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A Review on the Synthesis and Physical Properties of SiC Nanoparticles

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Abstract

Here, a literature review was carried out on the topic of research studies on the synthesis and properties of Silicon carbide (SiC)-based nanocomposite materials investigated in the scientific literature were conducted and the obtained results were obtained. Here, various synthesis methods, the effect of temperature, structure, optical thermal conductivity, resistance, paramagnetic properties, free Gibbs energy, enthalpy, and entropy values were analyzed by evaluation of the obtained results.

Keywords: SiC nanostructures, 3C-SiC, 6H-SiC, the synthesis temperature
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1. Introduction

Silicon is the second most common element on earth after oxygen (27.7%), and has complete thermal stability [1]. SiC is found rarely (in small amounts) in nature [2]. At the end of the 19th century, the discovery of a new production method resulted in its use as a ceramic material. SiC is the most stable of the carbides due to the protective layer of silicon formed on its surface. The global production market has shown that it is primarily used as an abrasive, high-temperature, and wear-resistant product, as well as in metallurgy. SiC is the only carbide used as a ceramic

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material. In nature, SiC is also found in meteoroids. In 1891, a chemist named Edward Goodrich Acheson tried to make a diamond by passing an electric current through clay using a carbon rod. What he made was not a hard crystal diamond, but carborundum, i.e. SiC. Edward Goodrich thought that this material would be useful, created the Acheson furnace, and began to develop an abrasive product from SiC. To get SiC, petroleum coke with low sulfur as carbon and sand with a very high degree of purity (99.4%) as silicon was used. The reaction between silicon and carbon starts when the temperature reaches 1400 ^{o}C. When the temperature is up to 1800^{o}C, the cubic form of SiC (β-SiC) is obtained, and when it is above 1800^{o}C, its hexagonal form (α-SiC) is obtained. SiC is divided into three different types based on color; green, black, and metallurgy. Green SiC has a high degree of purity (99%). Black SiC is made using unreacted petroleum coke and sand. SiC, which has 3C, 4H, and 6H crystallographic structures, has a wide range of applications, having different electrical conductivity [3].

2. Synthesis methods and physical properties of SiC

In one of the research studies, the synthesis of SiC from waste materials and the study of its structural properties [4]. Thus, the synthesis of SiC by the sol-gel method using a system consisting of amorphous silicon additional foreign matter, and activated carbon was carried out at temperatures of 1200^{o} and 1300^{o}C. As a result, SiC with a purity of up to 99.45% was obtained. It was determined that the structure of SiC synthesized at these temperatures mainly consists of 3C-SiC and 6H-SiC. At the same time, the resistance of SiC at 1200^{o} C and 1300^{o} C demonstrated the ohmic property is 9.8 Ω·cm to 138Ω·cm is determined to vary in the interval.

In another research work [5], cubic 3C-silicon carbide (beta-SiC) 1D-structures were synthesized using graphite flakes and microfine silicon through a carbothermal reduction process at different temperatures (1600°C, 1650°C and 1700°C). From the X-ray analysis, it was observed that two different silicon carbide structures were formed: ribbon type (d=2-5 μm) and rod type (d ≤ 2 μm). It was noted that 1D nanostructured SiC has high heat, low density, and high flexibility and temperature conductivity compared to bulk SiC. Synthesis at different temperatures showed that at temperatures higher than 1650°C, the 3C-SiC phase was formed without any residual material. It was determined that ribbon-type structures were formed at 1600°C, and rod-type structures were formed at temperatures higher than 1650°C.

In one of the studies [6], 3C-SiC was exposed to neutron radiation and irradiated for up to 20 hours. Paramagnetic centers and nature were comparatively studied before and after neutron irradiation. The number of paramagnetic centers for different values of the G factor was calculated according to the local conditions around 3300G. As a result of calculations, a strong signal was observed at g = 2.006. After neutron irradiation, an increase in the existing signal intensity and new signals were observed. At different values of the g factor, the total number of paramagnetic centers increased from 1.5×1020 centers/g to 2.7×1020 centers/g (about twice). In addition, the number of centers corresponding to free electrons (g = 2.006) doubles after neutron irradiation (from 1.03×1018 centers/g to 1.9×1018 centers/g). The results of the study demonstrated that neutron irradiation significantly affects the paramagnetic properties of nanocrystalline 3C-SiC.

