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Site-Specific Measurement of Cathodic Pulse Shape and Plating Current Density for Optimization of Pulse Plating Lines

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Abstract
Two important aspects concerning optimum performance of a (reverse) pulse plating line are (i) the uniform and correct pulse shapes anywhere on the PCB and (ii) the uniformity of the plating current density (thickness distribution) over the whole plating window of a vertical line or the entire width of a PCB in a horizontal line. To measure both precisely, comfortably, and quickly the island method was enhanced to Optipulse 80. Special test boards with measurement islands and calibrated shunts on both sides are used to check site-specifically the cathodic plating current density as close as possible to production conditions. Sampling frequencies up to 20 kHz precisely resolve pulses as short as 0.5 ms. Up to 80 channels are sufficient to obtain a well resolved overview over the plating window of most vertical lines within less than ten minutes. Statistical data evaluation and visualization features make this a powerful tool for optimization of pulse plating lines (also applicable to DC plating, of course). The system now has been successfully in use for more than three years. This paper presents a short review of its history and the actual features as well as some examples from recent data.

Introduction
During the past two decades electronics has found its way from specialized applications into all spheres of everyday life. Miniaturization and falling prices have supported this rapid capture of the market. However, miniaturization at a progressive rate requires new production techniques such as (reverse) pulse plating, which was established as a major technique in recent years. Ever stricter quality requirements can only be met with optimally performing plating lines. One key point is the uniformity of Cu plating thickness over the whole plating window of a vertical plating line or over the entire width of a printed circuit board (PCB) in a horizontal plating line. In the case of pulse plating the pulse shapes have to be correct and equal at each location of the plating window.

Testing the uniformity of Cu plating thickness by means of plating dummy boards and measuring the Cu thickness with a probe such as eddy current, four-wire resistance, or x-ray fluorescence (XRF) is time-consuming and material-intensive and thus not favorable for optimizing a plating line. (Of course, these conventional methods of plating thickness measurement offer also some advantages.[1] As the current efficiency of acid Cu electrolytes is constantly close to 100 %, plating thickness is proportional to plating current density. Measuring the plating current and pulse-shapes at the cathode clamps with a clip-on ammeter gives a first idea about the situation and the performance of the line, but provides no insight into the detailed current density distribution on the panels themselves. A site-specific *in-situ* method for current density measurement on the cathodes is thus required.

Island Method
For this purpose the island method was developed and patented at Atotech in the late 80's.[2, 3] As this new site-specific method is based on the island method, the latter is outlined in the following paragraphs.

For the island method special test boards are used. As shown in Figure 1 PCB base material with clad foil on both sides is structured in a photo and develop-etch-strip process to generate five islands on each side (seven or nine islands are also possible). There ought to be no electrical contact between the clad foils on the front and on the rear side of the panel in order to monitor the plating conditions on both sides independently. Usually the test boards show no further pattern than the islands (full panel mode), but it is also possible to use them in a sort of pattern plating mode with structured dry film (Figure 5). Of course, the islands and their current paths to the cathode clamps may not be affected by the pattern. The detailed design of an island can be seen from Figure 2: an isolated circle of radius r is connected via a shunt of length l and width w with the unstructured surface of the test board; the thickness of the clad foil is t. Wires can be soldered to the lands at each end of the shunt.

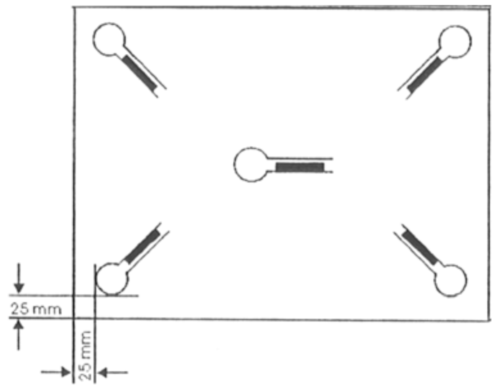


Figure 1 - Typical Design of a Test Board with Five Islands on Each Side (other layouts are also possible)
White means Copper Clad and Black is Base Material (copper etched away) - The Usual Panel Size is 18”×24”

