A NOVEL WET PROCESSING TECHNOLOGY

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Abstract

We have evaluated the hydrodynamics of current wet processing techniques for high density pattern etching. The diffusion layer proved to be the main obstacle for a controlled manufacturing of patterns smaller than 100 microns. The result is a limited line resolution and acuity with unacceptably low yields. By utilizing mechanical action at the interface, a novel technology accelerates the transport of matter. Moreover, it was shown that by controlling the mechanical activity one can achieve uniform processing conditions across the entire area of the substrate. Elements of this novel technique are discussed and several results of its application in various patterns and copper laminates are shown.

The controlling factor, the transport of matter at the interface

Conventional wisdom in interconnects fabrication utilizes the same liquid to achieve two objectives: the chemical activity and the transport of matter. The first objective is to provide the chemicals needed in the process. For instance, a solution of Cupric Chloride is utilized to etch metallic copper away from the imaged copper laminate. It is the chemical activity of this solution that makes the etching process possible. The second objective is to provide the exchange of matter at the reacting interface. For this activity we use the same solution. We supply the reactants to and remove the reaction products from the reaction site by providing kinetic energy to the solution. This is typically achieved with specially designed liquid handling systems such as interactive spray nozzles or impinging jets.[1,2]

The above approach is viable for etching process application in the fabrication of larger scale items. There the size and the shape of features being formed are far greater than the microscopic interfacial stagnant layers. Under such circumstances the transport of matter will not interfere with the process and the features specified by the designer will be achieved without difficulties.

In contrast to the above, high density interconnects manufacturing process utilizing the same approach is not viable. The concept of dual use of the chemical solution for both, to provide chemicals and to act as the working body for the transport of matter at the interface, suffers from a serious deficiency. For example, an attempt to etch 50 micron lines in a working solution having stagnant layers of the same order of magnitude will certainly fail. At this manufacturing step, the motion of active species and the resulting dissolution process is beyond the operators control. In the end, one obtains unacceptable interconnect resolution, coarse line finish and uneven geometry.

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The equipment used in the state-of-the-art PWB technology can not overcome the above hydrodynamic barrier. As a result, the industry is producing 75 micron features with 50% or lower yields. In order to compensate for this deficiency, the industry utilizes the additive process which is plagued by maintenance and QC issues. This status in the electronic packaging industry calls for a better etching technique.[3,4]

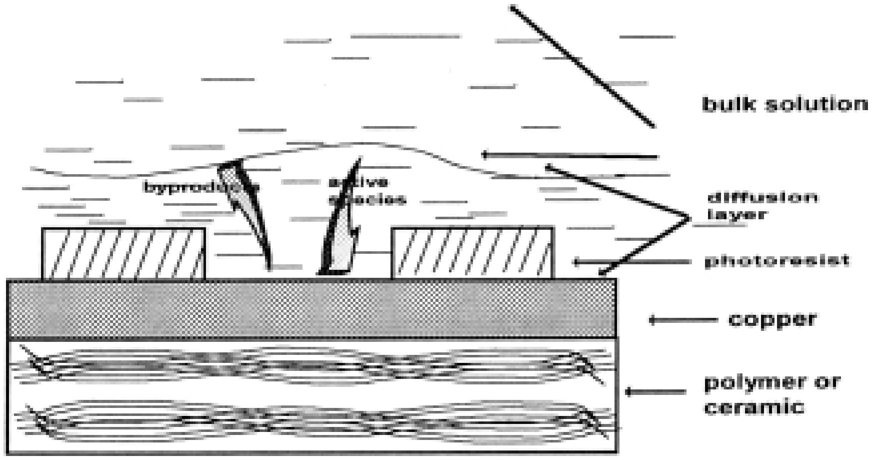
The interface of wet processing

The problems in conventional processing arise from the nature of wet processing and the interconnect design. Originally developed for larger interconnect features, wet processing can not be simply adapted for the fabrication of the high density designs that meet today's demand.

Figure 1 is a schematic presentation of conventional wet processing. Numerical values have been attributed to the hydrodynamic phenomena at the interface. At the same time, these values have been compared to the actual geometry and magnitudes of the patterns, lines, spaces, and pads that are intended as a part of the interconnect structure. For this example we have assumed that a 50 micron space between two 50 micron lines is being formed by etching in a 35 micro copper laminate. A 25 micron dry film resist delineates the intended circuitry.

Figure 1.

