Practical Aspects for Subtractive Etching of High Density Interconnects

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Introduction

The fully subtractive etching process is still the most economical and fastest way to produce large numbers of printed circuit boards but it has its limitations. First and foremost is the fact that the etch process etches sideways as well as down at a ratio of an approximately 1 unit increase in the width of a space to every 3 or 4 units down, depending on the etchant and etching conditions. This means there is a limit to the thickness of the copper foil in relation to the widths of the lines and spaces for HDI. Presently the practical limits for lines and spaces are 75μm (3 mil) lines and spaces in 35μm (1 oz.) foil, 50μm (2 mil) lines and spaces in 18μm (1/2 oz.) foil and 25μm (1 mil) lines and spaces in 9μm (1/4 oz.) or 5μm (1/8 oz.) foil. So far the seemingly insatiable demand for smaller, lighter electronic devices with more and more capabilities built in have been met, in part, by decreasing the size of the lines and spaces on the interconnect boards and using thinner foils to accommodate the narrower lines and spaces. However, thinner foils also limit the amount of amperage that can go through those high density interconnects. In the past year or so we have begun to get requests to look at the feasibility for the near future of production based on 50μm lines and spaces in 35μm foil and 25μm lines and spaces in 18μm foil using 30μm (1.2 mil) dry film. This initiated some internal tests and it is the results of these tests, which include some insights on what the problems with HDI etching really are, some proposed solutions for these problems, and tests of the proposed solutions, that are presented here. The conclusion reached is that the proposed objectives are possible but attaining them, especially in a production environment, will be extremely difficult.

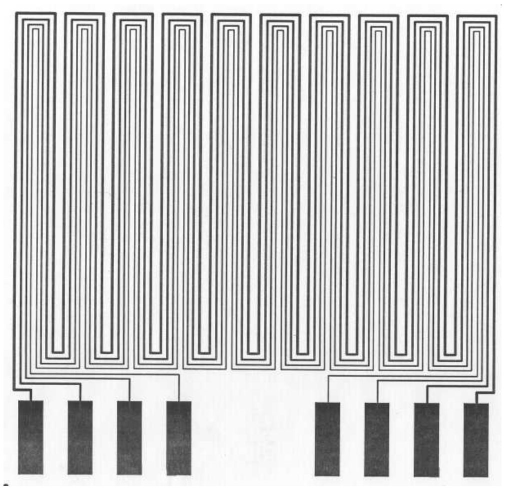
Preliminary Etch Tests and a Clearer Understanding of the Problems Involved

Since almost all of our testing in the last several years have been based on the practical limitations expressed above the obvious first step was to run some etch tests with 50μm lines and spaces in 35μm foil and 25μm lines and spaces in 18μm foil to see exactly what we were up against.

Test Patterns – For testing the 25μm lines and spaces a Conductor Analysis Technology (CATs) 1,1,1 multi-pitch test pattern was used. Figure 1 on the next page shows the layout of one of the test patterns. Each pattern is about one inch square (2.54 cm) and there are 352 of these patterns in a 22x16 grid on a 24" x 18" inch (601mm x 457mm) panel. The multi-pitch designation means there are four different line and space combinations within each test pattern. The 1,1,1 means this pattern starts with a 1 mil line and space on the innermost pad and line and space widths increase by one for each subsequent pad up to 4 mils. Therefore we have a 1 mil line, 1 mil space, 2 mil line, 2 mil space, etc. There is a 1.5 mil (37μm) space between the two 25 μm lines where they run side-by-side. For testing the 50μm lines and spaces on 35μm foil a CATs 2,2,1 multi-pitch pattern was used. This is essentially the same layout but starting with a 2 mil line and space increasing in steps of one mil to a 5 mil line. Where the 2 mil lines run side-by-side the space between them is 2.5 mils (63.5μm).

