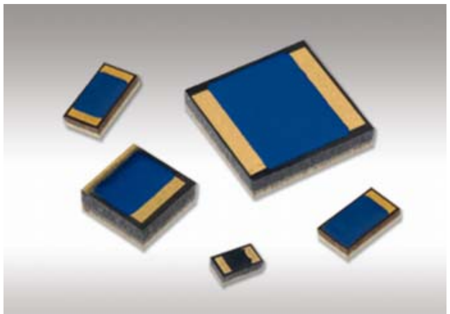
CVD Diamond High Power Resistors and Terminations

Application Note 0022



General Description:

There are many applications in RF design where it is necessary to absorb large amounts of RF power. In order to effectively absorb large amounts of power, resistors and terminations must be constructed on materials that have a high coefficient of thermal conductivity.

Commonly used substrates for high power resistors and terminations are Beryllia, Aluminum Nitride, and to a lesser extent, Boron Nitride and Silicon Carbide. While these materials are known for their superior thermal properties, none of them come even close to matching the thermal conductivity of CVD Diamond.

For example, while Beryllia and Aluminum Nitride have thermal conductivities of 285 and 185 W/m-K respectively, CVD Diamond comes in at a whopping 1000 to 1800 W/m-K. This is about 3 to 4 times that of copper. This huge increase in thermal conductivity enables RF Component Designers to produce RF components such as resistors, terminations, attenuators, power dividers, and couplers that are smaller, dissipate more power, and can operate at higher frequencies. These devices typically can provide superior RF performance for any specified power level up to 26.5 GHz and beyond.

But the outstanding thermal properties of CVD Diamond are only part of it's allure. CVD Diamond is also an incredibly stable material since it is essentially chemically inert at temperatures below 300°C. In air, CVD Diamond is unconditionally stable at temperatures up to 600°C while in a vacuum or reducing atmosphere it is unaffected by temperatures exceeding 1,200°C . This makes it unquestionably the material of choice for high reliability and space applications.

Mounting Instructions:

CVD Diamond components manufactured by EMC Technology are designed to be mounted using conventional mounting techniques. The backside ground plane of the device is sputter coated with a solderable metal and finished with about 150 nm (5.9 micro-inches) of pure gold.

The easiest method of attaching the device to a suitable heat sink is by soldering the unit with Sn96 solder (96.5% Tin / 3.5% Silver). This is a eutectic alloy that melts at 221°C (430°F) and gives excellent results. It is permissible to bring the CVD device momentarily to 300°C for 10 seconds or less to ensure adequate wetting of the surface.

These devices can also be mounted using conventional Gold-Tin Eutectic Die Bonding techniques which melt at 280ºC for the ultimate in thermal management. As with soldering, the CVD Device temperature should be kept to 300ºC or less and for not longer than 10 seconds.

Dissipating the Heat:

Resistors and Terminations manufactured on Diamond Substrates have the ability of dissipating huge amounts of thermal energy in spite of their extremely small size. Therefore, the heat sink should be constructed of a high thermal conductivity material such as copper and sized according to good thermal management practices. The physical size of the heat sink will be approximately the same as with any conventional device dissipating the same amount of thermal energy.

Aluminum heat sinks can also be used, but it should be noted that the thermal conductivity of aluminum is approximately one-half that of copper. In situations where weight is a concern, an acceptable compromise would be to mount the CVD Diamond device on a copper heat spreader which in turn is attached to the aluminum heat sink.

For particularly demanding applications, insulating or electrically conductive diamond heat spreaders are available to effectively transition the heat from the CVD device to an external chassis or bulkhead for further removal. Diamond heat spreaders are extremely small and lightweight providing a highly efficient and convenient method of removing the heat from a circuit board to an external heat sink when space and weight is limited. Please contact the factory for additional details.

Good Thermal Practices:

Figure 1 shows the typical thermal path of a CVD device mounted on a copper heat sink.

