Thermal Management of High Frequency Circuits by Blind Hole Technology

Dr Sundaram N Kumar
American Standard Circuits, Inc.
475 Industrial Drive
West Chicago, IL 60185
www.asc-i.com
Email: skumar@asc-i.com

Abstract

For effective thermal management of high power and dense electronics, the heat sink forms the bulkiest component, and aluminum, owing to its light weight and easy machinability, is the preferred choice for airborne PCB devices used in aerospace and defense telecommunications. In this paper, we present a versatile and robust fabrication method to build circuit boards used for RF and microwave telecommunication devices over a large frequency of interest from MHz up to several tens of GHz range. Typically, 1 mil of copper is plated in the blind holes, followed by the desired final finish applied to it (nickel/gold, tin/lead, chromate). There can be several inner copper layers anchored to the blind holes. Cross sectional examination showed that the connectivity of the inner layer(s) with the barrel wall was very good and no delamination of the hole wall occurred even after 1,000 thermal cycles of (-40°C to +100°C) excursions were carried out in an automated thermal cycling chamber. Resistivity of the blind hole coupons with the 1 mil copper layer (protected by a 0.1 mil tin coating), with 300 mA of current applied, was always less than 0.0006 milli ohm even after 1000 thermal cycles.

Introduction

In a printed circuit board used typically in any advanced type of electronic assembly, significant amount of heat is generated during its operation when it is powered by electrical energy[1,2]. One way to classify the electronic devices is whether they use any active semiconductor electronic junction or use a high frequency telecommunication circuitry, such as, the one used in radio frequency (RF) or microwave (MW) frequency communication. In the former case, it is the collision of electrons (carriers) with the atoms in the semiconductor that generates the major portion of heat, while in the later case, it is the so called "skin effect" in the copper conductor trace that results in the generation of heat, which, again, nevertheless, is due to the resistance offered to the movement of electrons in the conductor metal. The higher the transmission frequency is, the more pronounced will be the skin effect and temperature rise. Heat is also generated due to the core losses in inductors, transformers and switching losses in high speed transistors.

It is important to recognize the great potential and accompanying challenges in the emerging high frequency telecommunication industry. The market in the wireless sector is forecast[3] to be more than 30 billion devices by the year 2020, including the fast growing market sector of RF/MW circuitry in advanced missiles, unmanned aerial vehicle (UAV), radars, rockets, planes, and the defense/public sector telecommunication industry. Rapid advances in telecommunication industry have forced populating larger number of electronic and RF/MW devices and using ever increasing frequencies. These constraints require efficient thermal management. Thermal management plays a very important role in the design of RF and microwave (MW) electronic devices, (see, for example, S. Maurya et. al.[4]). A fairly large quantity of heat is generated when signals are processed in high-frequency applications. This is particularly true in the amplification of high frequency signals. Options for thermal management in RF/MW circuits are more limited when compared with those available for the semiconductor devices. In thermal management of PCBs containing semiconductor devices, the main consideration is given to the amount of maximum heat generated and the corresponding material selection of the system to manage the heat transfer, the dielectric breakdown voltage, and thermal mismatch of CTEs of materials chosen. The temperature dependence of dielectric constant and its value have no significant role in the semiconductor device performance, whereas for RF/MW circuits used in telecommunication, the dielectric constant plays the central role. Reliable performance of an RF or a MW device depends on maintaining a constant value of the dielectric constant of the printed circuit board (PCB)'s dielectric layer. Since the dielectric constant varies with temperature, a good understanding of the flow of heat through the device will greatly help to improve the performance and reliability of the RF/MW circuit.

The dielectric constant varies as a function of temperature and it will have a direct impact on the high frequency performance of the circuit since changes in the dielectric constant will result in changes in the RF/microwave circuit impedance. Variation in dielectric constant occurs because any rise in temperature results in an increase of thermal conductivity and, consequently, a decrease in the dielectric constant (since the dielectric constant is inversely proportional to the thermal conductivity). As the device temperature increases, the molecules of the dielectric material would have more thermal energy, and, therefore, the amplitude of random motion would be greater. This means that the molecules are less closely aligned with each other (even in the presence of an electric field), thereby resulting in a decrease of the dielectric constant. The transfer of high frequency signals of RF or microwave devices through a PCB should occur with minimum signal amplitude loss or phase distortion. Signal loss occurs when some of the electrical energy is converted into heat and signal phase distortion occurs when the heat is not quickly dissipated away from the active junction. Loss of signal amplitude or distortion in phase will severely impact the device performance. Tightly controlled thermal coefficient of dielectric constant and coefficient of thermal expansion (CTE) characteristics are required to ensure that PCB material will deliver reliable and good performance of the active device signal, particularly when handling high power levels. Elrashidi et. al.[5] have done a detailed study on the effect of temperature on the resonance frequency of RT/Duroid 5880 PTFE substrate (manufactured by Rogers Corporation) which is one of the common substrate materials chosen for RF or microwave circuit fabrication. These authors have observed that a decrease in resonance frequency of almost 20 MHz occurs for a 50 C rise in temperature. Such a decrease in resonance frequency would obviously result in an increase in the return losses. Thus, for a reliable performance of the RF/MW device, it is critical that the temperature of the circuitry does not increase due to the heat build-up.

It is important to dissipate the heat from the conductor traces quickly so that its temperature remains below the threshold value (temperature at which signal distortion happens). Further, the underlying dielectric material is kept sufficiently thick so as to reduce the thermal build-up in narrow pathways of the dielectric. Performance degradation due to excessive heating becomes particularly severe for high bias line current circuitry since this line must be quite narrow to meet the required impedance value, and hence would generate considerable heat.

The materials and dimensions of the conductor trace, dielectric layer material and the heat sink material are chosen depending on the functionality of the communication device (which is decided by the frequency of operation, effective dielectric constant, dissipation factor, tangent loss factor and the impedance value). Proper fabrication process, material selection and circuit design of PCBs for good thermal management are the central issues in making a successful RF/MW circuit. As we move towards more complex, high speed and high frequency signal processing, increasing amount of input power is converted into heat due to higher insertion loss in the skin depth zone of the copper traces. As the frequency increases, the amount of heat generated also increases due to decreased cross sectional area of the skin zone, through which the signals propagate. For example, the skin depth for 10 MHz is 0.822 mil thick whereas for 10 GHz frequency the skin depth is only 0.026 mil. Heat is generated due to high insertion losses on the copper conductor traces of the microstrip and stripline configurations (Insertion loss is the loss of signal power resulting from the insertion of a device in a transmission line and is usually expressed in decibels (dB)). Heat flows from the hotter to cooler areas of the system by conduction (physical contact), convection (energy flow through a fluid by temperature dependency of density), and by radiation (energy flow by infrared radiation release). Of these three modes of heat transfer in a circuit board, it is the conduction mode that enters as the principal means to dissipate heat from the conductor trace to the heat sink.

Fabrication of thermally managed RF circuits:

Thermal management of an RF/microwave component, circuit, or system is simply a matter of removing heat from sensitive areas of a design that can suffer damage or performance degradation from the heat. Basically there are two broad categories of making thermally managed circuits: One is post-bonded laminate and the other is the pre-bonded laminate. As the name suggests, in the post-bonded PCB, the circuit layers are fabricated first and the ground plane of the PCB is firmly bonded to a heavy heat sink layer that has enough heat capacity to completely absorb all the heat generated during the operation of the devices. The ground plane layer of the PCB is thermally connected to all the active and passive electronic devices of the PCB that would generate heat, so that heat from various heat generating sources is efficiently transmitted to the heat sink. The PCB layers have plated through holes and the heat is transmitted through these plated through holes to the bottom ground plane that is bonded to the heat sink body. The heat collected by the heat sink is then emitted out to the ambient, away from the electronic device cluster. There are some serious structural stability issues of the bonded heat sink as discussed below. In the pre-bonded laminates, the PCB layers come already bonded with a heavy heat sink that would have adequate heat capacity to absorb the heat generated by the functioning of various devices and effectively transmit to the ambient. Heat generated in various circuit layers is transferred to the heat sink through various blind holes of the PCB structure. These two configurations are discussed below:

(a) Post-bonded Laminates: In the post-cladding process, the circuit board is first fabricated as a multilayer through-hole plated board. The ground plane of this multilayer board is then electroplated with layers of electrolytic gold over electrolytic nickel (Cu/Ni/Au). The gold plated ground plane is then sweat soldered with the aluminum heat sink. The heat from the ground plane is thus quickly dissipated into the heat sink body. Since the heat sink and the ground plane surfaces are joined by a thin molten layer of sweat solder, *the reliability of bonding between the sweat soldered ground plane and the heat sink surface is limited because the flow of the molten solder is difficult to control.* Open circuits may thus result from a lack of solder (solder starvation) connecting the ground plane with the heat sink surface. Further, sweat soldering technique requires the fine tuning of multiple process parameters such as, solder volume, solder composition, solder flow, bonding temperature, pressure, and, most important, the planarity/flatness and parallelness between the layers being bonded. Solder composition controls the tensile strength and melting point of the solder, for example, a higher percentage (than the eutectic composition) of lead results in more malleable (preferred) bonded interface that would be less sensitive to cracking, but unfortunately it would significantly increase the melting point (much above 520 F). The higher melting point would require higher bonding temperature. Conversely, higher percentage of tin would result in higher tensile strength, with more brittleness and lower melting point. Therefore, the limited range of usable melting points restricts the number of times an assembly can be processed. Each sequential processing step must be performed at a relatively lower temperature in order to avoid re-melting solder from a previous step. This limitation restricts the number of RF circuits that can be reliably interconnected in a sub-assembly and, therefore, limits the functionality. Further, solder joints are very susceptible to failure due to fatigue from temperature excursions encountered at high altitudes. Overall, the fabrication process using sweat solder approach is more of a judgmental procedure than a precisely defined process. The difficulty in controlling board flatness further complicates the soldering process problems because no two boards to be interconnected are perfectly flat. Soldering limitations require two PCBs to be flat and parallel within, e.g., 0.003″-0.004″, in order to assure the solder will bridge the gap evenly between connections on the boards to be interconnected. Providing boards having flatness within 0.003″-0.004″ requires relatively demanding tolerances during the design and fabrication of the PWBs.

(b) Pre-bonded Laminates using Metalized Blind-Holes: The starting material for the pre-bonded version is a composite material consisting of a relatively soft dielectric substrate and a thick metal plate. The optimum parameters for mechanically processing these materials differ widely. The metals to choose from may have different plating properties. For example, copper and brass can be plated without much difficulty. However, aluminum, which is a preferred material for air-borne telecommunication devices due to its much lighter weight than copper or brass and easy machinability, requires special pretreatments and coatings before copper metallization of blind vias and other subsequent surface finishes.

One efficient way to dissipate the heat by conduction from the conductor traces is connecting them to the heat sink through metalized blind holes. These blind holes go into the metal base and the cylindrical barrel of such a hole should have a sufficiently thick copper plating (typically, 0.7 mil to 1.0 mil thickness) so that the heat is efficiently transferred to the heat sink. A schematic of the blind hole construction is shown in Figure 1 below. The heat generated on the XY plane of the circuitry, during the operation of devices, is transported through these vias to the heavy heat sink. The thickness and width of copper conductor traces, the thickness of copper plating in the holes, heat sink's heat capacity and the ability of the later to radiate out the heat efficiently will control the cooling of the overall device.

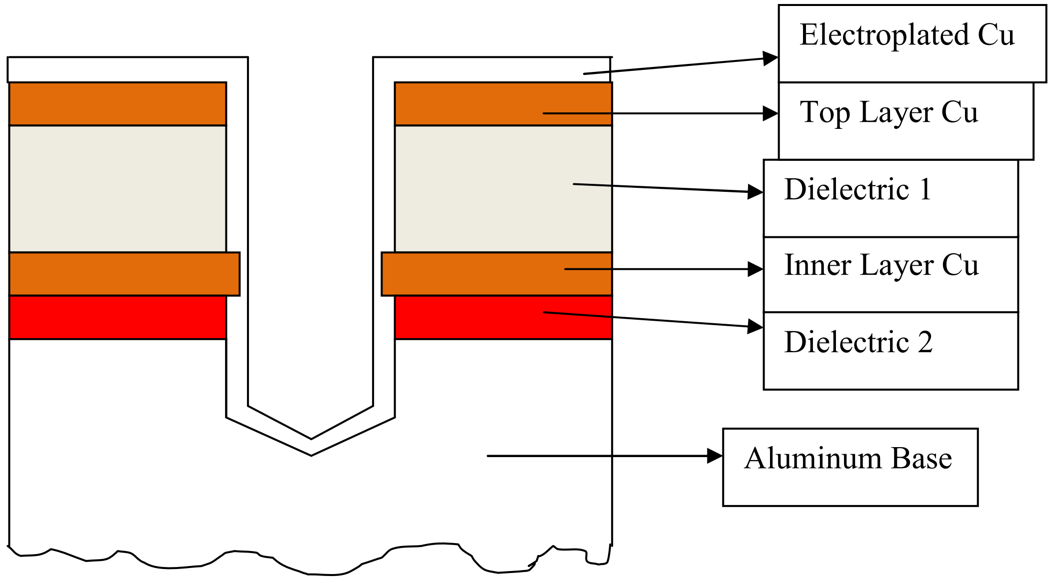


Figure 1: Schematic of multilayer dielectrics and copper layers with drilled blind hole in a pre-bonded laminate with a heavy aluminum backing. The chemically and physically conditioned blind hole (by suitable wet process zincating and magnetron copper sputtering) is subsequently electroplated with copper.

The blind hole plating quality becomes the gating factor for efficient thermal management of the device. The copper must plate uniformly in the hole wall, and be preferably 1 mil or more thick in the hole wall. In order that the hole wall plating successfully withstands the rigorous thermal cycling and thermal stress for airborne hostile applications, it is necessary that the plated copper has a minimum of 36 kpsi of tensile strength and an elongation of a minimum of 12%. Our copper plating in the holes has typical tensile strength and elongation of 44.37 kpsi and 22.17%, with a standard deviation of 4.2 kpsi and 2.5% respectively. The mechanical properties of our copper plating in the holes thus exceed the airborne applications' requirements. More important is the robustness of the metallic layer to anchor firmly with the hole wall during the thermal cycling and stress tests. It is in this respect that our fabrication process deposits copper film that has a very good adhesion to the hole wall. The unique combination of chemical and physical process steps have demonstrated high quality hole wall integrity as seen by the cross section and electrical resistivity measurements after more than 1000 thermal cycles between -40C and +100C.

The RF/MW circuitry should be designed in such a way that all conductor patterns are thermally well connected via the blind-holes to the heat sink. It is important that there are no hot spot is created by even a single improperly plated or defective blind hole. A defective blind hole may result due to peeling away or blistering of plated copper or insufficient copper plating thickness in the hole wall. The heat sink should have a high specific heat to absorb the maximum total heat that would get generated under extreme, practical situations. It is also preferred that the outer surface of the heat sink (so called carrier plate) has a high thermal emissivity so that any heat retained by the carrier is quickly emitted to the ambient.

The blind-hole approach is a very robust and reliable metallization process for the RF/MW circuits deployed in hostile air-borne applications, such as, in defense navigation systems, missiles, and military and non-military satellite communication devices. The thick aluminum heat sink comes pre-bonded with the dielectric and copper layers. This method of fabrication does not have any of the disadvantages mentioned in the above two approaches. The fabrication process uses pre-clad RF dielectric materials, such as Rogers RT Duroid, PTFE, ceramic or epoxy layer, or similar materials made by Taconic, Nelco, etc. These laminates have the circuit copper foil clad to a dielectric that is thermally stable and has low tangent loss factor. Tangent loss factor is a measure of how much of the electromagnetic field travelling through a dielectric is absorbed or lost in the dielectric. This property is one of the least well understood of all those that characterize RF/MW laminates. As a result, expensive, ultra-low loss materials are unnecessarily used in digital applications when they are not actually needed. The dielectric is bonded on the other side with thick aluminum, brass or copper heat sink. Here our interest is primarily on the aluminum based laminates since, being light in weight and having excellent machininability, they are obviously preferred as heats sinks for air-borne MW or RF circuits. Unfortunately, aluminum is one of the most difficult metals to plate on. Due to its extremely high electrochemical reactivity, aluminum is incompatible with most of the chemical processing used in printed circuit manufacturing. To plate on aluminum, the oxide layer must first be removed and then immediately zincated in a wet process condition to form a thin (displacement type) zinc coating. The zinc layer is then plated with electroless nickel. Once the aluminum surface of the blind-hole is metalized, the entire barrel of the blind-hole is coated with a thin layer of sputtered copper and then electroplated with a thick copper layer. We call this process as the Chemical Physical Metallization (CPM) process. Details of the CPM process are described below in a later section.

