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Synthesis and Properties of Silicon Carbide (Review)

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Silicon carbide is an extremely hard material that exhibits exceptional corrosion resistance as well as thermal shock resistance. Its high mechanical properties determine the increased performance of materials based on it. The combination of high thermal conductivity and low thermal expansion coefficient determines the stability of silicon carbide at high heating rates and under stationary thermal conditions. To date, significant progress has been made in the development of methods for the synthesis of various materials based on silicon carbide. The main synthesis methods that scientists use in their research are the sol-gel method, sintering, pyrolysis, microwave synthesis, chemical vapor deposition, etc. The use of "green" techniques in the synthesis of SiC has gained wide popularity due to environmental friendliness, renewability, and ease of implementation. This review analyzes modern research in the field of silicon carbide synthesis published in peer-reviewed professional journals.

Key words: silicon carbide, polytype, "green" synthesis, ceramic nanomaterials.

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Content

Introduction

Silicon carbide plays an important role in many industries and various areas of production due to its exceptional physical and chemical properties and characteristics. Among the most significant properties are the following: low density, high thermal conductivity, very low coefficient of friction, refractoriness, low coefficient of thermal expansion, high chemical, corrosion and radiation resistance, high hardness, etc. [1, 2].

Silicon carbide has improved ballistic characteristics, since it has excellent mechanical properties, including strength, fracture toughness and hardness, so it is used in the production of bulletproof vests and composite armor [3,4]. Silicon carbide is used in the metallurgical industry as a refractory material, in the production of abrasive, cutting and grinding tools, in the nuclear power industry, in the production of jewelry, in heating elements, in electronics, etc. [5].

Silicon carbide has such electronic properties as high thermal and electrical conductivity, high ion mobility and high electron drift velocity. It is these properties that contribute significantly to making SiC based materials the best for applications in electronic devices such as power electronics, field emission, sensors, etc. [5]. In addition, SiC is used as blue and ultraviolet diodes due to its ability to emit high intensity and stable ultraviolet and blue-green light. Nanotechnology-based silicon carbide is becoming

an increasingly economical and efficient material in engineering and industry. Thus, the use of SiC in optoelectronics, microelectronics, nanodevices, nanocomposites, hydrophobic devices, biomedical technology is important and useful for humanity [5].

Silicon carbide and mesoporous structures based on it are actively used in many catalytic applications, in the field of optical spin defects, and as substrates for growing other wide gap semiconductors [6].

Materials based on silicon carbide absorb microwaves well due to their thermal and chemical stability, as well as good resistance to the environment [7].

All these properties and applications pose an extremely important task for scientists to develop efficient and economical methods for the synthesis of high-quality crystals, films, and porous structures of silicon carbide.

In this work, the goal was to elucidate the possibilities of modern methods for the synthesis of silicon carbide, especially the preparation of nanoparticles in the form of whiskers, rods, fibers, tubes, etc. with cubic and hexagonal crystal structure.

I. Crystal structure of silicon carbide

Silicon carbide is known as a wide bandgap semiconductor that exists in many different polytypes. All polytypes have a hexagonal framework with a carbon atom located above the center of the triangle of silicon atoms and below the silicon atom belonging to the next layer [8]. The distance between neighboring silicon or carbon atoms is approximately 3.08 Å for all polytypes. The carbon atom is in the center of a tetragonal structure outlined by four neighboring silicon atoms, so that the distance between the C atom and each of the Si atoms is the same and is 1.89 Å. The difference between the polytypes lies in the stacking order of successive double layers of carbon and silicon atoms. Fig. 1 shows the stacking sequence for the most common silicon carbide polytypes [9]. If the first double layer is called position A, the next layer that can be placed according to the closed packed structure will be placed at position B or position C. Different polytypes will be built by permuting these three positions.

In 1947, Ramsdell systematically identified different types of silicon carbide. The type of SiC was marked as nX, where "X" represents the Bravais lattice, including cubic (C), hexagonal (H), and rhombic (R), and "n" indicates the number of diatomic layers contained in one lattice period [10]. That is, the number indicates the periodicity, and the letter indicates the resulting structure. Cubic 3C, hexagonal 4H and 6H, and rhombohedral R are the most common atomic arrangements in SiC. Silicon carbide has only one type of cubic (3C) SiC, which is called β-SiC, and all hexagonal and rhombohedral hexahedra can be called α-SiC [5]. The 3C-SiC polytype has the ABCABC… or ACBACB… stacking sequence, the 4H stacking sequence is ABCB…, the 6H stacking sequence is ABCACB…, and the 15R stacking sequence is ABCABCBCABACABCB… (Fig. 2) [9]. There are about 250 polytypes, some of which have a stacking period of several hundred double layers [10].

II. Physical properties of silicon carbide

Since silicon carbide is a ceramic material, it has excellent properties such as corrosion resistance, wear resistance, high strength, and high hardness. SiC also has good high-temperature properties, in particular, oxidation resistance, high thermal conductivity, and low thermal expansion coefficient [10].

In electronics, silicon carbide materials are valued for their wide bandgap [10]. The bandgap for various modifications of SiC can be in the range from 2.72 to 3.34 eV. The large bandgap makes it possible to create semiconductor devices on its basis that remain operational at temperatures up to 600℃.