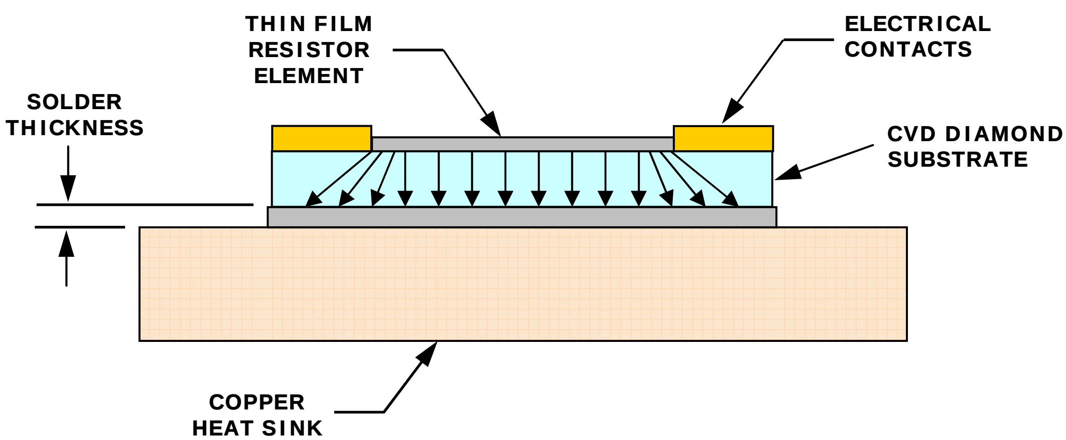


Figure 1

The thermal resistance across the attachment interface has a significant affect on the performance of the device. For instance, at 50 watts, the temperature differential across a Sn96 solder interface that is only 0.002 inches thick would be about 39°C for a device measuring 50 mils square. This is greater than the temperature differential across the entire CVD Diamond substrate at the same power level. Therefore, it is important to maintain the thickness of the solder to between 1 and 3 mils. For every 1 mil increase in the thickness of the solder, the temperature of the device will increase by approximately 20°C therefore reducing it's ability to absorb power.

When soldering the CVD Diamond device to the heat sink, avoid introducing small pockets of air and flux, called solder voids, between the device and the heat sink. It is essential that solder voids be eliminated or at least reduced as much as possible in order to maximize the power handling capability of the device. Even small solder voids can substantially reduce the efficiency of the thermal interface resulting in devices that run considerably hotter than necessary.

The thermal integrity of the soldered connection can easily be determined by measuring the temperature of the top surface of the device and comparing it with calculated data. For example, for a 50 mil square resistor running at 50 watts, the top surface of the device would normally measure about 60°C to 70°C higher than the heat sink temperature. If the device temperature is substantially higher than this, the solder interface should be considered suspect and be evaluated for voids or other discontinuities.

Other silver-tin solder compositions such as Sn95 and Sn94 and many Lead-Free formulations can also be used with almost no degrading of performance. However, when using Tin-Lead solders such as Sn63 which have a melting temperature of 183°C, the maximum permissible input power or the heat sink temperature should be reduced to prevent the solder from melting. For example, a part rated at 50 watts on a 100°C heat sink should be derated by about 30% to 35 watts maximum when attached with Sn63 solder.

Silver Filled Epoxies can provide a very high-strength mechanical bond, however, they should be used with caution due to their generally lower thermal performance. Consult with the manufacturer of the epoxy for the correct curing profile. The thermal conductivity of the epoxy can vary widely depending on how the curing is performed. We recommend derating the maximum power rating of the CVD Diamond device by 50% when using epoxies.

Temperature Differential:

As a general rule of thumb, the temperature differential across the attachment material, whether it be solder or epoxy, should not exceed 40°C at the maximum rated power of the device. It can be calculated by the following expression:

$$\Delta T = \frac{100 \times P \times t}{K \times A}$$

where: ΔT = Temperature Differential in °C

t = thickness of the interface in cm

P = Power in watts

A = Area in Square-cm

K = Thermal Conductivity in W/m-K

Typical values for the Coefficient of Thermal Conductivity of commonly used attachment materials are listed in the table below (Figure 2):

