Tech Brief

Selecting the Right Substrate Materials for High Power Electronics

INTRODUCTION

The previous era of power electronics involved large amber-glowing vacuum tubes and knife switches similar to the hallmark of Frankenstein movies. This era's power electronics are highly integrated assemblies driven by solid-state power electronics that are built, or attached, to highly reliable, thermally conductive substrates. Due to the densification of power electronics, the thermal stresses and energy channeled by these power transistors, diodes, switches, and passive electronics require much more capable materials and substrates in configurations precisely chosen to meet the needs of a specific application.

Among the choices for electronics and microelectronics for high-power applications are composite substrates composed of metals and ceramics, as well as insulating semiconductor substrates. Depending on the component or device being constructed, the device stackup may include semiconductor substrates used at the chip/package level and ceramic-based power electronic substrates used at the package and/or circuit board level. Some thin- or thick-film processes may also leverage ceramic materials as the base layer for the film-based components.

This technical brief is aimed at educating designers and system integrators on the critical material properties and performance parameters used to evaluate and compare ceramic substrates and semiconductor materials used in high-power electronics applications.

Critical Power-Electronic Applications and Criteria

Where previous power electronics exhibited only moderate reliability over a relatively short usable lifetime—such as with vacuum tube amplifiers—the economics surrounding many solid-state, power-electronics applications require ever increasing power levels, efficiency, reliability, and ruggedness. For applications, such as LEDs for industrial lighting, high-power RF and microwave transmitters, power conversion/charging electronics for hybrid/electric vehicles, and data center computer-power distribution systems, reliability under stress is certainly key. Hence, the materials and substrates that these solid-state power electronics are built upon must be of a robust nature that can be described with common and comparable criteria. These criteria are typically, maximum operating temperature (MOT), coefficient of thermal expansion (CTE), electrical insulation (resistivity), thermal conductivity, and relative permittivity.

Military Radar and Air Surveillance
The latest high power radar systems require both extreme RF power density and long-term reliability, for which careful design and material choices are necessary.

Maximum Operating Temperature (MOT)

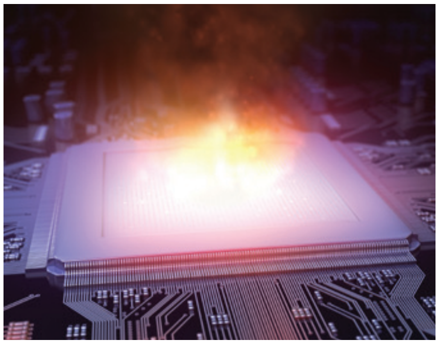
The maximum operating temperature of a material or a substrate is often specified by the manufacturer to a point where the material or substrate will still meet its specified criteria and have a higher likelihood of failing after that point. If the material or substrate is brought to the MOT for a sustained period of time, many materials will degrade and their performance will be derated. This is why some materials and substrates will list a maximum operating temperature peak value and a length of time for which that temperature can be sustained.

It is important to note that a material's or substrate's MOT may need to exceed the temperatures expected in an environment in order to prolong device life and prevent catastrophic failure under stress. Most materials and substrates used in electronics experience derated physical robustness as a function of temperature.

Coefficient of Thermal Expansion (CTE)

Thermal expansion is the phenomenon of physical materials changing dimensions in a way that relates to their present temperature. The coefficient of thermal expansion helps to describe and compare various materials on how significantly their dimensions change with temperature. As demonstrated with the equation for linear thermal expansion, the greater a material's CTE, the greater that material will grow in length as a function of increasing temperature.

The CTE of a material is important, especially in multi-layered, solid-state, power-electronic applications. If materials closely stacked together and adhered to each other have different CTEs, the CTE mismatch between the materials could cause a loss of adhesion or damage to either of the materials during temperature cycling. This is often experienced with more delicate semiconductors with high CTEs being stacked on ceramic materials with low CTEs, or with semiconductors attached to metals with much higher CTEs. As the temperature rises the high CTE semiconductor may expand, experiencing resistance from the adhesion method with the ceramic substrate, and the force of thermal expansion may eventually exceed the semiconductors' mechanical strength causing cracking, chipping, or other mechanical damage. Similarly, a higher CTE metal may induce strain in a lower CTE semiconductor, causing damage. Hence, ceramic/metal power-electronic substrates are typically balanced to have a relatively close CTE match with that of the chip package/semiconductor.



Power Density and Thermal Management
High power devices tend to produce excess thermal energy, that if managed poorly, can lead to thermal degradation of the semiconductor material and possibly catastrophic failure.