A schematic comparison of through and blind-hole cross section is shown below in Figure 2.

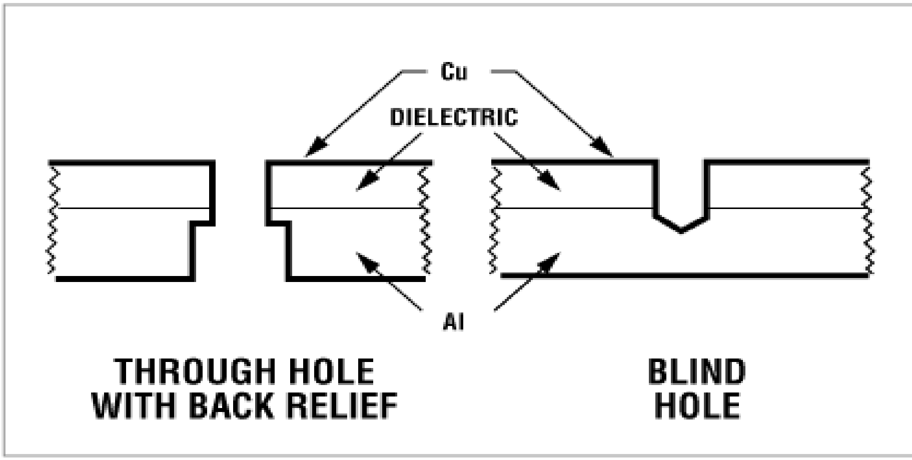


Figure 2: Cross sectional schematic view of the through-hole drilled and blind-hole drilled samples. The bottom base is the thick heat sink, for which an aluminum alloy is preferred for air-borne devices, owing to its light weight. For ground applications, like antenna, copper or brass can also be used (Reference 6).

A completely wet process approach to metalize the barrel (without using physical vapor deposition technique of sputtering) is to electroless copper plate, using the classical aqueous formaldehyde alkaline electroless copper chemistry, to plate the blind holes. However, it is quite difficult to do successful electroless copper metallization of the dielectric layer(s) in a blind hole (there could be a single dielectric or multilayer dielectric barrel) by wet process chemistry, since the holes are blind and the hydrogen gas that evolves during the copper reduction step in the alkaline electroless copper bath will remain trapped inside the blind holes and would not permit the deposition of copper: since one molecule of hydrogen gas is produced for every atom of copper metal deposited, the process carries an inherent risk of entrapped hydrogen over the substrate that will prevent the copper to deposit. Hydrogen gas can pass through a through hole and escape out, but will have no escape route in a blind hole. Entrapment of hydrogen bubbles is particularly serious in a vertical electroless copper bath. In a horizontal bath, hydrogen gas, being lighter than air, may escape out by vigorous shaking or ultrasonic vibration of the panel and may allow copper to deposit, but even then, a complete coverage may not be guaranteed.

Blind holes with aluminum heat sink can also be metalized by anodization. Here the blind holes are anodized by forming a porous oxide film in an oxidizing electrolytic bath by passage of electric current. Under proper anodization conditions, it is possible to create porous oxide film with correct pore size and density[7]. These pores can then be electrolytically filled with copper particles in a copper electroplating solution. Since there is a thin aluminum oxide barrier layer between the filled copper particles porous oxide matrix and the base aluminum, there is some electrical resistivity of blind holes due to the thin aluminum oxide layer.

The design of the thermal pathway via blind holes to the aluminum heat-sink can be used successfully for the thermal management of the RF/microwave high-power circuits. For air-borne applications, aluminum is a preferred heat sink material due to its light weight and good machining properties, thus making it ideally suited for aerospace applications. Good machining capability of aluminum is necessary for fabricating intricate three dimensional shapes. Also, aluminum has a high specific heat value and thus can extract more heat from the circuitry. However, aluminum poses serious problems in PCB fabrication due to its highly electropositive chemical nature that prevents any metal to chemically deposit on it. Under normal ambient conditions, a continuous and blocking aluminum oxide (Al_2O_3) layer of about 5 nm forms on the surface of Al or its alloys upon exposure to oxygen or dry air. This oxide layer prevents electro-deposition or electroless deposition of any metal on its surface that is essential to build up the electrical continuity with the ground plane.

To overcome the problem of this inherent limitation of aluminum of not allowing any metal to plate on it, we have developed a unique sequence of processes to plate copper over drilled blind holes in the copper cladded dielectrics with thick aluminum backing used for RF and microwave PCB fabrication. The dielectric used can be PTFE based dielectrics, polyimides or suitable ceramic loaded high temperature microwave composites (such as Rogers TMM). We have also developed sputtering processes to build HF circuits on ceramic substrates such as alumina, aluminum nitride, quartz or cordierite, which we plan to report and discuss in another paper.

The electrical energy converted into thermal energy at various component levels needs to be efficiently transmitted from the PCB assembly to the underlying heat sink quickly so that no distortion in the electronic signal due to temperature rise happens at any location. One way to dissipate all the heat away from the heat-generating active and passive components is to mount them in sufficiently thick copper plated blind holes that are properly thermally coupled to an aluminum (or brass or copper) heat sink of sufficient thickness/heat capacity, such that the electronic junctions always remain below their critical operating temperature. Obviously, blind holes with electroplated copper barrel, is a preferred material for heat transfer, since it has a high thermal conductivity (of about 400 W/mK).

PRESENT APPROACH

In this paper, we describe the process technology to fabricate boards that find applications in HF circuits, over a wide spectrum, ranging from MHz to up to 80 GHz frequencies. This is accomplished by a sequence of chemical and physical treatments as described below.

We call the metallization process presented herein as the Chemical Physical Metallization (CPM) process. Using this CPM process, we have successfully plated prebonded laminates with various types of dielectrics. We have developed a fabrication technology that encompasses complex circuits with mixed dielectrics and multiple inner layers of copper connected to the ground heat sink body. With mixed dielectric multi layer circuits using appropriate heat sink and blind-hole technology, these circuits are suitable for a wide spectrum of applications, from high frequency range to analog and digital devices.

In the CPM technology of PCB fabrication, we use a series of wet processing steps to metalize aluminum interface of the blind-hole as well as not to significantly damage the copper layers (which occurs particularly during the aluminum conditioning process), such that once the aluminum surface in the blind hole is metalized, the inner Cu layers exhibit a slight positive etch back on copper edge. The subsequent thick copper built up on the entire barrel will thus have a slight protrusion of the copper inner layers – a highly desired feature.

The blind-hole drilled panels with inner layer copper are drilled such that there is a positive copper protrusion of inner copper layers. By proper surface treatments, we cover the aluminum blind-hole wall with a layer of zinc and a layer of nickel. The entire barrel of the blind-hole is then metalized by a thin copper layer (about 30 to 40 μinch) using a proprietary sputter deposition technology. The barrel metalized with this thin copper layer is subsequently electroplated with a thick copper layer, usually from 0.7 to 1.2 mil thickness. The exact plated copper thickness is dictated by the power load requirements. The board is then processed through the usual PCB fabrication steps.

In a RF/MW substrate, a sputtered blind-hole performs the same way as a chemically plated hole. The electrical properties are exactly the same since the bulk of conduction takes place through the electroplated Cu in both cases. A blind-hole is mechanically stronger as the barrel of Cu is firmly anchored inside a cavity surrounded by the bulk metal. As part of the manufacturing process, substrates with blind holes are routinely subjected to solder reflow in hot oil or IR oven at temperatures of up to 250°C. The resulting thermal shock and cycling does not affect the integrity of the blind-hole as confirmed by examining metallurgical cross section of such holes.