Commonly Used Attachment Materials

Material	Composition	Thermal Conductivity (W/m-K)	Melting Temperature (°C)
Gold-Tin Solder	80% Gold / 20% Tin	57	280
Lead-Free Solder	99.3% Tin – 0.7% Copper	65	227
Lead-Free Solder	96.5% Tin / 3.5% Silver	78	221
Lead-Free Solder	95.5% Tin / 3.8% Silver / 0.7% Copper	55 to 60	217 - 220
Sn-63 Solder	63% Tin / 37% Lead	50	183
Conductive Epoxy	Silver Filled	1.7 to 29	N/A

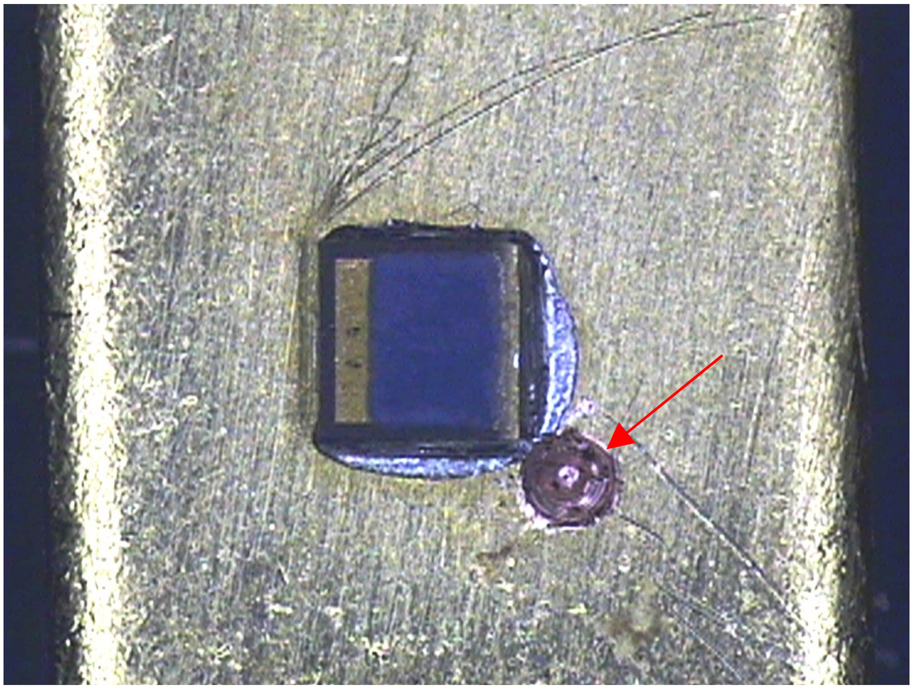
Figure 2

Flange Mounting:

A convenient way of mounting diamond resistors and terminations for good thermal performance is to first solder the devices to a copper flange, then screw the flange to a suitable heat sink. A small amount of thermal grease between the flange/heat-sink interface will assure a good thermal contact. This method of assembly eliminates the necessity of bringing the entire heat sink up to soldering temperature. Also, it allows the use of the existing external case or enclosure to be used as a heat dissipating surface instead of a dedicated heat sink, thereby saving space and weight.