Hydrodynamics in Conventional Processing - Initial Stage



Processing of this pattern in typical spray etching equipment would produce ill defined lines, probably within a 20-30% variation in linewidth with serious deficiencies in wide space areas, the "necking" effect, and a low yield of probably 40-50%. Though some deficiencies can be attributed to a variety of causes such as copper laminate inconsistency or imaging deficiency, the fact remains that the etching of such features presents a major hurdle which is typically the cause of the majority of the defects.

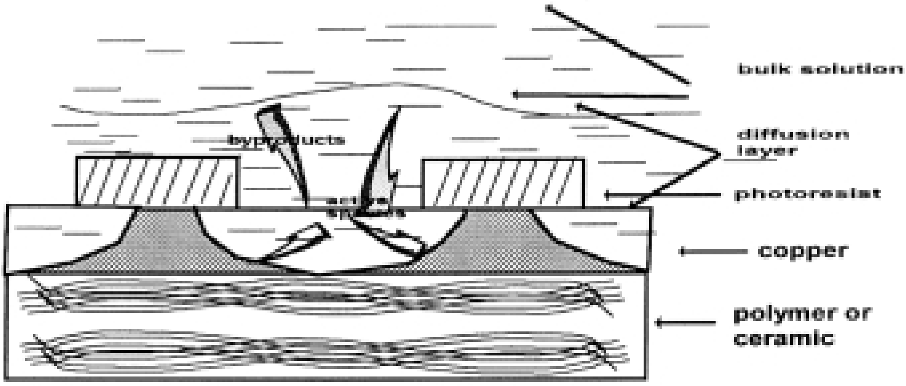
The cause of the above inefficiency is in the nature of wet processing. Whether a spray etching or an immersion etching process is utilized, control over the processing ceases at the most critical site that is the mouth of the groove above the exposed copper. At this point the liquid motion, caused by the spray or other sources, slows down to a virtual standstill (this stagnant layer of liquid is referred to as the diffusion layer.) From this point to the copper surface, the active species contained in the liquid travel only by spontaneous motion, typically controlled by the difference in concentration of the traveling species (this motion of species is usually referred to as diffusion.)

Diffusion layer thickness is defined as the distance from the solid at which the velocity of liquid is similar to the speed by which the active species travel through the solution on their own.[5] Closer to the solid surface the motion of liquid has little effect on the motion of species. Conventional tools that are utilized in current processing cause a fast flow rate of the bulk liquid but have only a limited effect on the liquid velocity against the surface of the imaged laminate. As a result, diffusion layers are typically of the order of 50-100 microns (see Figure 1.)

Thus, the active species will diffuse from the bulk liquid at the mouth of the groove (higher concentration level) towards the copper interface where it becomes consumed (lower concentration level.) The same applies to the “spent etchant.” The “reacted” etchant, for example CuCl, diffuses upwards to the groove’s mouth where it becomes diluted in the bulk of the etchant. These two main motions of species control the wet processing. In conventional wet processing, however, they are entirely beyond the reach of the operators control. As a result, the etching process proceeds with an approximately equal rate in every direction, both under the photoresist as well as into the copper layer. That is how severe undercutting occurs. Under such circumstances the smallest patterns achievable are about 75-100 microns wide. In addition, fluctuations in this motion caused by sporadic uncontrolled convective flow will also cause frequently observed severe distortions in features.

Figure 2.

Hydrodynamics and Results in Conventional Processing



R.C. Alkire et. al.[6] show, through a numerical computation of dimensionless hydrodynamic parameters such as Peclet:

$$Pe=(W/2)V/D_d, \qquad (1)$$

where W=width of the groove (cm), V=solution at the interface (cm/s), D_d=diffusion coefficient of species (cm^2/s)

how inadequate operating conditions can bring about sever distortions in subtractive processing. The authors indicate that a minimum value of Pe=100 must be achieved in order to minimize the concentration gradients which can cause deficient processing. In reality, with typical values for W at 5×10^{-3} cm, V in the range of 10^{-3} to 10^{-2} cm/s and D_d at 10^{-5} cm^2/s, the resulting features are ill defined. Figure 2 shows the species' motions and the resulting distortions of the image.