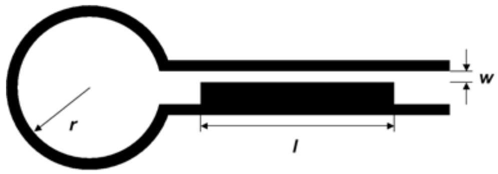


Figure 2 - Typical Design of an Island on the Test Boards
White means Copper Clad and Black is Base Material (copper etched away).

The shunt acts as a resistor R_s. Theoretically its resistance can be calculated as

$$R_s = \rho_{Cu} \cdot \frac{l}{w \cdot t} \qquad \text{Eq. (1)}$$

with ρ_{Cu} being the specific resistance of copper. The contact points of the soldered wires, the etched shape of the shunt, and the clad thickness are sources of uncertainty. For precise experiments it is better to measure the resistance of the shunt by means of the four point method. A constant calibration current I_c is applied across the shunt and the voltage drop U_c is measured using the soldered wires (Figure 3):

$$R_{s,c} = \frac{U_c}{I_c} \qquad \text{Eq.(2)}$$

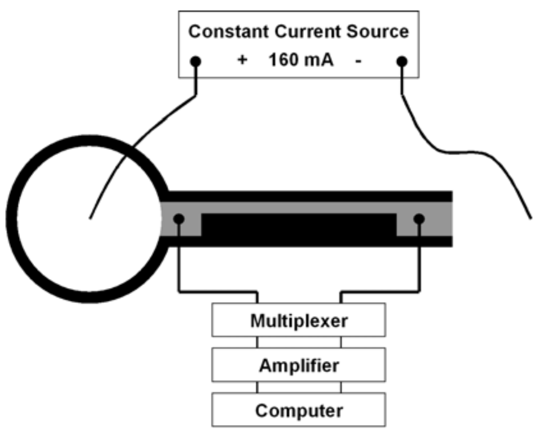


Figure 3 - Calibration of the Shunts
(Grey depicts protective lacquer)

Before starting the experiment in the plating line the shunts have to be covered with an electroplating stop-off lacquer in order to keep their resistance constant during measurement. Then the test boards are fixed at the flight bar of a vertical plating line. The wires from each island are lead to an amplifier and data logging unit. When the rectifiers are switched on, current flows from the anodes through the electrolyte to the test boards. Plating current I_p arriving on an island can only flow via its shunt to the cathode clamps. At the shunt a voltage drop proportional to the plating current occurs:

$$U_p = R_s \cdot I_p \qquad \text{Eq. (3)}$$

As the shunt was calibrated before the measurement, the absolute value of the current can be determined:

$$I_p = \frac{U_p}{R_{s,c}} \qquad \text{Eq. (4)}$$

Furthermore, the area *A* of the island is known by design, such that the plating current density on the island can be calculated as follows:

$$J_p = \frac{I_p}{A} = \frac{I_p}{\pi r^2} \qquad \text{Eq. (5)}$$

The dimensions of the shunt have to be chosen according to the normal plating current density of the line: (i) The current flow through the shunt may not alter its properties; the current density in the shunt, i.e. I_p / wt, should not exceed 600 A/cm^2. (ii) The resistance of the shunt, R_s, must be high enough to obtain voltage drops, U_p, of a few mV.

A first system was developed using the island method (Figure 4). It was designed for DC plating lines and could handle up to 90 islands, i.e. 9 test boards like those in Figure 1. Multiplexers switched each pair of islands (front / rear side) to a 2 channel plotter, which wrote the plating current as a function of time on a paper chart – effects from flight bar agitation or air injection could be checked. Furthermore, the signal was digitized and statistics on the data was calculated by a computer, e.g. average current density per island and for the whole flight bar, or the deviation of each island from the average.

