UDC 666.3-16
IRSTI 67.09.05
REVIEW ARTICLE

TUNING THE THERMAL CONDUCTIVITY OF POROUS SILICON CARBIDE CERAMICS: A REVIEW

S. Kultayeva*, E.B. Kurmanbekova

International Educational Corporation, Almaty, 050043, Kazakhstan

Abstract. *Porous silicon carbide (SiC) ceramics possess unique thermal and structural properties, making them highly valuable for applications requiring high-temperature stability, corrosion resistance, and controlled thermal conductivity. Due to their superior characteristics, porous SiC ceramics are widely used in industrial and environmental applications, including thermal insulators, thermoelectric energy converters, fusion reactors, water purifiers, molten metal and hot gas filters, diesel particulate filters, heatable filters, heating elements, membrane supports, and catalyst supports. This paper reviews the key factors influencing the thermal conductivity of porous SiC ceramics, such as porosity, pore size, additive composition, and necking area. Understanding how each of these factors affects thermal conductivity can facilitate the design of SiC ceramics tailored to meet specific thermal and mechanical requirements. As the porosity of porous SiC ceramics increases, their thermal conductivity generally decreases. However, at a constant porosity, the thermal conductivity tends to increase with larger pore sizes. Additionally, the incorporation of conductive phases, thermally insulating secondary phases, or excess carbon or silicon significantly impacts the thermal conductivity. The development of the necking area between SiC grains also plays a critical role: a well-developed necking area improves heat transfer across the ceramic, thereby enhancing thermal conductivity. Based on these critical factors influencing thermal properties, a novel strategy for tuning the thermal conductivity of porous SiC ceramics is proposed.*

Keywords: *SiC ceramic, thermal conductivity, porosity, pore size, necking area, additive composition.*

***Corresponding author**
Shynar Kultayeva, e-mail: sh.kultayeva@kazgasa.kz

https://doi.org/10.51488/1680-080X/2024.4-15
Received 03 June 2024; Revised 12 July 2024; Accepted 22 July 2024

ӘОЖ 666.3-16
ҒТАМР 67.09.05
ШОЛУ МАҚАЛА

КЕУЕКТІ КРЕМНИЙ КАРБИДІ КЕРАМИКАСЫНЫҢ ЖЫЛУ ӨТКІЗГІШТІГІН РЕТТЕУ

Ш.М. Құлтаева*, Э.Б. Құрманбекова

Халықаралық білім беру корпорациясы, Алматы, 050043, Қазақстан

Аңдатпа. *Кеуекті кремний карбиді (SiC) керамикасы бірегей термиялық және құрылымдық қасиеттерге ие, бұл оларды жоғары температуралық тұрақтылықты, коррозияға төзімділікті және бақыланатын жылу өткізгіштікті қажет ететін қолданбалар үшін өте құнды етеді. Жоғары сипаттамаларына байланысты кеуекті SiC керамикасы өнеркәсіптік және экологиялық қолданбаларда кеңінен қолданылады, соның ішінде жылу оқшаулағыштары, термоэлектрлік энергия түрлендіргіштері, термоядролық реакторлар, су тазартқыштар, балқытылған металл және ыстық газ сүзгілері, дизельдік бөлшектер сүзгілері, қыздырылатын сүзгілер, қыздыру элементтері, мембраналық тіректер және катализатор тіректері. Бұл мақалада кеуектілік, кеуек өлшемі, қоспа құрамы және мойын аймағы сияқты кеуекті SiC керамикасының жылу өткізгіштігіне әсер ететін негізгі факторлар қарастырылады. Осы факторлардың әрқайсысының жылу өткізгіштікке қалай әсер ететінін түсіну белгілі бір жылу және механикалық талаптарға сай жасалған SiC керамикасын жобалауды жеңілдетуі мүмкін. Кеуекті SiC керамикасының кеуектілігі жоғарылаған сайын олардың жылу өткізгіштігі әдетте төмендейді. Дегенмен, тұрақты кеуектілік кезінде жылу өткізгіштік кеуектердің үлкен өлшемдерімен ұлғаяды. Сонымен қатар, өткізгіш фазалардың, жылу оқшаулағыш қайталама фазалардың немесе артық көміртектің немесе кремнийдің қосылуы жылу өткізгіштікке айтарлықтай әсер етеді. SiC дәндері арасындағы мойын аймағының дамуы да шешуші рөл атқарады: жақсы дамыған мойын аймағы керамика арқылы жылу беруді жақсартады, осылайша жылу өткізгіштігін арттырады. Жылу қасиеттеріне әсер ететін осы маңызды факторларға сүйене отырып, кеуекті SiC керамикасының жылу өткізгіштігін реттеудің жаңа стратегиясы ұсынылады.*