The processing sequence of the CPM technology is given below.

1. Drill controlled depth blind holes as per the circuit design
2. Drill out the standard coupon with blind holes with aspect ratio and diameter close to those in the circuitry
3. Zincate and electroless nickel plate the aluminum surface of the blind holes using wet chemical plating process (see Figure 2 below)
4. Sputter deposit a thin layer of copper on the barrel of the blind holes
5. Electroplate copper to the required thickness on the barrel of the blind holes
6. Proceed with the remaining normal circuit fabrication steps.

   Note: The back side of aluminum heat sink is given (a) zincating, electroless nickel, electroplated copper, nickel and gold, or (b) a chromating treatment. Since this aluminum surface is a planar surface, usually no other special treatment is required.

Description of the CPM process:

A. Blind-hole Drilling

Precise Z axis control is required for blind-hole drilling. For the purpose of drilling controlled depth blind holes, a three axis computer controlled machine, with high incremental accuracy of the machine on all the three axes, is used. The small drilling head should have a continuously variable speed of up to at least 60,000 rpm and should take standard drill/rout bits of 1/8" shank.

A microscope/video camera assembly that enables precise alignment of holes with respect to circuit features would be required.

Typically, blind holes with 20 to 50 mil diameter and up to 50 mil deep are drilled. By the use of specially selected tool bits and proper entry material, blind holes of consistently smooth surface finish can be obtained.

B. Zincating and nickel plating of blind holes

The panel with drilled blind holes on the copper/dielectric/thick aluminum laminate undergoes a series of chemical steps to properly zincate and nickel plate all the blind holes (Figure 3). The thickness and uniformity of zinc film and proper conditioning of aluminum surface of blind holes are critical to produce a robust film of zinc and nickel in the barrel of blind holes. The entire sequence of process is optimized to produce plated blind holes that successfully passed thermal cycle tests as per military requirements (1000 cycles of -40 C to +100 C with 10 minutes residence time, each at -40 C and +100 C).

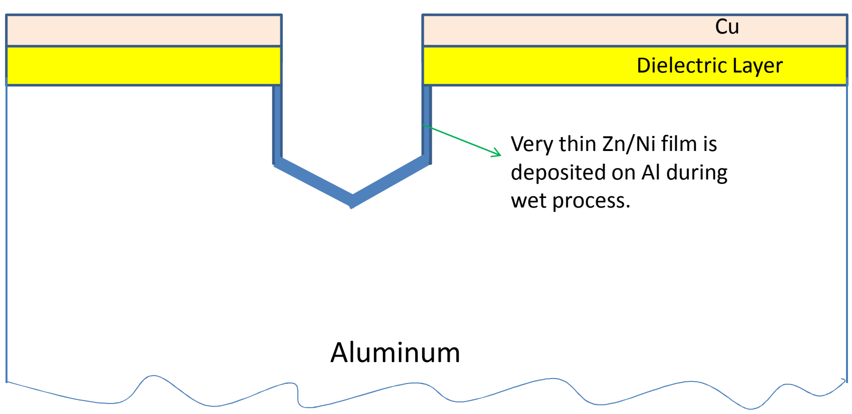


Figure 3: Zincating and electroless nickel plating of drilled blind holes

C. Sputtering

Vacuum metallization by magnetron sputtering is a well-established technique in the semiconductor industry. However, the high capital cost of equipment and the complexity of processing have precluded economical application of such methods in printed circuit board fabrication. In the present CPM technology, the zincated blind holes are plated with a thin layer of copper using magnetron sputtering. After extensive process optimization studies, the CPM process has been made economically feasible to process large volume of 18”x12” laminates.

Sputtering is a "line of sight" deposition process and the sputtered material cannot reach around a corner. Chemical plating in a liquid medium is not subjected to this restriction as long as the liquid can freely flow along the surfaces. In processing thick backed substrates by sputtering, this limitation can be overcome by the use of shallow "blind-holes" just deep enough to expose the metal backing. Sputtering can be considered to be a molecular spray of metal taking place inside the vacuum system. This spray is generated when inert gas plasma, such as, of argon ions, Ar^+, created by electric and magnetic fields, bombard a target made of the metal or alloy to be deposited. The sputtered copper atoms with high kinetic energy will get firmly anchored to any normal, clean and conditioned surface, such as the zincated and electroless nickel deposited surface by metallurgical bonding. Similarly, materials of other nature with proper surface texturing should have strong anchor points on their surfaces to enable the sputtered atoms to bond strongly on the surface. In the case of PTFE surface, its surface is known to possess highly anti-stiction properties and therefore special treatment on its surface is required to create dangling bonds (by removing fluorine atoms) to make the PTFE surface active for deposition. In our deposits, we have noticed that the sputter deposited copper bonds very strongly with the PTFE surface of the blind-hole barrel, as shown by metallurgical cross section (of the blind-holes) of the solder stressed and thermally cycled (between -40 C and 100 C) samples. No delamination of the copper-PTFE interface was noticed. Copper deposited on an unbiased glass substrate, however, peeled off, thus proving that the copper was not bonded strongly to it. Though the mechanism of strong bonding of the sputtered copper with the PTFE surface is not very clear, it appears that the energetic Ar^+ ions likely knocks off the highly electronegative fluorine atoms from the C-F bond and creates the dangling bonds on carbon, thereby allowing the Cu atoms to anchor to those sites. This process is schematically depicted below in Figure 4. The deposition process has been optimized to give a strong bonding of copper to the barrel wall.

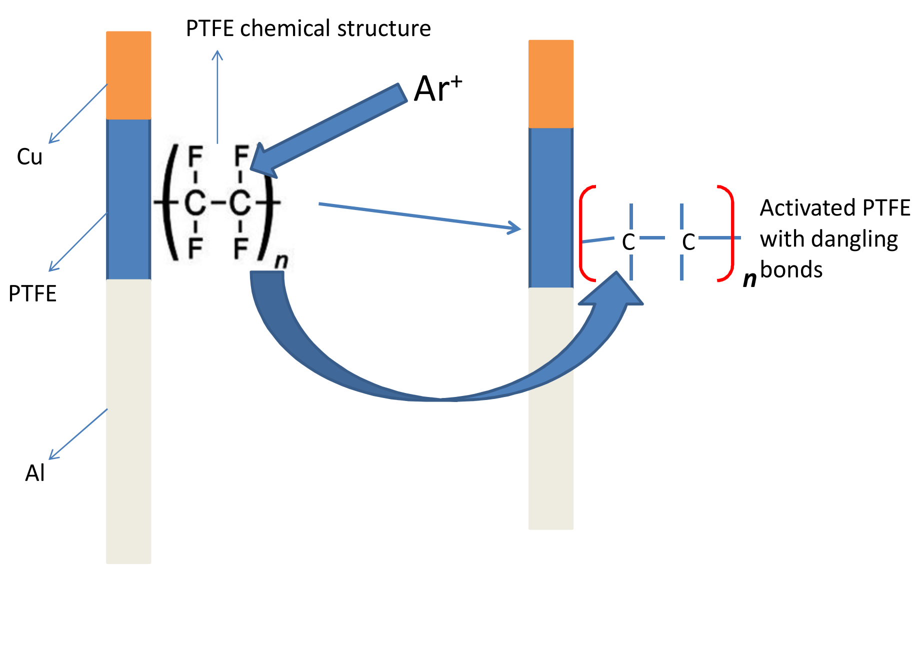


Figure 4: Proposed activation mechanism of PTFE by Ar^+ bombardment

The laminate is sputter deposited with a 100 micro inch thick copper layer by copper sputter deposition process and subsequently plated with 1 mil thick copper by acid copper electroplating. The sputtering system can process up to three 18”x12” panels in a single run and the entire process of copper deposition on the three panels takes less than 45 minutes. Argon is used to create the metal plasma. Careful system design eliminates unwanted substrate bombardment and subsequent contamination of the deposited film. The copper sputtering targets are so located that line of sight coverage occurs on the curved surfaces as well as the bottom of blind holes for an aspect ratio of up to 2. Chemical etching of the machined PTFE substrate is not necessary since the energetic Cu particles adhere to the activated PTFE interface by a strong covalent bonding. Further additional copper monolayers are gradually added by metal bonding.