Foil Considerations – Reverse Treat Foil was used for these tests for two reasons. First, with the rough side profile facing up, it maximizes the surface area for the dry film to adhere to, an important consideration when the finished line width is likely to be only 12μm or less across the top of the line. Second, with the smooth side laminated to the fiberglass sub-strate there is less copper imbedded in the epoxy to remove and a slightly decreased etch time.

Figure 1 – CATs Test Pattern



Etchant Chemistry and Considerations – Cupric chloride is the first choice for etching copper because, with regeneration, it maintains a constant etch rate and generates the least amount of etchant to have to eventually dispose of. Ferric chloride gives a little less undercut and slightly better etch factors when used to etch copper but, when used with copper, it can't be regenerated so the cost of new etchant and the cost of disposal of the old etchant far outweighs the slight etch quality advantage. Undercut and etch factor have been a concern for many years and we have done extensive testing in the past on different chemistry parameters to minimize undercut and maximize etch factors (to be covered in a little more detail in the next section). The most important factors for cupric chloride etching are specific gravity and free acid content with higher specific gravities and lower free acid contents giving noticeably better results for both undercut and etch factors. The cupric chloride for the tests was run at a specific gravity of 1.330 (36^{o} Be) and a free acid level of 0.8N (29.2 gpl).

Preliminary Etch Test Results and Analysis – The test panels were cleaned and laminated with Dupont FX 930 dry film paying special attention to the lamination parameters to be sure that pressures, lamination roll temperatures and exit temperatures were all within the recommended ranges. The exposure unit was a Tamarack 161B and the major parameter here for HDI was a full one minute drawdown time on the vacuum to be sure of the most intimate contact possible between the photo tool emulsion side and the surface of the protective coating on the dry film. The panels were developed and checked to see that the narrowest spaces were cleaned out and then etched and stripped.

The results of the 50μm lines and spaces on 35μm copper were encouraging with over 80% yields for the 50μm lines in terms of opens and shorts. This is not great but certainly much higher than expected. The major problem was a very tight window for conveyor speed between over and under etching.

It was hoped that similar results could be obtained with the 25μm lines and spaces in the 18μm micron foil since everything was cut by half except for the thickness of the resist. Such was not the case, however, as the test patterns displayed a 100% failure rate due to opens when etched long enough to clean out the 25μm spaces so there were no shorts. The good news was that none of the opens were caused by resist adhesion failures even though the widths at the tops of the lines were as low as 8.2μm (0.33 mils). There were two places where there were always opens. The first were the isolated 25μm lines leading to the pads, which are easy enough to fix with some artwork compensation. The other place was where the 25μm lines took a 90° turn. This was a little puzzling until a little simple geometry was applied as shown in Figure 2 below. Where the 25μm space makes a right angle turn the hypotenuse of the right triangle formed is 35.8μm, giving the etchant a little more space to work in, resulting in a little faster etch rate at this point. By the time the 25μm spaces to either side are etched clean the line at the corner has etched through.

