Adhesiveless Copper on Polyimide Flexible Substrates and Interconnects for Medical Applications

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Abstract
Flexible circuit interconnects for ultrasound transducer applications are among the most difficult to fabricate and make good representative circuits for medical applications. The polyimide dielectric can be as thin as 12 micron. They often contain ultra-high density regions that are push the edge of currently available technology. Lines and spaces can be as small as 20 to 30 micron, and via diameters can be as small as 25 micron. The interconnects are typically fabricated starting with adhesiveless copper on polyimide flexible substrates manufactured using sputtering and electroplating techniques. High performance polyimides provide mechanical and thermal stability needed to metallize thin dielectric without significant wrinkling or creasing. The availability of thin copper and smooth interfaces facilitates fine-line etching and high density features. Good adhesion is critical to ensure fine-line features remain intact throughout the fabrication process. Peel strength exceeding 6 lb/in is achieved by pretreating the polyimide surface with plasma and applying a suitable tiecoat metal between copper and polyimide. Laminate dimensional stability after etching and heating exceeds the IPC specification and promotes good alignment and registration of circuit features. Fine-line features imply strict copper quality requirements. Pinholes represent an important aspect of copper quality. Systematic analyses have been done to classify pinholes and link different types to their likely causes. The classification scheme and detailed analyses serve as a basis for pinhole quality control in the manufacturing environment. The approach has been used to help reduce pinholes and serves to allow rapid containment if pinholes become an issue.

Introduction

Flexible circuit interconnects have been used in products for medical applications for over 25 years. During that time, the number of applications has expanded tremendously and today end uses include ultrasound transducers, catheters, sensors, instrumentation, digital medical imaging, pacemakers, and hearing aids. The flexible interconnects of today are highly advanced. They typically incorporate COF technology. Double-sided and multilayer flex are common. Circuit size, thickness, and weight have been reduced. Ultra-high density regions with fine feature sizes consistently push the limits of available fabrication technology. Higher functionality and reliability are required, and there is constant pressure to reduce costs. Due to their advanced capabilities, flexible interconnects will increasingly be the means used to create interfaces for biomedical devices.

Medical ultrasound imaging is used as a non-invasive diagnostic tool in which reflected sound waves are processed to image structures within the human body. A central element of one device is a hand-held transducer head assembly that transmits and receives ultrasound energy into the patient. The assembly contains a piezoelectric ceramic layer that converts mechanical signals to electrical signals. A flexible circuit interconnect is used to route electrical signals between the piezoelectric layer and the imaging system. These interconnects are among the most sophisticated and difficult to fabricate in the industry. They make a good model circuit for discussing material requirements for interconnects for medical applications.

There are three primary types of laminate that are commercially available for making flexible circuits. They are lamination based, cast, and direct deposited materials. Lamination based material is formed by bonding copper foil to fully cured dielectric using an adhesive. It can also be made by laminating copper foil directly to thermoplastic dielectrics at elevated temperature and pressure. Cast materials are produced by coating copper foil with dielectric resin then curing the dielectric. Direct-deposited adhesiveless constructions are made by sputtering and electroplating conductive layers on fully cured dielectric. Direct deposited adhesiveless materials are commonly used to make interconnects for ultrasound transducer applications.

This paper describes design features of flexible circuit interconnects for medical ultrasound transducer applications. Direct deposited adhesiveless copper-on-polyimide laminate technology is discussed in relation to requirements established by the interconnect technology.

Interconnect Technology

A flexible circuit interconnect for an ultrasound transducer head assembly is illustrated in the literature[4]. The interconnect is moderate in size; anywhere from 6 - 12 individual circuits can be positioned on a 12" x 18" panel. The circuit is typically double-sided today, with one side being a ground plane. However, designs are moving to multilayer constructions at some locations on the circuit. Microvias connect signal and groundsides. They are created using a laser process because of their small size.