Thermal Conductivity (Thermal Resistance)

The thermal conductivity of a material is a method of describing the heat transfer characteristics of a material and is typically generated following Fourier's Law for heat conduction. Given in watts per meter kelvin (W/(m*K)), the thermal conductivity value of a material indicates that the material conducts heat through its volume more efficiently. Thermal conductivity is an important metric for solid-state power electronics, as materials and substrates are often used to "wick" heat from a device to a heat spreader, heatsink, or assembly package. If a material or substrate with too low of a thermal resistance is chosen, thermal build-up could occur in a device, causing high temperatures that derate performance and that could possibly lead to damage.

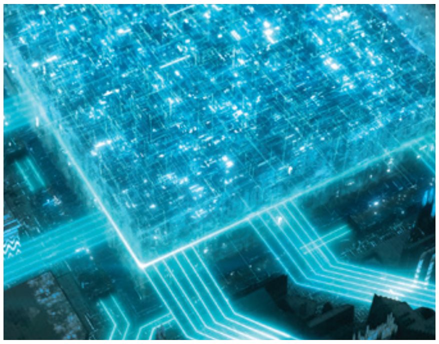
Electrical Insulation (Resistivity or Bulk Conductivity)

The electrical insulation characteristics of materials and substrates are a measure of how poorly the material conducts electricity. Often measured as the bulk resistivity, this characteristic describes the amount of electrons conducted through a material. As power electronics often use high voltages, the higher a material's bulk resistivity, the better that material will be at preventing stray currents developing within the material. The total insulation capability of a material is thickness dependant, so a material with greater resistivity will be comparably thinner than a material with less resistivity for the same total resistance.

Relative Permittivity (Dielectric Constant)

The dielectric constant (k) of a material is a method of measuring the quality of a material at storing electrons in an electrical field, Coulomb force. This is a critical metric for materials and substrates in power electronics, as the high voltages and currents passing through power devices and their leads produce substantial electromagnetic fields. These strong fields could unintentionally induce electrical responses in nearby circuitry or the assembly housing if the relative permittivity is too high.

The dielectric constant is a measure of relative permittivity compared to vacuum and can be used, along with material thickness, to calculate a material's capacitance. Higher dielectric materials and substrates must be made thicker than lower dielectric constant materials to achieve the same capacitance value. Hence, using lower dielectric constant materials can lead to a reduction in size and weight of a substrate. Also, lower k dielectrics allow for trace leads to be placed at closer pitches, further leading to more compact power circuitry.



Electrical Characteristics of Substrates
Though thermal conductivity and electrical insulation may be some of the top considerations of a ceramic substrate or semiconductor used as an insulator, there are a range of key characteristics that must properly match the application to enable reliable high power operation.

Six Key Ceramic and Semiconductor Material Performance Factors Worth Weighing

Several different power electronics technologies rely on ceramic materials, such as alumina (Al2O3), beryllium oxide (BeO), and aluminum nitride (AlN) and fused silica as substrates and base materials for substrates. Additionally, other power electronics leverage semiconductors, such as silicon (Si) and silicon carbide (SiC), as microelectronic semiconductor substrates for high-power gallium nitride (GaN), gallium arsenide (GaAs), Si, and SiC power devices. Each of these materials and substrates has specific characteristics that lend themselves to certain applications, and selecting a ceramic material or substrate is a design decision with substantial ramifications throughout the design process—especially considering that power electronics are often connected and incorporated into complex and expensive systems that depend on long-term reliability and high efficiency.

Each material and substrate has its own sourcing, processing, supply, mechanical, and electrical features that must be measured and weighed prior to choosing a material or substrate for a particular application. The following is a description of a few of the top ceramic materials used to fabricate and power electronic substrates and devices, as well as two common semiconductor substrates used to make high-power, solid-state devices.

Ceramic Materials and Substrate Key Factors Table

Material	**Alumina (99.5%)**	**Alumina (96%)**	**Beryllium Oxide (99.5%)**	**Aluminum Nitride**	**Fused Silica**	**Silicon**	**Silicon Carbide**
Chemical Formula	Al2O3	Al2O3	BeO	AlN	SiO2	Si	SiC
Melting Point (°C)	2072	2072	2514 to 2626	2397 to 2507	1713	1414	1478 to 1722
Maximum Use Temperature (°C)	1750	1700	800 to 2045	1027 to 1727	1100	477 to 527	297 to 697
Coefficient of Thermal Expansion (micrometer per ° C)	7 to 8.4	8.2	7.4 to 9	4.3 to 5.6	0.55	2.56 to 3	5 (7.9 to 11)
Specific Heat (joules per kilogram*kelvin)	880	880	750 to 1020	740 to 820	740	668 to 715	510 to 750
Thermal Conductivity (W/(mK))	25.5 to 35	20 to 25	209 to 330	60 to 177	1.38	84 to 156	70 to 120
Dielectric Constant (relative) @ 1MHz	9.8	9	6.1 to 7.5	8.3 to 9.3	3.82	11 to 12	-
Bulk Resistivity (Ω per centimeter)	> 1e14	>1e14	>1e16	>1e14	>1e10	1e6 to 1e10	1e2 to 1e6

Alumina/Aluminum Oxide (AlO)

Aluminum Oxide, or alumina, is one of the most cost-effective and predominate of engineering ceramics. Alumina experiences a wide range of uses in virtually every application where engineering ceramics are used, and has a well-developed supply chain. As Alumina is available in a variety of purities, the performance of Alumina can be catered to an application, potentially reducing material costs.