Figure 2

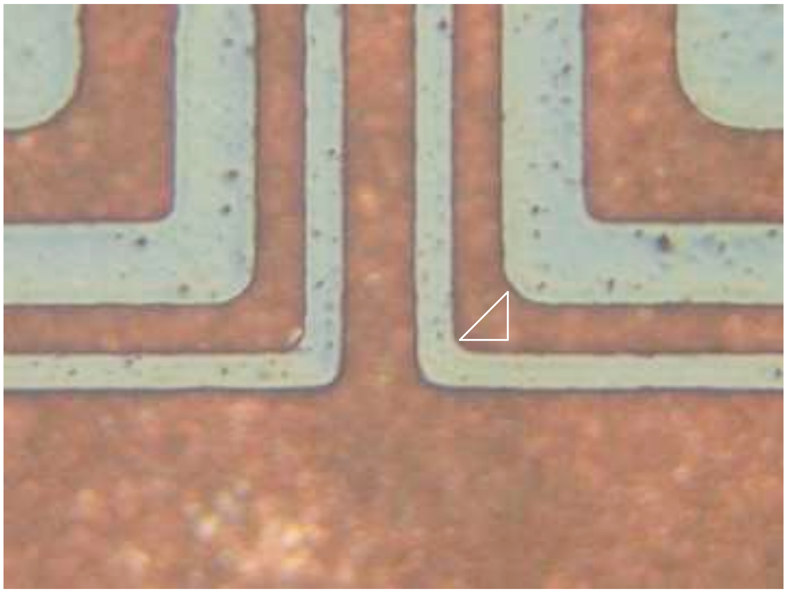
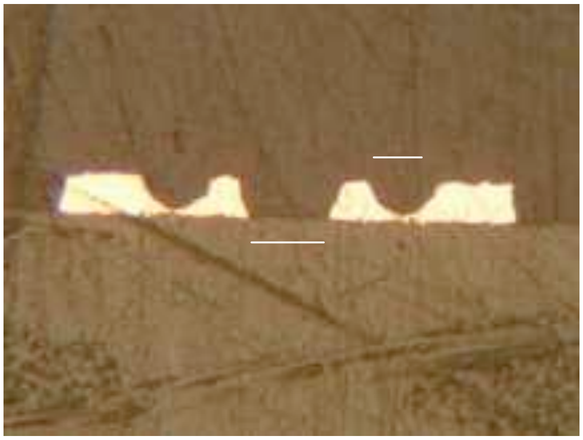


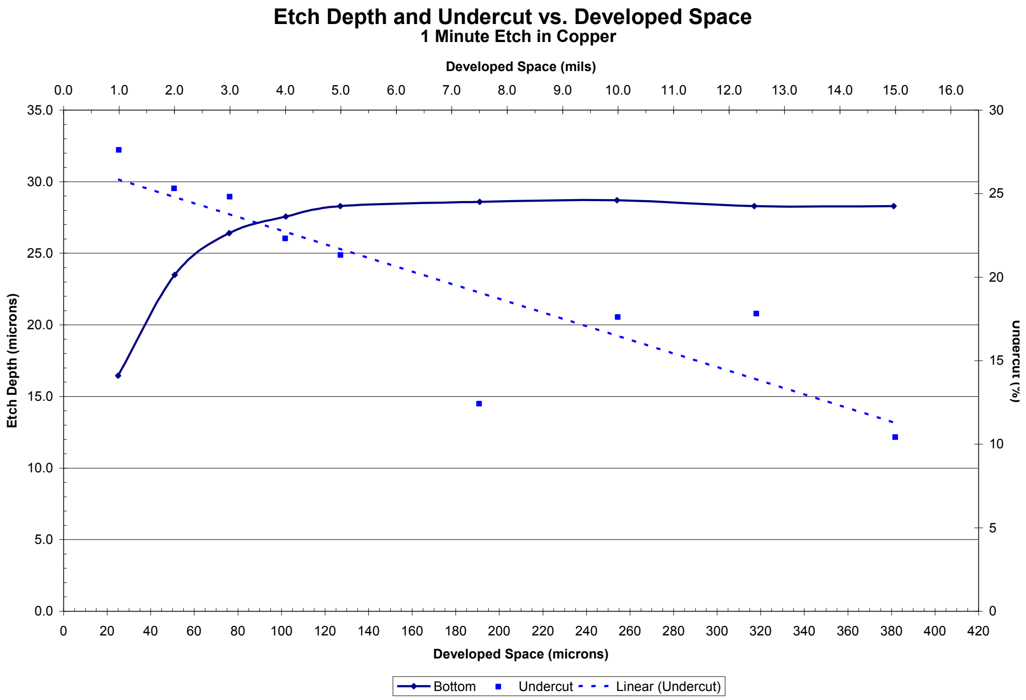
Figure 3 illustrates a little more clearly the difference in etch speed in a 36 to 37µm space as opposed to a 25µm space. This is a cross section showing the 37µm space between adjacent 25µm lines and the 25µm spaces between the adjacent 25µm and 50µm lines after etching. It is quite evident that the 37µm space is nicely cleaned out before the bottom of the 25µm space has even been reached.