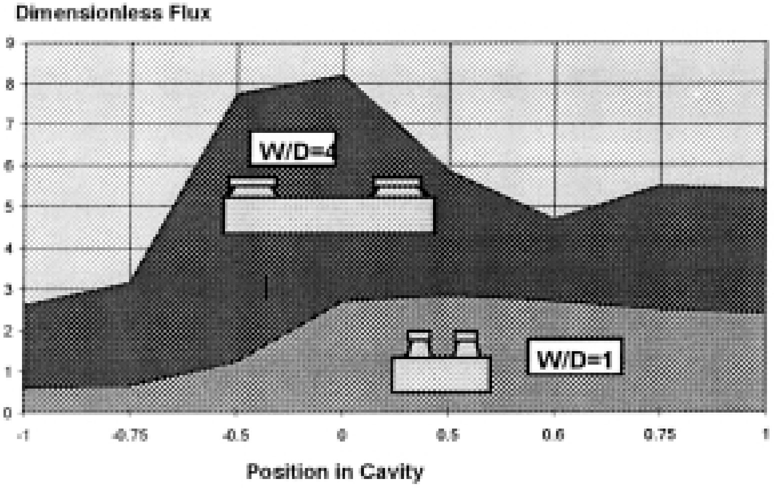
Can we achieve a better processing by enhancing the liquid motion at the interface? Yes. If the increased flow rate at the interface has a directional motion. Later, we will see how an increased flowrate can make things worse if the flow is not "directed."

Another cause of deficiencies in conventional processing lies in the dimensional variations caused by the nature of the interconnect design. In most instances a design will require lines and spaces to vary from 50 microns to a maximum of 10mm or more. The fact that the transport of matter at the interface is partly caused by surface features now becomes an even more serious cause for concern. Clearly, a space of 10 mm is quite accessible to the bulk liquid. In such instances one obtains a fast rate dissolution in the wide space between the lines, while the narrower 50 micron space remains barely disturbed.

J.M. Occhialini et al.[7] describe the transport of matter in their evaluation of relatively wide or narrow spaces utilizing the Peclet number as a measure of efficiency. Figure 3 shows their numerical results for two width-to-depth (W/D) ratios, 4 and 1. Clearly there is a 3-4 times slower rate of reaction product removal in the deep groove, W/D=1, than the shallow groove, W/D=4. The result is a much faster etching in the wider spacing.

Figure 3.

Convective Mass Transport from Cavities Carried Out by the Working Solution Itself, J.M. Occhialini et al. (2)

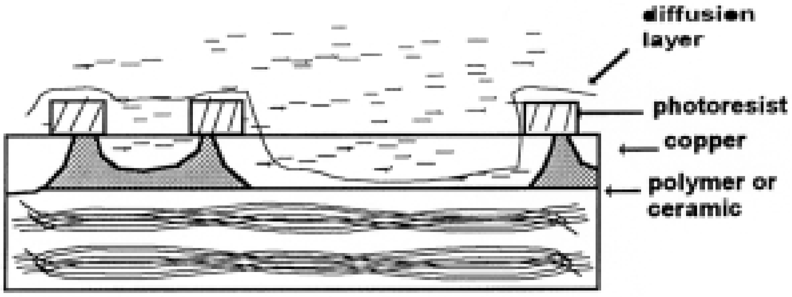


The results of the above described theoretical circumstances are depicted in Figure 4, where one obtains severe undercutting in open spaces while the etching has hardly started in the narrow spaces. This is a serious problem. An upward correction of the flow rate at the interface with the goal of enhancing the etching rate in the narrow spaces will undoubtedly cause even more severe problems in the open spaces.

This mechanism is a major cause for the “necking effect” frequently encountered in interconnect designs with a wide range of space widths. For example, a line of a designated width is more severely undercut as the space around it gets wider. As a result, one sees the narrowing effect often referred to as “necking.”

Figure 4.

Hydrodynamics and Space Width Effect in Conventional Processing-Uneven Resolution Rate with Varying Space