Key Features

- Hard and resistant to wear
- Low cost
- Good dielectric performance from DC to GHz frequencies
- Resistant to strong acid and alkali at high temperatures
- Good thermal conductivity
- Can be readily formed
- Available in 90%, 96% and 99.5% purity for various applications

Alumina is one of the hardest and strongest of the engineering ceramics, and exhibits good thermal and dielectric properties. Alumina is less thermally conductive than both AlN and BeO, as is typically used with applications that benefit from the relatively low cost of the ceramic.

Alumina/Aluminum Oxide (AlO)

Beryllium Oxide (BeO)

Beryllium Oxide is second only to Diamond as an insulating material, and has an extremely low dielectric constant and dielectric loss tangent. Many RF, microwave, and millimeter-wave applications leverage BeO for its excellent high-frequency performance at high temperatures. BeO also exhibits very high thermal conductivity. These factors allow for circuits developed on a BeO substrate to operate at high powers and high temperatures with extremely narrow pitches between traces.

Key Features

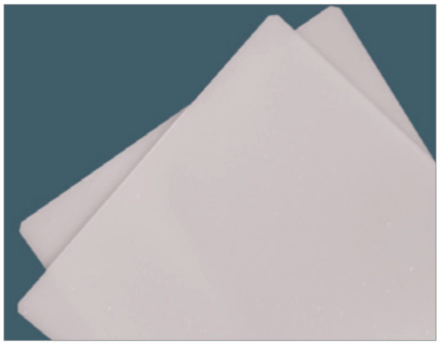
- Extremely high bulk resistivity
- Very low dielectric constant and loss tangent
- Excellent thermal conductivity
- High operating temperature

Additionally, compared to the other common ceramic substrates, a BeO substrate can be made much thinner and lighter than an equivalent alumina or AlN substrate with the same dielectric properties and with better thermal conduction. However, beryllium is toxic for humans, so it must be sourced and handled with care during fabrication and processing—though the material is safe to handle as long as dust is not generated during machining or handling.

Beryllium Oxide (BeO)

Aluminum Nitride (AlN)

Relatively recent as a viable engineering ceramic, AlN exhibits good thermal and mechanical properties and is often used as a non-toxic replacement for BeO. Though AlN doesn't exhibit the same insulation, dielectric, or thermal properties as BeO, it still outperforms Alumina in these regards, and is often used in IC packages, power transistor bases, microwave device packaging, and semiconductor processing chamber fixtures and insulators.



Aluminum Nitride (AIN)

Key Features

- Good dielectric properties
- Low CTE, similar to silicon
- Non-reactive to process chemicals and gases used during semiconductor fabrication
- High thermal conductivity

Fused Silica (Quartz Sand)

Fused silica is a noncrystalline glass made of high-purity quartz sand. As fused silica is amorphous when heated, it can readily be formed and shaped into workable geometries. Fused silica is often used in microwave and millimeter-wave components, as well as high-powered optics. Examples of this include temperature-insensitive optical components and radar windows used in aerospace applications.

Key Features

- Almost zero CTE
- Good resistance to thermal shock
- Very chemically inert
- Can be lapped and polished to extremely fine finishes (optical quality)
- Low dielectric constant and loss tangent from DC to GHz frequencies
- Good UV transparency

Fused Silica (Quartz Sand)

Fused silica is extremely stable dimensionally and resistant to thermal shock, making it an ideal material to use in applications exposed to repeated thermal cycling. Fused silica is also chemically inert up to high temperatures. Moreover, fused silica exhibits dielectric properties which are stable through the gigahertz frequencies.

Silicon (Si)

Silicon (Si) is the predominate semiconductor used for electronics and microelectronics. Hence, there are many fabrication facilities, manufacturing equipment, and supply chains that are well established, highly efficient, and low-cost compared to other semiconductor technologies, some of which are fully depreciated. Silicon wafers can also be made much larger and at higher yields than other substrates. There is also the potential that a Si process can benefit from integration synergies with digital, analog, and RF on the same chip.