After sputtering the seed layer of Cu inside the blind holes, subsequent Cu plating is done in a standard acid copper electroplating bath, which has adequate throwing power to reach inside the blind holes. The electroplated copper is anchored to the thick aluminum heat sink as shown in Figure 5, even though the surrounding dielectric material may have a very low value of thermal conductivity. It is to be noted that although the dielectric material serves as a thermal insulator, the copper barrel of the blind-hole with a thickness of 1 mil is more than adequate to efficiently transfer most of the heat.

Figure 6 shows a magnified optical micrograph of the cross section which shows a positive etch back of copper, a highly desired feature for good inner copper layer connectivity. Figure 7 shows exploded metallurgical cross section of a copper electroplated blind-hole with multiple dielectric layers and aluminum heat sink for RF/microwave circuitry application.

Solder stress test for structural integrity of the plated blind holes (Figure 8 below) and the effect of multiple thermal cycling (more than 1000 thermal cycles between +100 C and -40 C, with 10 minutes at +100 C and -40 C for each cycle) on electrical resistivity have repeatedly shown the excellent robustness of the entire blind hole metalized structure. No delamination of any kind or increase in electrical resistivity of the electrically isolated blind holes occurred after performing these Mil tests. Such a robust nature of these blind holes makes the current sputtered blind hole technology ideally and practically suitable for making high frequency circuits for air borne applications in extreme conditions, such as, the circuits used in missiles and other similar hostile environments.

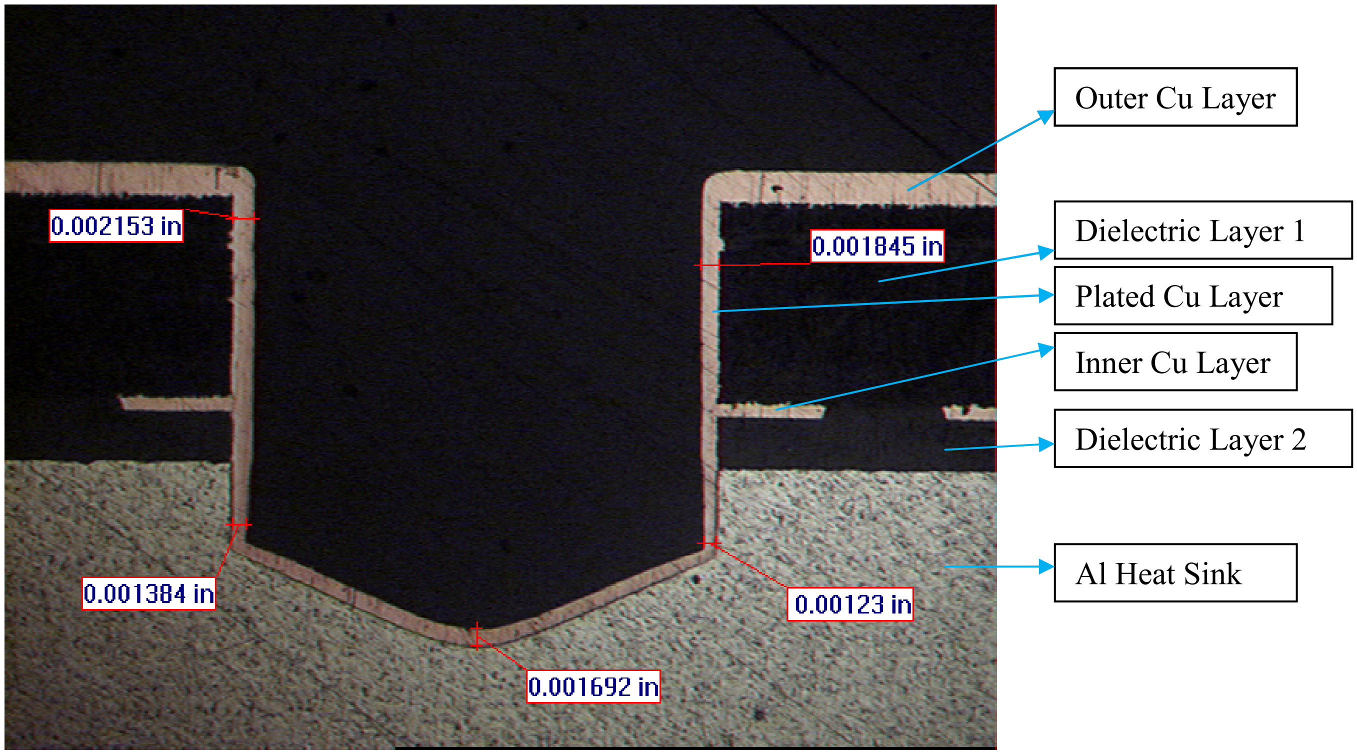


Figure 5: Copper plated blind-hole with inner copper layer with two dielectric layers and 6061 aluminum heat sink

Copper plated blind holes can help the flow and dissipation of heat from the top circuit layers through the dielectric layer(s) to the bottom ground layer, provided the copper plating thickness is sufficient to quickly conduct all the heat to the heat sink so that the circuit layer's equilibrium temperature is low and below the specified critical operating device temperature. At the same time, the interfaces of dielectric/zinc/nickel/copper of the hole-wall should strongly adhere to each other after repeated thermal stresses.

The wet chemistry for zincating and electroless nickel plating has been optimized in such a way that the inner copper layer has a positive etch back and, at the same time, the smut layer on the aluminum is completely removed to enable a thin and strongly adherent zinc layer on the aluminum hole wall. A positive etch back of inner copper layer is highly desirable for good integrity of the inner copper layer to the plated barrel. This is illustrated in figure 6 below:

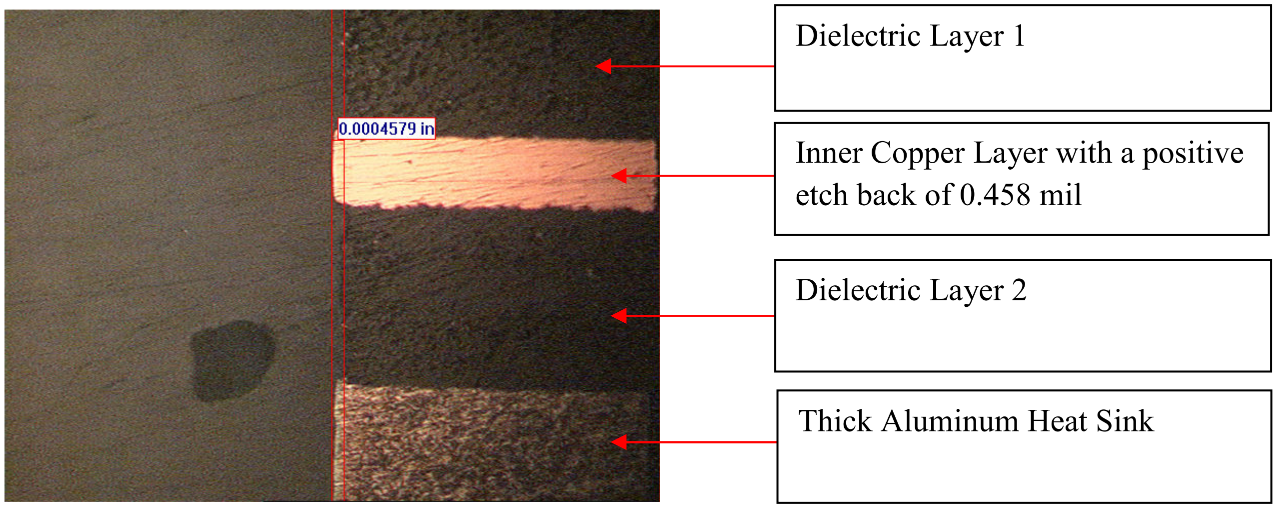


Figure 6: This figure shows the positive etch back of inner copper layer. Dielectric layer 1 is a Rogers Duroid 4003 is 20 mil thick (and is only partially shown here); dielectric layer 2 is polyimide 5.6 mil thick.

