Properties and Reliability of Silicon Nitride Substrates with AMB Copper Conductor

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Abstract

This paper focuses on the properties of Si_3N_4 substrate material with AMB (active metal brazing) copper conductor.

A recently developed type of tape casted, gas pressure sintered silicon nitride ceramic with a three times higher thermal conductivity than known from typical standard silicon nitride materials and with good flexural strength was applied. The increase of thermal conductivity is the result of using different species of sintering aids and the optimization of their ratio in the material. The high bending strength allows creating a thinner substrate compared to other standard ceramic materials for power electronics, e.g. aluminum nitride. This reduction in thickness leads to a decrease of the total thermal resistance of the substrate which improves heat dissipation. For the AMB process a silver based active brazing solder composition optimized for Silicon Nitride was used. This optimization could be obtained by an investigation of the physical and chemical interactions between the brazing and the base material. A void free joint without short circuits between adjacent structures could be formed. The copper surface can be coated on demand with Nickel or Nickel/Gold for improved solderability and wire bondability as well as for corrosion protection.

The silicon nitride substrate with AMB copper conductor lines and fully covered back side ground shows a higher reliability than comparable substrates made out of common, well known ceramic materials. The heat dissipation is comparable with conventional AMB substrates made of high thermal conductive ceramic such as Aluminum Nitride, but thermal cycling behavior exceeds the limits well known from AlN-AMB or AlN-DCB.

Keywords: AMB, Si_3N_4, thermal conductivity, reliability, copper conductor lines

1. Introduction

Silicon nitride is a well-known material for applications where extreme conditions occur. The material is characterized by typical properties like high fracture toughness, an extreme high mechanical strength even at high temperatures which is only beaten by zirconia. In addition it shows an excellent thermal shock resistance combined with a low thermal expansion and low density, a good wear resistance, corrosion resistance against fused metals (especially non-ferrous metals) as well as high hardness.

The main fields of application are the metal processing with indexable inserts, the engine building with highly stressed components, antifriction bearings and melting crucibles for the production of silicon devices.

The low coefficient of thermal expansion gives a good match to silicon and other semiconductor materials. Due to that silicon nitride could be a promising substrate material for power electronics.

Also with regard to reliability, silicon nitride is a perfect substrate material for power electronics. Despite all that, silicon nitride was not able to be established in that market segment because of different reasons. First of all, the high manufacturing costs, especially for the hot pressing process and the expensive finishing by hard grinding, are to mention. Another disadvantage from the technical point of view is the comparable low thermal conductivity of about 20 - 24 W/mK for standard silicon nitride qualities. Table 1 shows typical values of gas pressure sintered silicon nitride (GPSSN).

Table 1: Typical characteristics of GPSSN [1]

	Si_3N_4
Density ρ [g/cm³]	3.2
Flexural strength σ_B [MPa]	900 - 1200
Young's modulus E [GPa]	300 - 310
Fracture toughness K_{1c} [$MPa \cdot m^{1/2}$]	8,0 - 9,0
Thermal conductivity λ [W/mK]	20 - 24

A recently developed type of tape casted, gas pressure sintered silicon nitride ceramic with a three times higher thermal conductivity than known from common silicon nitride materials is able to neutralize these drawbacks.

2. Silicon nitride substrate with high thermal conductivity

The new developed silicon nitride is produced by economic technologies. The shaping is made by a tape casting process. For that, it is necessary to produce a slurry that is adapted to the specific sintering aids from the group of rare earth oxides like Y_2O_3 and Sc_2O_3 or other oxides like SiO_2 and MgO. These additives help to raise the thermal conductivity. Two effective compositions SiN-YS and SiN-YMS were identified. SiN-YS contains yttria, and scandia. SiN-YMS contains yttria, magnesia and silica. The use of Al_2O_3 should be avoided, because the aluminum ions are integrated into the silicon nitride lattice and cause lattice imperfections, which interfere the phonon transport and thus lower the thermal conductivity.

The casted tape is compacted by gas pressure sintering under a moderate nitrogen pressure. After grinding, the substrate is finished and can be metalized optionally. This silicon nitride material is called SiN80.