When (reverse) pulse plating became common, another system was needed, which was capable of monitoring short pulses. For good resolution at least ten data points were required per pulse. In the late 90'sthe minimum pulse duration was 0.5 ms such that an amplifier and an A/D converter with a sampling frequency of up to 20 kHz were built. This unit featured two channels for one pair of islands. Data logging and evaluation was completely done by a software running on a laptop PC with Windows 2000 operating system (older versions are not able to handle the high data rates). Due to the high AC frequencies, twisted cables had to be used in order to exclude capacitive and inductive effects.

This previous system however, handled only one pair of islands and did not offer comfortable statistics for the flight bar. Thus, after proving its ability to measure pulses *in-situ*, site specifically, and precisely, the current system was enhanced in 2001 (Figure 5). Similar to our first system of the 1980s, a multiplexer with up to 80 channels is used to switch pairs of islands to the amplifier and A/D converter unit. The multiplexer is configured for either up to eight panels with five pairs of islands each, or for up to five panels with seven pairs of islands each, or for up to four panels with nine pairs of islands each. A laptop PC controls both units and runs the system software. The multiplexer includes a constant current source for calibrating the shunts. Wiring of the boards is done with pairs of twisted Cu wires, twisted together and contained in a larger cable with 20 or more leads, which ends in a common 25 pin sub-D plug for the five island version and in similar plugs with more pins for the seven or nine island versions.

Figure 4 - Island Method Controller from the Late 80's

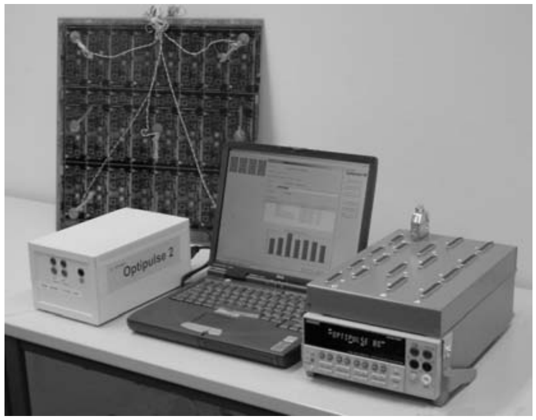


Figure 5 - 80 Channel Test Equipment Together with a Test Board
(special pattern plating version)

The system software organizes the measurements in projects. Usually one plating line optimization constitutes a project. The number of islands per board (five, seven, or nine) and the arrangement of the boards on the flight bar has to be entered, then the calibration of all shunts is done once for the project. Of course, re-calibration is always possible. Thereafter the boards can be placed in the plating line and the individual tests are performed. The usual test time per pair of island is 10 s at sampling frequencies of up to 20 kHz. Thus, one complete test run with all 80 channels takes about 7 minutes and produces roughly 125 MB of raw data. Directly after finishing the test run the computer evaluates the data and calculates the following statistical data:

(a) Average plating current density (time average) for each single island (in a table and as a bar graph, Figures 6 and 7).
(b) Average plating current density (spatial average from the time averages) for the front side and the rear side of the flight bar separately and together (in a table, Figure 7).
(c) Deviation of the average current density of each single island from the overall / front side / rear side average current density (in a table, Figure 7).
These tools help decide which action should be taken in order to optimize the plating current density distribution over the whole plating window. Optimization means that the numbers calculated with tool (c) have to be minimized, that no outliers are tolerated, and that the bar graph from tool (a) is smoothened. Tool (b) calculates also the standard deviation of the plating current density distribution.
(d) Three times the standard deviation (normalized to 25 µm expected plating thickness) are displayed in a bar graph showing the optimization progress as a function of test runs (Figure 8).
(e) As a fifth tool the time-dependence of the plating current density (raw data) can be displayed with zoom in and zoom out functions for each pair of islands individually (Figure 9). With this tool pulse shapes, pulse duration, ripple, low-frequency oscillations etc. can be checked. Furthermore, it is possible to export raw data as ASCII files for individual evaluation.
As the data is stored on the hard disk of the computer it can be re-evaluated at a later time. One set of test boards can be used for 40 or more test runs when the rectifiers are switched on for recording data only.