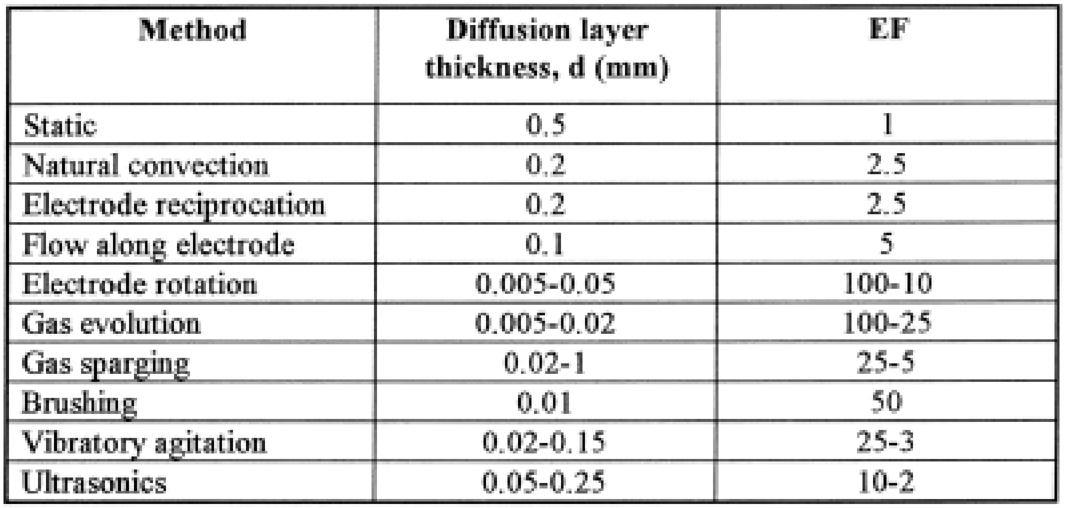


What are the possible remedies for such processing deficiencies? Two critical process optimizations must be made. First, the transport of matter must be enhanced to limit the diffusional motion of the active species. Second, the transport of matter must be controlled. Meeting these requirements simultaneously is essential. It was demonstrated that an increased motion of liquid at the interface would lead to more severe distinction between the narrow and wide space interconnects. An ability to control the process with the increased motion of liquid would enable an efficient manufacturing operation.

Options for enhanced transport of matter are numerous. For example, in a general survey of the transport phenomena in electrochemical processing, D.R. Gabe[8] shows that diffusion layer thickness can vary in a wide range, depending on the method applied for liquid agitation, Table 1.With natural convection the effect is a 2.5X enhanced agitation compared to static conditions. Gas evolution offers a 100X magnified effect of transport at the interface. Clearly, not all options are amenable to the specific processing required in interconnect manufacturing.

Particularly important is the need for a controlled processing. One should be able to conduct the process so that the etching occurs preferentially at the bottom of the imaged patter. The walls of the newly formed lines should be kept nearly vertical.

Table 1. **Enhancement Factors (EF) for Various Methods of Solution Agitation**



Method	Diffusion layer thickness, d (mm)	EF
Static	0.5	1
Natural convection	0.2	2.5
Electrode reciprocation	0.2	2.5
Flow along electrode	0.1	5
Electrode rotation	0.005-0.05	100-10
Gas evolution	0.005-0.02	100-25
Gas sparging	0.02-1	25-5
Brushing	0.01	50
Vibratory agitation	0.02-0.15	25-3
Ultrasonics	0.05-0.25	10-2

Mechanical processing - a novel technology[9-11]

In a novel technology (a proprietary process developed by ElectroChemical Systems, Inc.[9-11]), the transport of matter is successfully carried out with mechanical applicators. While the chemicals are still being supplied by the active solution, the work of exchange of matter at the interface is performed by dedicated equipment. A controlled and monitored mechanical action is applied perpendicular to the processed substrate. As a result, one obtains a precise reproduction of the imaged resist.

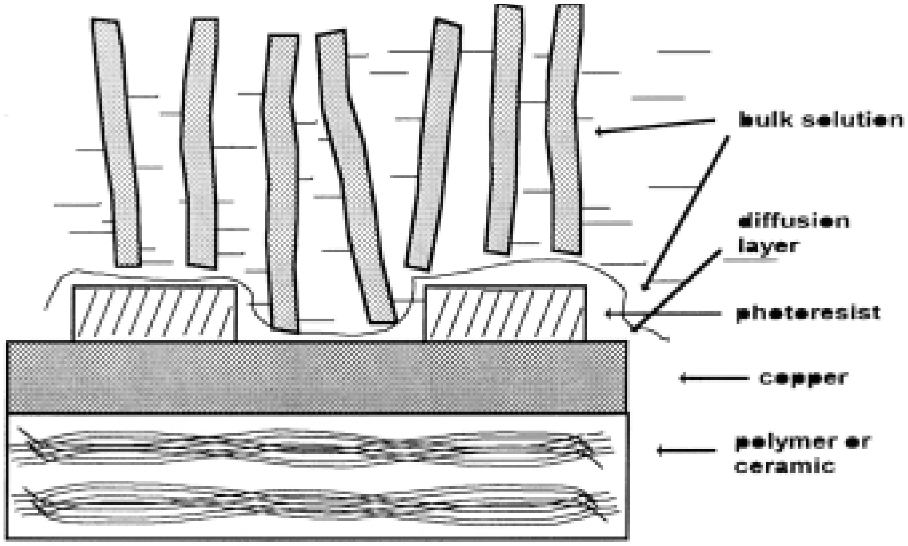
Transport of Matter

The new technology utilizes mechanical means to control the transport of matter at the interface. Three important aspects of efficient processing are met: a. the motion of liquid at the interface exceeds the spontaneous motion of species, b. the motion of liquid is predominantly perpendicular to the plane of the laminates so that the etching proceeds in same direction and, c. the mechanical action does not depend on space width. Consequently, the lines' resolution and acuity is identical across the panel regardless of the space. These functional effects are successfully achieved with fibrilic applicators.