Figure 3



Etch Rate and Etch Factor vs. Developed Space – Intellectually it is known that, as the space between lines decreases, the time needed to etch them out increases. It was clear after these initial etch tests that the rate of drop off in etch rate was much greater than we anticipated A simple test was devised to quantify the change in etch rate with decreasing spaces. A test pattern was prepared with 15, 12.5, 10, 7.5, 5, 4, 3, 2 and 1 mil spaces (381, 317, 254, 191, 127, 102, 76, 51 and 25µm). The patterns were etched for one-minute cupric chloride and cross-sectioned. Measurements were taken of etch depth and etched width across the top of the space. The etch rates were calculated as were the etch factor. In this case the etch factor is the ratio of the increase in width of one side of the space to the depth of etch expressed as a percentage. A higher percentage generally means more undercut (less undercut is more desirable). Figure 4 is a chart showing the results of these tests. The solid line and the left axis are the etch rates and the dashed line and right hand axis are the undercut percentages. These tests were done with a 15µm dry film.

Figure 4



As can be seen, the etch rates in the spaces remains constant until the space gets to 5 mils (125µm). There is a small decrease between 4 and 5 mils (100 and 125µm), a little more decrease between 3 and 4 mils (75 and 100µm) then a large drop off between 2 and 3 mils (50 and 75µm) and an even larger relative drop off between 1 and 2 mil (25 and 50µm) spaces. The fall off in etch rate between the 2 mil (50µm) spaces and 5 mil (125µm) spaces is 17% and the fall off between the 1 mil (25µm) spaces and 5 mil spaces is almost 42%. The difference in etch rates between the 2 mil and 1 mil spaces is almost 30% by itself.

It can also be seen that the etch factor percentage also increases as the spaces decrease. This is a little misleading, as the actual increase in the widths of the etched spaces remained fairly constant over the range of spaces in this test; the ratios went up because there was less etch depth in the same amount of time.

The best explanation, without getting into such things as fluid viscosity, grain boundary attacks and diffusion layers, for the above phenomena is probably the easiest one. As the depth to be penetrated by the etchant (resist thickness plus foil thickness) increases in relation to the width of the opening available for the etchant to get into, the difficulty of getting fresh etchant to the copper surface and spent etchant away from the copper surface increases and the slowdown in the exchange rate slows the rate of etch. In addition, the above chart shows that the slowdown in etch rate is not linear but exponential. It should also be noted that the fall off in etch rate will be sharper for a thicker resist than the 15μm dry film used in this test and a little shallower for a thinner resist but still substantial. At this point it is possible to get bogged down in all kinds of theoretical explanations and mathematical calculations. Since the title of the paper is Practical Aspects of HDI Etching it is time to back off and determine what we have learned from the above testing.

Conclusions after Preliminary Etch Tests

50μm lines and spaces can be done in 35μm foil though it is difficult. 25μm lines and spaces in 18 μm foil are almost, but not quite, possible at present. Further testing was done using 25μm lines and spaces in 18μm foil with 30μm dry film since anything learned here will also be applicable to other resist and space width combinations.

The etch rate slows down dramatically in the 25μm spaces to the point that any 25μm line that is bounded by a 37μm space or more will etch out before the 25μm spaces are fully cleaned out.

Some of the above problems can be resolved by careful artwork design but, from an equipment suppliers view, it would also be beneficial to find a way to increase downward etch without increasing sideways etch. In other words find a way to increase the etch factor.