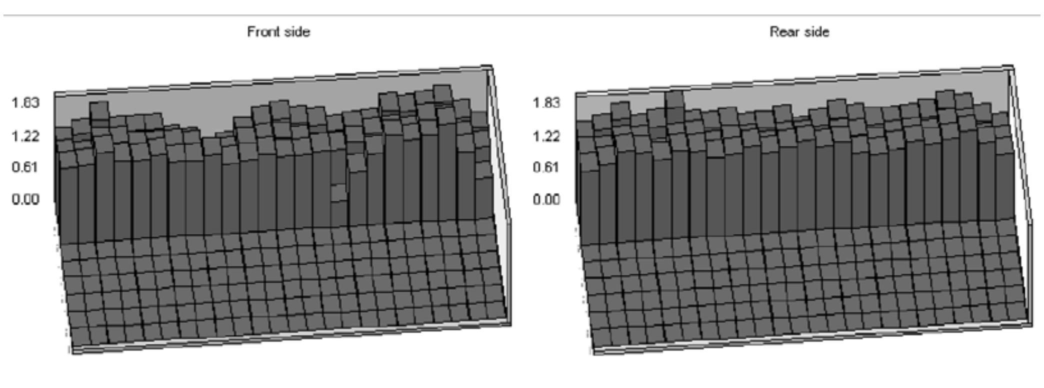
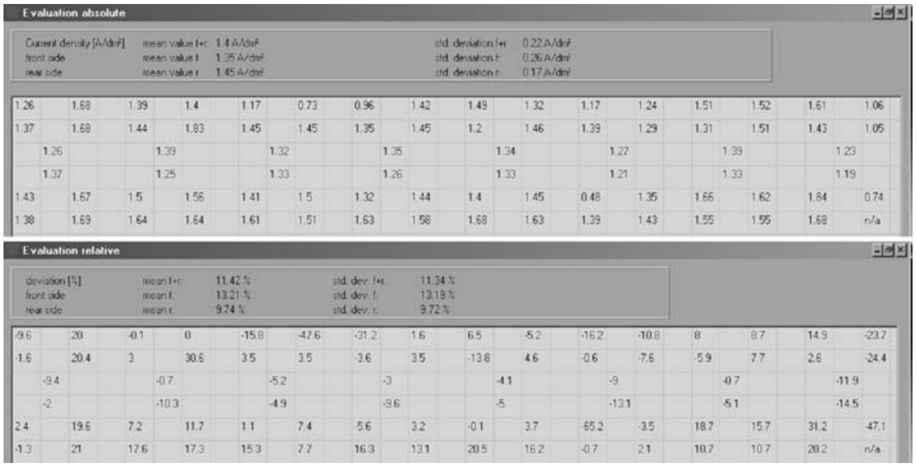


Figure 6 - Bar Graph of the Plating Current Densities Over the Flight Bar
(left panel: front side; right panel: rear side)
Nine Bars Corresponding to Nine Islands are Displayed. Missing Values in the Five and Seven Island Modes are interpolated. The data shown in this figure is from a test in five island mode.