The narrower, central region of the circuit can be formed and bonded directly to the structure on which the piezoelectric ceramic layer is located. Other approaches include wire bonding to traces that come to the edge of the structure. In some cases more than one circuit is used. Copper thickness is typically less than 5 µm in the area where connections are made to the piezoelectric layer. Copper is plated to 18 µm at the outer areas of the circuit, where connections are made to the imaging system. Nickel and gold, indium, or solder finishes are applied to copper surfaces to ensure good connections and high reliability.

Thin dielectric is frequently a necessary design requirement for ultrasound interconnects. The dielectric can be as thin as 12 µm, although 25 µm is more common. Thin dielectric facilitates the forming operation, is more transparent to ultrasound energy, and provides improved electrical performance for the double-sided circuit. More generally, dielectric with good mechanical, thermal, and chemical properties are required for thin laminate to withstand laser via, print and etch, and surface finish processes.

The connection requirements of the piezoelectric ceramic layer are challenging. Many connections must be made. The piezoelectric layer is divided into individual array elements, and each element represents a channel of information. A 2D technology array can have well over 1000 elements[5]. Each element requires an independent electrical connection, although all elements need not be sampled. Newer 3D technology is under development and will have an even greater number of elements.

The physical space available to make connections is limited. Connections to the piezoelectric layer must be made in the vicinity of the central area of the interconnect. The area is small to maintain the hand-held character of the assembly and maintain appropriate scale for human body measurements. Furthermore, interelement spacing depends on the operating frequency of the device. Operating frequencies for today's devices imply interelement spacings that can be roughly 150 to 350 µm[5]. Some catheter based applications have interelement spacings as low as 50 µm.

Since many closely spaced connections must be made in a small area, high-density circuitry and fine-feature sizes are key design characteristics of ultrasound interconnects. Lines and spaces can be as small as 20 to 30 µm, and via diameters can be as small as 25 µm.

Feature locations on the interconnect must be fixed and predictable throughout fabrication processes. One potential issue arises in the vicinity of the piezoelectric elements. Exceptional location control is required to ensure interconnect terminations and piezoelectric elements are aligned and can be connected properly. Similar considerations apply to vias. Pad to via ratio is often 3:1 or smaller. Via generation is accomplished prior to pad formation in the fabrication process. Exceptional location control is needed to ensure each pad is centered under the corresponding via. Tight tolerances and good dimension control, including true position geometric control, are needed for both alignment and registration. Line and space tolerances of 5 to 10% and critical dimension control to 0.1% are required for modern transducer interconnect features.

Strict copper quality standards are required to achieve functional, reliable interconnects and high yields during the fabrication process. Suspended or cantilevered traces are often present. Exceptional copper quality is required to ensure these types of features have good structural integrity and remain intact. High density areas and small feature sizes have implications with respect to fabrication. One aspect is that even small copper surface defects can create a problem for fine-line circuit traces. For example, a 50 µm pinhole that happens to be located on a 25 µm trace creates loss of electrical continuity. A second aspect relates to high-density circuitry. One of even a small number of surface defects has greater chance of being located on a circuit feature when many traces are present on the circuit. Finally, copper quality must be persistent and robust. Cosmetic defects that arise during interconnect fabrication can reduce overall confidence in the quality of the interconnect.

The interconnect overview defined four key areas that are influenced by the laminate material technology. These are dielectric characteristics, high-density fine-line features, alignment and registration, and copper quality. Each of these will be discussed from the laminate point of view after a brief overview of adhesiveless laminate manufacturing.

Adhesiveless Laminate Technology

Laminate Manufacturing

Adhesiveless copper on polyimide laminate is manufactured using sputtering and electroplating technologies. The starting material is fully cured polyimide film, typically 25 or 50 µm thick. The film is plasma treated to activate the surface. The next step is to sputter a thin metal tiecoat, which is between 50 and 200 angstroms thick. A copper seedcoat, usually about 2000 angstrom thick, is sputter deposited over the tiecoat. The plasma treatment and sputtering processes can be done on one or both sides of the polyimide. They are done using a roll-to-roll operation in a vacuum chamber.

