Advantages and limitations of ceramic packaging technologies in harsh applications

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Abstract

Rising operating temperatures, environmental restrictions, harsh conditions around our electronics, shortage of space, expectations for long-term reliability and cost are some of the driving forces we all have to deal with during electronics design. While microelectronics and semiconductor industries are running in Moore's beat bringing out impressively small analog, digital or MEMS chips, their packaging is more often the actual challenge for developers and system designers. Advancing systems-on-package, smart sensors, modules for signal processing under extreme conditions need special packaging technologies and materials as well. There, at the front of the application sector, the availability of striking silicon dies alone does not automatically deliver solutions for some advanced applications. Some of the drawbacks with traditional PCB's and housings can be resolved using ceramic boards and suitable connection technologies. A good combination of miniaturization potential and advantageous characteristics from ceramic materials is given with ceramic multilayer boards, which are available in various types. The conference lecture will show an overview about advantages and handicaps of materials, components and technologies. Traditional thick film, LTCC and HTCC as well as thin films on ceramic carriers will be illuminated in terms of pro's and con's from compatibility, cost, performance and availability points of view. Finally ceramic packages have to be technologically completed by suitable interconnection techniques, where wire bonding, adhesive bonding and soldering are just a choice of, each of them in many versions that fit to the specific requirements and to best possible connections.

Key words

Advanced packaging, Ceramics, Harsh environment, LTCC, High temperature, High reliability

I. Introduction

Ceramics are somehow traditional materials for electric and especially for highly reliable electronic applications. These high-rel utilizations survived the history of the previous 100 years, while other operating ranges of ceramics found competitive technologies. After isolators and lightbulb sockets in the 19th century, military electronics around 1910 was build on perforated alumina plates, radio devices in the 1930's were built on the first thick film boards, radio tubes in the 2nd war and already early generations of pacemakers were built of ceramic parts. Combined with conductors made from noble metals such modules profit from their durable properties. Until today ceramics remain interesting for long lasting products, not least because ceramics itself didn't remain these plain materials from thence. Conditioning of feedstock, material sciences with completely new mixtures, nanotechnology as well as manufacturing technologies enhanced the material class amazingly. Today's technical ceramics do not have much in common with Hewlett's isolator or the painted pottery in the arts shop.

Main reasons are their special durability, inertness and chemical characteristics. Even physical properties are striking, although one might think about dishware shattering into a thousand pieces when dropping down on the floor.

The questions behind this matter are more complex and require an overview about the different needs of a particular application. In the most cases it is much more then only a single reason for the decision to use ceramic as the appropriate material system. On the other hand ceramics material is only a category and not a definition of the specific chemistry or the technology. When we talk about ceramics we don't mean a single particular ceramic but a large group of technical materials with good opportunities to enable advanced requirements.

One favor of the characteristic of Ceramics are their thermal mechanical behavior. Thermal characteristics are among others the coefficient of expansion, thermal conductivity, aging under the influence of thermal cycling, thermal capacity and the ability to withstand higher temperatures. Each of them as well as combinations of them are advantages in terms of the usability for electronic applications. Additionally, ceramics do not show the decomposition we know from polymers and epoxies, their chemical bonding does not suffer from heat and UV radiation as organics do, ceramics do not soak or absorb humidity, at least not in a significant scale.

II. Limitations and challenges

Why and where are ceramics limited regarding their usability in harsh environments? Even the best matching physical characteristics are never the ideal equality, e.g. when we think about thermal mismatch of solder or adhesive joints under the influence of temperature gradients. Especially large areas, extensive chip and package lengths, the homogeneity of the heat transport in and through cooling parts are roots of tensions and stress causing damages in the assembly stack. Ceramics may overcome some limitations known from organic PCB, they can benefit from the advantages they bring into an electronic system. But finally physical and chemical laws have to be accepted as true of ceramic materials, components and modules.

Additionally, electronic parts, modules and systems are hybrid stacks made of a variety of materials, compounds, complicated technological sequences suffering from their different properties and the interfaces between. This phenomenon is matter of reduction by means of ceramic components. Reduction means: just partially and if decided carefully, but ceramics can never eliminate everything having been wrong with other material combinations.

Furthermore it cannot overcome restrictions of joint materials, of own interfaces, necessary handling and treatment. And finally ceramic materials do have own limits, even if it is considered to be the suitable high-temp material par excellence.

Ceramic materials need to be structured for electronic functionalities by different technologies and with other materials than common FR based carriers, at least if the goal is to enable working on higher temperatures. As an example we have a closer look to PCB made of ceramic and copper: alumina or aluminium nitride could generally be covered by copper foils using epoxy adhesive as we do with FRx, but this would not be an advantage in thermal applications. Additionally we would obstruct the established process flow of metallizing vias, multilayer lamination etc. Other technologies had to be developed and the consecutive product solution is DBC (direct bonded copper) and comparable covering techniques for AlN, widely used for IGBT’s and other power chips assembly. This business has grown fast and in large volumes, however fancy miniaturizations are not the main target and hardly to get with these power dominated technology.