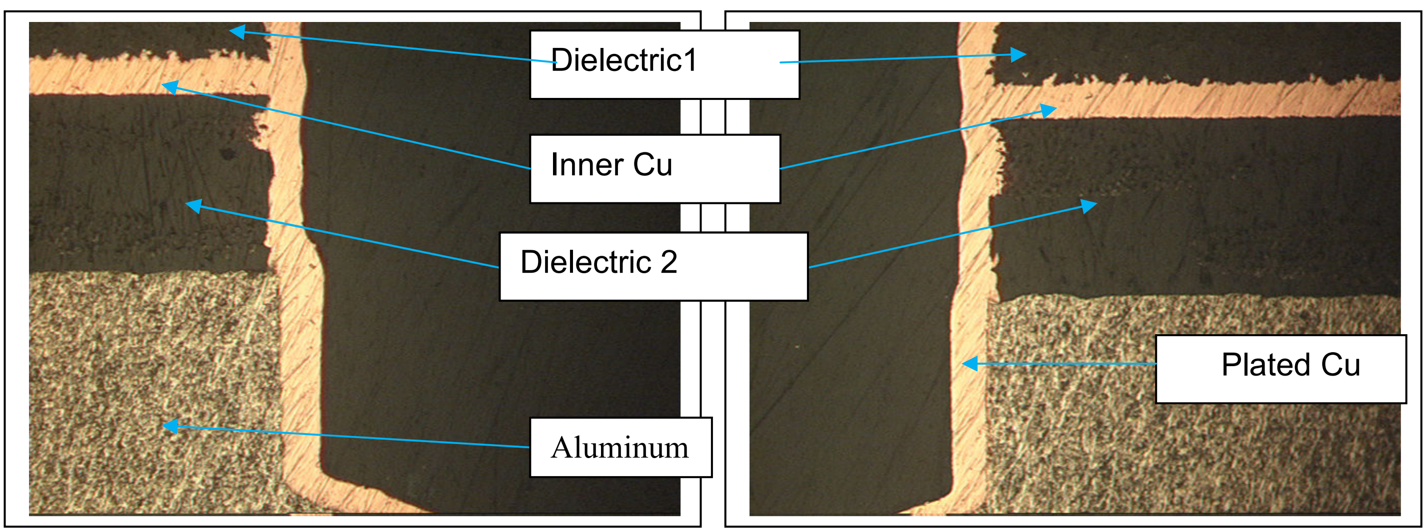
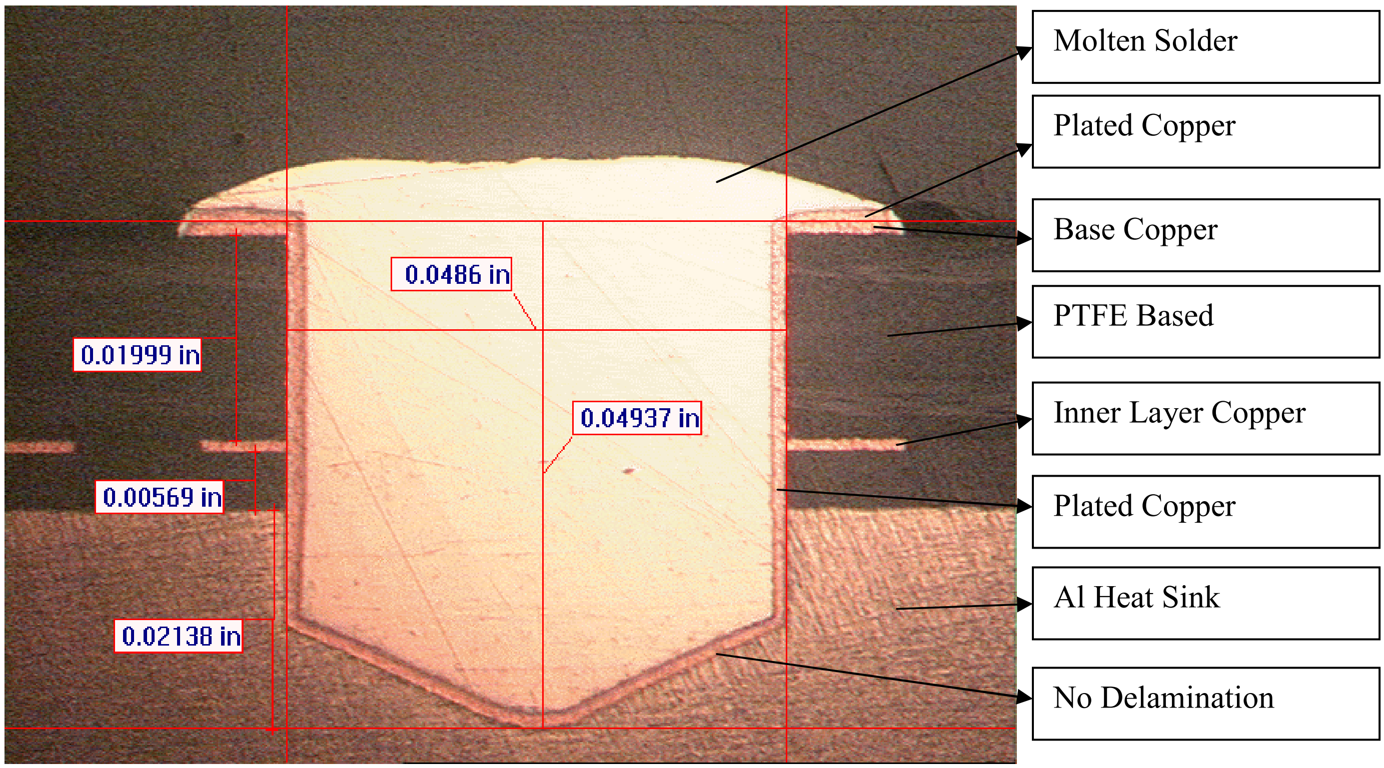


Figure 7: Exploded view of the cross section of a CPM processed blind-hole. Note the robust bonding of the 1 mil thick electroplated copper to the dielectric, inner layer copper and aluminum.

Figures 8(a) and (b) show coupon cross section after subjecting it to the IPC thermal reliability standard solder stress test, (IPC-TM-650, Method 2.6.8.). In this thermal stress test, the coupon was fluxed and then floated on the top of a molten solder pot at 288°C (550.4 °F) for 10 seconds. No delamination between aluminum and blind hole interface is noticed, with excellent integrity.

(a)



(b)