Copper electroplating is performed also using a roll-to-roll operation. The copper seedcoat is subjected to a mild preconditioning to clean and activate the surface. Copper is electroplated sequentially in zones using the copper seedcoat and plating from earlier zones to conduct current. Final copper thickness is tailored to customer requirements and is typically less than 18 µm thick. After plating, the copper is rinsed, anti-tarnish is applied, and the roll is slit to final width.

Dielectric Characteristics

The dielectric material used to make ultrasound interconnects is typically high performance polyimide. Thin dielectric can be obtained using polyimide. PI that is 25 µm thick is common, and thinner 12 µm films are available. With the direct deposit approach to laminate manufacturing, there is no added thickness due to adhesive. Properties of Kapton-E[6] from DuPont are given in Table 1. The mechanical properties help to minimize tearing, wrinkling, and other issues that arise when handling thin films. The high Tg and good shrinkage properties help minimize thermal issues during plasma pretreatment and sputtering. Plasma pretreatment and sputtering are performed on a cooled drum to further minimize thermal wrinkling.

Table 1 – Typical properties of Kapton-E polyimide[7]

Property	Kapton-E
Thermal	
Tg (°C)	355
CTE (ppm/°C)	16 (50 - 200 °C)
Shrinkage (%)	0.05 (200 °C, 1 hr)
Mechanical (1 mil film)	
Modulus (ksi at 25 °C)	700
Tensile Strength (ksi at 25 °C)	45
Elongation (% at 25 °C)	55
Electrical (1 mil film)	
Dielectric Constant (at 1 kHz)	3.2
Dissipation Factor (at 1 kHz)	0.0015
Dielectric Strength (V/mil)	7200
Chemical	
Water Absorption (% after 24 hrs at 23 °C)	1.8
Etch with Hot KOH	Yes
Other	
Laser Ablation	Yes

Feature Size and Density

High density regions having fine features are achieved primarily by the technology of the interconnect fabricator. Standard flex circuit fabrication technology is used. However, all aspects of the imaging, developing, and etching processes must be carefully controlled; keeping in mind that the materials involved are thin and flexible. From the material side, copper thickness directly influences the size and density of features that can be successfully fabricated. A key reason for this is that mass transfer limitations from counterproductive hydrodynamics arise when aspect ratio within an evolving etch cavity becomes sufficiently large[8]. Hence, thin copper improves fine-line resolution.

Thin copper arises naturally from the direct metallization approach. The thinnest metallization layers can be handled roll-to-roll since the dielectric provides mechanical support during all phases of the build-up process. A 2um thick copper is achieved routinely using sputtering and plating technology. This compares favorably to copper foil based approaches, where freestanding foil to 5 um is at the limit of current technology[9]. Thinner copper can be provided as sputtered only material for even better line and space resolutions. In this case, semi-additive process would be used.

Fine-feature formation is also enhanced by smooth interfaces. Foil based laminates have metal to dielectric interface topography determined by copper foil surface profile and nodular adhesion treatments[9]. The profile and treatment penetrate into the dielectric creating interfacial roughness. Direct metallized laminates have interface roughness determined primarily by the roughness of the PI base film. This is typically much smoother than copper foil surfaces. The smoother interface facilitates the last stages of the etching process because etchant need not penetrate recesses in the dielectric to remove the last remnants of the conductor materials.

The morphology of the copper surface also impacts fine-line capabilities. In this case, the smooth interface reduces light scattering during imaging and improves resolution. Surface roughness depends primarily on substrate roughness and the electroplating process[10]. Additives can be included in the plating bath to promote smooth surfaces. Figure 1 illustrates a 5 um copper surface of direct deposited laminate obtained at 600X magnification. The surface roughness was obtained by profilometry, and the results were 45 nm Ra and 785 nm Rt.