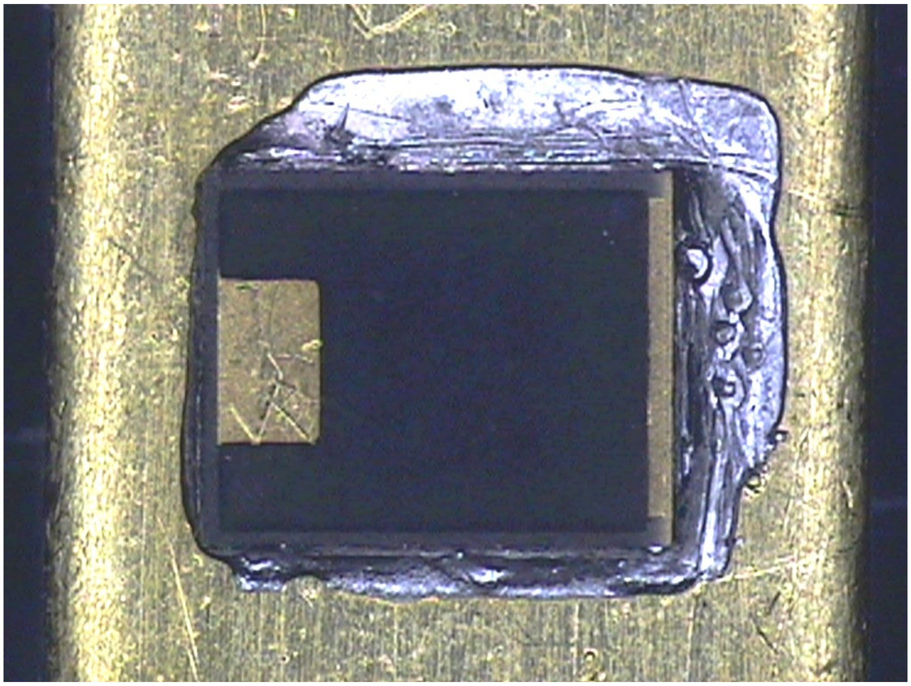
Shown below are typical views of diamond terminations mounted on gold plated copper flanges. Sn96 solder (96% Tin / 4% Silver) was used for attachment. (Liquidus at 221ºC)

CT0505D & CT1310D Soldered to Gold Plated Copper Flange.



Close-up View of CT0505D Soldered to Copper Flange

The counterbore to the bottom-right of the device is for a thermocouple to measure flange temperature during power testing.



Close-up View of CT1310D Soldered to Copper Flange

Flip Chip Mounting:

The preferential method of mounting diamond resistors and terminations is with the bottom of the chip securely attached to a suitable heat-sink of sufficient size to ensure maximum power dissipation. However, flip chip mounting can be considered when other considerations such as RF performance or capacitance to ground are of paramount importance. When using flip-chip mounting, most of the thermal energy will be dissipated by conduction through the electrical contacts. A small amount of the heat will also be dissipated from convection and radiation. Therefore, the maximum power rating of the device should be derated based on the physical geometry of the surrounding circuit.

As an example, a CR0505D 50 Ohm resistor was attached to a microstrip line in a flip-chip configuration. The device was submitted to various power levels and the chip temperature was monitored. The graph in Figure 3 below shows the actual measured temperature on the exposed (top) side.