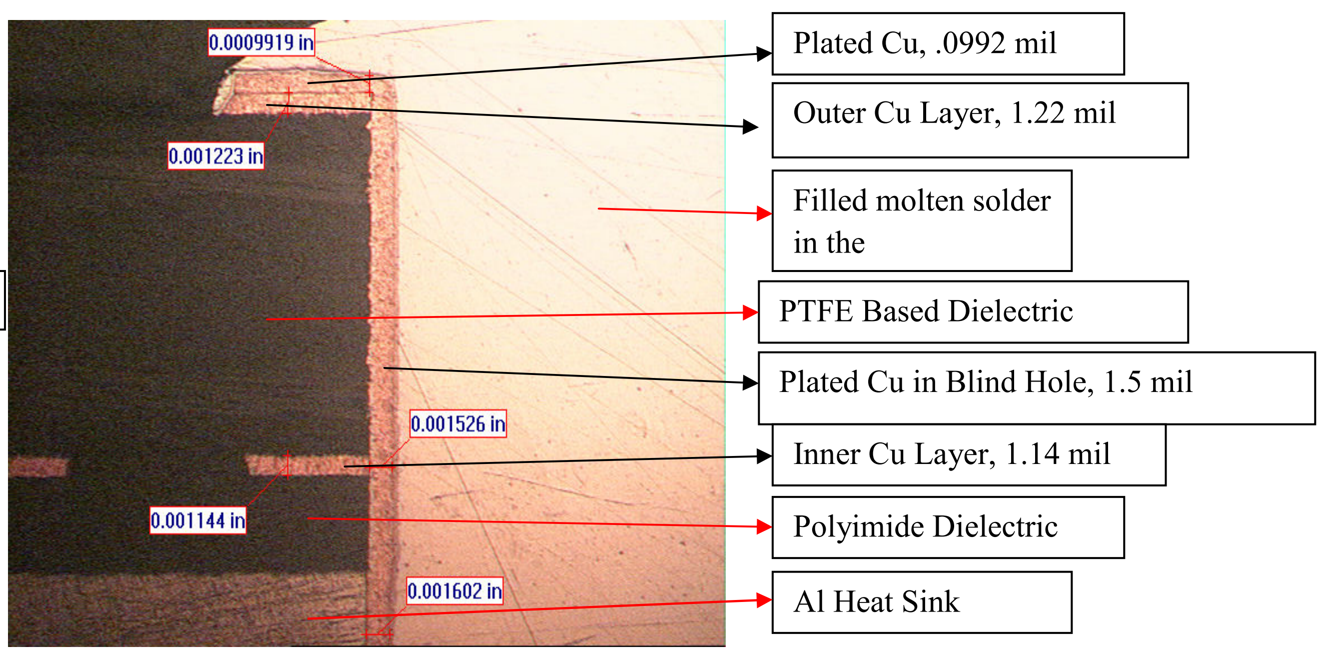


Figure 8(a): Solder Stressed Blind Hole Cross Section. The measured thickness are: PTFE based dielectric = 19.99 mil, polyimide = 5.69 mil, hole diameter=48.6 mil, hole depth=49.37, hole depth into aluminum=21.38 mil. Figure 8(b): Exploded View of Solder Stressed Section.

Excellent integrity between the blind hole-wall and the aluminum heat sink is further demonstrated in the cross section of a solder stressed coupon below (Figure 9):

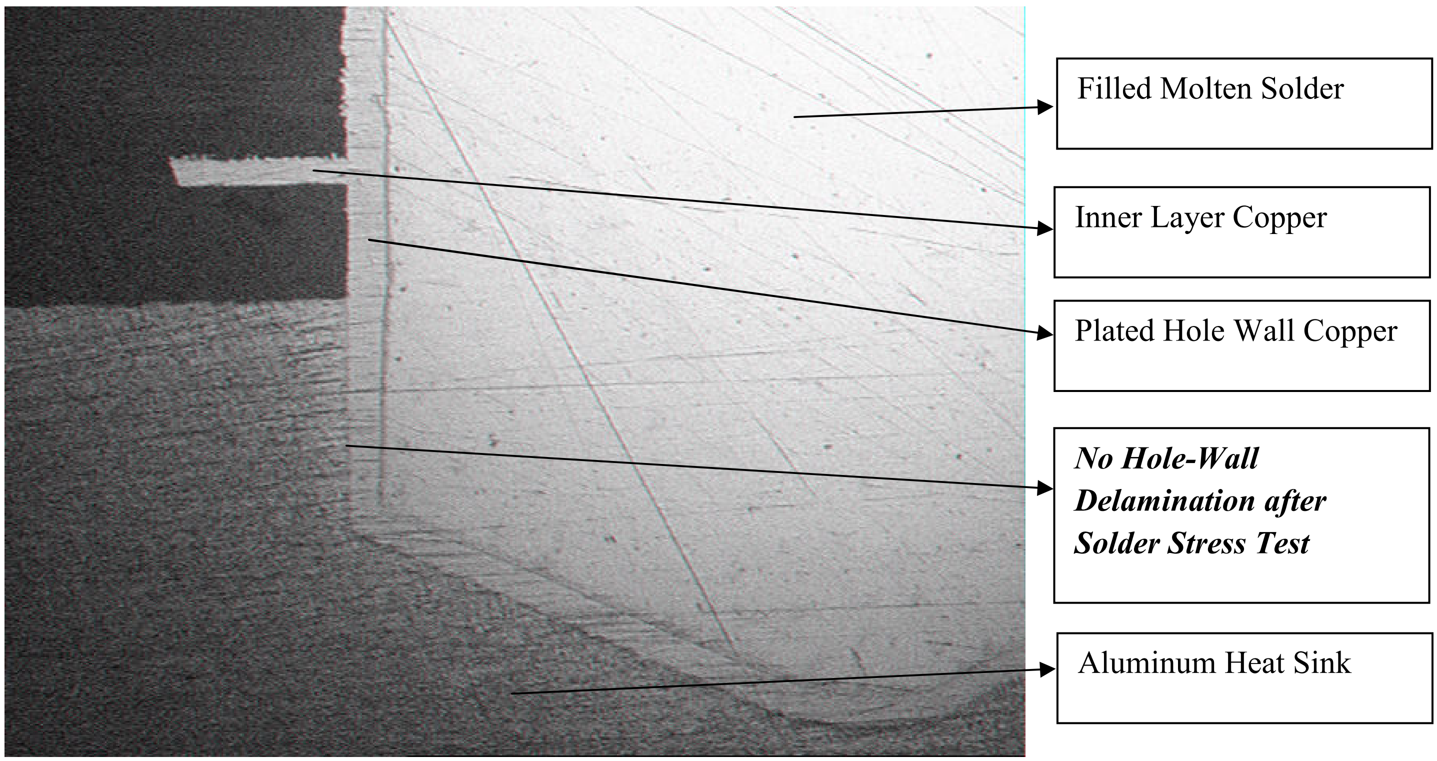


Figure 9: Another blown-up view of the solder stressed metalized blind hole coupon demonstrating the hole-wall integrity with the aluminum heat sink.

Several PCBs fabricated using the presented approach were subjected to thermal cycling tests of 1000 cycles and above, as per the MIL thermal cycling test procedure. Thermal cycling test method consists of thermal excursions of the PCB samples from -40 C to +100 C cycles, keeping for 10 minutes at each extreme temperature of this cycle. Each cycle takes about 230 minutes to complete, therefore the PCBs are subjected to a total thermal excursion period of (1000 times 230) minutes, that is, about 160 days. The resistivity of blind holes of coupons was measured after every 100 thermal cycles and no noticeable increase in resistivity across the blind-hole (see the schematic of testing shown below in Figure 10), or hole delamination was noticed, even after completing 1000 cycles. Examination of the cross section of the hole wall in all the three cases showed excellent integrity of the plated copper all along the hole wall.

After the final copper electroplating, the circuit is patterned by conventional means of photo-lithography using dry film or liquid photo resist image transfer process, and usually given a final finish of electrolytic nickel and gold.

Performance Evaluation

Since these circuits are air-borne for aerospace applications including hostile conditions, military specs require the circuits to be subjected to 1000 continuous cycles of -40 C to +100 C. To do these tests, we routinely keep our test coupons in an automated Heraeus Votsch Model VM

08/500 thermal cycling chamber that takes the coupon through this cycle for 1000 times continuously. The coupon stays for 10 minutes at each extreme of the temperature. The resistivity of the blind holes is measured before and after these thermal shocks. A schematic of the electrical resistivity measurement set-up[5] is shown in Figure 10. Tables below show the resistivity values in milli ohm of three test coupons. A current of 300 mA was passed through each electrically isolated hole and the voltage measured, and from these values the resistivity was calculated. In all the measurements the voltage reading was very low, thus showing excellent electrical conductivity of the plated blind holes and high stability of the plated holes. Tests are also planned to characterize the microwave properties of the blind holes, especially the effective inductance and the path length to ground plane.