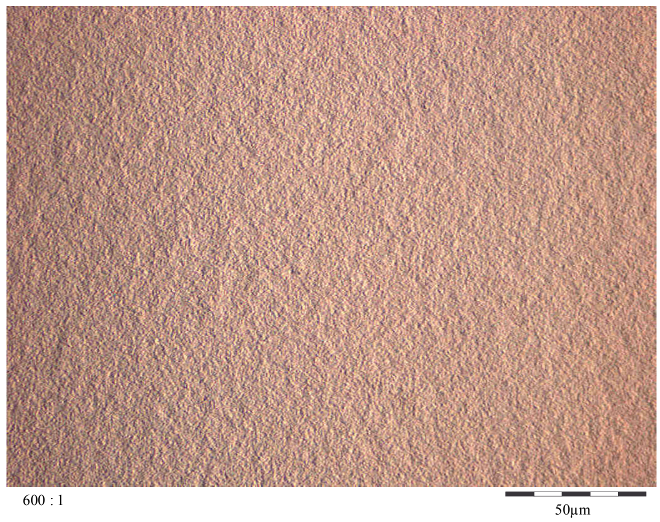

Figure 1 – Typical 5 Micron Copper Surface

An important consideration when fabricating fine-line features using thin copper is the adhesion of conductor to dielectric. Thin copper is less structurally rigid, and it is more likely to delaminate during processing that imposes mechanical stresses, spray etching for example. Fine-line features are more susceptible because small features have less contact area with dielectric than large features. Small features are also more affected by chemical undercut, since undercut is a progressive attack that begins at the perimeter of the feature.

Adhesiveless copper on polyimide laminate relies on plasma pretreatment and tiecoat technologies to achieve adhesion. The plasma pretreatment utilizes an oxygen environment. The treatment makes the polyimide surface more oxygen rich and changes the functionality[11,12]. The oxygen rich PI surface interacts chemically with copper, nickel, and particularly chromium metals to promote adhesion. Plasma treatment also roughens and cleans the surface. Approximately 100 to 200% improvement in peel strength can be achieved by using an optimized, oxygen based plasma pretreatment of polyimide.

Peel strength values for adhesiveless laminates having three common tiecoat constructions are shown in Table 2[13]. Less copper and more chromium in the tiecoat benefit as-received peel strength to some degree. Nickel and chromium in the tiecoat are more effective at reducing adhesion loss after thermal processes, as indicated by the after-solder peel strength values. Processes that apply the nickel and gold surface finishes to the interconnect are among the most severe and can degrade adhesion significantly. Tiecoats containing chromium provide the best adhesion retention under these circumstances and are preferred[14].

Table 2 – Typical Peel Strength Values for Adhesiveless Laminate

Tiecoat	Peel Strength (lb/in)	
	As-Received	After Solder
Monel	8.5	4.5
NiCr	10.1	6.7
Chromium	11.0	9.3

The etching process must be considered when selecting which tiecoat to use to enhance adhesion. Monel is readily etched in cupric chloride etchant, which is commonly used to etch copper. A single etch process is suitable. Nickel-chromium can also be etched in cupric chloride, though not quite as readily. Beginning with thinner tiecoat and higher chloride concentrations in the etchant can be beneficial[14]. A secondary etch, typically basic potassium permanganate, is required to etch chromium tiecoat. Nickel-chromium tiecoat provides a good balance between adhesion and etchability considerations for high density interconnects for medical applications.

Alignment and Registration

Laminate material influences tolerances, alignment and registration primarily through dimensional stability. The ideal situation is one in which laminate material exhibits no relative motions during interconnect fabrication. However, real materials expand or contract with temperature and applied stress. Residual stresses can be present in the laminate and released during interconnect fabrication. Release of residual stresses is most evident after the etching process. The resulting movement can cause the misalignment and misregistration of features discussed earlier. The goal is to maximize dimensional stability of the laminate. Dimensional changes that do occur should be consistent and predictable to allow for compensation during interconnect fabrication.

Shrinkage and coefficient of thermal expansion (CTE) of Kapton-E base film are included in Table 1. Shrinkage is the reduction in length or width of the base film when it is exposed to a fixed temperature for a fixed period of time. It is caused by residual stresses created in the polymer during the manufacturing process. Shrinkage increases with temperature and time but reaches a limiting value after the stresses are relieved. Subsequently, the thermal expansion characteristics are determined by CTE.

