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Key Technologies Used in Today's High Frequency Power Devices

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This tutorial reviews some of the most important materials and fabrication technologies currently used in power devices for high frequency applications

Generating, amplifying, switching, filtering—and all the other tasks of managing power at RF and microwave frequencies—requires specialized materials and fabrication methods. Power devices must be able to handle the necessary voltage, current and heat that accompany high power circuits. We'll begin with materials for conducting heat away from power devices.

Thermal Materials

Beryllium oxide (BeO) is perhaps the most important material for thermal management of semiconductor devices. This ceramic material, also known as beryllia, is an inorganic compound with the formula BeO. The white crystalline solid is an electrical insulator with a thermal conductivity higher than any other non-metal except diamond. Beryllia has a thermal conductivity of 280 W/(m°K).

Power semiconductor devices use beryllium oxide ceramic between the IC chip and the metal mounting base of the package in order to achieve a lower value of thermal resistance than for a similar construction made with other insulating ceramics.

Beryllium is a highly toxic metal, although when stabilized as a BeO ceramic, it is not dangerous. However, BeO dust from machining processes or damage can be inhaled, which exposes the victim to the toxic beryllium.

Diamond as a thermally conductive insulator has been used for very small devices mounted on diamond crystals. Recently, research into diamond "powder" composed of very small diamond crystals has shown promise as a non-toxic, yet high performance alternative to BeO.

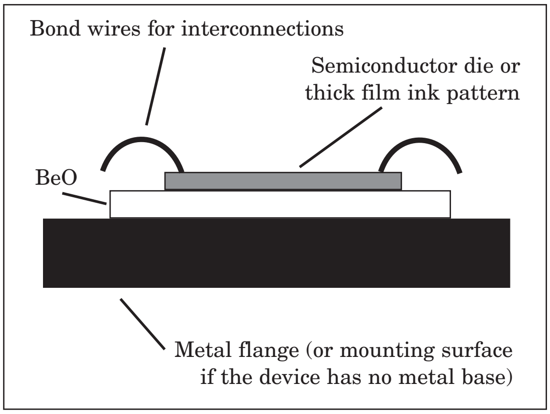

Figure 1 · Power semiconductor and high power thick film passive circuit packages usually have a layer of beryllium oxide as a thermally-conductive insulator between the die and package flange.

Aluminum Nitride (AlN) is a newer material in the technical ceramics family. While its discovery occurred over 100 years ago, it has more recently been developed into a commercially viable product with controlled and reproducible properties within the last 20 years. AlN has good dielectric properties, low thermal expansion coefficient (close to that of silicon), and it has a relatively high thermal conductivity of approximately 150 W/(m°K).

Aluminum nitride has become popular for passive devices, such as thick film resistive products, since most of those devices are manufactured without a metal substrate or package. If these devices were constructed using BeO, the potential for mechanical damage or abrasion could release toxic beryllium dust into the local environment, endangering those handling the devices. However, BeO is still used in these types of passive devices when maximum thermal performance is required.

Silicon Carbide (SiC) may be used for high power devices, although it has only a modest 60 W/(m°K) thermal conductivity. Still, that figure is higher than the most common dielectric material for RF/microwave applications, *aluminum oxide* (alumina), which has thermal conductivity of just 32 W/(m°K).

Thermal grease (ceramic powder suspended in silicone) has lower conductivity than the ceramic alone, but is usually applied in a very thin layer, ideally only filling gaps in contacting metals. Some thermal compounds are filled with metal powders (most often silver, and occasionally copper). This results in a higher thermal conductivity, which may be useful when the insulating properties of a ceramic-filled compound are not required.

As a comparison to the dielectric materials noted above, the thermal conductivity of common metals are: copper (Cu) 380, silver (Ag) 429 and aluminum (Al) 237 W/(mºK).

Semiconductor Materials

Power semiconductors have recently explored several new materials and processes that offer enhanced RF performance, better thermal performance, or some unique behavior that supports a specific types of applications.

Silicon is still the material of choice for lowest cost and high reliability at frequencies from DC to the low microwave region. Si bipolar junction transistors offer high gain and straightforward design, but have unwanted behavior with elevated die temperature. MOSFETs (VMOS and LDMOS are most common) do not have these thermal runaway problems, but have more complex processing, which results in somewhat higher cost.

Variations on Si device fabrication processes offer a wide range of tradeoffs in high voltage operation, low “on” resistance, high current handling, fast turn-on/turn-off times, and other features required for specific applications.

Gallium arsenide (GaAs) has become a mature technology for medium and high power devices at higher microwave frequencies. At present, the majority of handheld wireless devices have GaAs power amplifiers.

Gallium Nitride (GaN) offers RF performance at high frequencies similar to GaAs, but with higher temperature of operation and higher breakdown voltage. These characteristics allow easier fabrication of high power devices, with potentially higher reliability than GaAs. GaN may be fabricated as a thin layer on a Si substrate, or on a SiC substrate for higher temperature applications.

Silicon Carbide (SiC) is another III/V semiconductor material like GaAs and GaN, which can operate at an even higher temperature. High power devices in smaller packages (less thermal contact area) have been developed mainly for military applications, since cost remains high. As noted above, SiC has become an important substrate material for GaN power devices.

Indium Phosphide (InP) supports some of the highest frequency microwave circuits on record. However, drawbacks to this technology include very high cost, limiting nearly all present use to research. The operational semiconductor is InGaAs, which is grown onto an InP substrate. Also, at these frequencies, high power is rarely achieved.

Other exotic microwave semiconductor materials are available, but few have any near-term potential for power devices, and thus are not included in this discussion.

Other Technologies

A wide range of device design, fabrication, manufacturing methods are employed to enhance the performance or usability of power devices.

Flip-chip construction deposits a copper metal layer on the top side of an RFIC, with an intervening insulating passivation layer. The purpose is to have a shorter thermal pathway from the die to the heat sink. Many wireless handset power amplifier devices use this technology.

Metal tab or *metal slug* packaging places a heat dissipating copper segment into an epoxy molded package, such as a SSOP or the various leadless package styles. These packages allow much higher heat dissipation than the encapsulating material alone would support. Low and medium power devices (up to a few watts) are the target for this assembly method.

Heat pipes have been around for many years, as a result of research early in the space program. They have gotten new attention due to the small size and concentrated heat sources of today's miniaturized electronics. Heat pipes are self-contained vapor-phase heat transfer systems that can extract heat at a much higher rate than a metal heat sink alone.

Thermal modeling in the design of both devices and circuits is a rapidly growing part of circuit simulation and analysis. As the above techniques illustrate, the need to extract heat from ever-smaller packages and circuits requires more than a simple heat sink with performance that is only approximated.

Summary

High power devices, active and passive, are a critical part of most RF and microwave systems. This tutorial is an introduction to the materials and technologies used to design and manufacture those devices. Hopefully, our readers will use this as a starting point when seeking additional information needed for their particular applications.