Key Features
- Low cost
- Well established fabrication processes and supply chain
- Large wafers
- High yield
- Good insulative substrate
- Mixed-signal integration potential

Si vertical MOSFETS (VMOS), super junction MOSFETs (SJMOS), bipolar junction transistors (BJTs), insulated gate bipolar transistor (IGBT), and new laterally diffused metal oxide semiconductor (LDMOS) are all used in DC, AC, and RF power applications to reasonable power levels and up to a few gigahertz in frequency. Compared to other insulative substrates, Si is in the middle range of thermal conductivity, but benefits from the well developed Si supply chain and technology advancements and can be used to make very large wafers and larger die at much lower cost. Using epitaxial grown GaN on Si is technology with growing adoption in the RF and power LED markets, due to the cost benefits of leveraging the Si fabrication process and equipment while benefiting from the high-power capability of GaN.

However, Si is typically a weaker material that exhibits poorer thermal conductivity than other high-performance semiconductors. Si itself is also limited in power and frequency performance, which is why using Si as an insulative substrate for higher performing semiconductors, such as GaN, is more attractive for high-power applications than simply using Si.

Silicon (Si)

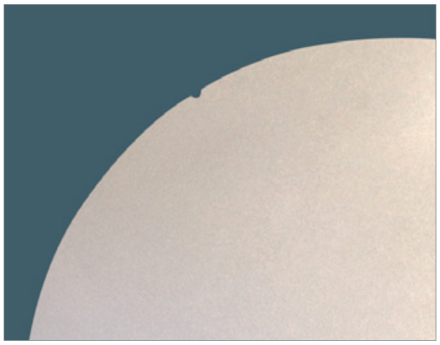
Silicon Carbide (SiC)

Silicon Carbide (SiC) is a strong and thermally stable material that is used in a wide variety of mechanical, ceramic, and semiconductor applications. In reference to power electronics, SiC is commonly used as an insulative substrate for high-power and high-frequency applications. The strength and low CTE of SiC matches well with GaN, and the enhanced thermal conductivity of SiC enables the creation of very high-power and high-frequency GaN on SiC devices. Though these devices are more expensive than GaN on Si devices, they are typically capable of much greater energy densities, and GaN on SiC devices are much more physically rugged than GaN on Si devices.

Key Features

- High strength and hardness
- Good dimensional stability and low CTE
- High thermal conductivity
- High elastic modulus
- Great thermal shock resistance
- Very chemically inert

Efficiency for high-power electronics is also a major consideration, especially in electric vehicles, rails, and grid applications, as higher voltages lead to less resistive losses. This is another area where SiC and GaN on SiC devices are strong, as the substrate is capable of operation from hundreds to thousands of volts before breakdown.

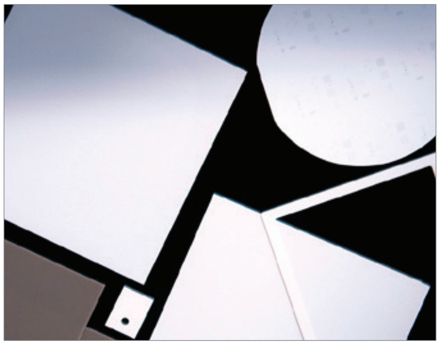


Silicon Carbide (SiC)

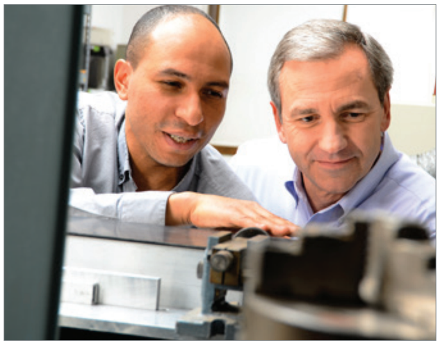
CONCLUSION

The latest silicon and wide-band gap semiconductors are being used to create solid state power electronics that are many times more energy dense than previous technologies. Hence, a greater burden is being placed on power electronic substrates, materials, and insulative semiconductors. The reliability, performance, and yield of the manufacturing of a power electronic substrate depends on the precision and quality of a ceramic base materials or insulative semiconductor, it is essential for a designer to be aware of the options available.

Proper design and materials selection is only the beginning of the substrate material challenge, and further considerations involve sourcing and pre-processing steps (lapping and polishing) necessary to ensure yields. This is where stocking suppliers and preprocessing specialists are able to add value in the supply chain for the next-generation of solid-state power electronics.



Accumet stocks name brand ceramics and substrate materials and provides fast, expert processing services. To request pricing or technical assistance, visit www.accumet.com



Next Steps:
Learn more by downloading these pieces of related content: Solid State Power Electronic Fabrication and 5 Keys to Successful Processing of Ceramic Substrates Brief.

You can access our entire library of technical briefs and design guidelines by visiting our support page.