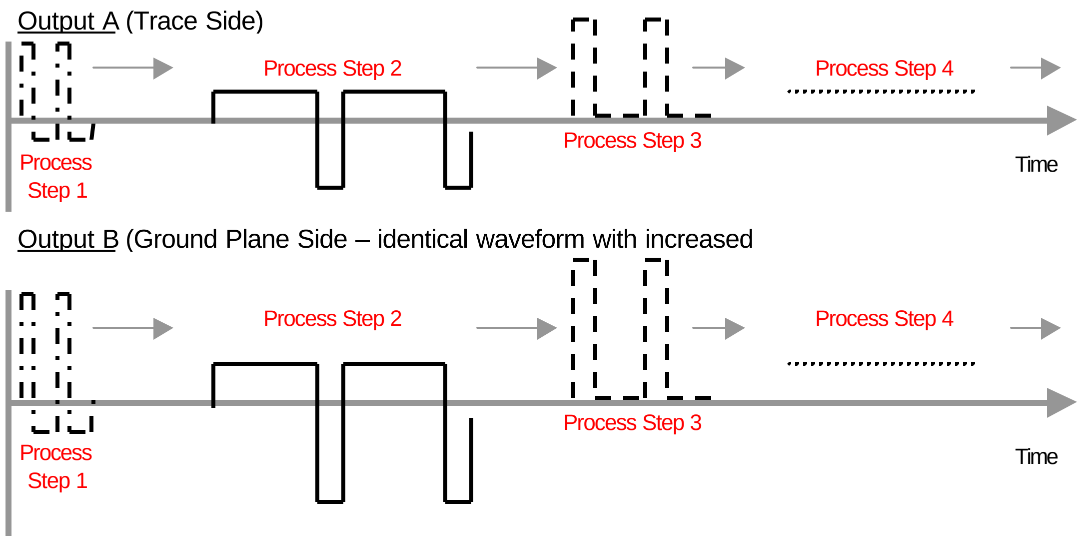


Fig. 16 *Duo synchronized WS output for a two sided PCB with PTH's and blind vias*

Process Step 1	*PR waveform levels blind vias*
Process Step 2	*PR waveform deposits into PTH*
Process Step 3	*PP waveform deposits over s urface*
Process Step 4	*DC helps achieve bright finish*

Results – Wave Sequencing has been demonstrated to properly plate multiple feature sizes in a common bath without the need for masking[3]. Further E.J Taylor and team have demonstrated successful implementation with out the need for chemical additives such as levelers or brightners.

8. WAFER CASE STUDY EXAMPLE

Cathodic Surface – Semiconductor wafer with 100 micron trenches

Fig. 17 *100 µM feature*

PCB feature details – 100 µM feature

Requirement – Leveling of surface with minimal over-plate

Brief Feature Analysis –

<u>Trench</u> - Smallest feature and therefore requires the least amount of material. This feature is well below the diffusion layer thickness and is inaccessible using traditional DC at production current densities.

<u>Surface</u> - Considerable process savings can be realized if the final surface requires minimal machining.

Waveforms Analysis –

<u>Seed layer</u> - First waveform should produce a thin conformal coat to help with heat dissipation enabling faster plating.

<u>Trench</u> - Second waveform in sequence to access the smallest features before they are rendered inaccessible by the other waveforms.

Will require a short I_{FWD} pulse of high amplitude to reduce the diffusion layer thickness for accessibility and to increase nucleation sites in this low current density region.

Will require a long low amplitude anodic pulse to remove material in a "*DC like*" fashion

<u>Overplate</u> - PR waveform which simultaneously deposits over the surface and levels the high current density regions.

Assumptions – Plating system is optimized for DC plating including; cell geometry, agitation, anode spacing and other critical factors. Including mass transport.

Wave Sequence –

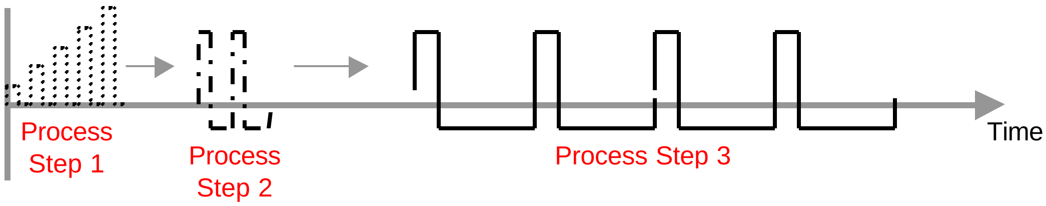


Fig. 18 *WS waveform*

Process Step 1	*PP waveform to cover seed layer*
Process Step 2	*PR waveform deposits into trench*
Process Step 3	*PP waveform to level the surface with minimal over-plate*

Results – Wave Sequencing has been demonstrated to properly level or conformably coat small features with minimal over-plate. Further E.J Taylor and team have demonstrated successful implementation with out the need for chemical additives such as levelers or brighteners.