Figure 5 shows the elemental schematic of this novel technology. First, the motion of fibrilic material in contact with the imaged surface causes the liquid to move with it. That allows the exchange of matter at the interface to take place predominantly at the operator's will. The speed of the applicator is adjusted to eliminate diffusional effects. Most importantly, the process takes place all over the areas that are in contact with the fibrilic material. Secondly, specially devised motion patterns and frequencies cause the predominately vertical motion of matter. That causes preferential vertical etching. The two combined effects result in a highly efficient processing of imaged substrates.

Figure 5.

Hydrodynamics in Novel Advanced Processing - Initial Stage



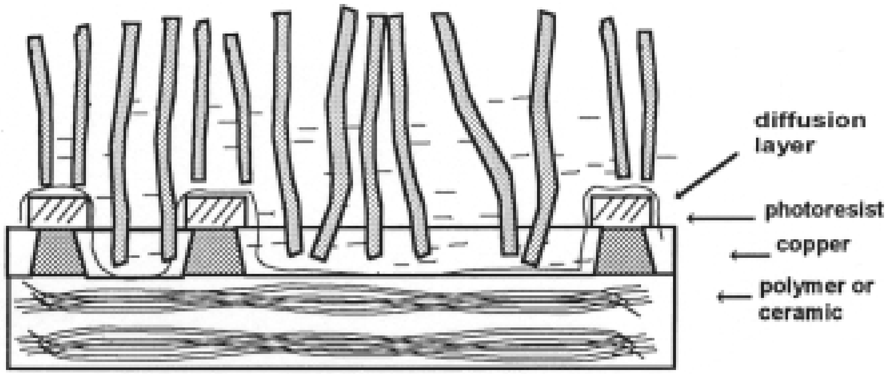
Motions and Friction

The transport of matter is achieved with a mechanical action which by itself may be considered damaging to the image. Mechanical damage is absent, however, even with a fine line width of the order of 7.5 microns. The combined effect of controlled pressure and applicator motion with the lubricating effect of the solution preserves the conductor integrity. 5 micron thick resist has been demonstrated to withstand these operating conditions. In addition, the novel process has so far proven compatible with all types of resist material including dry film,liquid film, and electroforetic resist.

Figure 6 shows the typical etching profile achieved with this novel technique. Conductor walls are smooth and nearly vertical, and the pattern is virtually identical to the image regardless of the space width around the line.The necking and puddle effects of the conventional technique have been virtually eliminated.

Figure 6.

Hydrodynamics and Results in Novel Advanced Processing – Resolution Uniformity with Varying Space Width.



Cross sections and typical results in a range of applications

Figure 7 shows the scanning electron microscope (SEM) cross section and plane view of a 75/100 micron line/space pattern in a 34 micron thick copper laminate. The resist was preserved so that the cross section could be utilized to evaluate the degree of undercut. In this example, a uniform 8-10 micron undercut gives a thickness to undercut ration of 3.8.

Figure 8 shows a cross section of an outer layer pattern with solder etch resist. On the left is the SEM photo of the pattern obtained with the novel processing. For comparison, on the right side is the same figure is the SEM photo of the identical site of the board design after etching in conventional processing. The ten fold magnified cross section shows that for the same image quality the novel process preserved over 40% of the copper conductor material.

This ability to control the transport of matter permits the fabrication of high density patterns in the range of 25 to 50 microns. Figure 9 shows a representative cut through 100 test patterns utilized in process development. A “Pyralux” laminate, 17 micron copper-polyimide laminate was imaged with dry film resist. A high density patter was utilized in process development. 1, 1.5, 2 and 2.5 mil lines were spaced 1.5, 2, and 2.5 mils apart. The etching was performed with $FeCl_3$, and also with $CuCL_2$ etchant in approximately 30 seconds. Both samples, the $FeCl_3$ and the $CuCl_2$ etchant, show undercut of 3-7 microns throughout the patterns regardless of the spacing. A uniform reproduction of the original image was achieved across the entire area.