Knowing the limits and restrictions, the interactions and necessary process conditions combined with calculating and balancing pros and cons one can definitely benefit from this group of materials.

III. What have ceramics to offer?

Since the intensions to use ceramics for highly reliable electronics are pretty different, it is worth to watch for partial motivations bringing developers towards the right decisions. As everybody knows, decisions in terms of materials, technologies and their combinations are always complex, increasingly under more complicated specifi-cations and operating conditions.

When we list up some advantageous characteristics of ceramics for electronic purposes they are e.g.:

- Coefficient of thermal expansion CTE (close to silicon and far below the most usual metals)
- Excellent isolators (even in elevated temperatures and over lifetime)
- Fair thermal conductivity as an isolator (heat spreading and distribution)
- Stable dielectric properties and low loss at radio frequencies
- Chemical stability (against many chemicals, moisture, solvents, consumables)
- Very slow aging (due to consistency of substance)
- Compatibility to noble metal paste sintering technology (for highly reliable conductors)
- High processing temperatures (far from later operating range)
- Thermal resistance (no classic melting, decomposition, softening)
- Mechanical stiffness (allow rigid carriers), Hardness and Wear resistance (for sensors working in fluids, industrial pollution)
- Resistance to EUV, plasma and ion bombardment as well as practically no outgassing in high vacuum (sensors for EUV semiconductor equipment)

Absolute values of the CTE

The comparably low CTE is one of the most important characteristics making ceramics extremely interesting for highly reliable electronics. This is because the usual materials for semiconductor chips, LED, detectors, MEMS etc. are in a similar range in terms of this parameter. Brittle and stress sensitive chip materials and structures need stable conditions during thermal cycles and storage. Since chip size and temperature lift is usually application related and heavily to be reduced, delta CTE remains the only variable term in the equations of stress inducing length differences. Ceramics come along with values between 4-10 ppm/K and are so far comparably close to Si, GaAs, Ge. This helps to keep differences in CTE low and reduces the thermally induced stress, especially in the joints and interfaces of large dies or stress and tension sensitive MEMS. This is the view towards the chip, but on the other hand there is also the packaging. Ceramic substrates provide advantageous conditions to be mounted on metal heatsinks, favored by the intermediate CTE between chips and usual metals for hermetic housings of mounting plates made of Kovar, CuMo of fiber composites like CarfAl. The ceramic carrier and its solder or adhesive joint moderates between components and housing / cooling parts. We find typical examples in the high reliability and hermetic business as well as in optical sensors with hard requirements in terms of clean and stable conditions inside the package.

Temperature dependency of CTE

The CTE of ceramics is comparably stable in the course of usual process and operating temperatures of electronics, let’s talk about -100°C up to 350°C. While organic substrate suffer from softening, viscosity and glass transient temperatures somewhere in this range, ceramics have if that Tg far out of this range of temperature. Sophisticated stacks of multilayer materials like glass fabrics, resins or acrylates to fill and to glue them, prepreg sheets, copper or aluminium sheets and foils lead to physical properties that are not easy to calculate. Ceramic, even multilayers, are monolithic bodies after sintering and do not have significant anisotropy. This allows an easier process design, enables stable conditions along the operating temperature and if necessary, provides easy to manage values of physical characteristics when simulation tools have to be fed.

This characteristic is important for systems, that have to survive wide ranges of temperature during production. Let's think about cooling down from brazing to room temperature or far below, e.g. -100°C for space, because not only the CTE @ RT is relevant, even if is equal there, but different in heat or cold.

Thermal conductivity

Good thermal conductivity provides good preconditions in terms of spreading, distributing and transporting heat away from heat sources, e.g. power dies. As an example small LED dies mounted on ceramics hand over their power loss with the restricted area of their foot print and spread them fast into the bulk material of the ceramic. Metal carriers can do it better, but they have to be structured and isolated, which is also a challenge. So far the involved area and depth beneath the die is growing fast and effectively. Such functional heat spreading substrates help keeping the temperature at the semiconductor low. Although some competing technologies like insulated metal boards or metal inserts in PCB come along with higher thermal conductivity, ceramics appear quite universally and take advantage from their monolithic, inorganic nature.