SiN80 shows excellent properties. Remarkable is a thermal expansion coefficient with values between 3.0 and 3.8 10^{-6} K^{-1} at a temperature range from room temperature to 200 °C and thus it fits better to the CTE (coefficient of thermal expansion) of silicon or other semiconductor materials than other substrate materials. The reduction of the CTE mismatch minimizes the stress during thermal cycling. Due to that, the reliability increases dramatically. Figure 1 shows the CTE of different substrate materials.

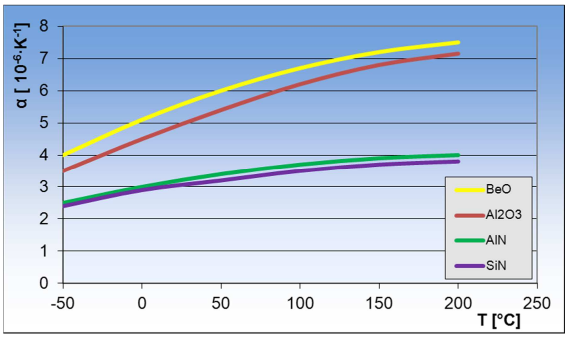


Figure 1: CTE of different substrate materials

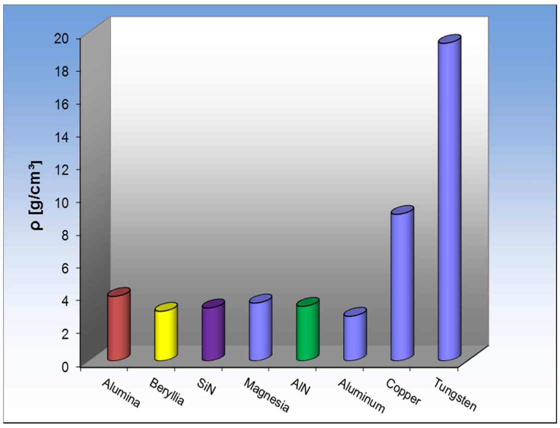


Figure 2: Specific weight of various electronic materials

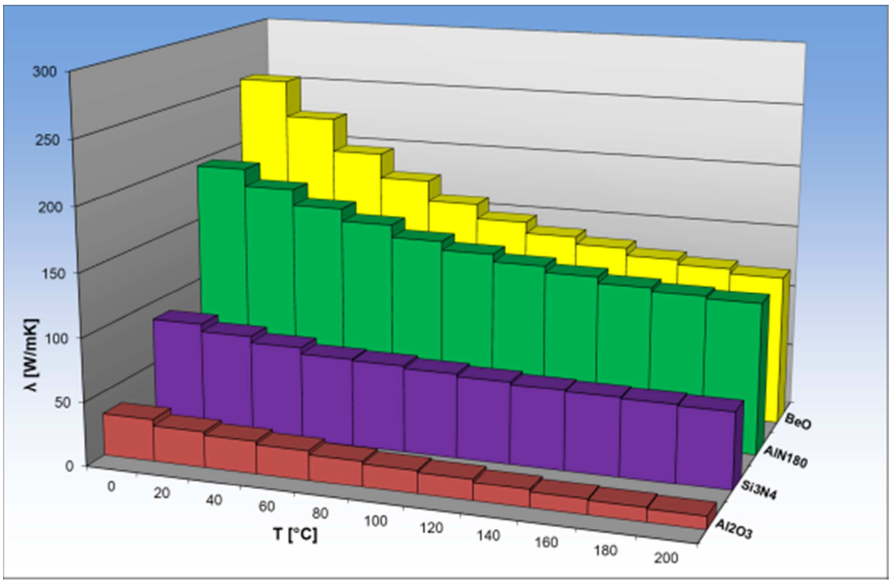


Figure 3: Thermal conductivity of different ceramic materials

Another advantage is the relative low specific weight of SiN80 compared to other electronic materials, especially for applications where weight reduction is an important item. Figure 2 shows a comparison of the specific weights of some materials used in electronics.