Түйін сөздер: *SiC керамикасы, жылу өткізгіштік, кеуектілік, кеуек өлшемі, байланыс аймағы, қоспа құрамы.*

***Автор-корреспондент**
Шынар Құлтаева, e-mail: sh.kultayeva@kazgasa.kz

https://doi.org/10.51488/1680-080X/2024.4-15
Алынды 03 маусым 2024; Қайта қаралды 12 шілде 2024; Қабылданды 22 шілде 2024

УДК 666.3-16
МРНТИ 67.09.05
ОБЗОРНАЯ СТАТЬЯ

РЕГУЛИРОВАНИЕ ТЕПЛОПРОВОДНОСТИ ПОРИСТОЙ КЕРАМИКИ ИЗ КАРБИДА КРЕМНИЯ

Ш.М. Құлтаева*, Э.Б. Құрманбекова

Международная образовательная корпорация, Алматы, 050043, Казахстан

Аңнотация. *Пористая керамика из карбида кремния (SiC) обладает уникальными теплофизическими и структурными свойствами, что делает ее очень ценной для применений, требующих высокотемпературной стабильности, коррозионной стойкости и контролируемой теплопроводности. Благодаря своим превосходным характеристикам пористая керамика SiC широко используется в промышленности и охране окружающей среды, включая теплоизоляторы, термоэлектрические преобразователи энергии, термоядерные реакторы, очистители воды, фильтры для расплавленного металла и горячего газа, сажевые фильтры для дизельного топлива, нагревательные фильтры, нагревательные элементы, мембранные подложки и катализаторы. В данной статье рассматриваются ключевые факторы, влияющие на теплопроводность пористой керамики SiC, такие как пористость, размер пор, состав присадок и площадь сужения. Понимание того, как каждый из этих факторов влияет на теплопроводность, может облегчить разработку керамики SiC, отвечающей конкретным тепловым и механическим требованиям. С увеличением пористости пористой керамики SiC ее теплопроводность, как правило, снижается. Однако при постоянной пористости теплопроводность имеет тенденцию к увеличению с увеличением размера пор. Кроме того, на теплопроводность существенно влияет наличие токопроводящих фаз, теплоизолирующих вторичных фаз или избыток углерода или кремния. Важную роль также играет наличие зоны сужения между зернами SiC: хорошо развитая зона сужения улучшает теплопередачу по керамике, тем самым повышая теплопроводность. Основываясь на этих критических факторах, влияющих на тепловые свойства, предложена новая стратегия настройки теплопроводности пористой керамики SiC.*

Ключевые слова: *SiC керамика, теплопроводность, пористость, размер пор, область соединения, композиция добавок.*

***Автор-корреспондент**
Шынар Құлтаева, e-mail: sh.kultayeva@kazgasa.kz

https://doi.org/10.51488/1680-080X/2024.4-15
Поступило 12 июня 2024 г.; Пересмотрено 12 июля 2024 г.; Принято 22 июля 2024 г.

ACKNOWLEDGEMENTS/SOURCE OF FUNDING

The research was conducted with the financial support of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan within the framework of the scientific project IRN AP19174518.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің ЖТН AP19174518 гранттық қаржыландыру шеңберінде жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан ИРН AP19174518.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

Silicon carbide (SiC) based porous ceramics are among the most significant materials in advanced ceramics. They gain significant attention and have an important role in various industrial fields due to their low density, high-temperature stability, high thermal shock resistance, excellent heat resistance, good corrosion resistance, low thermal expansion coefficient and excellent mechanical strength. These unique combinations of properties make the porous SiC ceramic a potentially useful material in various advanced applications such as energy, aerospace, and environmental engineering, where thermal conductivity is a critical parameter. By controlling porosity, pore size, and other structural factors, the thermal conductivity of porous SiC ceramics can be finely tuned to optimize performance in applications such as high-temperature insulation, filtration, and heat exchangers.

