# High Thermal Conductivity Silicon Nitride Ceramic

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# Introduction

Since the confirmation that nonmetallic single crystals with a diamond-like structure, such as SiC, BP, and AlN, have high intrinsic thermal conductivities of over 300 W m<sup>-1</sup> K<sup>-1,1,2</sup> a great deal of effort has been focused on the development of nonoxide polycrystalline ceramics with high thermal conductivity. SiC and AlN ceramics with high thermal conductivities of over 200 W m<sup>-1</sup> K<sup>-1</sup> have been successfully fabricated, and they are used commercially as high thermal conductivity substrates, heatsinks, and so on. However, widespread use of these materials is still restricted, owing to the low reliability that arises from their poor mechanical properties. In addition, application of SiC ceramics is further limited by their low electric resistance and high dielectric constant. Hence, electrical industries actively search for alternative materials with both high thermal conductivity and superior mechanical properties in order to manage the everincreasing heat generated by electric devices.

Silicon nitride  $(Si_3N_4)$  ceramic, on the other hand, is well known as a high-temperature structural ceramic having high strength and fracture toughness. The excellent mechanical properties of  $Si_3N_4$  result from its unique microstructure, which is composed of hexagonal, rodlike grains, bonded together and reinforcing each other.<sup>3–5</sup> Recently, a  $Si_3N_4$  ceramic with thermal conductivities of over 100 W m<sup>-1</sup> K<sup>-1</sup> was reported.<sup>6–9</sup> In addition, considering the similarity of chemical bonding and crystal structure of  $Si_3N_4$  to those of SiC and AIN, Haggerty and Lightfoot<sup>10</sup> pointed out that single-crystal  $Si_3N_4$  has a high intrinsic thermal conductive.

tivity of over 200 W m<sup>-1</sup> K<sup>-1</sup> at room temperature. These facts, combined with the excellent mechanical properties of Si<sub>3</sub>N<sub>4</sub> ceramic, make it a serious candidate for high-performance substrates. This article summarizes recent results on the thermal conductivity of Si<sub>3</sub>N<sub>4</sub> and discusses the extrinsic factors governing the thermal conductivity of Si<sub>3</sub>N<sub>4</sub> ceramic in terms of microstructural parameters such as lattice defects in single-crystal Si<sub>3</sub>N<sub>4</sub> and the morphology of grain-boundary secondary phases, comparing Si<sub>3</sub>N<sub>4</sub> with the cases of SiC and AlN ceramics. In addition, high thermal conductivities achieved in textured Si<sub>3</sub>N<sub>4</sub> are also introduced.

### Processing and Microstructure of Nonoxide Ceramics

In general, because of their low selfdiffusion coefficients even at high temperatures, nonoxide ceramics with high covalent bonding, such as Si<sub>3</sub>N<sub>4</sub>, AlN, and SiC, are densified with the aid of sintering additives. SiC is generally densified through solid-phase sintering by adding small amounts of additives such as B, C,<sup>11</sup> and Be compounds,12 although liquid-phase sintering of SiC using oxides or carbides has recently attracted attention as a method for developing anisotropic grains that act as reinforcements.<sup>13</sup> On the other hand, AlN and Si<sub>3</sub>N<sub>4</sub> are densified by liquidphase sintering to lower the sintering temperatures because these nitrides, in particular Si<sub>3</sub>N<sub>4</sub>, are not very stable at higher temperatures, as shown in Table I. A wide variety of oxides, such as alkalineearth oxides and rare-earth oxides, are used as sintering additives for AlN and Si<sub>3</sub>N<sub>4</sub>. During sintering, these additives react