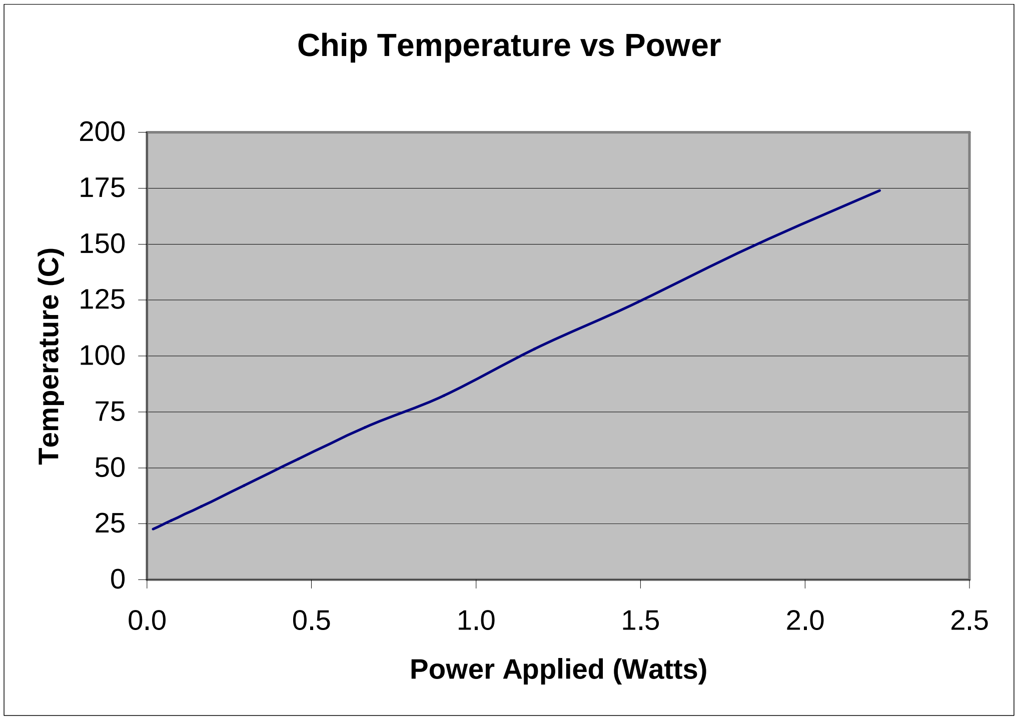


Figure 3

NOTE: Operation above 150ºC is not recommended.

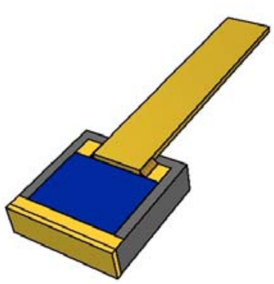
Input Connections:

The top side connections are finished with about 2.5 microns (99 micro-inches) of sputtered gold over a proprietary solderable metal. These electrical contacts are designed to be soldered or wire bonded to the external circuit.

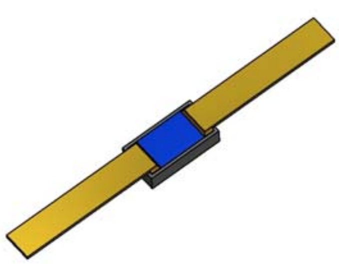
When wire bonding, conventional ultrasonic and thermo-compression wedge bonding techniques are recommended. The attachment wires can be either 1 mil diameter gold wire or 1x3 mil gold ribbon. Multiple wires should be used to reduce the input inductance and to increase the current capability of the connection.

Soldering Tabs to Diamond Resistors and Terminations:

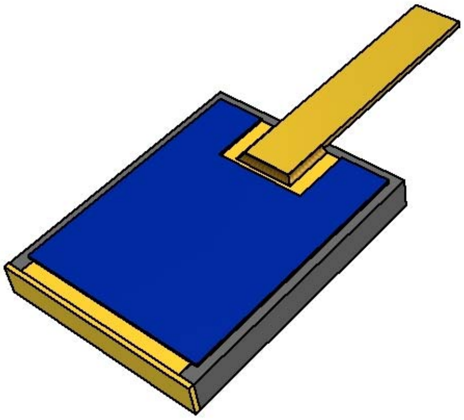
Diamond terminations and resistors with attached tabs



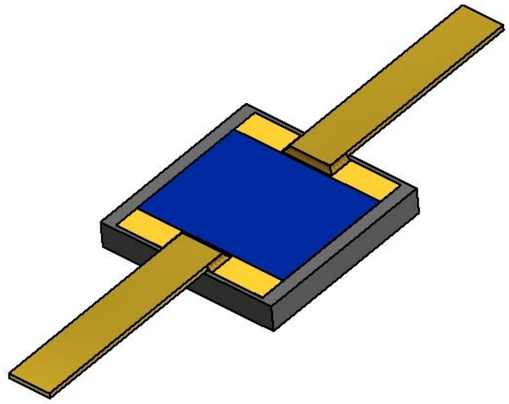
CT0505D TERMINATION



CR0402D RESISTOR



CT1310D TERMINATION



CR1010D RESISTOR

Technical Background:

Diamond resistive components manufactured by EMC Technology typically have input/output contact metallization consisting of 2.5 microns (98 u-inches) of pure gold over a 0.25 to 0.50 micron (10 to 20 u-inches) nickel underplate. Soldering to gold with either Sn63 Tin-Lead or Sn96 Tin-Silver solders can, under some conditions, lead to gold embrittlement problems due to the substantial thickness of the gold.

Gold Embrittlement is a condition in which a brittle and weak alloy is formed during the soldering process by the formation of $AuSn_4$ needle-like crystals. It becomes most apparent when the gold surface thickness exceeds approximately 20 micro-inches. During the soldering process, the gold goes into solution with the tin forming gold-tin intermetallic compounds (IMC's). These IMC's degrade the integrity of the soldered connection. Fortunately, there is a way to reduce or completely eliminate these IMC's by careful soldering practices.