Attempting to Improve Etch Factor and Reduce Undercut

Summary of Past Explorations – Etch factors and undercuts have been important considerations for both the printed circuit and photo chemical machining industries for many years. There have been many investigations into these areas in the past that have affected the approach taken here for HDI. Following is a brief summary of past tests and conclusions. (For those who would like more detail on the test methods and data used to reach these conclusions go to our website at www.chemcut.net, click on Technical Info and download "Thoughts on Undercut").

Nozzle Type – One of the first things that always comes up in any discussion on etch factors and undercut is whether fan nozzles or cone nozzles are better and the debate sometimes can get quite passionate. However, the data from extensive testing shows there is very little, if any, difference in the undercut characteristics of fan or cone nozzles.

Nozzle Flow Rate/Droplet Size – This is the second thing that comes up most often in the etch factor/ undercut improvement discussions. In the world of spray nozzles the droplet size is directly related to the flow rate so lower flow rate nozzles have smaller openings and thus smaller droplets. The thinking goes that if you have narrower opening to get the etchant into then a smaller droplet size will be better at penetrating into that opening. The truth is that even the lowest flow rate nozzles practical to use in a spray etcher still have droplet sizes in 400+μm range, still far larger than a 25μm space. In any case, the droplets do not impact directly on the space anyway. They impact on the static diffusion layer on the surface of the copper (yes, even on the bottom side). The ability to get fresh etchant to the copper surface is directly dependant on the force with which the droplet strikes this surface but a droplet with half the radius has eight time less mass than the larger droplet and the etch rate falls off. In the end you wind up with the same etch factor and a slower etch rate.

Nozzle Distance from Work – Moving the nozzles closer to the work means the force of the spray is increased thus improving the efficiency of the exchange of etchant in the narrow spaces. This is also the source of some of the fans versus cones controversy. Testing has shown that undercut performance does indeed improve for cone nozzles as they get closer to the surface but for fan nozzles the undercut improves as they get farther from the work surface. Thus, replacing fan nozzles with cone nozzles in equipment designed for fan nozzles showed a loss in undercut performance and vice versa. Also, moving the nozzles closer to the work means more nozzles are needed for complete coverage, meaning more solution on the surface, which in turn negates some of the advantage of the increased force. In short, there was a small improvement in undercut performance but nothing to get excited about.

Spray Pressure – Testing showed very little improvement in undercut with increasing spray pressure from 20 to 80 psi (1.4 to 5.4 bar). The increase in fluid flow negates the benefits of the higher droplet velocity.

Etchant Temperature – No significant difference in undercut performance was found from 100° to 160° F (38° to 71° C).

Cupric Chloride Specific Gravity and Free Acid Level – As noted in the beginning of this paper specific gravity and free acid levels were the only things that lead to noticeable improvements in undercut performance. It should be noted that the improvements were incremental and not drastic but at least measurable. Higher specific gravities drastically reduced etch rates without improving undercuts while lower acid levels actually led to undercut performance getting worse.

Revisiting Some of the Above Parameters

The data for the above tests was gathered during tests for a company making lead frames which were etched through from both sides in 150μm (6 mil) copper with fairly large developed openings in the resist. Also, this was rolled, annealed copper, which has slightly different etch characteristics than electroplated copper. It was felt that in the case of 25μm spaces in electroplated 18μm foil it might be worthwhile to retest some of the above parameters. So the effects of nozzle type (this debate never really ends, no matter what the data says), etch temperature and spray pressure were revisited.

These tests were basically a repeat of the tests done to determine the etch rates for the various widths of developed spaces. A one minute etch followed by cross sectioning and measurements of etch depth and final etched width across the top. Tests were conducted from the bottom side to avoid complications introduced by topside etchant puddling. The tables below show the results for each test.

Figure 5 - Comparison of Cone and Fan Nozzles

Developed Line Width	Etch Depth		Etched Width		Etch Factor	
	Cones	Fans	Cones	Fans	Cones	Fans
25μm	20.8μm	16.1μm	33.3μm	31.7μm	20%	20.8%

The fan nozzles etched a little slower than the cone nozzles under equal conditions but the etch factors were virtually identical, confirming that nozzle type has little to do with final undercut.