The above test pattern is a Conductor Analysis Technologies, Inc. (CAT)[12] proprietary pattern utilized in conductor manufacturing process development and product evaluation. The CAT technology provides useful and significant data related to conductor quality and process performance.

Conclusion

We have performed an analysis of the hydrodynamics of wet processing as related to high density printed wiring board fabrication. We have shown that the high density circuitry, which is increasingly becoming a matter of interest for the electronic packaging industry, can not be efficiently manufactured with conventional subtractive techniques. Peclet numbers lower than 100 are typically encountered in such processes leading to ill defined circuitry and typically obtained at unacceptably low yields. A novel technology that is based on mechanical applicators has been analysed. This technology has demonstrated a significant advancement of the state-of-the-art in interconnect manufacturing.

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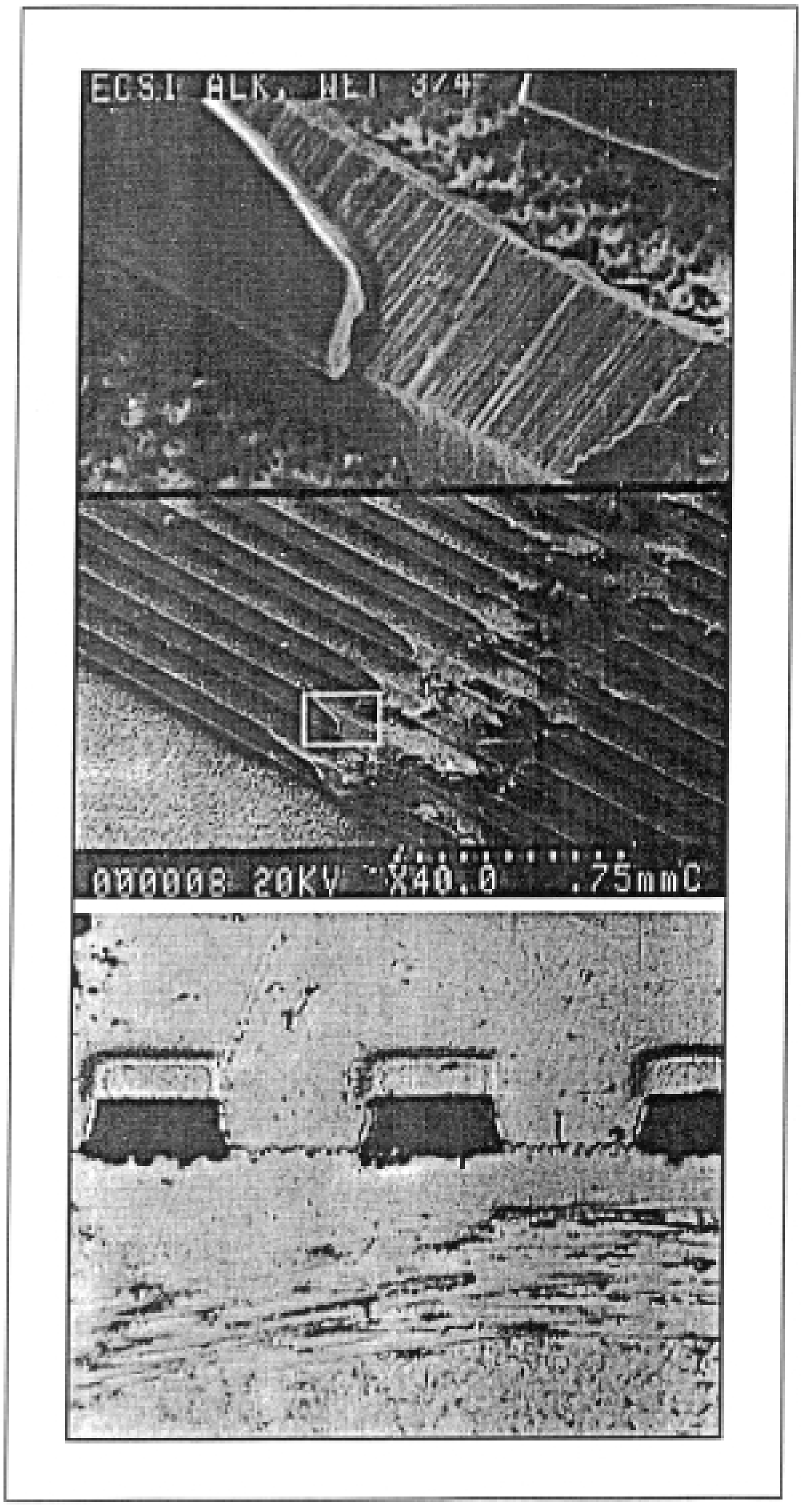

Figure 7.