The thermal conductivity of about 80 W/mK is three times higher than standard silicon nitride qualities. The value lies between aluminum nitride and alumina, which is illustrated in figure 3. Beryllium oxide and aluminum nitride have admittedly a higher thermal conductivity but they both have only a low mechanical strength of 150 MPa for BeO and ~400 MPa for AlN, whereas SiN80 shows values for the flexural strength of at least 800 MPa. The high mechanical strength allows the use of a thinner substrate. This reduction in thickness leads to a decrease of the total thermal resistance of the substrate which improves heat dissipation and similar results compared to materials with higher conductivity like aluminium nitride can be obtained. Another interesting property for power electronics is the dielectric behavior. With a relative permittivity of about 8.4 to 8.5 at 1 MHz and a low dielectric loss angle tanδ of $1.0 \cdot 10^{-3}$ at 1 MHz, these characteristics are comparable to common substrate materials.

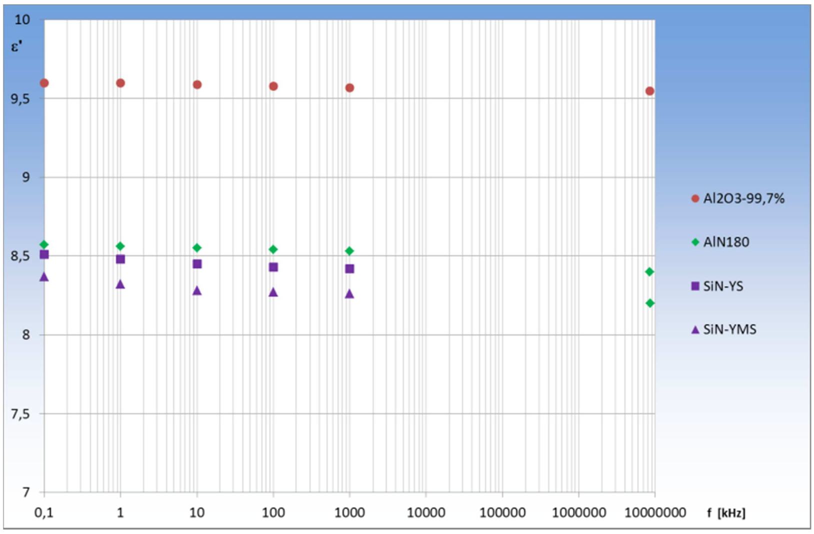


Figure 4: Relative permittivity of different ceramic materials

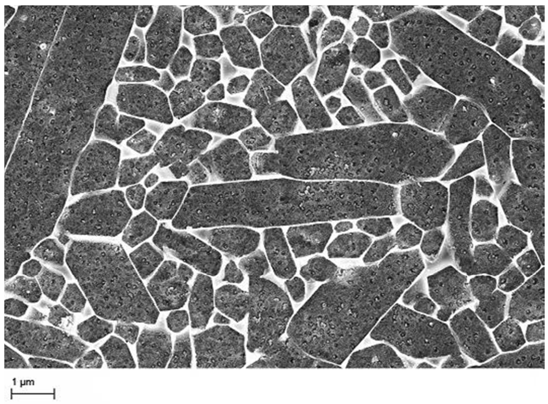
Table 2: Overview of the main properties of the new developed silicon nitride

Properties			Method	SiN 80
ρ_{th}	Density (theoretical)	(g/cm^3)	calculated	3.25
ρ_m	Density (as measured)	(g/cm^3)	buoyancy	3.22
σ_B	Flexural strength	(MPa)	Ball on ring	> 800
E	Young's modulus	(GPa)	Ultrasonic	336
λ	Thermal conductivity	(W/mK)	Laser flash	80 ± 10
α	Coeff. of thermal expansion RT - 1000 °C	(10^{-6} K^{-1})	Dilatometric	3.0 – 3.5
c_P	Specific heat	(J/kgK)	Calorimetric	632 ± 20
	Volume resistivity	(Ωcm)	at 5 kV	> 10^{12}
	Dielectric strength	(kV/mm)	in fluorintert	> 15
ε_r	Dielectric constant	(at 1 MHz)	LCR meter	8.4 – 8.5
tan δ	Loss tangent (at 1 MHz)		LCR meter	$1.0 \cdot 10^{-3}$
Max. working temperature under air			---	800 °C
	Thermal shock resistance		---	excellent

In figure 4, the relative permittivity of some electronic materials is shown. Due to the high dielectric strength (≥ 15 kV/mm AC) and insulation resistance (>10^{12} Ωcm at 5kV) it is suitable for high voltage utilizations. Last but not least, the excellent resistance to thermal shock is one of the outstanding properties of this ceramic.