The thermal conductivity of SiC ceramics is influenced by their porosity, pore size, addition of thermally insulating secondary phases, dopant content, necking area, and additive composition. Generally, the thermal conductivity of porous SiC ceramics increases with decreasing porosity (**Rajpoot et al., 2020; Pappacena et al., 2017; Jana et al., 2017; Jang & Sakka, 2007; Wan et al., 2017; Eom et al., 2008**). For example, in one study, porous LPS-SiC with 3 vol% Y_2O_3-AlN exhibited an increase in thermal conductivity from 4.5 to 37.9 W/(mK) with a decrease in the porosity from 62.7% to 28.3% (**Rajpoot et al., 2020**). Similar trends have been observed for porous SiC ceramics derived from wood precursors (**Pappacena et al., 2017**), SiC foams (**Jana et al., 2017**), porous SiC ceramics without additives (**Jang & Sakka, 2007**), β-SiC nanoparticle-packed beds (**Wan et al., 2017**), polysiloxane-derived porous SiC ceramics (**Eom et al., 2008**). The thermal conductivities of the porous SiC ceramics were highly dependent on their pore sizes. Specificially, The thermal conductivity of porous SiC ceramics is significantly increased from ~14 W/(mK) to ~ 26 W/(mK) by increasing the pore size from ~ 7 µm to ~ 98 µm at an equivallent porosity of ~54% (**Das et al., 2024**), owing to less phonon-pore scattering in porous SiC with larger pores because of the smaller pore/strut interface areas at the same porosity. The thermal conductivity of porous SiC ceramics is greatly decreased by introducing thermally insulating secondary phases and incorporating excess carbon or silicon. These additions create heterophase boundaries (SiC/C and SiC/Si), which enhance phonon scattering at the boundaries (**Kim et al., 2020, Kang et al., 2021**).

Understanding the thermal conductivity of porous SiC ceramics is crucial due to their wide-ranging applications in extreme environments and advanced technologies. The thermal conductivity of porous SiC ceramics directly impacts their role in thermal management systems like heat exchangers, gas turbines, and thermal barrier coatings, where efficient heat transfer or insulation is essential. Tailoring thermal conductivity through control of porosity and microstructure enables the design of materials optimized for energy systems, such as fuel cells and thermoelectric devices, improving efficiency and sustainability. Accurate knowledge enhances reliability by mitigating risks like thermal shock and ensuring long-term performance in safety-critical applications. Additionally, understanding heat transport mechanisms in porous SiC advances fundamental science and aids industries in meeting stringent performance standards while maintaining cost efficiency. Together, these factors underscore the significance of thermal conductivity in unlocking the full potential of porous SiC ceramics.

A comprehensive understanding of the thermal conductivity of porous SiC ceramics is essential for enhancing their performance, extending their applications, and addressing energy, environmental, and safety challenges in modern technology. It serves both scientific progress and practical advancements in critical industries.

The goal of this review is to summarize the effects of porosity, pore size, additive composition, and necking area on the thermal conductivity of porous SiC ceramics.

2. FACTORS AFFECTING THERMAL CONDUCTIVITY OF POROUS SiC CERAMICS

The thermal conductivity of ceramic materials is mainly dependent on the transfer of thermal elastic waves known as phonons. Phonons collide with imperfections in materials such as grain boundaries, pores, impurities, and defects, causing phonon scattering, which decreases the mean free path. The relationship between thermal conductivity (κ) and the mean free path (l) can be estimated as follows (**Watari et al., 2003**)

$$\kappa = \frac{1}{3}(\upsilon\, l\, Cp), \quad (1)$$

where υ is the velocity of sound in the solid, and Cp is the heat capacity. This equation shows that the conductivity of a material primarily depends on its mean free path. The higher the mean free path, the higher the thermal conductivity of the material becomes (**Jang et al., 206**).

The intrinsic thermal conductivity values of single crystalline 6H (α-SiC), 4H (α-SiC), and 3C (β-SiC) are 490-500 W/(mK) (**Bhatnagar et al., 1993; Shenai et al., 1989**), 400 W/(mK) (**Trew, 1997**), and 490 W/(mK) (**Bhatnagar et al., 1993**), respectively.