Figure 6

Etch Factor Comparison for Etchant Temperatures of 38° C and 54° C

	54° C (130° F)	38° C (100° F)
Etch Time	1.2 min.	2.0 min.
Etch Depth	25.8µm	25.4µm
Final Etched Width	41.4µm	40.9µm
Etch Factor	30.9%	30.5%

As expected the etch rate was slower for the lower temperature but the etch factors were the same in the end. The equipment used in this test was made of PVC so the maximum temperature allowed was 54° C. However, there is nothing in past testing that suggests that any higher etch temperatures would change anything other than etch rate.

Figure 7

Etch Factor Comparison for 25µm Space at Different Spray Pressures

Spray Pressure	Etch Time	Etch Depth	Etched Width	Etch Factor
10 psi (0.7 bar)	2.10 min.	20.6µm	40.0µm	35.4%
20 psi (1.4 bar)	1.60 min.	24.8µm	40.2µm	29.8%
30 psi (2.0 bar)	1.40 min.	26.3µm	39.5µm	26.8%
40 psi (2.7 bar)	1.20 min.	27.4µm	40.5µm	27.6%
50 psi (3.4 bar)	1.10 min.	28.2µm	41.0µm	27.7%
60 psi (4.1 bar)	1.05 min.	30.4µm	41.8µm	27.0%

This also confirms results obtained in earlier testing. Once the spray pressure gets above 20 psi the etch factors remain constant, the only change being etch rate.

At this point we have only confirmed that the test results obtained in the early 1990's when working to reduce undercut in high pin count lead frames. There were many other equipment and chemistry parameters tested than those covered here but those that showed improvement in etch factor (optimum placement of spray nozzles, reduction in topside etchant puddling) were incremental improvements rather than huge revelations and most of those have already been designed into the new generation of equipment beginning in the early 2000's. Unfortunately, some of the most obvious things that one might think of to improve etch factor (different nozzles, smaller droplet sizes, higher spray pressures) have been confirmed as ineffective.

One complicating factor in all these tests was that, no matter what changes we made, the spray was not impinging directly on the copper surface. On the topside there is always an etchant puddle that the spray impacts upon while on the bottom side the spray has to deal with the conveyor rods and wheels which scatters and reduces the velocity of the droplets. The bottom side situation is made even worse by the fact that most HDI is done on thin or flexible substrates, which require more wheels than normal for support. This complicating factor might have disguised any improvements in etch factor that may have occurred in the previous tests. A quick screening test was set up where the conveyor rods containing any wheels that masked the lower spray nozzles were removed giving the nozzles a clear shot at the copper surface without an etchant puddle or masking objects. Tests were run with cone and fan nozzles at several different spray pressures. The results reconfirmed that there is no inherent advantage of one type of nozzle over the other and different pressures changed the etch rate in the fine spaces (as well as that in all the other spaces) but had little, if any, effect on etch factor. Changing the etch speed without changing the etch factor just produces bad test patterns faster. Unfortunately, all the other tests that dealt with equipment modifications to improve etch factor produced the same results, the etch speed could be changed but the etch factor remained the same.

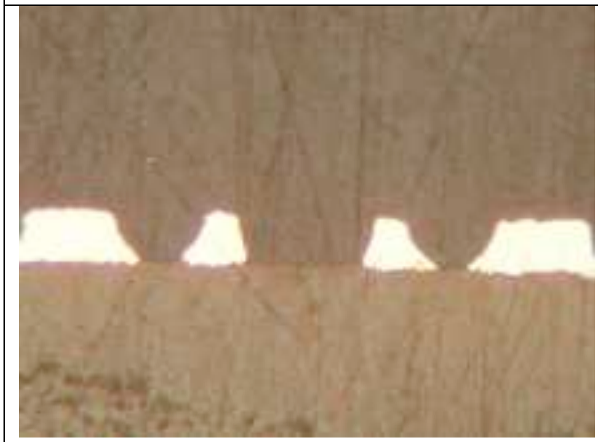
Quite frankly, at this point there is very little that can be done to the equipment design that is going to improve undercut without some radical redesign to test some other concepts, but even this is no guarantee of success. So, is there anything else that might be done to improve the situation? An old saw from the days when HDI meant going from 200μm lines and spaces to 100μm lines and spaces says "Under expose and over develop for fine lines". The question is whether there was and still is any truth to this bit of sage's wisdom especially considering the considerable improvements in dry film since those years. A screening test was set up to see if this concept was worth following through.