Table 2 sums up the main characteristics of the new developed tape casted and gas pressure sintered silicon nitride substrate. The combination of a low coefficient of thermal expansion with a high flexural strength and fracture toughness as well as a good thermal shock resistance leads to a high reliability, particularly with regard to thermal cycling. SiN80 is therefore predestined for application, where heat dissipation meets rough conditions like thermal or mechanical stress.

Picture 1: Microstructure of sintered SiN80 [3]



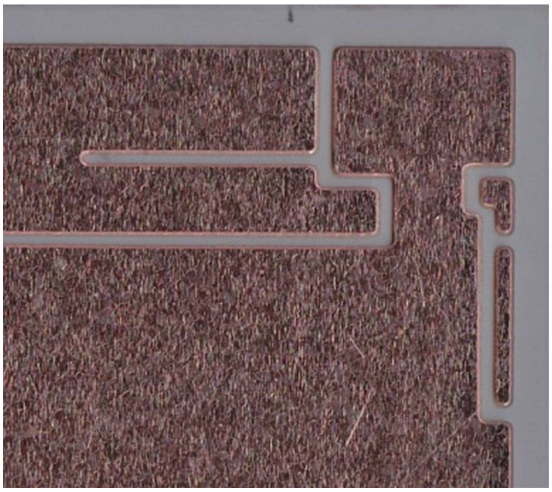
3. AMB with copper conductor lines on silicon nitride

Silicon nitride substrates with AMB copper conductor lines are the right choice when the following requirements are applicable:

- High power density of semiconductor components
- High dissipated heat of semiconductor components
- High ampacity
- Good thermal cycling resistance

This requirement profile could not be covered by substrates with printed thick-film conductor lines or a low thermal conductivity. Therefore, the gas pressure sintered silicon nitride with copper conductor lines could be a superior option.

In picture 2 an example of an AMB substrate with copper conductor lines is shown.

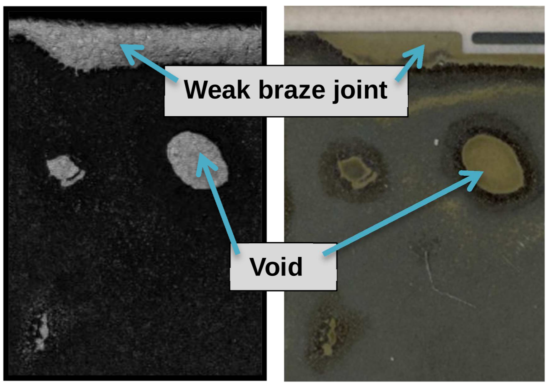


Picture 2: Detail of Si_3N_4 substrate with AMB copper conductor lines

The copper conductor lines were applied by the so called AMB process. AMB is the acronym for active metal brazing. The AMB technique is a method for joining ceramic with metal without previous metallization of the ceramic component. The silver based brazing solder, containing surface active elements like Ti, Zr or Hf, is applied via screen printing. This brazing layer shows already the layout of the later conductor lines. On top a copper foil with a thickness between 100 µm and 500 µm is placed. During the heating-up in a vacuum or protective gas furnace a diffusion of the active component to the ceramic/braze interface takes place. The interaction between the active metal and the ceramic forms a well adherent reaction layer that can be wetted by the liquid braze. After cooling, the copper foil can be structured by an etching process to achieve the required layout of the conductor lines.