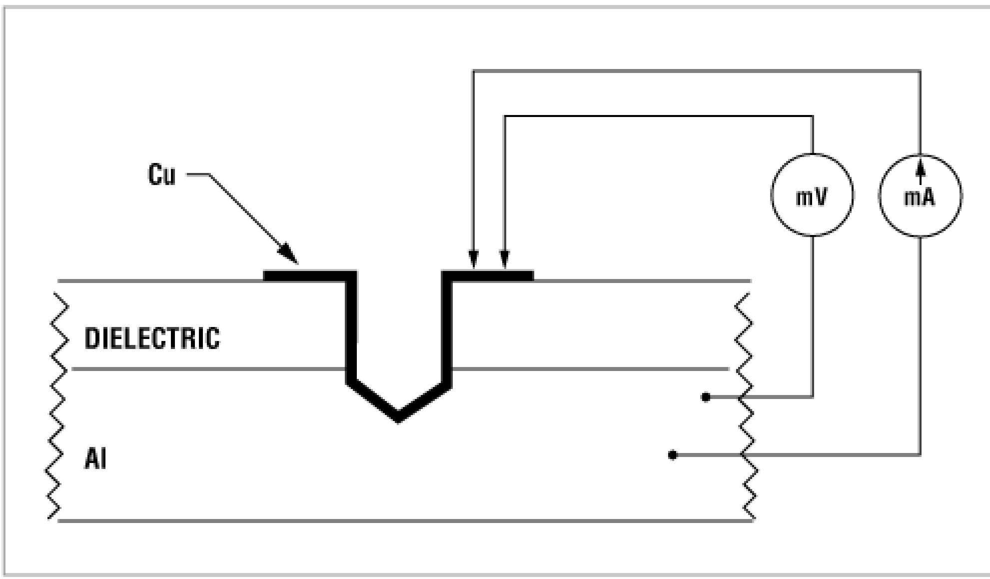


Figure 10: Schematic of the measurement of electrical resistivity of 1 mil copper plated blind-hole. Cu is mostly plated with a thin tin or tin-lead (60:40) layer. Tin-lead or tin plating ensures protection of the copper plated blind holes against oxidation during thermal cycles, thereby ensuring no increase in the resistivity due to copper (Reference 6).

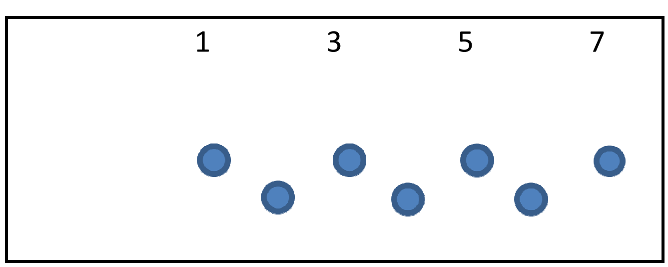
The following Tables 1 to 3 give electrical resistivity values of three blind-hole coupons in milli-ohm up to 1000 thermal cycles: Table 1 gives electrical resistivity of coupon 1 - it is a 2.7 mil layer of Cu over a 20 mil layer of Rogers Duroid 6003 with ¼" thick Al heat sink as the base, plated with 1 mil of Cu and 0.1 mil of tin in the blind holes and on top copper traces; Table 2 gives electrical resistivity of coupon 2 - it is a 2.7 mil thick Cu top layer over a single layer of 20 mil thick Rogers Duroid 6003, with ¼" thick Al heat sink, and the copper is electroplated with 1 mil of Cu; Table 3 gives electrical resistivity of coupon 3 with two layers of copper (see Fig. 5)- Outer Cu layer is 2.7 mil thick and inner Cu layer is 1.5 mil thick, and has a 20 mil thick Rogers Duroid 6003 (dielectric layer 1) and 5.3 mil polyimide layer (dielectric layer 2) with ¼" thick Al heat sink, and electroplated with 1 mil of Cu.

Table 1: Blind hole resistivity in mΩ for Coupon 1 (copper and tin electroplated)

# of Cycles	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
0	0	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0	0	0	0
		A	X	X	X	X						
		B	X	X	X	X	X: Isolated blind holes					
		C	X	X	X	X						
			1	2	3	4						

Table 2: Blind hole resistivity in mΩ for Coupon 2 (only copper electroplated)

# of Cycles	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5	Hole 6	Hole 7
0	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
100	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
200	0.0006	0.0006	0.0006	0.0006	0.0009	0.0006	0.0006
300	0.0006	0.0006	0.0006	0.0006	0.0009	0.0006	0.0006
400	0.0006	0.0006	0.0006	0.0006	0.0009	0.0006	0.0006
500	0.0009	0.0003	0.0003	0.0006	0.0009	0.0003	0.0003
600	0.0006	0.0003	0.0006	0.0006	0.0009	0.0006	0.0003
700	0.0006	0.0006	0.0003	0.0006	0.0006	0.0003	0.0006
800	0.0006	0.0006	0.0006	0.0009	0.0006	0.0006	0.0009
900	0.0003	0.0006	0.0006	0.0006	0.0009	0.002	0.002
1000	0.0006	0.0006	0.0009	0.0009	0.0009	0.002	0.002



Coupon # 2 and 3

Table 3: Blind hole resistivity in mΩ for coupon 3 of a multilayer structure (only copper electroplated)

# of approx. Cycles	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5	Hole 6	Hole 7
0	0	0	0	0	0	0	0
100	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
200	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
300	0.0	0.0	0.0	0.0	0.0	0.0	0.0
400	0.0	0.0	0.0	0.0	0.0	0.0	0.0
500	0.0	0.0	0.0	0.0	0.0	0.0	0.0
600	0.0003	0.0006	0.0006	0.0006	0.0009	0.0009	0.0006
700	0.0003	0.0003	0.0006	0.0006	0.0006	0.0006	0.0003
800	0.0006	0.0006	0.0006	0.0009	0.0006	0.0006	0.0006
900	0.0009	0.0009	0.0006	0.0009	0.0009	0.0006	0.0009
1000	0.0009	0.0006	0.0009	0.0009	0.0009	0.0009	0.0006

Conclusions

We have presented a practical approach to address the thermal management issues in demanding RF and microwave circuits. These circuits are fabricated on pre-clad Cu/ PTFE/thick Al using blind-hole metallization technology. The circuits are fabricated by using a unique combination of chemical and physical deposition processes of zincating, magnetron sputtering and electroplating. Circuits have also been successfully fabricated with multiple layers of copper (outer and inner layers) connected via blind holes to the thick aluminum heat sink. All of these circuits have successfully passed the military specs for air-borne RF/microwave device applications. Very good blind-hole wall integrity with near zero resistivity was obtained even after 1000 cycles of -40^0 C to 100^0 C thermal excursions, with 10 minutes at each extreme.

Acknowledgement

Valuable discussions with Mr. Anaya Vardya, CEO, American Standard Circuits, Inc., and the technical help and guidance of Dr K. Ramachandran of Ottawa, Canada are gratefully acknowledged. I am also indebted to Mr. Gordhan Patel, founder of American Standard Circuits, Inc., in undertaking this project.

References

1. S.N. Kumar, Educational Whitepaper, http://www.magazines007.com/pdf/ASC-WP0312.pdf; http://www.microwavejournal.com/ext/resources/whitepapers/2012/Thermal-Management-of-RF-and-Digital-Electronic-Devices-Feb-22-2012-Rev5.pdf?1378753220

2. http://www.asc-i.com/technology_articles.htm

3. https://www.abiresearch.com/press/more-than-30-billion-devices-will-wirelessly-conne

4. S. Maurya *et al.*: Effect of Temperature Variation on Microstrip Patch Antenna and Temperature Compensation Technique, International Journal of Wireless Communications and Mobile Computing. **1** (1), 35-40, (2013)

5. A. Elrashidi et. al., Effect of Temperature on the Performance of a Cylindrical Microstrip Printed Antenna for TM_{01} mode using Different Substrates. International Journal of Computer Networks & Communications, **3,** No. 5 (2011)

6. K. Ramachandran, *Sputtered Blind* Holes: A *Superior Alternative* to Chemical Plated Through Holes on Al-backed PTFE Substrate, Filtran Microcircuits, Inc., Ottawa, Ontario, Canada, Dec. 2001; www.filtranmicro.com. (Fluoroplastics, **2**: Melt Processible Fluoroplastics, ISBN=0815517289, (2002))

7. S.N. Kumar, L.K. Malhotra and K.L. Chopra, Solar Energy Materials, **7** (1983) 439-452; (*see also,* D. Mu and Y. Jin, J. Materials Science: Mats. In Electronics, **11** (2000) 239-242).