Kapton-E has shrinkage that is comparable to other high performance polyimides[15], lower than Kapton-HN (0.3%, 150, 1 hr)[7], and lower than the IPC specification for shrinkage (0.1%, 150 deg C, 30 min)[16]. The CTE of Kapton-E is about the same in the machine and transverse directions and is closely matched to the CTE of copper, about 17 ppm/°C[17]. Matching dielectric and copper CTE minimizes interlayer stresses that are induced when the laminate is exposed to temperature changes.

Laminate characteristics are evaluated by the dimensional stability tests defined in IPC-TM-650 Method 2.2.4C, Methods B and C. In Method B, machine direction (MD) and transverse direction (TD) reference lengths are marked on the clad laminate. Conductors are etched, and the change in MD and TD lengths are measured. In Method C, the samples used in Method B are exposed to 150 °C for 30 minutes and the overall total length changes in the MD and TD are determined. In each case, the length changes are expressed as a percentage of the initial length marked on the clad laminate.

Adhesiveless laminate dimensional stability based on the IPC test methods is given in Figure 2. The data are for 254 production lots and are based on 50 µm Kapton-E dielectric and 2 – 4 µm copper on both sides. IPC specification limits[18] are also included in the figure. After etching, the laminate tends to expand in both the MD and TD. The amount of expansion is small, less than 0.05% on average. This exceeds the IPC specification of 0.15%. The expansion after etch varies within a narrow range. The ±6σ limits were calculated and are within the IPC specification as well.

After heating, the laminate tends to shrink in the MD and expand in the TD. The dimension changes are typically less than 0.1%, and the ±6σ limits are within the IPC specification of 0.2%. The small and uniform dimension changes of the laminate after etching and heating help assure tight tolerances and good dimension control during the interconnect fabrication process. This enables side-to-side registration and good termination alignment.