In another research work [7], various thermal properties of 3C-SiC were investigated. The characteristic heat capacity, free Gibbs energy, enthalpy, and entropy of 3C-SiC nanocrystallites were studied at synthesis different temperatures. As a result of the research, it was determined that the value of specific heat capacity is negative when T≥800K, and the general approach was suitable for exothermic processes. In the temperature range of 300K-800K, the value of the specific heat capacity is positive, and the general approach is consistent with endothermic processes. The enthalpy of the system decreased with the increase of the thermal processing rate across the entire temperature range. The free Gibbs energy value was inversely proportional to the temperature, the Gibbs energy value was negative in the low-temperature range. At the temperature T<800K, the value of free Gibbs energy changed around zero, which showed that the system was in equilibrium. At temperature T>800K, the Gibbs free energy value was positive. At this time, the process was not spontaneous, changes in the opposite direction were observed in the system.

In another research work [8], the synthesis, structure, and physical and chemical properties of functionalized SiC are discussed. Especially, its potential application in supercapacitors has been consummately examined.

In the next work [9], the synthesis methods used in the production of nanostructured SiC (carbothermic reduction, chemical vapor deposition, laser ablation, sol-gel, etc.), physical properties, and application prospects are discussed. It was noted that changes in synthesis parameters, including temperature and the size of the nanoparticles changed (30-50 nm at 1400°C and 15-17 nm at 1580°C, respectively). In the carbothermal reduction method, it was observed that the main β-SiC was formed, and a small amount of α-SiC (at values above 1400°C). Next, conductivity (increased) as a function of temperature was discussed.

This research work [10] reported on the synthesis, structure, and properties of SiC materials and their potential applications. The main objective of the study was to investigate the properties of SiC, production methods, and how these properties can be optimized for electronic devices, sensors, and other applications. As a result, it was noted that SiC thermal stability, mechanical strength, and radiation resistance. Therefore, SiC is ideal for applications such as biosensors, power electronics, and neutron detectors.

In another work [11], ballistic ceramic alumina (Al_2O_3), SiC, and boron carbide (B_4C) were compared and these materials' mechanical strengths were discussed.

The research has focused on assessing these materials based on key factors such as hardness, density, strength, and capacity to resist impact forces. Al_2O_3 is noted for being widely available and affordable but has less hardness than other options. SiC offers a balance of high stiffness and fracture toughness, which makes it more effective at absorbing impact energy while remaining lightweight. B_4C is one of the toughest and lightest ceramics used in ballistic applications, but its brittleness can be a disadvantage under certain conditions, particularly against high-velocity impacts. The study concluded that material selection depends on the specific application and the required trade-offs between hardness, strength, and weight.

Another study on porous SiC [12] was the subject of the development and optimization of high-temperature ceramic materials based on SiC, which is known for its exceptional thermal stability, oxidation resistance, and high strength. The purpose of this work is to increase the density of SiC through liquid phase sintering methods and to obtain a unique structure of the material such as polyplicity was to understand its characteristics. It was noted that the use of sintering agents such as Al_2O_3 and rare earth oxides (such as Y_2O_3) significantly reduced the sintering temperature and facilitated the densification of SiC at lower temperatures (up to 1850 ° C). This made it possible to create SiC ceramics with fine-grained microstructures and improved mechanical properties.

3. Applications of SiC

The aim of the presented work [13] was to develop and improve silicon-based anode materials for lithium-ion batteries to improve their cycling performance, stability, and capacity. Silicon is a promising anode material due to its high theoretical capacity and environmental benefits, but its practical application is hampered by poor electrical conductivity and strong capacity reduction caused by significant volume changes during the charge-discharge cycle. The work aims to solve these problems by designing advanced silicon structures such as nanostructures, anchored, flexible, sandwich, core-shell, and porous structures. These designs aim to reduce volume expansion, improve mechanical stability, increase electrical conductivity, and suppress solid-electrolyte interface (SEI) formation, resulting in better performance in terms of capacity retention, rate capability, and overall longevity for practical battery applications.