75 micron lines and 100 micron spaces in 35 micron copper laminate etched in a novel mechanical processing. Top, SEM plane view with resist partially removed to show the undercut extent. Bottom, cross section with resist (light) and copper (dark.) Both photos show the line uniformity and minimum extent of undercut.

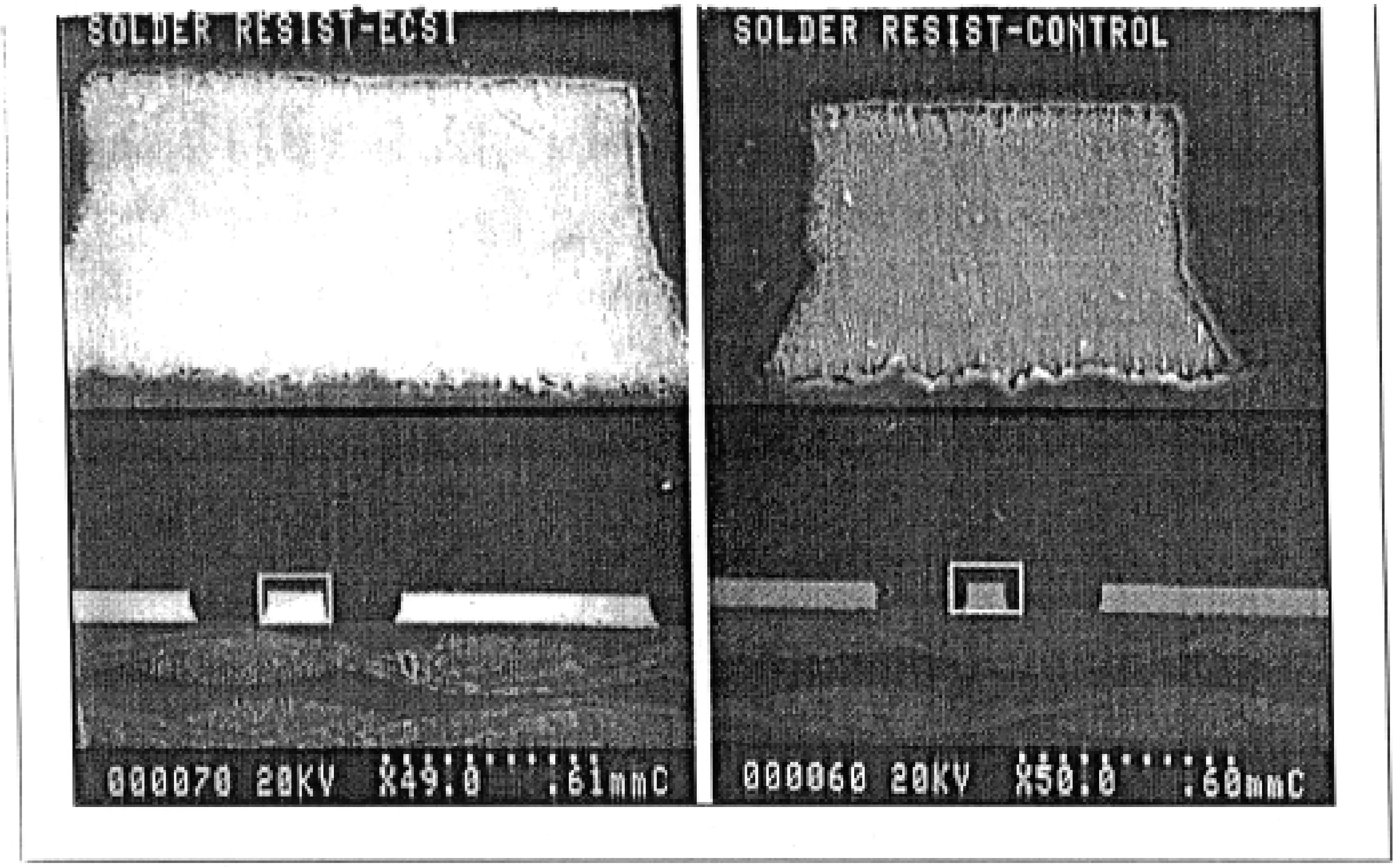

Figure 8.

75 micron copper laminate etched in mechanical processing, solder resist applied in outer layer. Left, new processing, right, conventional processing; for the identical pattern new processing preserves 40% more metal in the conductor line.