2.1 POROSITY

Porosity is one of the most significant factors affecting the thermal conductivity of porous SiC ceramics. The introduction of porosity into SiC ceramics is an extremely versatile and powerful strategy for greatly extending the range of engineering properties offered by SiC ceramic components. It`s well known that the porosity is a nonconductive portion of the material which contains a gaseous phase, that is, air. In addition, sintering temperature also affects the thermal conductivity of porous SiC ceramics, for example, Kultayeva et al. investigated the effect of porosity on the thermal properties of porous SiC ceramics. They found that the porous SiC ceramics sintered at 2000°C and 1900°C exhibited the thermal conductivities of 14.1 and 9.4 W/(mK), respectively, at the equivalent porosity of~ 52.3% (**Kultayeva et al., 2020**). The higher sintering temperature exhibited the higher thermal conductivity because of the coarser microstructure.

Table 1 shows the reported literature data of the thermal conductivity of porous SiC ceramics. Generally, the thermal conductivities of porous SiC ceramics decrease with increasing porosity (**Kultayeva et al., 2020; Eom et al., 2008, Kultayeva et al., 2023; Kim et al., 2020**). Specifically, the thermal conductivity of porous SiC ceramics sintered with 10 vol% Y_2O_3-AlN additives decreased from 37.9 to 5.8 W/(mK) as the porosity increased from 30% to 63% (**Kultayeva et al., 2020**). The thermal conductivity of SiC foams decreased from 14.0-4.0 W/(mK) with an increase in porosity from 69% to 88% (**Jana et al., 2017**).

Table 1
The thermal conductivity data of porous SiC ceramics

Porous SiC ceramics	Porosity (%)	Thermal Conductivity, (W/(mK))	References
Porous SiC ceramics with 1 vol% of BN	~62 – ~66	11.6 – 8.4	**Kultayeva et al., 2021**
Porous SiC-SiO_2 composites	~62 – ~64	0.21 – 0.15	**Malik et al., 2020**
Porous silica-bonded SiC ceramic	55.9 – 70.2	0.186 – 0.057	**Kim et al., 2020**
Polysiloxane-derived porous SiC ceramics	~43 – ~74	~21 – ~2	**Eom et al., 2008**
Porous SiC ceramics with 10 vol% Y_2O_3-AlN	30% – 63%	37.9 – 5.8	**Kultayeva et al., 2020**
SiC foams	69 – 88	14.0 – 4.0	**Jana et al., 2017**
Wood-derived porous SiC ceramics	43% – 67%	41.5 – 15.0	**Papacenna et al., 2007**
Porous SiC ceramics containing 10 vol% nitride	40.2 – 66.1	22.7 – 4.8	**Rajpoot et al., 2020**
Porous SiC ceramics without additives	30.4 – 40.5	83 – 60	**Jang & Sakka, 2007**

The thermal conductivity of porous SiC ceramics fabricated by adding boron carbide additive and sintered in Ar and N_2 atmospheres increased from 7.6 to 19.8 W/(mK) and 3.3 to 5.5 W/(mK) with decreasing porosity from 68.2 to 58.3% and from 70.3 to 61.7%, respectively (**Kultayeva et al., 2023**). Similar results were reported for porous SiC-SiO_2 composites (**Malik et al., 2020)**, porous silica-bonded SiC ceramic (**Kim et al., 2020)**, polysiloxane-derived porous SiC ceramics (**Eom et al., 2008)**, wood-derived porous SiC ceramics (**Papacenna et al., 2007)**, porous SiC ceramics containing 10 vol% nitride (**Rajpoot et al., 2020)**, porous SiC ceramics without additives (**Jang & Sakka, 2007**). These results were attributed that the porosity interrupts the direct heat conduction paths available in the bulk material, increasing the average path length for heat transport and thus reducing thermal conductivity.

These results suggest that the thermal conductivity of porous SiC ceramics can be maximized by adjusting porosity.