Another research work [14] mainly provides extensive information on the applications of SiC. It has been noted that the unique structure of silicon has a number of physical properties, including thermal stability, flexibility, and chemical resistance. These properties have led to silicone being used in a variety of applications, from household products to medical devices and automotive components. It has also been noted that the ability of silica to be converted into adhesives, gels, and coatings has expanded its potential use in sectors such as construction and electronics. SiC semiconductors have emerged as a transformative force in power electronics. Here demonstrated SiC power semiconductors have found that SiC devices have outperformed conventional silicon devices, especially in high-temperature and high-voltage applications. It was noted that SiC's wide range facilitates high switching frequencies and reduces energy losses, making SiC an ideal material for modern industrial applications, electric vehicles, and renewable energy systems. It has been found that SiC's high thermal conductivity has helped improve reliability and efficiency in electronic systems, leading to advances in technologies that require higher performance and lower power consumption.

In another research study [15], SiC diodes were reported. It was noted that SiC semiconductors are superior to traditional silicon semiconductors by offering increased breakdown voltage, superior thermal conductivity, and wider range. These properties have made SiC devices highly efficient in high-temperature and high-energy environments where conventional silicon devices have weakened. It was found that switching to SiC reduced energy losses, resulting in reduced operating costs and environmental impact. SiC devices also facilitate faster charging and improved range, thereby alleviating consumer concerns about performance. It was noted that the ability to operate at higher voltages has enabled lighter and more compact designs, which are both important factors in optimizing vehicle aerodynamics and energy consumption. Additionally, it has been found that the integration of SiC into renewable energy systems such as solar inverters and wind turbines has increased overall system efficiency.

One of the research work [16] discussed micromachine control circuits for broadband semiconductor switching devices, stable gallium nitride (GaN) high-mobility transistors (HEMTs), and SiC metal-oxide-semiconductor field-effect electronic transistors (MOSFETs). It was noted (Si) emphasizes the advantages of MOSFETs such as higher switching frequency and low loss. This work emphasized the importance of understanding the differences between wideband and Si devices in order to exploit their capabilities in medium and high-power applications. This was retained to provide engineers with drive requirements, specifications of those additional WBG devices, design considerations for drive circuits, and design according to materials. Power electronic converters are driven by increasing performance requirements of capacity, voltage level, quality, and size, and it is becoming common to replace conventional Si devices with broadband devices. The article details the superior properties of GaN and SiC, indicating specific applications based on their power levels. It also addresses high-speed issues with broadband devices that can create technologies such as electromagnetic interference (EMI) and instability. It also explains the structure and operation of GaN HEMT and SiC MOSFETs, showing their performance characteristics such as controllability, ruggedness and temperature capabilities. GaN HEMTs are assigned to depletion mode, enhancement mode, and cascaded devices, each with different operating characteristics and driving requirements. SiC MOSFETs are distinguished by their high power capability and similar operating structure to Si MOSFETs.

4. Conclusion

The structural analysis of the samples obtained by the solid state reaction synthesis method of SiC at different synthesized temperatures. At the low temperature, mainly amorphous phases were observed, at the same time, residual elements used in the initial part of the reaction were also observed. As increasing of the reaction temperature, the amount of residual elements decreased, and the crystalline phase formed. At the higher synthesized temperature, the residual elements disappeared, and high crystallinity was obtained. The increase in the temperature resulted in getting well crystalline materials for SiC. Also, the effect of the temperature crystalline structure transforms from 3C-SiC to 6H-SiC. The reason for the conversion between 3C-SiC and 6H-SiC is that temperature affects the crystal structure. 3C-SiC (zinc alloy structure) is stable at low temperatures, but as temperature increases the need for tighter regulation and higher energy levels leads to 6H-SiC (hexagonal structure). This causes the atoms to move into a more regular arrangement. High temperature allows atoms to move to a more stable structure with higher kinetic energy. Thereby, as the temperature is increased, the formation of 6H-SiC becomes possible. In the EPR analysis, strong signals of g=2006 for free electrons are observed, and the intensity of these signals increases after neutron irradiation, which indicates an increase in the concentration of free electrons or newly created parametric centers. At the same time, Gibbs energy increases with increasing the synthesis temperature. The reason for this is the increase of internal energy and chemical potential of the system at high synthesis temperatures. Here, the system tries to minimize its potential energy, but as the temperature increases, this energy approaches the maximum, and the system loses stability and becomes unstable. An increase in the synthesis temperature has led to an increase in conductivity, and the reason for this is an increase in the thermal motion of the atoms and molecules of the material. This creates conditions for electrons to reach their energy levels and cross the conduction band, and as a result, the conductivity increases.

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