| Table I: Comparison of $Si_3N_4$ with AIN and SiC. |                                                                                                  |                                                                               |                                                      |  |  |  |
|----------------------------------------------------|--------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|------------------------------------------------------|--|--|--|
|                                                    | Si <sub>3</sub> N <sub>4</sub>                                                                   | AIN                                                                           | SiC                                                  |  |  |  |
| Single-Crystal Form                                |                                                                                                  |                                                                               |                                                      |  |  |  |
| Crystallography                                    | $\beta$ -Si <sub>3</sub> N <sub>4</sub> : hexagonal ( <i>P</i> 6 <sub>3</sub> )                  | Hexagonal (wurtzite)                                                          | Polytypism (3C, 2H, 4H, 15R, etc.)                   |  |  |  |
| Decomposition temperature                          | 1850°C                                                                                           | 2200°C (sublimation)                                                          | 2800°C (sublimation)                                 |  |  |  |
| Intrinsic thermal conductivity                     | 200 W m <sup>-1</sup> K <sup>-1</sup> or 320 W m <sup>-1</sup> K <sup>-1</sup><br>(Reference 10) | 320 W m <sup><math>-1</math></sup> k <sup><math>-1</math></sup> (Reference 1) | 490 W $m^{-1} k^{-1}$ (Reference 1)                  |  |  |  |
| Polycrystalline Form                               |                                                                                                  |                                                                               |                                                      |  |  |  |
| General sintering process                          | Liquid-phase sintering                                                                           | Liquid-phase sintering                                                        | Solid-phase sintering<br>(Liquid-phase sintering)    |  |  |  |
| Secondary phase                                    | Mainly amorphous<br>(~1 W m <sup>-1</sup> K <sup>-1</sup> )                                      | Mainly crystalline<br>(~10 W m <sup>-1</sup> K <sup>-1</sup> )                | _                                                    |  |  |  |
| Morphology of secondary phase                      | Glass pocket<br>Thin film                                                                        | Dispersion (Thin film)                                                        | _                                                    |  |  |  |
| Highest experimental conductivity                  | 155 W m <sup>-1</sup> K <sup>-1</sup> (Reference 33)                                             | $\sim$ 260 W m $^{-1}$ K $^{-1}$ (Reference 39)                               | 270 W m <sup>-1</sup> K <sup>-1</sup> (Reference 12) |  |  |  |
| Bending strength*                                  | 600–1500 MPa                                                                                     | 300–350 MPa                                                                   | 380–800 MPa                                          |  |  |  |
| Fracture toughness*                                | 5–7 MPa m <sup>1/2</sup>                                                                         | 3–4 MPa m <sup>1/2</sup>                                                      | 3.5–4.5 MPa m <sup>1/2</sup>                         |  |  |  |

\* Data taken from catalog of commercially supplied materials.



Figure 1. Fractured surfaces of (a)  $Si_3N_4$ , (b) AIN, and (c) SiC ceramics.

with impurity oxides largely present as a surface film on the nitride powder,  $Al_2O_3$ in AlN and SiO<sub>2</sub> in Si<sub>3</sub>N<sub>4</sub>, respectively, to form a liquid phase, which enhances densification through the rearrangement of particles and a solution re-precipitation reaction. In silicon nitride, there are two crystalline phases designated as  $\alpha$  and  $\beta$ , which are the low- and high-temperature phases, respectively. Since the  $\alpha$ -to- $\beta$  phase transformation during liquid-phase sintering promotes the development of elongated  $\hat{\beta}$ -Si<sub>3</sub>N<sub>4</sub> grains,<sup>14</sup>  $\alpha$ -Si<sub>3</sub>N<sub>4</sub> powder is generally used as a starting raw powder. After sintering, the liquid phase remains in the corners of or along the matrix grains as a glassy phase or crystalline phases (referred to as secondary phases), the volume fractions of which are typically 5–10%.

Typical fractured surfaces of liquid-phasesintered Si<sub>3</sub>N<sub>4</sub>, as well as of liquid-phasesintered AlN and solid-phase-sintered SiC, are shown in Figures 1a, 1b, and 1c, respectively. SiC and AlN exhibit homogeneous microstructures composed of equiaxial grains. In addition, SiC shows a transgranular mode of fracture, owing to the strong bonding between grains. Poor fracture toughness of SiC and AlN is ascribed to such homogeneous microstructure. In contrast, Si<sub>3</sub>N<sub>4</sub> is composed of rodlike grains, reflecting the preferential growth in the [001] direction in  $\beta$ -Si<sub>3</sub>N<sub>4</sub>.<sup>15</sup> These rodlike grains, in turn, act as reinforcements that promote crack-bridging processes and toughen the Si<sub>3</sub>N<sub>4</sub>. Figure 2 illustrates the microstructural factors of Si<sub>3</sub>N<sub>4</sub> affecting thermal conductivity. Lattice defects in  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains and grainboundary phases are considered to be extrinsic factors affecting the thermal conductivity of Si<sub>3</sub>N<sub>4</sub>. Although the microstructures of AlN and Si<sub>3</sub>N<sub>4</sub> are different, the chemistry and processing of them are similar in many ways, as summarized in Table I. The extrinsic factors governing the thermal conductivity of Si<sub>3</sub>N<sub>4</sub>, therefore,

can be discussed based on the results obtained for AlN, as described next.