Dry Film Exposure Tests – The recommended exposure for the dry film used in these tests was step 6 to step 8 on a 21 step density tablet. On the 5000 watt exposure unit used this translated to a 4.9 second exposure time for a step 6 and a 5.5 second exposure time for a step 7. All the previous tests were done using the 5.5 second exposure time. Six test panels were prepared and exposed at times of 5.5, 5.3, 5.1, 4.9, 4.7 and 4.5 seconds respectively. The panels were developed and etched together and the tops and bottoms of the 25μm lines and 75μm lines were measured for comparison. There was not much improvement until the 4.9 second exposure was reached and the resist exposed at 4.7 and 4.5 seconds had adhesion problems. The results for the 5.5 second and 4.9 second exposures are shown below in the table and cross sections.

Figure 8 – Line Width Measurements

Exposure Time	25μm line Top	25μm line Bottom	75μm line Top	75μm line Bottom
5.5 sec.	13.7μm	27.7μm	54.1μm	60.7μm
4.9 sec.	8.4μm	20.3μm	54.8μm	57.4μm

Figure 9 – Cross Sections

5.5 second exposure	4.9 second exposure
	

The results above show that, under the same developing and etching conditions, the 25μm space has etched out more completely for the 4.9 second exposure. More importantly, while the 25μm line is obviously etched more, the dimensions of the 75μm line did not change all that much demonstrating that a lower exposure level may actually help clean out the 25μm spaces faster in relation to the wider spaces. The etch factor for 25μm line did not improve that much but the etching was definitely better. It was hoped that, at the time this paper was solicited, that a full set of tests to confirm these results would be completed by the time the paper was due but other duties have intervened and they have not yet been started. However, the preliminary tests shown here do show that this line of inquiry is worth pursuing.

<u>Developing Time Tests</u> – Another preliminary test was run with the 4.9 second exposure to compare developing at a conveyor speed set for a 60% breakpoint, as used on the above exposure tests, with a speed set for a 40% breakpoint. Visually, the results seem to show a further slight improvement in the clean out of the 25μm space in relation to the wider spaces. Again, the full set of tests to confirm this conclusion has yet to be completed but the outlook is hopeful.

<u>Tests for the Near Future</u> – Others have indicated that replacing the free hydrochloric acid by saturating the cupric chloride with sodium chloride, table salt, greatly improves etch factors. This is on the list to be done as soon as possible. Also, there have been developments in spray nozzles and chemical additives for cupric chloride. Samples of both of these will be available by the time this paper is delivered (March, 2011) and are also high on the priority list for immediate testing as time allows.

Practical Aspects for HDI Etching That Have Been Learned During the Course of These Tests

The original impetus for this investigation was a request to look into the feasibility of etching 50μm lines and spaces in 35μm foil and 25μm lines and spaces in 18μm foil while using a 30μm dry film. This has to be the ultimate worst-case scenario for HDI production but the initial trials clearly defined the problems faced, namely: 1) The etch rates in spaces less than 50μm fall off drastically when compared to wider spaces and 2) because of this, any place where a line of 25μm or less is bounded by a space greater than the line width will be etched out before any spaces the same width as the line can be cleaned out enough to prevent shorts. The ultimate solution to the problems would be to find a way to increase the rate of downwards etch while not increasing the rate of sideways etch.