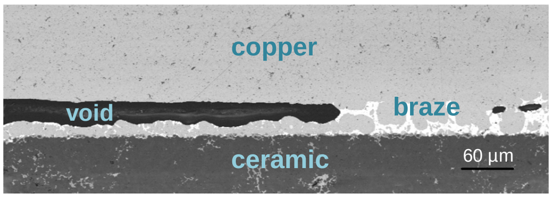
The AMB process is a standard process for several substrate materials, for example aluminum nitride. But this knowledge could not easily be converted to silicon nitride. The AMB-copper brazed silicon nitride substrates shows various brazing defects, like weak braze joints at edge regions, voids beneath the copper foil and braze spreading between adjacent structures. Within the scope of a research project together with Fraunhofer IKTS Dresden and Umicore AG & Co. KG - Business Line BrazeTec and government-funded by the Federal Ministry of Economnics and Technology (BMWi) the failure mechanisms were examined.

Picture 3 and 4 shows the initial state of the brazed substrates at the beginning of the research project. Picture 3 is the image of a scanning acoustic microscope (SAM). This method allows a nondestructive testing of the AMB substrate. Picture 4 shows the same substrate with etched off copper. The scanning acoustic microscopy is an adequate method for evaluating the quality of the braze joint. Picture 5 shows a cross section trough a typical void. Picture 6 illustrates the braze spreading defect.



Picture 3: Brazing defects - SAM image [2]

Picture 4: Brazing defects - surface image with etched off copper

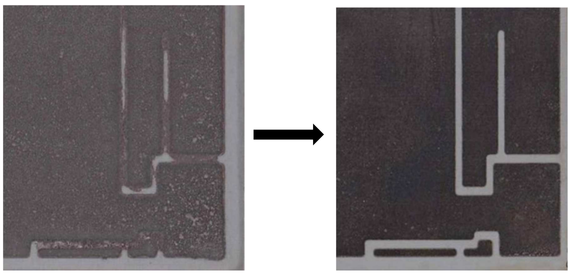


Picture 5: Cross section through a void [2]

After the detection of all brazing defects, an investigation shows the physical and chemical interactions between the braze and the ceramic substrate. The used braze is a silver and copper based material with TiH_2 as an active component.

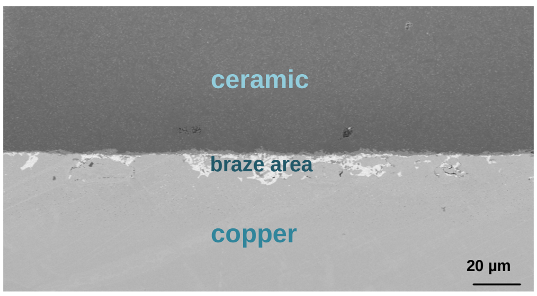
With the content of the active metal component and the surface condition of the silicon nitride two main influence parameters could be identified. Another critical parameter is the process control during debindering phase of brazing paste. The AMB process can be carried out in vacuum atmosphere as well as in protective atmosphere.

With the combination of all the options it was possible to eliminate all occurring brazing defects.



Picture 6: Braze spreading before improvement

Picture 7: Braze spreading after improvement



Picture 8: Cross section of a faultless brazed joint [2]

Picture 2, 7 and 8 show details of the defect free silicon nitride substrate with AMB copper conductor lines.

The copper surface of the finished AMB substrate can be coated on demand with nickel or nickel/gold for improved solderability and wire bondability as well as for corrosion protection.

Such a defective free silicon nitride substrate with AMB copper conductor lines and fully covered back side ground shows a higher reliability than comparable substrates made out of common, well known ceramic materials. The heat dissipation is comparable with conventional AMB substrates made of high thermal conductive ceramic such as aluminum nitride, but thermal cycling behavior exceeds the limits well known from AlN-AMB or AlN-DCB (direct copper bonded). But to obtain these properties it is necessary to be aware of some essential design rules.

4. Design rules for a higher reliability

The layout design is decisive for the longtime reliability.