2.2 PORE SIZE

Pore size is another critical factor that influences thermal conductivity. Larger pores typically lead to a decrease in thermal conductivity, as the effective path for heat transfer becomes longer and more interrupted. In contrast, smaller, more uniform pores tend to support higher thermal conductivity due to shorter heat transfer paths and reduced scattering. Additionally, when pore sizes are in the nanometer range, phonon scattering increases, which can further reduce thermal conductivity. Generally, thermal conductivity of porous SiC ceramics increases with increasing pore size (**Lucio et al., 2022**). Rajpoot et al. studied the influence of SiC powder particle size on the pore structure of porous SiC ceramics. Their findings revealed that larger initial particle sizes resulted in larger pore sizes within porous SiOC-bonded SiC ceramics. As the average pore size increased from 218 nm to 778 nm, the thermal conductivity initially increased from 0.78 to 0.86 W/(mK), but further enlargement of the pore size to 1013 nm caused the thermal conductivity to decline to 0.58 W/(mK). The study also demonstrated that changes in the starting particle size influenced not only pore size but also the overall porosity of the porous SiC ceramics (**Rajpoot et al., 2021**). Das et al. investigated the effect of pore size on the thermal conductivity of porous SiC ceramics by varying pore sizes from ~7 μm to ~98 μm with the same porosities (~54% and ~63%). They found that the thermal conductivity of porous SiC ceramics increased from ~14.3 to ~26.2 W/(mK) with an increase in average pore size from ~7 to ~98 μm, respectively, at the porosity of ~54%. The increase in thermal conductivity with increasing pore size (larger pores) was attributed to reduced phonon-pore scattering because of the smaller number of pores, that is, smaller pore/strut interface areas at the same porosity, which leads to an increase in the mean free path of the phonons (**Das et al., 2023**).

These results suggest that the thermal conductivities of porous SiC ceramics can be successfully tuned for various applications by adjusting the pore size at a constant porosity.

2.3 ADDITIVE COMPOSITION

Additives are frequently introduced to improve densification or modify the microstructure of SiC ceramics. Common additives like aluminum oxide (Al_2O_3), boron carbide (B_4C), and yttrium oxide (Y_2O_3) can affect thermal conductivity by altering the sintering behavior, grain structure, and phase composition of the ceramics. Additives can either increase or decrease thermal conductivity depending on their influence on grain boundaries and secondary phase formation.

Additive composition influences the necking area and grain boundary structure of porous SiC ceramics. Kultayeva et al. reported that the thermal conductivity of undoped porous SiC ceramic (~11 W/(mK)) at a constant porosity of ~61.3% increased by 48% (~17 W/(mK)) when 1 vol% B_4C was added and decreased by 31% (~8 W/(mK)) when 1 vol% Sc_2O_3 was added (**Kultayeva et al., 2021a**). Additionally, **Taki et al. (2018)** and **Kim et al. (2020)** found that adding excess carbon or silicon to porous SiC ceramics deacreased their thermal conductivity. Similarly, **Malik et al. (2020)** and **Kang et al. (2021)** observed that introducing a thermally insulating secondary phase into porous SiC ceramics significantly increased interfacial thermal resistance, leading to a decrease in thermal conductivity. **Rajpoot et al. (2020)** demonstrated that the electrical conductivity of porous SiC ceramics can be adjusted independently of thermal conductivity by incorporating metal nitrides such as AlN, BN, or TiN. **Yeom et al.** investigated the influence of rare-earth oxide composition on the thermal conductivity of porous liquid-phase-sintered SiC ceramics. They found that, at the same porosity of 54.2%, the thermal conductivity increased by approximately 56%, increasing from ~9 W/(mK) for porous SiC ceramics sintered with 5 vol% AlN-Lu_2O_3 to 14.4 W/(mK) for those sintered with 5 vol% AlN-Sc_2O_3. Dense SiC ceramics sintered without Al-containing additives exhibited thermal conductivities as high as 167–262 W/(m·K) (**Jang et al., 2016; Cho & Kim, 2017; Seo et al. 2017**), while those with Al-containing additives showed much lower values, ranging from 32 to 80 W/(m·K) (**Zhan et al., 2002; Eom et al., 2016**).

These results suggest, that the thermal conductivity of SiC ceramics is strongly affected by porosity and potentially by the incorporation of dopant atoms into the SiC lattice. These findings demonstrate that Al-containing additives are detrimental to improving the thermal properties of porous SiC ceramics, whereas B-containing additives effectively enhance their thermal conductivity.