While this goal of increasing the downwards etch without increasing the sideways etch has not yet been attained there were many practical things learned in preparing and etching the test samples that could save a lot of time and effort for anyone engaged in HDI. These observations are listed below although not necessarily in order of importance.

1. The original task of etching 25μm lines and spaces in 18μm foil and 50μm lines and spaces in 35μm foil can be done but it won't be easy, especially in a production situation. While I would like to be able to say that getting the latest, greatest new etching equipment will solve all your HDI problems this would be untrue. Every step in the production process will have to be looked at and improved.
2. There is very little that can be done, mechanically, to present etching spray machines that will improve the yields for HDI. The need is to increase downward etch rates without increasing sideways etch rates. Such things as different types of nozzles, smaller droplet size nozzles, increasing operating pressures and temperatures, removing obstacles to the spray, etc., either have no effect or just increase the overall etch rate without improving etch factor. At best there is no change, at worst they merely allow you to make scrap at a faster rate.
3. Experimenting with exposure times (less exposure time) and developing times (more developing time) seems to improve the overall etch rates in the narrowest spaces without affecting the etch rates in the wider spaces as much. This is definitely worth taking a look at.
4. The best way to improve HDI output may be a careful look at artwork design and creative compensation of the artwork at weak points. This may take the form of making sure the space between lines remains the same at right angle turns and shading the line width towards the side where a line is bounded by a wider space than the other side.

The above conclusions are a direct result of the testing done on HDI. The following conclusions are general observations made during the course of sample preparation and testing:

5. Soft contact exposure where the photo-tool is attached to the glass of the exposure frame and brought into contact with the resist at relatively low vacuum pressures of 4 to 6 psi may not be adequate for exposing sub-25μm lines and spaces even with a highly collimated light source. Harder contact and longer vacuum drawdown times have improved yields dramatically.
6. Lasers plotters used for imaging, either for exposure of the photo-tool or direct imaging of the resist, need to be looked at carefully for sub-25μm lines and spaces. The dot size used for lines perpendicular to the laser travel is of particular importance since the edge of the line must be as smooth as possible. Too coarse a dot size may result in added difficulties in cleaning out the space. Smaller dot sizes are better but can greatly elongate plotting time. Some experimentation should be done to find the optimum compromise.
7. The original request to explore the feasibility of using 30μm dry film for these HDI tests was basically economic. Thinner dry films are more expensive and even thinner liquid resists require capitol investment for application and curing as well as time needed for a learning curve. The company originating the request was anticipating high production runs and was hoping to avoid adding cost to the product. While the conclusion based on testing is that it is possible to use a 30μm resist it may not be viable in a high production situation. A thinner resist will definitely

make things easier. Experience shows that one should seriously consider a liquid or electrophoretic resist that allows resist coatings of 5µm or less.

8. Finally, it can be extremely frustrating making adjustments to the etching equipment to get optimum results due to the extremely narrow working windows for conveyor speeds when etching lines and spaces below 50µm. While etching machines are made to exacting standards they are still hand built to order and each individual machine has its own quirks with sweet spots, cold spots and hot spots in different places. In the ordinary course of events these quirks are hardly noticeable but they can become important players in HDI. It is unlikely that any individual etcher is going to give even results on large format HDI panels without a lot of individual spray tube adjustments. To further complicate the situation, the nozzles used in spray etchers are mass-produced using a molding process. They must meet certain specifications as to flow rate, spray angles, etc. but these specifications are fairly broad. Again, in the ordinary course of events any variations in individual nozzles tend to be unnoticeable but when sub-50µm lines and spaces are involved a nozzle at one or the other end of the acceptance criteria can cause problems. Most etchers today allow adjustments to individual spray tube pressures, either automatically or manually, to even out differences in the spray pattern but if HDI is involved it may be necessary to track down and replace individual nozzles to get the best performance.