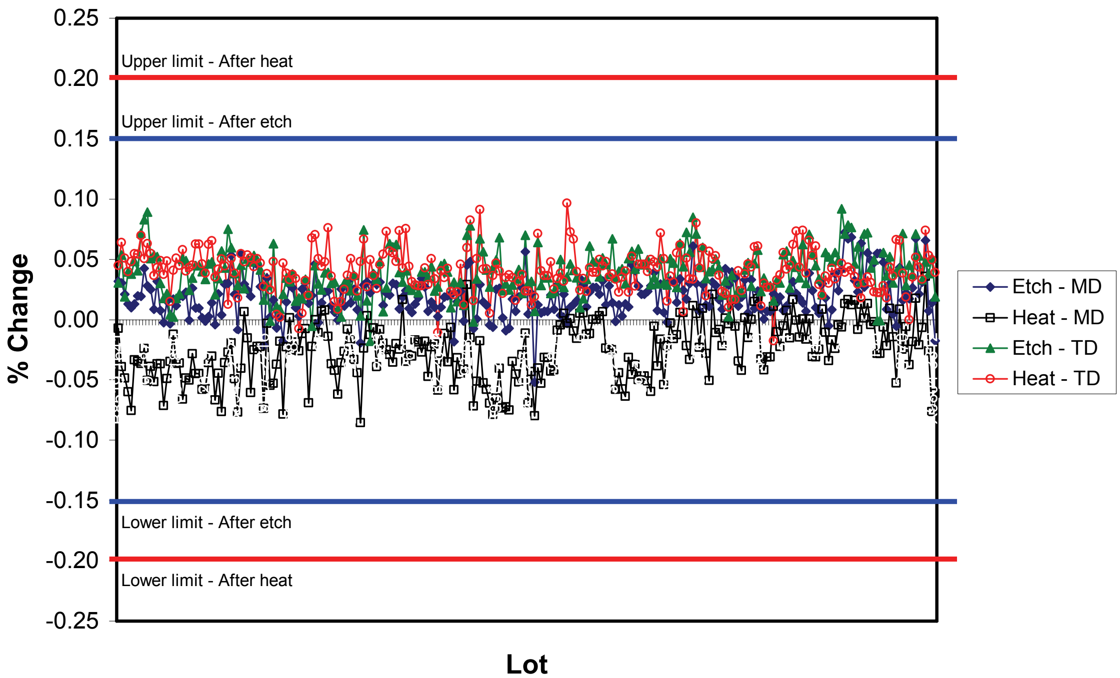

Figure 2 – Dimensional Stability of Adhesiveless laminate

Copper Quality

The ideal copper surface is smooth, flat, and has no defects such as pinholes, pits, dents, scratches, or stains. However, real surfaces do have defects. These defects can be functional or cosmetic. Functional defects are severe and affect interconnect operation and manufacturing yield. For example, a deep pit or scratch can cause poor photoresist adhesion and lead to a trace open during etching. Cosmetic defects are less severe and have negligible or marginal impact on interconnect performance. It is not always clear whether a specific defect is functional or cosmetic. This is especially true when the copper surface is shiny and mirror-like because any abnormality is easily visible. Close attention by the fabricator to incoming surface quality, yield losses, and failure analysis is necessary to differentiate the two and assure that quality improvement efforts address the issues.

Pinholes represent an important aspect of copper quality. There are two reasons for this. First, since pinholes penetrate the thickness of the copper, even a small pinhole can create a loss of continuity when located on a narrow trace. The second reason is that medical interconnects require laminate with thin copper. In general, pinhole size and frequency are inversely related to copper thickness.

Most pinholes arise from one of two general causes. The first is mechanical damage. As copper comes in contact with different surfaces during the laminate manufacturing process, asperities on those surfaces, or even normal roughness, can puncture or scratch the copper on small scales. An example of a pinhole caused by mechanical damage is shown in Figure 3. Careful attention to surface conditions and minimizing slip between surfaces reduces pinholes caused by mechanical means.

Figure 3 – Pinholes Caused by Mechanical Damage

The second primary cause is contaminants. Foreign material that is located on or near the surface of the polyimide substrate inhibits the normal deposition of metal layers. In some cases, the metal layers do not cover the contaminant, which immediately creates a pinhole. In others, the contaminant is covered initially, and the pinhole is created during subsequent steps in the laminate manufacturing process. An example of a pinhole caused by a contaminant is shown in Figure 4. Careful attention to the film substrate and maintaining clean environments at all times minimizes pinholes caused by contaminants.

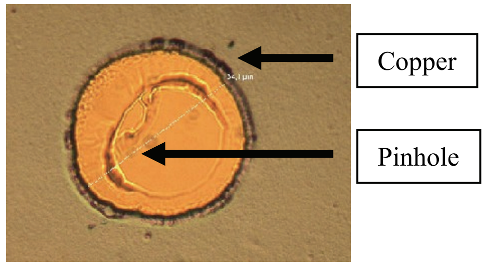

Figure 4 – Pinhole Caused by Contamination

Analytical tools can be used to characterize pinholes and indicate likely causes. As an example, the image in Figure 4 was obtained using optical microscopy. The pinhole has a regular, circular shape, a highly delineated edge, and is about 24 µm in diameter. There is no deformation of the surrounding copper. These features reduce the likelihood that the pinhole was caused by mechanical means. Inspection of the image suggests an abnormality is present on the exposed Kapton surface, and etching the copper from the surrounding area supports the idea. Analysis by focused ion beam cross-sectioning techniques is shown in Figure 5 and reveals that a contaminant is located on the surface of the polyimide. The contaminant is partially covered by metallization at the edges. Analysis of the contaminant spot by EDX indicates the presence of chlorine and fluorine. The analyses in this case indicated the pinhole is caused by a contaminant with some inorganic character, and determined the contamination occurred before sputtering. This type of information allows engineers to prioritize and focus efforts to locate the source of the contamination.