Avoiding Gold Intermetallic Compounds:

There is a substantial body of scientific evidence available showing that the formation of gold-tin intermetallic compounds can be practically eliminated when the gold thickness is kept to less than 15 micro-inches. For this reason, the back-side metallization on diamond resistors and terminations has been specified to be only 6 micro-inches thus enabling a reliable high thermal conductivity connection to the underlying heat sink material even when tin-bearing solders are used. Extensive testing of Diamond Resistors under substantial heat loads have confirmed the integrity of the attachment of the back-side metallization to the heat sink using conventional solders.

For Flip-Chip mounting applications using conventional Tin-Lead and Tin-Silver solders, it is preferable to pre-tin the contact terminations of the diamond resistor by dipping the entire component into a solder pot containing the appropriate solder. Prior to dipping, the component should be immersed into a suitable flux such as Kestor Type 182 or equivalent for approximately 10 seconds. This prepares the surface to receive the solder and assures a consistent even surface free of irregularities or bumps.

Pre-tinning the contact terminations provides a superior soldering surface and completely eliminates any IMC's by scavenging off the gold on the surface. However, if solder dipping is not possible, a good solder connection can still be possible with flip-chip mounting due the substantial amount of solder normally used which effectively absorbs the gold into solution and minimizes or prevents the formation of IMC's. The problem of gold embrittlement occurs most frequently when attempting to solder tabs onto the gold contact termination because of two reasons. First, the small amount of solder used and secondly, the IMC's become trapped between the tab and the termination thus resulting in a compromised solder joint.

Preferred Methods of Soldering Tabs:

Listed below are four industry recognized methods of attaching tabs to diamond resistors and terminations.

Method 1 - Pre-Tinning Terminations:

When the application requires the use of low temperature solders such as Sn63 Tin-Lead (Liquidus 183ºC) or Sn96 Tin-Silver (Liquidus 221ºC), the input/output contact terminations of the diamond resistor should be pre-tinned by dipping the entire component into a solder pot containing the appropriate solder using the method described above. This scavenges off the gold on the surface and provides a very solderable surface for the tab to adhere to. The tab should also be prepared in this way if it is gold plated. By removing the gold from the soldered surface, the formation of any IMC's will be prevented and the result will be a strong reliable connection.

Once the solder surface is pre-tinned, the attachment of the tab can proceed using a Hot Gas Reflow Station or a Hot Plate set to about 50ºC above the solder reflow temperature. The actual reflow temperature will depend on the type of fixturing used and how it affects the distribution of heat over time but generally should be adjusted to provide reflow in about 10 seconds or less.

Method 2 - Gold-Tin Solders:

80%/20% Gold-Tin solders, which melt at 280ºC, have an extensive history of providing a reliable connection for military and space applications. For die-attach applications according to the requirements of MIL-STD-883, the MTBF is in excess of 25 years. Joint strength can be as high as 40,000 lbs/sq. inch.

There are many advantages to using Gold-Tin solders. First, IMC's are not formed so the integrity of the soldered connection is not compromised. Secondly, the higher reflow temperature will prevent the tab from reflowing and separating from the contact area during the final soldering of the tab to the printed circuit board.

Gold-Tin solders are available both as preforms and solder pastes with various formulations of flux vehicles. Contact the solder vendor for recommendations of the type of flux to use for your application.

Tabs should be sized to the particular Diamond resistor being used. A tab measuring 0.020 wide x 0.200 long x 0.003 thick will work well for most applications. The base material should be soft copper, ASTM B152, Alloy C11000, Temper H02. Tabs should be plated with Gold per MIL-G-45204, Type II, Class 1 (50 to 80 u-inches) over a Nickel underplate. The Nickel plating should be kept as thin as possible to avoid making the tab too rigid and stressing the solder connections. Total tab thickness including plating should not exceed 0.003 inches.

Gold-Tin Soldering Procedure:

(1) Place a small amount of 80/20 Gold-Tin solder paste on the contact area of the Diamond resistor. It should completely cover the area under the tab.