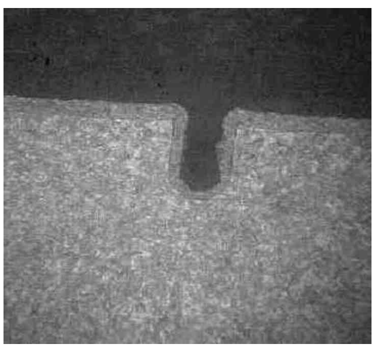


FIG. 19 *100 MICRON CONFORMAL*

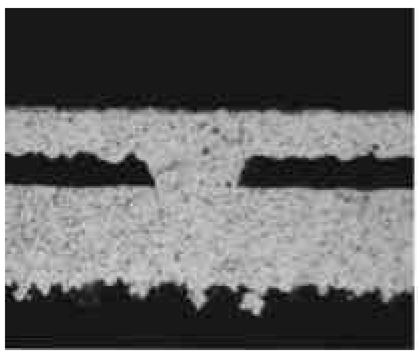


FIG. 20 *30 MICRON FILLED*

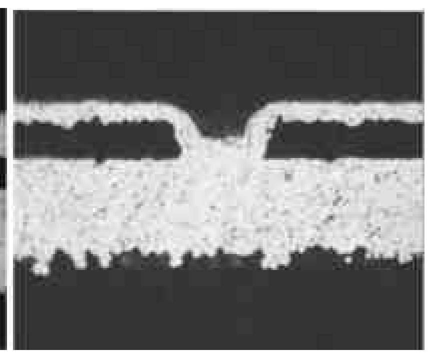


FIG. 21 *30 MICRON CONFORMAL*

9. ADDITIONAL CRITICAL NON-DC POWER SUPPLY REQRUIEMENTS

As mentioned previously the ability to properly level micron size features is not enough for today's fast paced ISO 9000 highly automated, cost and quality conscious manufacturing facilities. The following section will touch on a few other important WS Equipment characteristics and specifications.

Section 9 also provides limited details regarding non-DC power supply characteristics. Detailed technical explanations available from the authors past papers[9,10].

a. VARIABLE FORWARD TO REVERSE AMPLITUDE RATIO

Certain plating equipment which utilize multiple waveforms limit the forward and reverse amplitude to a common value, see figure 22.

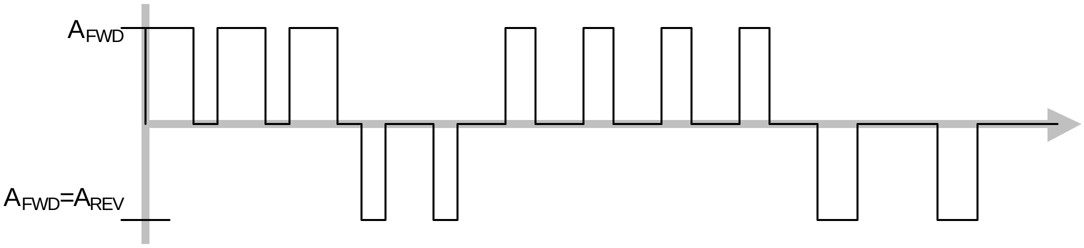


Fig. 22 *WS waveform limited to a 1:1 forward to reverse ratio*

A unit which forces a output current for forward and reverse seriously limits the pulse waveforms which can be generated. This creates various undesirable results. Chemical solutions react differently during forward and reverse currents requiring different forward and reverse amplitudes, common examples include the commonly used 1:3 (fwd:rev) amplitude waveform. Secondly, a fixed output amplitude slows the plating process by reducing the plating rate for low duty cycle waveforms.

b. LONG CATHODIC / SHORT ANODIC PULSE REVERSE CAPABILITY

It is very important that advanced plating equipment be able to generate not only pulse trains as demonstrated in figure 22 but also pulse reverse waveforms as shown in figure 23.

Pulse reverse waveforms can more effectively redistribute material over the cathodic surface and therefore improve throwing power. Most electrochemical power supplies are able to generate pulse reverse waveforms with long cathodic and short anodic times, as shown in Process Step 2 of figure 23. These are commonly used with low aspect ratio plated through holes.