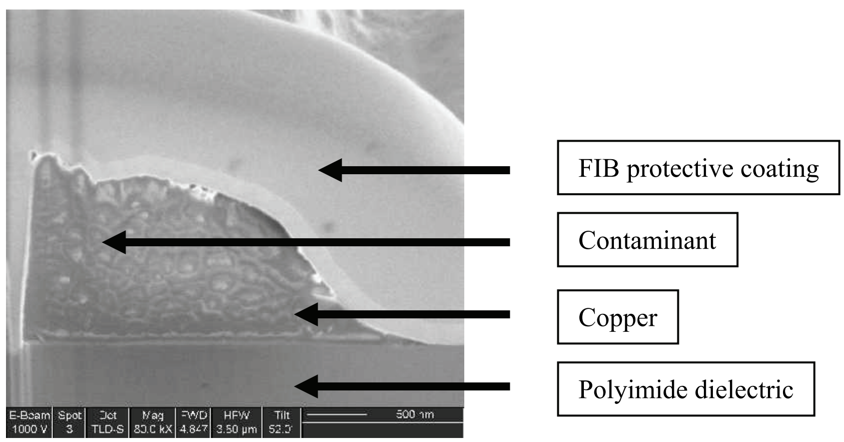

Figure 5 – Cross-Section of Contaminant Obtained by FIB

Pinholes in commercial adhesiveless laminate were systematically studied over the last couple of years. They have been classified based on size, shape, location, frequency, presence of debris, and other factors. Over two dozen pinhole types have been identified. Each pinhole type has been analyzed, as illustrated above, to determine most likely root cause. Relative frequencies have been ranked and serve to prioritize pinhole reduction efforts.

The classification scheme and detailed analyses serve as a basis for pinhole quality control in the manufacturing environment. A sample is analyzed using a laser scanning technique to determine the number and sizes of pinholes. If pinholes are out of specification, individual pinholes are viewed using an optical microscope. The pinholes are classified based on the optical results, and the most likely root cause is obtained from the pinhole study. Hence, the optical analysis points to root cause and most effective action. The approach has been used to help reduce pinholes significantly and serves to allow rapid containment if pinholes exceed specification.

Summary and Conclusions

Design features of flexible circuit interconnects for ultrasound transducer applications are described. These circuits are among the most sophisticated and difficult to fabricate in the industry and make good representative circuits for medical applications more generally. The polyimide dielectric can be as thin as 12 micron. Circuits are typically double-sided and contain a ground layer. They contain ultra-high density regions that push the limits of currently available technology. Lines and spaces can be as small as 20 to 30 micron, and via diameters can be as small as 25 micron. Tight spatial tolerance and good critical dimension control are required to maintain good alignment at terminations and side-to-side registration between vias and pads. Nickel and gold, indium, or solder surface finishes are applied to ensure good connections and high reliability.

The interconnect design features place stringent demands on the laminate base material. Adhesiveless, polyimide-based laminates made using sputtering and electroplating technologies fulfill the necessary requirements. High performance polyimides provide the mechanical and thermal stability needed to ensure thin dielectric can be processed without significant wrinkling or creasing. The direct deposited approach provides thin copper. Copper 2 µm thick is routinely plated, and 0.2 µm thick copper is available without plating. Thin copper and smooth interfaces facilitate fine-line etching and high density circuitry. Good adhesion is critical to ensure fine-line features remain intact throughout the fabrication process. Peel strength exceeding 6 lb/in is achieved by pretreating the polyimide surface with plasma and applying a suitable tiecoat metal between copper and polyimide. Laminate dimensional stability after etching and heating exceeds the IPC specification and promotes good alignment and registration of circuit features. Fine-line features imply strict copper quality requirements, particularly regarding pinholes. Systematic analyses have been done to classify pinholes and link different types to their likely causes. The classification scheme and detailed analyses serve as a basis for pinhole quality control in the manufacturing environment. The approach has been used to help reduce pinholes significantly and serves to allow rapid containment if pinholes arise.

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