(2) Place the tab on the contact over the solder paste. A fixture is recommended to hold the tab in place and to provide a small amount of pressure to the top of the tab over the contact area. The pressure should be sufficient to place the tab in direct contact with the solder paste but not enough to squeeze out excess amounts of the paste. The optimum solder joint thickness should be between 1 mil and 3 mils thick.

(3) Either one of the following two methods can be used to melt the solder:

a. Method 1:

i. Place the Diamond Resistor, tab and fixture onto a 350ºC Hot Plate.

ii. When the solder melts, immediately remove the fixture from Hot Plate carefully avoiding to disturb the melted solder.

iii. Do not allow the solder to remain in a molten state for more than 10 seconds to avoid leaching gold from the contacts.

iv. Allow solder to cool.

b. Method 2:

i. Place the Diamond Resistor, tab and fixture onto a 250ºC Hot Plate.

ii. Using a Hot Gas Reflow System, direct the hot gas to the tab-contact interface until the solder melts. The gas can be either air, pure dry Nitrogen, or a 95%/5% mixture of Nitrogen/Hydrogen (called Forming Gas) which facilitates the removal of surface contaminants and acts as a flux.

iii. When the solder melts, immediately remove the Hot Gas source, carefully avoiding to disturb the melted solder.

iv. Do not allow solder to remain in a molten state for more than 10 seconds to avoid leaching gold from the contacts.

v. Remove the fixture from the 250ºC Hot Plate and allow to cool.

(4) Note that the composition of Gold-Tin solders will change after soldering to pure gold contacts thereby raising the gold content. This has the affect of raising the melt temperature from 280ºC to about 350-400ºC depending upon the time the solder is exposed to the gold contacts while in a molten state. This is desirable for most applications since it prevents the solder from melting if the part is overheated. However, in the event that the tab needs to be removed for any purpose, it will require a melting temperature of up to 400ºC.

Method 3 - Ultrasonic Welding:

Ultrasonic welding is an excellent method of attaching tabs to diamond resistors or terminations. It requires only a few seconds per tab attachment and produces a strong reliable connection. The strength of the connection using ultrasonic welding is usually as strong as the base metal. The operation is simple and produces no residues as opposed to solder which requires post-operation cleaning. The only requirement is that the tab be gold-plated in order to insure a good bond.

The welding system should have a 40 KHz transducer and a power level adjustable up to about 800 watts. One particular welder that has shown excellent results is the Ultraweld 40 manufactured by AmTech of Danbury, CT. Other companies which manufacture similar equipment are: Sonobond Ultrasonics of West Chester, PA, Sonics & Materials of Newtown, CT, and Stapla Ultrasonics Corporation of Wilmington, MA.

Please note, EMC-RF Labs does not endorse or guarantee results from any of these welders. Contact the manufacturer of the equipment to obtain the best ultrasonic welding solution for your application.

The important parameter in using ultrasonic welding is to match the size of the tool head to the area of the tab/contact interface. This is critical in order to direct the ultrasonic energy efficiently to the tab-conductor connection. The manufacturer of the ultrasonic welding equipment can help you obtain the correct tool size for your particular application.

Method 4 - Epoxy:

The question of using epoxies for tab attachment comes up from time to time. Some users have reported excellent results using epoxies as there is nothing intrinsically incompatible on the diamond parts that would prevent their use. However, we discourage their use for these types of applications due to the high skill level required to get a reliable connection to the tab and the possibility of inconsistent results. If the user is well experienced in the use of epoxies, then there would be no technical reason why they could not be used.

References:

(1) Soldering to Gold - A Practical Guide, by Ronald A. Bulwith, Alpha Metals

(2) Microstructural and Performance Implications of Gold in Sn-Ag-Cu-Sb Interconnections, by Weiqun Peng, Steve Dunford, Puligandla Viswanadham, and Stephen Quander, Nokia Corporation, Dallas, TX 75039, USA.