Evaluation absolute

Current density [A/dm²] mean value f+r: 1.4 A/dm² std. deviation f+r: 0.22 A/dm²
front side mean value f: 1.35 A/dm² std. deviation f: 0.26 A/dm²
rear side mean value r: 1.45 A/dm² std. deviation r: 0.17 A/dm²

1.26		1.68		1.39		1.4		1.17		0.73		0.96		1.42		1.49		1.32		1.17		1.24		1.51		1.52		1.61		1.06	
1.37		1.68		1.44		1.83		1.45		1.45		1.35		1.45		1.2		1.46		1.39		1.29		1.31		1.51		1.43		1.05	
	1.26				1.39				1.32				1.35				1.34				1.27				1.39				1.23		
	1.37				1.25				1.33				1.26				1.33				1.21				1.33				1.19		
1.43		1.67		1.5		1.56		1.41		1.5		1.32		1.44		1.4		1.45		0.48		1.35		1.66		1.62		1.84		0.74	
1.38		1.69		1.64		1.64		1.61		1.51		1.63		1.58		1.68		1.63		1.39		1.43		1.55		1.55		1.68		n/a	

Evaluation relative

deviation [%] mean f+r: 11.42 % std. dev. f+r: 11.34 %
front side mean f: 13.21 % std. dev. f: 13.19 %
rear side mean r: 9.74 % std. dev. r: 9.72 %

-9.6		20		-0.1		0		-15.8		-47.6		-31.2		1.6		6.5		-5.2		-16.2		-10.8		8		8.7		14.9		-23.7	
-1.6		20.4		3		30.6		3.5		3.5		-3.6		3.5		-13.8		4.6		-0.6		-7.6		-5.9		7.7		2.6		-24.4	
	-9.4				-0.7				-5.2				-3				-4.1				-9				-0.7				-11.9		
	-2				-10.3				-4.9				-9.6				-5				-13.1				-5.1				-14.5		
2.4		19.6		7.2		11.7		1.1		7.4		-5.6		3.2		-0.1		3.7		-65.2		-3.5		18.7		15.7		31.2		-47.1	
-1.3		21		17.6		17.3		15.3		7.7		16.3		13.1		20.5		16.2		-0.7		2.1		10.7		10.7		20.2		n/a	

Figure 7 - Average Plating Current Densities
(upper table: absolute values, lower table: relative to the overall average) for Each Island
The position of the pairs of islands on the flight bar is indicated by the location in the table (here: five island mode). In each pair the upper number stands for the front side and the lower number for the rear side.

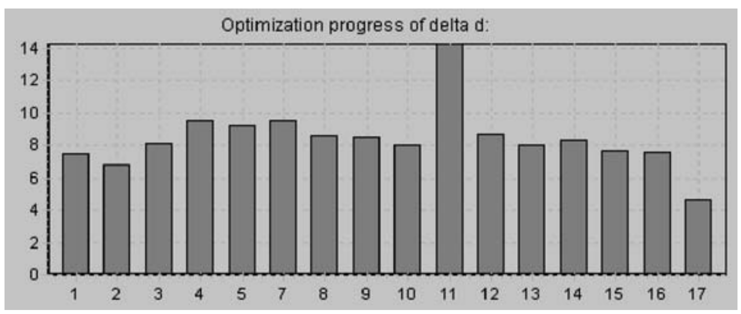


Figure 8 - Optimization Progress: the Bar Graph Shows Three Times the Standard Deviation of the Plating Current Distribution Over the Whole Flight Bar Normalized to 25 µm expected Plating Thickness