2.4 NECKING AREA

The necking area, or the bonding area between SiC grains, directly impacts thermal conductivity. A larger necking area increases thermal conductivity by allowing more direct solid-to-solid contact between grains, improving heat transfer across the porous SiC ceramic. Conversely, a smaller necking area restricts heat flow, decreasing thermal conductivity. The necking area can be controlled through sintering parameters, such as temperature, additive compositions, and atmosphere (Ar or N_2). High-temperature sintering generally increases the necking area between SiC grains by promoting grain growth, leading to higher thermal conductivity. **Kultayeva et al. (2021)** studied influence of BN additives and sintering atmosphere on microstructure and properties of porous SiC ceramics. Porous SiC ceramic with 1.5 vol% of BN sintered in Ar atmosphere exhibited higher thermal conductivity (11.6 W/(mK)) than that of porous SiC ceramic with 1.5 vol% of BN sintered in N_2 atmosphere (4.6 W/(mK)) at 65.9% porosity. Another study by **Kultayeva et al. (2023)** reported the similar trend for porous SiC ceramics with a boron carbide additive (B_4C) sintered in Ar and N_2 atmospheres. They found that the thermal conductivity of porous SiC ceramics increases as the necking area between SiC grains grows. A larger necking area facilitates a broader conduction path for phonons, resulting in higher thermal conductivity. In porous SiC ceramics sintered with B_4C or BN additives, the necking area can be controlled by adjusting the sintering atmosphere and the content of B_4C or BN. Additionally, the thermal conductivity of porous SiC ceramics sintered with 1 vol% B_4C (16.6 W/(mK)) was approximately 48% higher than that of a porous SiC ceramic without the addition of B_4C (11.2 W/(mK)) at an equivalent porosity of ~ 61.3%.

These findings indicate that boron doping within the SiC lattice plays a crucial role in forming a broader necking area between SiC grains, which significantly enhances the thermal conductivity of porous SiC ceramics. Additionally, the thermal conductivity of porous SiC ceramics can be optimized by carefully adjusting the amount of B_4C and BN additives and conducting the sintering process in an argon (Ar) atmosphere to achieve the desired microstructural and thermal properties.

3 CONCLUSIONS

This review highlights that factors such as porosity, pore size, additive composition, and necking area significantly impact the thermal conductivity of porous SiC ceramics. The following are the main comclusions:

(1) The thermal conductivity of porous SiC ceramics is influenced by its porosity, i.e. with an increase in porosity the thermal conductivity decreases. This is because the porosity interrupts the direct heat conduction paths available in the bulk material, increasing the average path length for heat transport and thus reducing thermal conductivity.
(2) The thermal conductivity of porous SiC ceramics increase with increasing pore size at constant porosity. The increase in thermal conductivity with increasing pore size (larger pores) was attributed to reduced phonon-pore scattering because of the smaller number of pores, that is, smaller pore/strut interface areas at the same porosity.
(3) The thermal conductivity of porous SiC ceramics is strongly affected by porosity and potentially by the incorporation of dopant atoms into the SiC lattice. B-containing additives are beneficial to improve the thermal conductivity porous SiC ceramics.
(4) B-doping into the SiC lattice plays a crucial role in forming a wider necking area between SiC grains, which significantly enhances the thermal conductivity of porous SiC ceramics. Additionally, the thermal conductivity of porous SiC ceramics can be optimized by carefully adjusting the amount of B_4C and BN additives and conducting the sintering process in an argon (Ar) atmosphere to achieve the desired microstructural and thermal properties.

4 FUTURE WORK

Developing innovative approaches to control the thermal properties of porous SiC ceramics holds immense potential for enabling diverse applications in the near future. Despite their promise, the influence of incorporating conductive phases like carbon nanotubes on the properties of porous SiC ceramics has not yet been investigated. Studying how carbon nanotubes affect the electrical and thermal characteristics of these ceramics offers an interesting area for future research. By advancing processing methods and deepening our understanding of microstructural influences, it will be possible to engineer porous SiC ceramics with precisely controlled thermal properties. This progress could unlock a broad range of high-performance applications, significantly enhancing the functionality and diversity of the advanced porous SiC ceramics