To obtain a flat AMB substrate it is necessary to cover both sides of the ceramic with copper. Due to the CTE mismatch between copper and ceramic the copper volume of both sides has to be equilibrated. During the heating up of the AMB process both components can expand independently. While the compound cools down, the brazing solder becomes solid and a strong joint is created. The ceramic (low CTE) impedes the shrinkage of the copper, which has the higher coefficient of thermal expansion. This mismatch induces tensile stress in the ceramic and the substrate gets bowed. This means, if the design has a structured top side and a fully covered backside, the thickness of the backside copper has to be thinner. If it is possible, the optimal solution is to design the copper layout of both sides nearly congruent. This helps to minimize the locked-up stress induced by the AMB process and the warp of the finished AMB substrate.

Table 3: Overview of AMB design rules for selected copper thicknesses

Chip side :		
Thickness of copper	300 µm	200 µm
Min. width of conductor lines (w)	700 µm	500 µm
Min. spacing (s)	700 µm	700 µm
Pullback (p)	> 1.0 mm	> 1.0 mm
Curvature radii of copper edges		
- On the outside of the pattern (R)	≥ R 5 mm	≥ R 4 mm
- On the inside of the pattern (r)	≥ R 3	≥ R 2.5 mm
Ground side:		
Thickness of copper	300 µm	200 µm
Pullback (p)	≥ 1.0 mm	≥ 1.0 mm
Curvature radii of copper edges (R)	≥ R 5.0 mm	≥ R 5.0 mm

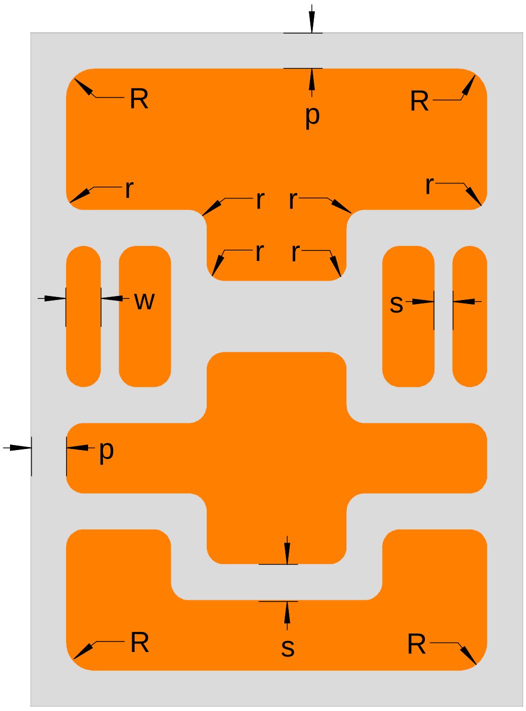


Figure 5: AMB design rules sketch to table 3

To prevent delamination during thermal cycling it is helpful to avoid sharp edges, especially at the corners of the copper structures. This minimizes the thermal and mechanical stress at the highly exposed areas. Table 3 shows an overview of some essential design rules for two assorted copper thicknesses. Copper thicknesses between 100 µm and 500 µm with gradations of 50 µm are feasible. Figure 5 is a sketch of an AMB substrate and clarifies the specification of table 3. Thicknesses of the silicon nitride ceramic substrate bigger than 0.32 mm are possible. The copper thickness has to be adapted to the ceramic thickness.

With due regard to this guidelines, the thermal cycling behavior and the reliability exceeds the limits well known from AlN-AMB or AlN-DCB.

5. Conclusion

The recently developed tape casted silicon nitride substrate is distinguished by a good thermal conductivity of 80 W/mK combined with an extremely high mechanical strength of 800 MPa. This combination of features results in an extraordinary thermal shock resistance and best resistance to temperature cycling, particularly if metalized with AMB copper. Dielectric features are similar to typical substrate ceramics like alumina, beryllium oxide and aluminum nitride.

Typical applications of silicon nitride ceramic substrates are found wherever thermal cycling behavior of metalized substrates and long term reliability are necessary: for example electronic systems facing extreme temperature cycles such as in oil drilling, mining industry and automotive power electronics.

6. Literatur

[1] Kollenberg, W. (ed.): Technische Keramik. 1. Aufl., Vulkan Verlag Essen, 1994.

[2] Courtesy of Fraunhofer IKTS, Dresden.

[3] Courtesy of Fraunhofer ISC, Würzburg.