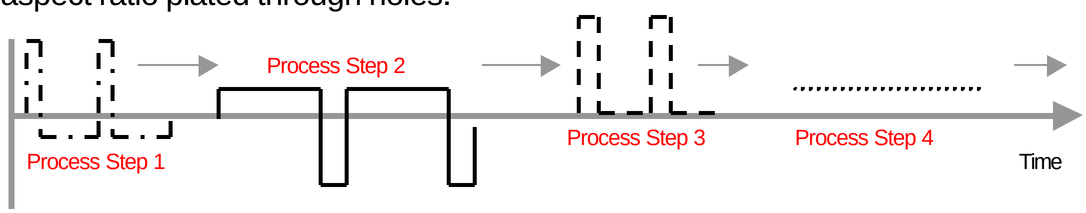


Fig. 23 *Pulse Reverse WS output*

c. LONG ANODIC / SHORT CATHODIC PULSE REVERSE CAPABILITY

Additionally your electrochemical power supplies should be capable of generating pulse reverse waveforms with long anodic and short cathodic times, as shown in Process Step 1 of figure 23. These waveforms have been demonstrated more effective with smaller features and higher aspect ratio plated through holes.[3,4,11]

d. FAST TRANSITION TIMES

Significant improvements have been made to improve waveforms transition times. Slow rise or fall times can significantly distort the wave shape. Numerous detrimental effects result from this distortion, including slower plating. Typical rise times for pulse power supplies range from 10 - 50 micro-second, enabling .1 millisecond pulses width.

e. MULTI-OUTPUT PULSE SYNCHRONIZATION

For two sided surfaces in a common bath, a power supply with multiple outputs or multiple power supplies may be required. Unlike DC power supplies, reversing polarity power supplies must be synchronized in time to minimize detrimental interaction between then.

Figure 22 helps visualize synchronized and un-synchronized outputs. Synchronized outputs means a common frequency, duty cycle and the pulse transitions occur simultaneously. Un-synchronized means that pulse transitions do not occur simultaneously. Note that the amplitudes of the various synchronized waveforms need not be the same. The problem with un-synchronized pulse outputs is that one power supply may have a positive polarity while the other has a negative causing the current to flow out of one power supply and into the other, adversely affecting the plating bath. This is analogous to having a second cathode and sharing the current between both. Negative interaction is minimized for synchronized power supplies.

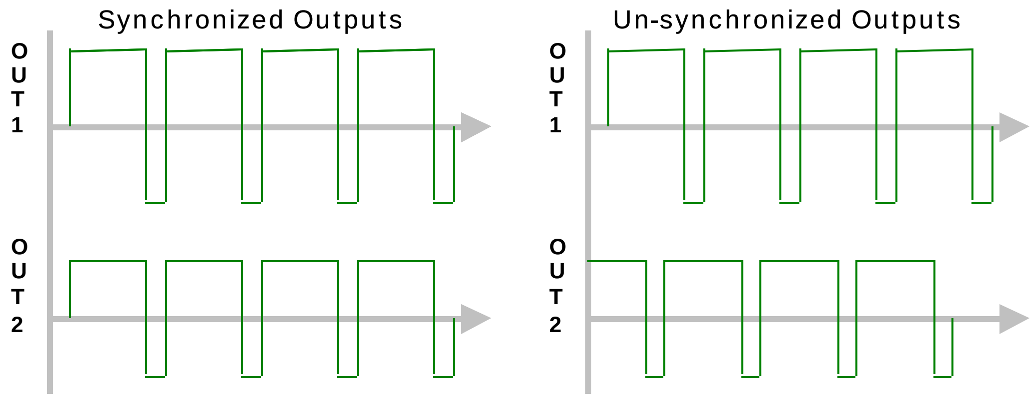


Fig 24 *The drawing on the left demonstrates synchronized and the right unsynchronized waveforms*

f. REDUCED CABLE INDUCTANCE

Inductance can be thought of as the magnetic resistance to the change in current in a conductor. Pulse waveforms by definition continually change current level with each pulse transition. Inductance therefore degrades pulse performance and is a critical factor in non-DC plating. Inductance degrades pulse performance by decreasing rise and fall times.

Plating power supply rise and fall times are typically rated at the output of the power supply and can be substantially different in the plating bath if no care is taken to reduce inductance.

In general the following guidelines should be followed to reduce inductance.