REFERENCES

1. **Pappacena, K. E., Faber, K. T., Wang, H., & Porter, W. D.** (2007). Thermal conductivity of porous silicon carbide derived from wood precursors. Journal of the American Ceramic Society, 90, 2855–2862. https://doi.org/10.1111/j.1551-2916.2007.01777.x
2. **Eom, J. H., Kim, Y. W., Song, I. H., & Kim, H. D.** (2008). Processing and properties of polysiloxane derived porous silicon carbide ceramics using hollow microspheres as templates. Journal of the European Ceramic Society, 28(6), 1029–1035. http://dx.doi.org/10.1016/j.jeurceramsoc.2007.09.009
3. **Rajpoot, S., Ha, J. H., Kim, Y. W., & Kim, K. J.** (2020). Electrical, thermal, and mechanical properties of porous SiC-nitride composites. Journal of the European Ceramic Society, 40(12), 3851–3862. https://doi.org/10.1016/j.jeurceramsoc.2020.04.018

4. **Jana, D. C., Sundararajan, G., & Chattopadhyay, K.** (2017). Effect of porosity on structure, Young's modulus, and thermal conductivity of SiC foams by direct foaming and gelcasting. Journal of the American Ceramic Society, 100, 312–322. https://doi.org/10.1111/jace.14544
5. **Wan, P., Gao, L., & Wang, J.** (2017). Approaching ultra-low thermal conductivity in β-SiC nanoparticle packed beds through multiple heat blocking mechanisms. Scripta Materialia, 128, 1–5. https://doi.org/10.1016/j.scriptamat.2016.09.027
6. **Jang, B. K., & Sakka, Y.** (2007). Thermophysical properties of porous SiC ceramics fabricated by pressureless sintering. Science and Technology of Advanced Materials, 8(9), 655–659. https://doi.org/10.1016/j.stam.2007.08.003
7. **Das, D., Lucio, M. D. S., Kultayeva, S., & Kim, Y. W.** (2024). Effects of pore size on electrical and thermal properties of porous SiC ceramics. International Journal of Applied Ceramic Technology, 21, 2651–2662. https://doi.org/10.1111/ijac.14620
8. **Kim, G. D., Kim, Y. W., Song, I. H., & Kim, K. J.** (2020). Effects of carbon and silicon on electrical, thermal, and mechanical properties of porous silicon carbide ceramics. Ceramics International, 46(10), PartA, 15594–15603. https://doi.org/10.1016/j.ceramint.2020.03.106
9. **Kang, E. S., Kim, Y. W., & Nam, W. H.** (2021). Multiple thermal resistance induced extremely low thermal conductivity in porous SiC-SiO_2 ceramics with hierarchical porosity. Journal of the European Ceramic Society, 41(2), 1171–1180. https://doi.org/10.1016/j.jeurceramsoc.2020.10.004
10. **Watari, K., Nakano, H., Sato, K., Urabe, K., Ishizaki, K., Cao, S., Mori, K.** (2003). Effect of grain boundaries on thermal conductivity of silicon carbide ceramic at 5 to 1300 K. Journal of American Ceramic Society, 86(10), 1812–14. https://doi.org/10.1111/j.1151-2916.2003.tb03563.x
11. **Bhatnagar, M., & Baliga, B. J.** (1993). Comparison of 6H-SiC, 3C-SiC, and Si for power devices. IEEE Transactions on Electron Devices, 40(4), 645–655.
12. **Shenai, K., Scott, R. S., & Baliga, B. J.** (1989). Optimum semiconductors for high-power electronics. IEEE Transactions on Electron Devices, 36(10), 1811–1823. https://doi.org/10.1109/16.34247
13. **Trew, R. J.** (1997). Experimental and simulated results of SiC microwave power MESFETs. Physica Status Solidi (A), 162(2), 409–419. https://doi.org/10.1002/1521-396X(199707)162:1%3C409::AID-PSSA409%3E3.0.CO;2-O
14. **Kultayeva, S., Ha, J. H., Malik, R., Kim, Y. W., & Kim, K. J.** (2020). Effects of porosity on electrical and thermal conductivities of porous SiC ceramics. Journal of the European Ceramic Society, 40(4), 996–1004. https://doi.org/10.1016/j.jeurceramsoc.2019.11.045
15. **Kultayeva, S., Kim, Y. W.** (2023). Electrical, thermal, and mechanical properties of porous silicon carbide ceramics with a boron carbide additive. International Journal of Applied Ceramic Technology, 20, 1114–1128. https://doi.org/10.1111/ijac.14113
16. **Kim, Y. H., Kim, Y. W., & Seo, W. S.** (2020). Processing and properties of silica-bonded porous nano-SiC ceramics with extremely low thermal conductivity. Journal of the European Ceramic Society, 40(7), 2623–2633. https://doi.org/10.1016/j.jeurceramsoc.2019.11.072
17. **Kultayeva, S., Kim, Y. W., & Song, I. H.** (2021). Influence of sintering atmosphere and BN additives on microstructure and properties of porous SiC ceramics. Journal of the European Ceramic Society, 41(14), 6925–6933. https://doi.org/10.1016/j.jeurceramsoc.2021.07.039
18. **Malik, R., Kim, Y. W., & Song, I. H.** (2020). High interfacial thermal resistance induced low thermal conductivity in porous SiC-SiO2 composites with hierarchical porosity. Journal of the