# Effect of Impurity Atoms on Thermal Conductivity

The conduction of heat in dielectric ceramics is dominated by phonon transport: at room temperature, a greater influence in phonon scattering is attributed to imperfections in the crystal lattice, for example, impurity atoms, interstitials, and vacancies. Slack et al. have systematically investigated the effect of impurities on thermal conductivities of nonmetallic crystals, and have revealed the strong correlation between the concentration of lattice oxygen and the thermal conductivity of singlecrystal AlN.<sup>1,2</sup> Several additional studies on polycrystalline AlN ceramic were carried out,16-18 and it is now well recognized that oxygen as an impurity is a dominant factor lowering the thermal conductivity of AlN ceramic. It is assumed that oxygen dissolved in an AlN lattice creates vacancies

in aluminum sites that scatter phonons and thereby lowers the thermal conductivity.<sup>1</sup> Therefore, in developing high thermal conductivity AlN ceramic, much attention has been paid to researching the sintering additives that are able to remove oxygen from AlN crystals.<sup>16,19</sup> Rare-earth oxides are known to be suitable additives for purifying the AlN crystals during sintering.<sup>16,19</sup>

In the case of Si<sub>3</sub>N<sub>4</sub> ceramic, it is well recognized that the use of Al<sub>2</sub>O<sub>3</sub>, one of the available sintering additives for Si<sub>3</sub>N<sub>4</sub> ceramic, considerably lowers the thermal conductivity because Al<sub>2</sub>O<sub>3</sub> reacts with Si<sub>3</sub>N<sub>4</sub> to form the solid solution of  $\beta$ -Si<sub>3</sub>N<sub>4</sub>, which has the chemical formula of Si<sub>6-z</sub>Al<sub>z</sub>O<sub>2</sub>N<sub>8-z</sub> (referred to as  $\beta$ -Sialon, 0 < z < 4.2).<sup>7,20</sup>  $\beta$ -Sialon is formed by the simultaneous equivalent substitution of Al-O for Si-N in  $\beta$ -Si<sub>3</sub>N<sub>4</sub>. However, there have been no reports on whether oxygen alone can be incorporated into the  $\beta$ -Si<sub>3</sub>N<sub>4</sub> crystal lattice. Recently, Kitayama et al.<sup>21</sup> succeeded in measuring the oxygen con-



Figure 2. Microstructural factors of  $Si_3N_4$  ceramic affecting thermal conductivity.

tent in the  $\beta$ -Si<sub>3</sub>N<sub>4</sub> crystal lattice by the hot-gas extraction method, revealing that oxygen can be dissolved into the  $\beta$ -Si<sub>3</sub>N<sub>4</sub> lattice up to at least 0.4% by mass. Based on electron spin resonance analysis,<sup>22</sup> they also reported that the incorporation of oxygen into the  $\beta$ -Si<sub>3</sub>N<sub>4</sub> lattice occurs by the dissolution of SiO<sub>2</sub> in the following plausible reaction:

$$2SiO_2 \rightarrow 2Si_{Si} + 4O_N + V_{Si}, \qquad (1)$$

where O<sub>N</sub> and V<sub>Si</sub> denote oxygen in a nitrogen site and a vacant silicon site, respectively. Applying these analytical methods to hot-pressed Si<sub>3</sub>N<sub>4</sub> with Y<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub>, they have established that the thermal conductivity of  $\beta$ -Si<sub>3</sub>N<sub>4</sub> ceramic increases with decreasing oxygen content in the Si<sub>3</sub>N<sub>4</sub> single-crystal lattice. This investigation also indicated that the lattice oxygen content varies with the  $Y_2O_3/SiO_2$  ratio. As the grain growth of  $\beta$ -Si<sub>3</sub>N<sub>4</sub> after phase transformation occurs such that smaller  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains dissolve into the liquid phase to re-precipitate on larger  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains, the lattice oxygen content might be closely related to the composition of the liquid phase. Kitayama et al. have explained the variation of lattice oxygen with the Y<sub>2</sub>O<sub>3</sub>/SiO<sub>2</sub> ratio, based on the thermodynamic consideration of the grainboundary phase.<sup>22</sup> In addition to the Y<sub>2</sub>O<sub>3</sub>/SiO<sub>2</sub> ratio, a family of rare-earth oxides,  $\text{Re}_2\text{O}_3$  (Re = Sc, Yb, Y, Nd, etc.), affects the thermal conductivity of Si<sub>3</sub>N<sub>4</sub> ceramic. It was revealed that as the ionic radius of the rare-earth element decreases, grain growth of  $\beta$ -Si<sub>3</sub>N<sub>4</sub> is enhanced, lattice oxygen of  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains decreases, and hence thermal conductivity of the specimen increases.23 The results indicated that  $Yb_2O_3$  and  $Y_2O_3$  are suitable additives for fabricating high thermal conductivity Si<sub>3</sub>N<sub>4</sub>, compared with other rare-earth oxides.

Hayashi et al.24 have further investigated the relation between lattice oxygen content and thermal conductivity, using  $\beta$ -Si<sub>3</sub>N<sub>4</sub> as a raw powder in order to exclude the influence of phase transformation. In their study,  $\beta$ -Si<sub>3</sub>N<sub>4</sub> with concurrent addition of Yb<sub>2</sub>O<sub>3</sub> and MgO was sintered at 1900°C under 0.9 MPa nitrogen pressure. Figure 3 shows the effect of sintering time on the lattice oxygen content and the thermal conductivity of sintered Si<sub>3</sub>N<sub>4</sub>. The lattice oxygen, which in raw  $\beta$ -Si<sub>3</sub>N<sub>4</sub> powders was about 0.4% by mass, decreased with increasing sintering time. As a result, the thermal conductivity of the specimen increased with sintering time, and a high thermal conductivity of about 120 W  $m^{-1}$  K<sup>-1</sup> could be achieved in a specimen sintered for a very long time. Considerable grain growth of  $\beta$ -Si<sub>3</sub>N<sub>4</sub>



Figure 3. Effect of sintering time on the lattice oxygen content and the thermal conductivity of  $Si_3N_4$  with  $2mol\%Yb_2O_3$ -5mol%MgO sintered at 1900°C under 0.9 MPa N<sub>2</sub>.

with sintering time was observed, as shown in Figure 4. It is therefore evident that a decrease in lattice oxygen content, namely, purification of  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains, is significantly affected by the solution reprecipitation process, which results in grain growth of  $\beta$ -Si<sub>3</sub>N<sub>4</sub>. Figure 5 summarizes the relation between the lattice oxygen content in  $\beta$ -Si<sub>3</sub>N<sub>4</sub> and the thermal resistivity of these specimens, along with the results obtained by Kitavama et al.22 Although processing method, type of raw Si<sub>3</sub>N<sub>4</sub> powder, and additive system used were quite different between these investigations, there is a clear tendency for thermal resistivity to decrease with decreasing lattice oxygen content. The result suggests that lattice oxygen content in  $\beta$ -Si<sub>3</sub>N<sub>4</sub> is a dominant extrinsic factor governing the thermal conductivity of Si<sub>3</sub>N<sub>4</sub> ceramic, as has been demonstrated in AlN ceramic. Moreover, by extrapolation, it can be said that  $\beta$ -Si<sub>3</sub>N<sub>4</sub> free from lattice oxygen should exhibit at least a thermal conductivity of about 180 W m<sup>-1</sup> K<sup>-1</sup>.