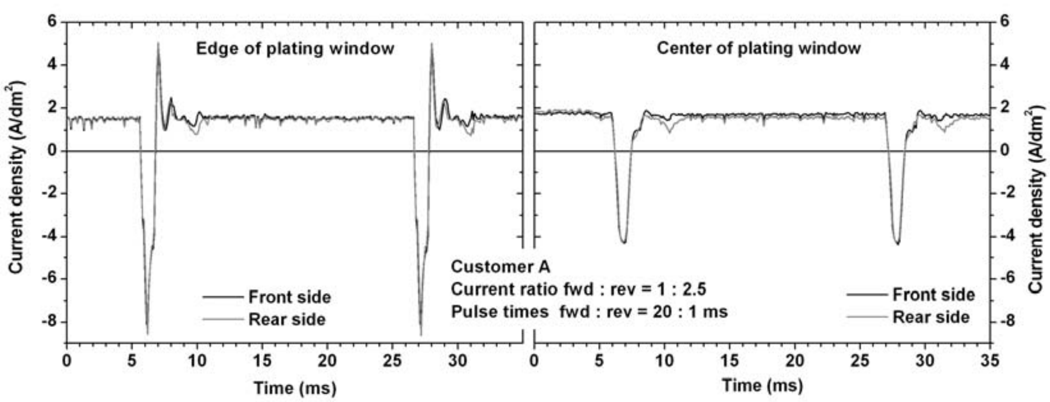


Figure 9 - Pulse Shapes Recorded in a Vertical Plating Line

Examples from Actual Production and Pilot Lines

The 80 channel system is in use worldwide to analyze and to optimize the performance of vertical pulse and DC plating lines at customers as well as in the technical centers. The software tools described in the previous section help interpret the data quickly and to decide the optimization steps to be taken. The result of each optimization step is immediately checked with further measurements, such that the optimization plan can be reviewed in real-time. In the remainder of this section, some interesting examples from the daily work with the current 80 channel system are presented. The presented data was recorded during service tasks at different customers as well as at a pilot line in our Berlin technical center.

At vertical pulse plating lines with a flight bar broad enough for six or more panels, it is frequently observed that the pulse shapes differ for different locations in the plating window. While the pulse shape is close to the theoretical shape on the central panels some “overshoots” can be observed at the outer panels (Figures 9-10).

Usually rectangular reverse pulses are desired. Sometimes the pulses experienced by the panel are indeed rectangular (Figure 10, upper panel), sometimes they show a considerable slope and appear triangular (Figure 9), sometimes long relaxation times can be observed (Figure 10, lower panel), and sometimes it takes some oscillations until the forward current is stabilized after the pulse (Figure 9). Furthermore, ripple can be low (Figure 10, lower panel), but also higher than expected (Figure 10, upper panel; Figure 11); and sometimes large differences between front and rear side of the board occur (Figure 11).

One of the latest trends in pulse plating is the use of complex pulse sequences. The 80 channel system is also able to check the correct settings for complex pulse sequences – a task which would be very difficult with an oscilloscope (Figure 12).