- Place the power supply as close to the tank as possible to reduce the cable or bus bar length.
- Use large diameter cables or large flat bus bars to increase surface area.
- Keep the distance between the conductors as short as possible. This is more feasible by using cables with thin insulation and twisting them together over the

length of the run from the power supply to the tank (twisted pair). For bus bars run them in parallel with minimal separation, as required for safe operation.
- Additional gains can be achieved by running multiple twisted pair cables dividing the current between them.

g. SMALL SIZE AND WEIGHT

Newer technology plating power supplies offer significant reduction in both the size and weight as compared to SCR or linear units. Higher frequency electronics result in a reduction in the size and weight of the power stage and related circuitry. As a result several advantages are realized:

- Smaller units are able to be placed near the plating tank, reducing inductance. If the unit cannot be placed near the tank, low inductance cabling cost can exceed the cost of the power supply.
- Smaller units require less floor space
- Lower weight units enable cost savings related to shipping freight.
- Lower weight units enable flexibility to move them from one location to another with out the requirement of a fork-lift for the purpose of routine maintenance, calibration, line changes and process modifications.

h. RELIABILITY AND PROPER ENVIRONMENTAL CONSTRUCTION

Power supply construction is critical to new technology power supplies. The primary reason is that industry standard components, printed circuit boards and assemblies are very susceptible to the corrosive environments found in most plating shops. This is especially true when companies take power supplies developed for the communications or medical industries and attempt to operate them in a plating environment. Unreliable power supplies mean production down time and loss of revenue.

The initial effort to compensate for the susceptibility to the corrosive environment, was to place the power supplies susceptible to the environment in sealed air conditioned environmental rack enclosures. This has several serious limitations;

- Racks force power supplies to be distanced from the tanks increasing cable inductance.
- Racks are very expensive.
- Racks are large and requiring additional floor space
- The rack seal is broken each time the enclosure door is opened to make adjustments or during routine maintenance.

WS power supplies should be housed in self contained, environmentally sealed enclosures. This enables the standard lower cost circuitry to function reliably in the plating environment. Additionally the units are able to be placed near the tank to reduce inductance and the operator access to the unit while standing next to plating tank.

i. Programmability and user ergonomics

The proper integration of microprocessor circuitry into a pulse plating power supply can simplify user operation, increase functionality, reduce errors and improve process efficiency and system integration.

An analogy would be the use of microprocessor circuitry in hand-held video camera operation. The complex and numerous controls have been replaced by soft key, menu driven controls and new features, such as titles, have been added with out overwhelming the user. Similarly WS power supplies with multiple adjustments can significantly benefit from the improved user ergonomics, microprocessor circuitry enables.

Along with the integration of microprocessor circuitry, new technology power supplies incorporate non-volatile memory in order to store vital information associated with power supply operation, communication, job recipes, waveform libraries and / or a number of other process and performance related benefits. Memory and programmability benefit plating shops to reduce errors, improve quality and increase efficiency, as well as reduced set-up time between jobs.

j. Advanced instrumentation and measurment

Internal microprocessors enables the software flexibility to create custom internal instrumentation. An example is an internal amp-hour meter for a WS power supply such that

Total A·H = {[Positive A·H]-K[Negative A·H]}* where K is a multiplier.

This enables the power supply to recognize that deposition and removal of metal from the cathodic surface does not necessarily occur at the same rate. In the case where the rate of deposition and removal are equal K may be set to 1. Considerable other instrumentation benefits are present in today's advanced WS power supplies

k. Digital control

Production facilities, driven by rising labor rates, a decreased labor pool, increasing competition and increased quality requirements by customers, are continually forced to find process and cost improvements.

The proper implementation of digital remote operation enables decreased process cost and increased process efficiency. Process parameters or "recipes" can be stored in a central controller and downloaded to each production location, critical factors such as chemistry, temperature, amp-hours, power supply status and system alarms can be monitored for quality control and to avoid time and material loss due to manufacturing or process error. Quality logs can also be made available for customers tracking each production lot.

10. Concluding remarks

Electroplating techniques and capability remains at an early stage of development. Today's periodic pulse reverse equipment and techniques represent at best, a limited initial approach. It is a good first step.

Wave Sequencing goes well beyond periodic pulse reverse, by sequentially combining appropriate waveforms to level real world electronic component surfaces. WS equipment also incorporates advanced microprocessor hardware and software to create advanced internal instrumentation and process integration capability.

Currently WS Equipment is the most viable and flexible means of properly leveling difficult to plate surfaces. WS is compatible with existing pulse plating recipes and can also generate low ripple DC for example. This makes WS a safe investment and not a technology fad.

Caution is recommend to insure any new equipment purchase, at a minimum, allows for:

- Variable forward to reverse amplitude ratio, not limited to 1:1
- Variable pulse width such that $T_{FWD} > T_{REV}$, $T_{FWD} < T_{REV}$ or $T_{FWD} = T_{REV}$
- Dual synchronization outputs for two sided surfaces
- Sealed & self contained unit enclosure to reduce inductance & floor space
- Simple user-friendly operation to reduce error and scrap

This author considers, WS equipment a bridge between the “waveform technology islands” of today, and tomorrows advanced electrochemical solutions leveraging both chemical and electrical signal mediation.

The future, independent of additive content will bring additional intelligent electrical signal control and increased computational capability to continue to improve metalization in the electronics industry.

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