#### Effect of Secondary Phases on Thermal Conductivity

The morphology of the secondary phases in AlN and  $Si_3N_4$  ceramics, in addition to the lattice oxygen content, negatively affects the thermal conductivity to some extent because these phases have thermal conductivities 1-2 orders of magnitude lower than pure AlN or Si<sub>3</sub>N<sub>4</sub> crystals. For example, the thermal conductivities of yttrium aluminate (typical secondary phase in AlN with Y<sub>2</sub>O<sub>3</sub> addition) and oxynitride glass (typical secondary phase in Si<sub>3</sub>N<sub>4</sub>) are about 10 W m<sup>-1</sup> K<sup>-1</sup> and 1 W m<sup>-1</sup> K<sup>-1</sup>, respectively. Considering the effect of distribution of a secondary phase with low thermal conductivity based on the simple dispersed model,<sup>25</sup> a continuous distribu-



Figure 4. Variation of microstructure of  $Si_3N_4$  with  $2mol\%Yb_2O_3$ -5mol%MgO with sintering time. Specimens were sintered at 1900°C under 0.9 MPa  $N_2$ .



Figure 5. Effect of lattice oxygen content on thermal resistivity of  $Si_3N_4$  fabricated by gas-pressure sintering ( $\textcircled{\bullet}$ ) and hot-pressing ( $\blacksquare$ ,  $\Box$ ).

tion around the matrix grains extensively lowers the thermal conductivity, while an isolated distribution does not appreciably affect the thermal conductivity. In the case of AlN ceramic, it has been confirmed that the secondary phases have little influence on the thermal conductivity because they are present largely as isolated crystalline phases, and that the amount of secondary phase in AlN ceramic has a major influence on thermal conductivity only if the lattice oxygen content in the AlN is very low and the amount of secondary phase is rather large.<sup>18,26,27</sup>

Compared with AlN ceramic, the microstructure of Si<sub>3</sub>N<sub>4</sub> ceramic is more complicated, owing to the well-faceted grains with a rodlike shape, as illustrated in Figure 2. Most of the secondary phase is generally present as a glassy phase because the liquid phase containing SiO<sub>2</sub> is difficult to crystallize perfectly. It should be noted that the thermal conductivity of glass can be as low as  $1 \text{ W m}^{-1} \text{ K}^{-1}$ , which is about one order of magnitude lower than the thermal conductivity of the crystalline secondary phase in AlN ceramic. In addition, this glassy phase is distributed not only as glass pockets surrounded by  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains, but also in the openings between two grains, as most of rodlike  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains incline toward each other. It is reasonable to think that the negative effect of the secondary phase on thermal conductivity is somewhat more pronounced in  $Si_3N_4$  ceramic than AlN ceramic.

In addition, grain-boundary thin films with an equilibrium thickness (typically 1–2 nm) are generally present between two-grain junctions in liquid-phase-sintered  $Si_3N_4$  ceramic.<sup>28</sup> A calculation based on a simple modified Wiener's model<sup>29</sup> for the thermal conductivity of a composite material predicts that the thermal conductivity of  $\beta$ -Si<sub>3</sub>N<sub>4</sub> ceramic having grain-boundary films of a few nanometers' thickness de-

creases quickly as the size of the  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains decreases to less than 1  $\mu$ m.<sup>30</sup> From this viewpoint, in addition to the role of purifying the  $\beta$ -Si<sub>3</sub>N<sub>4</sub> lattice, grain growth is necessary in order to improve the thermal conductivity of Si<sub>3</sub>N<sub>4</sub> ceramic. However, it should be noted that grain-boundary thin films have little effect on the thermal conductivity of Si<sub>3</sub>N<sub>4</sub> when the grain size exceeds certain critical values (about 1  $\mu$ m).

## High Thermal Conductivity in Anisotropic Microstructures

Another approach for achieving high thermal conductivity in Si<sub>3</sub>N<sub>4</sub> ceramic is to develop a textured microstructure in which elongated  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains are oriented almost unidirectionally. High thermal conductivity along the grain orientation is expected, compared with material with a random distribution of  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains, for the following reasons: the alignment of elongated  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains, in turn, causes the glassy phase to be distributed parallel to the grain orientation, which minimizes the negative effect of the glassy phase with low thermal conductivity; in addition, high-resolution thermoreflectance microscopy measurements of the extra large  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains reveal that the thermal diffusivity and conductivity of  $\beta$ -Si<sub>3</sub>N<sub>4</sub> crystals along the c axis, namely, along the length of the rodlike grains, are higher than those along the *a* axis.<sup>31</sup> Detailed microthermal characterization of grains in ceramic materials is mentioned in the article by Fournier in this issue.