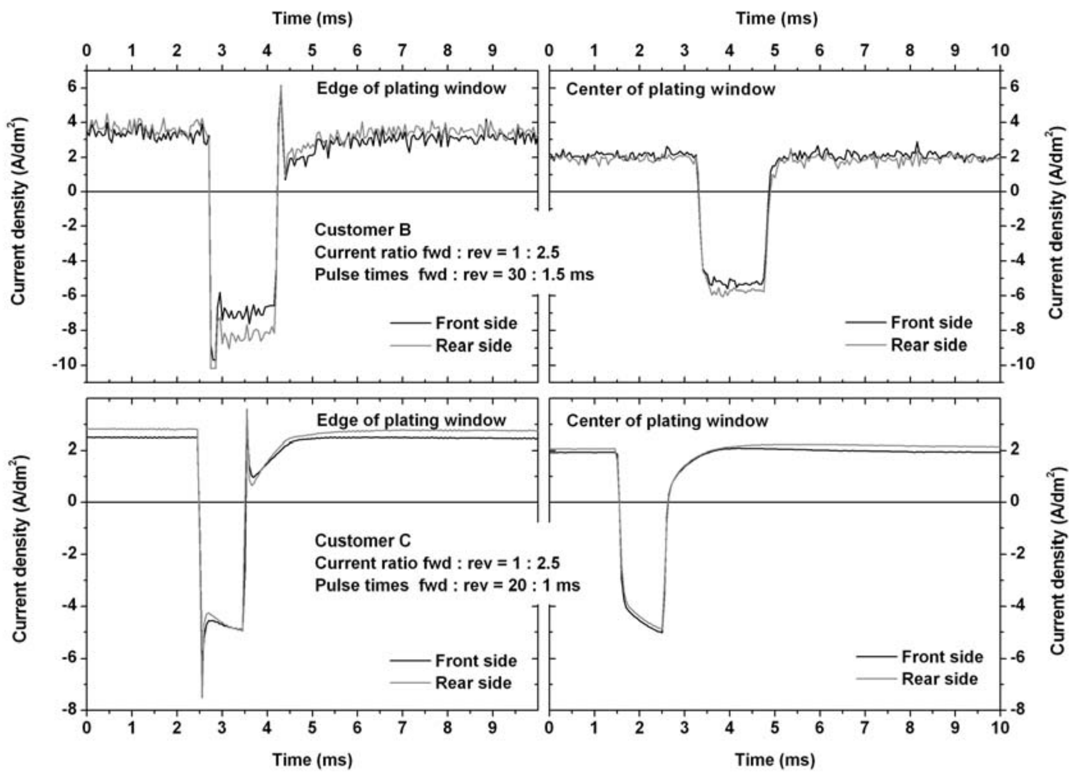


Figure 10 - Pulse Shapes Recorded in Vertical Plating Lines

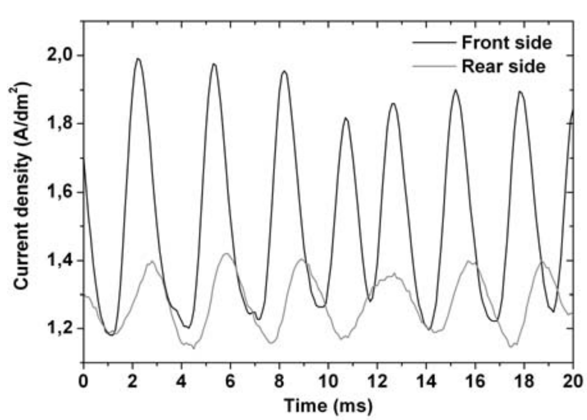


Figure 11 - Extraordinarily High Ripple Observed in a Vertical DC Plating Line (Customer D).

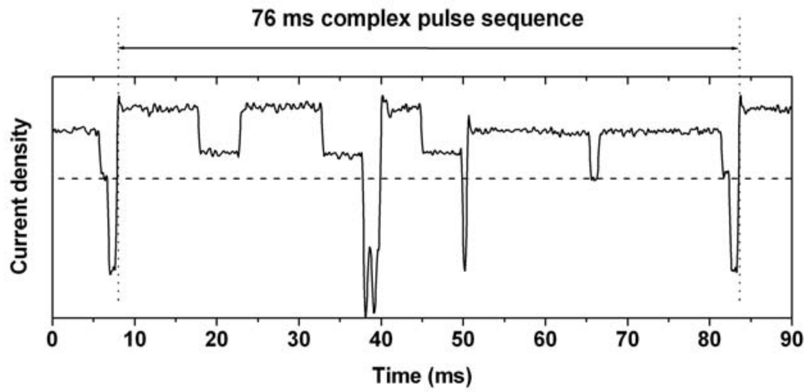


Figure 12 - Complex Pulse Sequence (from a Pilot Line)

Summary
With the combination of the island method and high data sampling frequencies, the 80 channel system is able to measure the cathodic plating current density *in-situ*, site specific, and time resolved. Full data logging and statistical evaluation offer tools for efficient optimization of plating lines – the effect of a corrective measure can be checked within only ten minutes. Pulse shapes and rectifier performance can be checked with high resolution. Test boards can be designed either for a general line optimization (full panel mode) or for specialized applications (with patterns); they can be configured for best sensitivity for a given maximum plating current density.

We have used the system successfully for more than three years and several pulse plating lines as well as some DC lines were analyzed and optimized. Its application is not limited to PCB production, the system was even used to optimize a plating line for sanitary parts. Influences of pulse shapes on crystal structure, throwing power etc. can be studied.

Acknowledgements
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