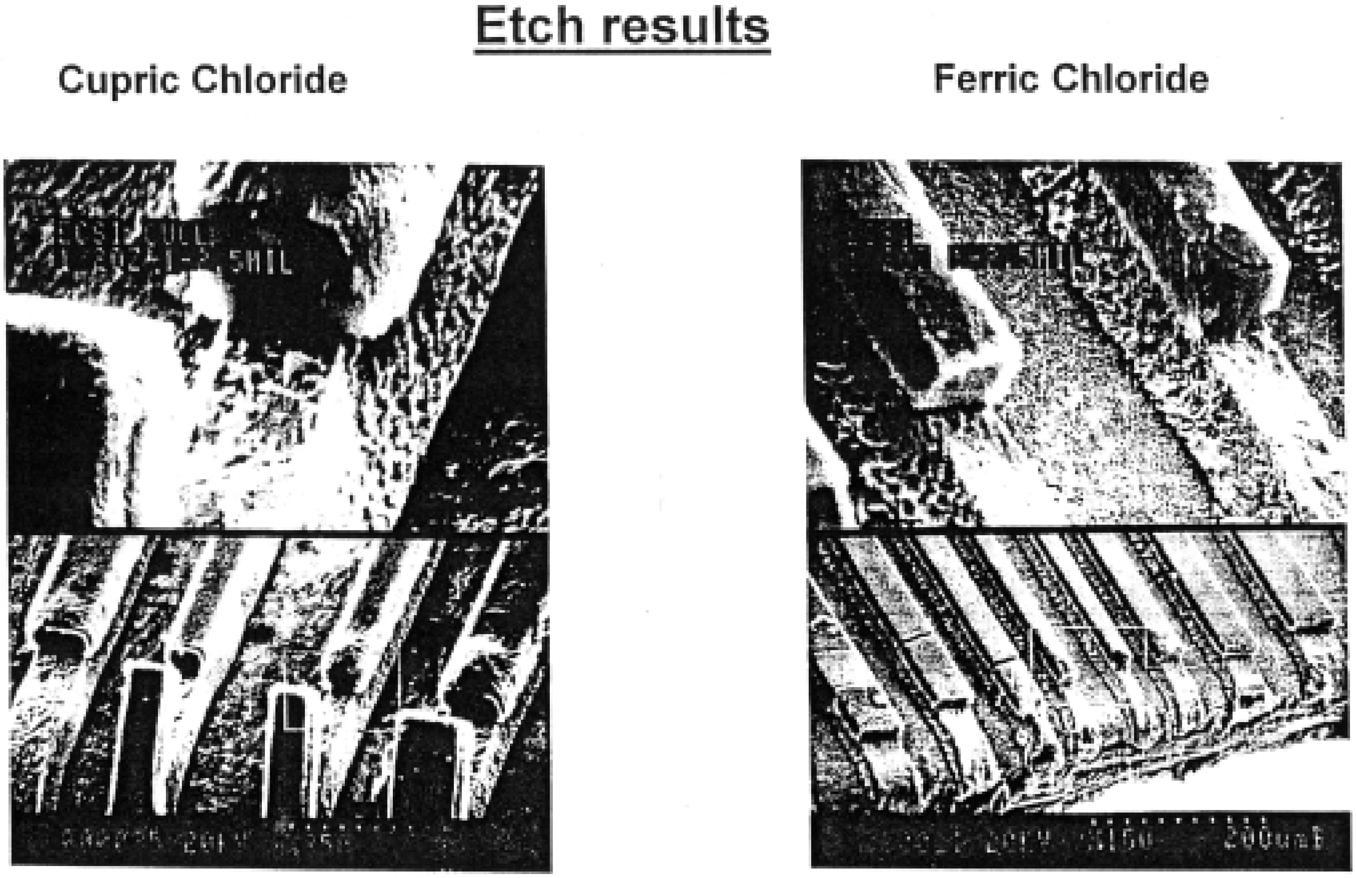

Figure 9.

Prototype process development, Conductor Analysis Technologies, Inc. multipitch test patters: 1,1.5,2 and 2.5 mil lines with 1.5, 2, and 2.5 mil spaces were utilized to obtain 0.6,1.1, 1.6 and 2.1 mil lines. “Pyralux”, 17 micron two side copper laminate on 50 micron polyimide was imaged with dry film with 100 patterns on each side. Both cupric chloride and ferric chloride etchants show uniform and minimal undercut, resist preserved for comparison.

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