Material nature of ceramics

Ceramics provide stable characteristics from chemical point of view. They do not consist of organic components that are product of polymerization or other chemical processes with any kind of reversibility or decomposition. Ceramics are sintered materials, usually containing crystallized matter and amorphic content, that keeps them together and is lowering the sintering temperatures for many technical materials. But all of them are monolithic bodies, even though they may be multilayers. In comparison to FRx materials HTCC and LTCC layers are not glued or bonded to each other, but they arose as an uniform body during the sintering process. They do not contain adhesive layers, in the best case the metallization could be called an intermediate layer, but it is sintered as well. Its metal particles stick on the adjacent ceramic surfaces by means of own glass content or participate from glass content of the ceramic (especially in the case of LTCC). Additionally, simply the elevated process temperatures, the point that the L in LTCC, sintered in furnaces working at 850°C, means low, while all others get up to 1600°C and higher. This illustrates that usual operating ranges, whether 200° or 300°C do not even touch these temperatures.
More or less these matters of fact are reasons for the interesting stability of ceramics for multiple use. The stability starts from isolator and dielectric characteristics and comes down to reliability under the influence of chemicals or extreme temperatures.
An additionally helpful feature is the extremely low tendency to water or rather moisture absorption, also a point that makes ceramics stable along changing moisture conditions, because a certain water content would affect many electrical characteristics.
The aspect slow aging does also fit in this category, one important argument in favor of ceramics, and a crucial advantage in comparison to degradable materials with self-limitating performance and durability.

Excellent isolators and dielectrics up to RF

One of the aspects participating from this interpretation of stability are the dielectric properties. This is in terms of dielectric strength and insulation resistance as well as the permittivity. Many technical materials in this class are highly crystallized and benefit from an, if at all very low grade of amorphic content. Except of some high dielectric ceramics with quite low glass transient temperatures, that have strong variations in dielectric constant above Tg. But the most technical ceramics, serving as substrates, isolators or package components are made of these materials being "stable" in this regard. Additionally they provide comparably values. The popular use of ceramics for RF is due to their behavior of permittivity and loss tangent in high frequencies. It is predictable over temperature, DC bias, frequency and lifetime. It is evidently an advantage for e.g. radio links, radar equipment, planar antennas etc. Usually RF applications, especially professional and safety ones, benefit additionally from many other aspects of the mentioned "stabilities".

Compatibility to metal paste sintering technology

Thick film technology is a well established technology for the production of ceramic carriers and multilayers. Classic thick film is based on already fired ceramic tiles that are provided with conductors, isolating layers, functional layers like resistive or capacitive ones, sequentially. Thixotropic pastes made of the functional content, several plasticizing agents, solvents, binders and often glass particles are printed e.g. with printing screens, ink jetters, dabber printing or transfer principles. Followed by the sintering step the respective layer is ready. Such steps have to be repeated according to the design. The metals for alumina based thick film as well as LTCC are sintered far below the melting point of the metals (Ag, Au, Pt, Pd, Ru..) by means of glasses, serving as sintering flux. Fortunately gold or silver conductors made in this technology have an advantageous conductivity. The higher melting Pt and Pd, forming alloys wit Au or Ag, help to create metallizations with low tendency to dissolution, while Ru and its oxides are substances to create thick film resistors.

Wear resistance, Resistance to EUV, plasma and ions

There is a group of very sophisticated applications for electronic microsystems, sensors that have to measure very narrow distances in the sub-nanometer range inside EUV semiconductor equipment, e.g. mask allígners. These machines work under high vacuum, the high power densities of UV light with extreme short wavelength put high requirements on the sensors that control the movements, energy and operating conditions in the system. Intelligent sensors with electronic components inside are not allowed to evaporate anything, whether from components nor from adhesives, solder materials nor from the PCB or packaging. Where polymers altogether would fail, ceramic sensors can break down these hard barriers of requirements, because of their mechanical characteristics and their stable, inorganic and dense nature from chemical point of view.

IV. Conclusion

Current electronic applications do not contain ceramic carriers, multilayer boards or multi chip modules any longer as a matter of simple miniaturization technology as they did in the 60ies. Ceramics grew up to high tech materials and are manufactured with elaborated technologies and are not a cheap replacement of materials that could be used in almost the same manner. To a greater degree ceramic materials became more and more the door opener into advanced applications without a large variety of alternatives. Ceramics are sometimes greeted with smiles as old fashioned, too expensive and obsolete. In fact, some former applications or the use of ceramics in some are replaced by cheaper materials and technologies or by new materials, that grew up into performances, that FRx did not reach a couple of years ago. This is increasingly the case in the temperature range of automotive electronics these days, roughly the range above 125°C up to 150° or 160°C. Since this range was not covered by organic substrates for a long period and ceramic PCB were used, many people put trust into organic substrates for this segment. It was told that FRx development was not driven for years really emphatically into that field, potentially on account of much lower volumes in the high-temp market, that provided too little incentive for expensive developments. Surprisingly the quite conservative sector for automotive electronics abided by ceramic carriers for a long time, although alternatives came up many years ago. In the meantime the situation began to change and the temperature “limits” moved upwards. The lower decision criterion to use ceramics is in movement, but the upper as well. Many new application arrived on the scene and established ones show an upward tendency in operating temperatures and thermocycling.