European Ceramic Society, 40(3), 594–602. https://doi.org/10.1016/j.jeurceramsoc.2019.10.056

19. **Lucio, M.D.S., Kultayeva, S., Kim, Y.W.** (2022). Improved mechanical strength and thermal resistance of porous SiC ceramics with gradient pore sizes. Journal of the European Ceramic Society, 42, 6785–94. https://doi.org/10.1016/j.jeurceramsoc.2022.09.001
20. **Rajpoot, S., Ha, J. H., & Kim, Y. W.** (2021). Effects of initial particle size on mechanical, thermal, and electrical properties of porous SiC ceramics. Ceramics International, 47(6), 8668–8676. https://doi.org/10.1016/j.ceramint.2020.11.238
21. **Kultayeva, S., Kim, Y. W., & Song, I. H.** (2021). Effects of dopants on electrical, thermal, and mechanical properties of porous SiC ceramics. Journal of the European Ceramic Society, 41(7), 4006–4015. https://doi.org/10.1016/j.jeurceramsoc.2021.01.049
22. **Taki, Y., Kitiwan, M., Katsui, H., & Goto, T.** (2018). Electrical and thermal properties of off-stoichiometric SiC prepared by spark plasma sintering. Journal of the Asian Ceramic Societies, 6(1), 95–101. https://doi.org/10.1080/21870764.2018.1446490
23. **Jang, S. H., Kim, Y. W., Kim, K. J., Lee, S. J., & Lim, K. Y.** (2016). Effects of Y_2O_3–RE_2O_3 (RE = Sm, Gd, Lu) additives on electrical and thermal properties of silicon carbide ceramics. Journal of the American Ceramic Society, 99(1), 265–272. https://doi.org/10.1111/jace.13958
24. **Cho, T. Y., & Kim, Y. W.** (2017). Effect of grain growth on the thermal conductivity of liquid-phase sintered silicon carbide ceramics. Journal of the European Ceramic Society, 37(11), 3475–3481. https://doi.org/10.1016/j.jeurceramsoc.2017.04.050
25. **Seo, Y. K., Kim, Y. W., Nishimura, T., Seo, W. S.** (2017). High thermal conductivity of spark plasma sintered silicon carbide ceramics with yttria and scandia. Journal of the American Ceramic Society, 100, 1290–1294. https://doi.org/10.1111/jace.14748
26. **Zhan, G. D., Mitomo, M., & Mukherjee, A. K.** (2002). Effects of heat treatment and sintering additives on thermal conductivity and electrical resistivity in fine-grained SiC ceramics. Journal of Materials Research, 17, 2327–2333. https://doi.org/10.1557/JMR.2002.0341
27. **Eom, J. H., Seo, Y. K., & Kim, Y. W.** (2016). Mechanical and thermal properties of pressureless sintered silicon carbide ceramics with alumina-yttria-calcia. Journal of the American Ceramic Society, 99(5), 1735–1741. https://doi.org/10.1111/jace.14114
28. **Yeom, J. A., Kang, E. S., Kim, Y. W., & Nam, W. H.** (2022). Microstructure and properties of porous SiC ceramics with AlN–RE_2O_3 (RE=Sc, Y, Lu) additives. Journal of the European Ceramic Society, 42(11), 4446–4455. https://doi.org/10.1016/j.jeurceramsoc.2022.04.050