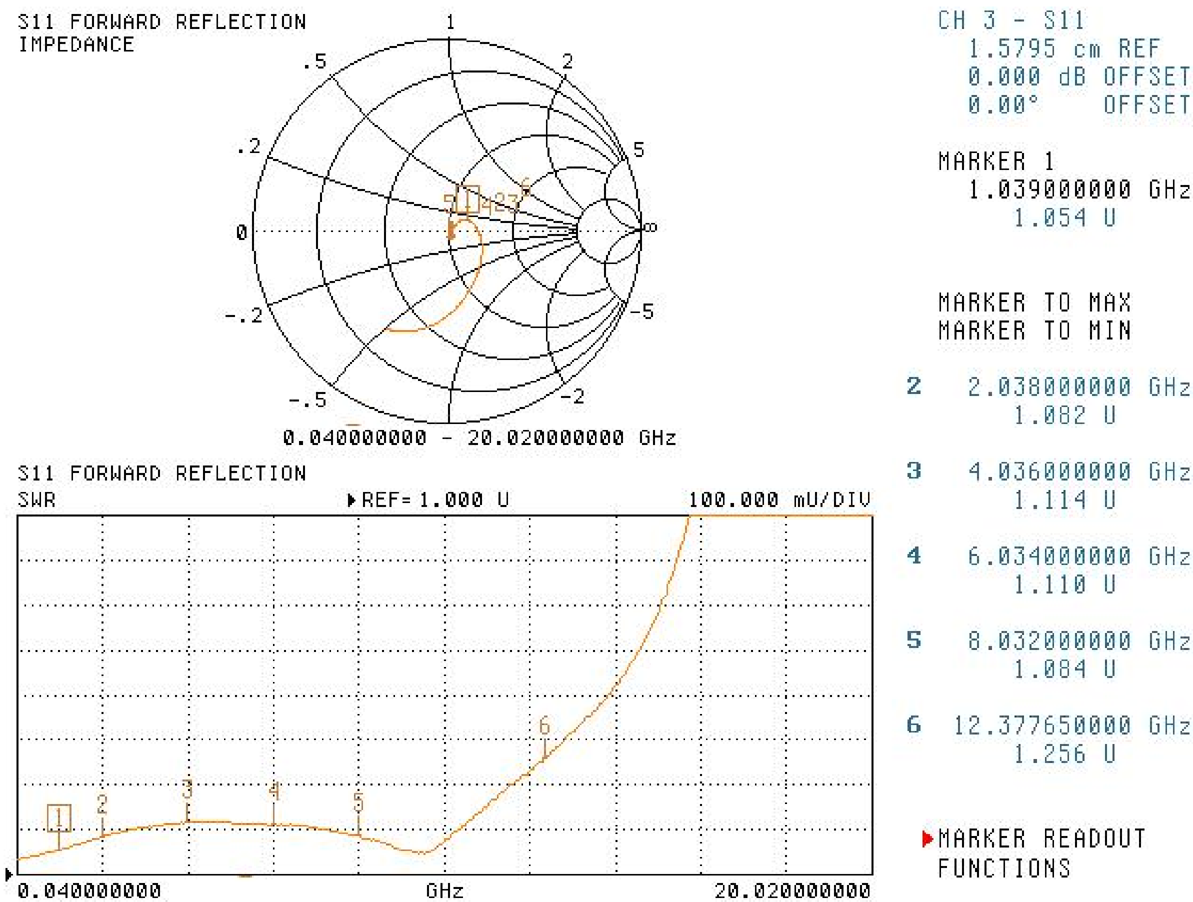
(3) Review of the Impact of Intermetallic Layers on the Brittleness of Tin-Lead and Lead-Free Solder Joints, by Erik Tegehall, Ph.D., IVF Industrial Research and Development Corporation, Molndal, Sweden. www.ivf.se

(4) Application Note, Gold Tin - The Unique Eutectic Solder Alloy, by Indium Corporation. www.indium.com/gold/PDF/98051.pdf

(5) Product Data Sheet, Indalloy 182 Gold-Tin Solder Paste, by Indium Corporation. www.indium.com/gold/PDF/98217.pdf

RF Performance:

Typical RF Performance for the CT1310D Termination



For RF performance of other part numbers, please see Specification Control Document.