Such anisotropic microstructures can be fabricated by the combination of the seeding of rodlike  $\beta$ -Si<sub>3</sub>N<sub>4</sub> nuclei and a forming process generating shear stress, such as tape casting and extrusion.<sup>6,32–35</sup> This process is based on the grain-growth behavior of silicon nitride: during  $\alpha$ -to- $\beta$ phase transformation, the preferential nucleation site of the newly formed  $\beta$ -Si<sub>3</sub>N<sub>4</sub> phase is pre-existing  $\beta$  particles, <sup>36,37</sup> and after transformation, only some large  $\beta$ grains selectively grow, particularly along the c axis direction, by a solution reprecipitation reaction.<sup>38</sup> Figure 6 shows the typical microstructure of seeded and extruded Si<sub>3</sub>N<sub>4</sub>. The material exhibits high anisotropy where large elongated grains, grown from seeds, are almost unidirectionally oriented parallel to the extruding direction.35 Table II summarizes the thermal conductivities, measured in three different directions, for textured Si<sub>3</sub>N<sub>4</sub> fabricated by this method with different sintering additives. As expected, for all of the specimens, thermal conductivity is highest along the grain alignment. In particular, highly anisotropic Si<sub>3</sub>N<sub>4</sub> with very long grains, fabricated under extreme conditions, exhibits a high thermal conductivity of about 150 W  $m^{-1}$  K<sup>-1</sup> in the direction parallel to the grain alignment.33



Figure 6. Microstructure of textured  $Si_3N_4$  ceramic.

| Table II: Thermal Conductivity in Three Directions for Textured Si <sub>3</sub> N <sub>4</sub> fabricated b | by Combined Seeding and Tape Casting |
|-------------------------------------------------------------------------------------------------------------|--------------------------------------|
|-------------------------------------------------------------------------------------------------------------|--------------------------------------|

| Sample No. | Sintering Additives                     | Annealing Conditions (temperature, time, pressure) | Thermal Conductivity<br>(W m <sup>-1</sup> K <sup>-1</sup> )<br>( <i>x</i> direction, <i>y</i> direction, <i>z</i> direction) | References                    |
|------------|-----------------------------------------|----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|-------------------------------|
| 1          | 5 mass% $Y_2O_3$                        | 2123 K<br>66 h<br>0.9 MPa Na                       | 121, 75, 60                                                                                                                   | Hirao et al.6                 |
| 2          | 5 mass% $Y_2O_3$                        | 2773 K<br>2 h<br>200 MPa N <sub>2</sub>            | 155, 67, 52                                                                                                                   | Watari et al.33               |
| 3          | 0.5 mol% $Y_2O_3$<br>0.5 mol% $Nd_2O_3$ | 2423 K<br>4 h<br>30 MPa N <sub>2</sub>             | 137, 97, 72                                                                                                                   | Hirosaki et al. <sup>34</sup> |

#### Summary

The thermal conductivity of Si<sub>3</sub>N<sub>4</sub> ceramic at room temperature is basically governed by the lattice oxygen content in the  $\beta$ -Si<sub>3</sub>N<sub>4</sub> crystal. Therefore, in order to improve thermal conductivity, it is important to purify the grains, as has been demonstrated in AlN ceramic. The purification of  $\beta$ -Si<sub>3</sub>N<sub>4</sub> grains can be achieved through a solution re-precipitation reaction during sintering using sintering additives that have a great affinity for SiO<sub>2</sub>, such as  $Y_2O_3$  and  $Yb_2O_3$ . As far as the authors know, Si<sub>3</sub>N<sub>4</sub> ceramic with a high thermal conductivity of over 100 W m<sup>-1</sup> K<sup>-1</sup> has been fabricated only by gas-pressure sintering. From a commercial point of view, it is very important to fabricate high thermal conductivity Si<sub>3</sub>N<sub>4</sub> ceramic by a conventional sintering technique such as pressureless sintering. Seeding, combined with careful control of grainboundary composition, may be one of the processing strategies for this purpose. In addition, microstructure design for harmonizing high thermal conductivity with good mechanical and electrical properties (such as low dielectric constant) is also very important for the widespread use of Si<sub>3</sub>N<sub>4</sub> ceramic as a high thermal conductivity material.

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