Silicon carbide single crystals doped with group V impurities (nitrogen, phosphorus, arsenic, antimony, bismuth), as well as lithium and oxygen, have *n*-type conductivity and green color. Group III elements (boron,

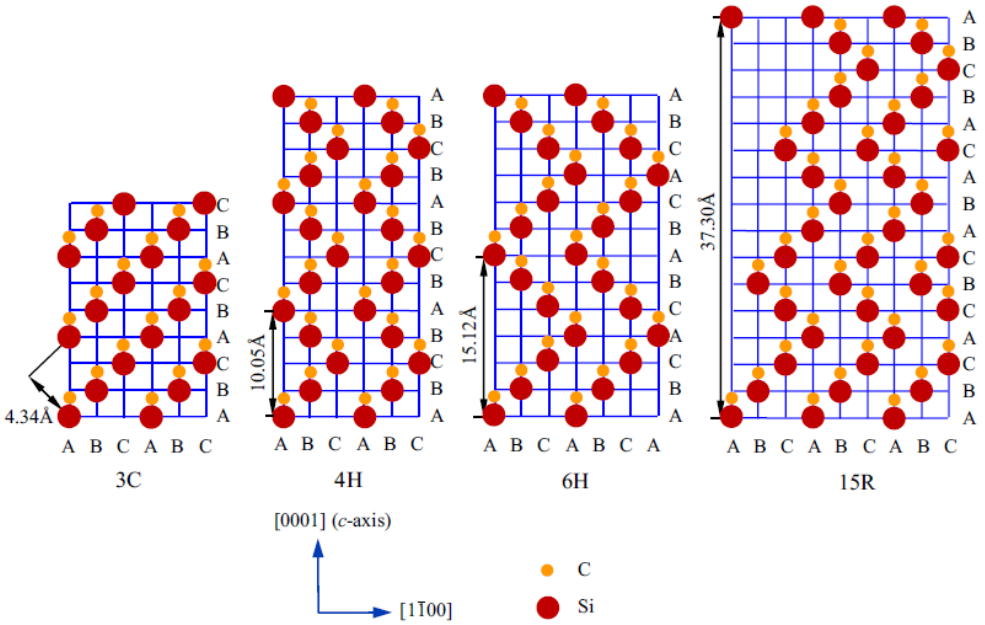

Fig. 1. Sequence of stacking double layers 3C-, 4H-, 6H- and 15R-SiC [9].

aluminum, gallium, indium) and group II elements (beryllium, magnesium, calcium) are acceptors; therefore, SiC crystals doped with them have *p*-type conductivity and blue or black color. When the composition deviates from stoichiometric towards an increase in the silicon content, the crystals have an n-type electrical conductivity, and with an excess of carbon, they have a p-type conductivity [1].

SiC is one of the hardest known materials with a pressure of about 25 GPa, similar to B_4C (boron carbide). Only diamond (60-120 GPa) and cubic boron nitride (borazon 40 GPa) are much harder [1]. The Mohs hardness of silicon carbide is 9.2, the Vickers microdensity hardness is 3000-3300 kg/mm^2, and the Knoop hardness is 2670–2815 kg/mm.

Silicon carbide does not melt, but sublimates at about 2700°C. When heated in air, SiC forms a strong surface film of SiO_2, which prevents its oxidation up to 1850°C for short periods of time (hours) and up to 1500°C for a long time (days). Thus, SiC is one of the most oxidation-resistant non-oxide ceramics [1].

III. Chemical properties of silicon carbide

Silicon carbide has high chemical resistance and stands out for its resistance to oxidation among many heat-resistant alloys and chemical compounds [11]. It oxidizes significantly only at temperatures above 800°C.

Concentrated acids oxidize silicon carbide, and acid solutions dissolve silicon carbide:

$$3SiC + 18HF + 8HNO_3 \rightarrow 3H_2[SiF_6] + 3CO_2 + 8NO + 10H_2O;$$

$$3SiC + 8HNO_3 \rightarrow 3SiO_2 + 3CO_2 + 8NO + 4H_2O.$$

Highly superheated steam decomposes silicon carbide:

$$SiC + 2H_2O \xrightarrow{1300^0C} SiO_2 + CH_4.$$

Silicon carbide is a very stable substance and decomposes in an inert atmosphere only at very high temperatures:

$$SiC \xrightarrow{2830^0C} Si + C.$$

In the presence of oxygen and alkali, silicon carbide dissolves:

$$SiC + 4NaOH + 2O_2 \xrightarrow{350^0C} Na_2SiO_3 + Na_2CO_3 + 2H_2O$$

$$SiC + 2NaOH + 2O_2 \rightarrow Na_2SiO_3 + CO_2 + H_2O.$$

When heated, silicon carbide reacts with oxygen [11]:

$$2SiC + 3O_2 \xrightarrow{950-1700^0C} 2SiO_2 + 2CO;$$

with active metals:

$$2SiC + 5Ca \xrightarrow{700^0C} 2Ca_2Si + CaC_2$$

and their peroxides:

$$SiC + 4K_2O_2 \xrightarrow{700-800^0C} K_2SiO_3 + K_2CO_3 + 2K_2O;$$

with nitrogen:

$$6SiC + 7N_2 \xrightarrow{1000-1400^0C} 2Si_3N_4 + 3C_2N_2;$$

with halogens:

$$SiC + 2Cl_2 \xrightarrow{600-1200^0C} SiCl_4 + C.$$

IV. Silicon carbide synthesis methods

Silicon carbide crystals are almost completely absent in nature, but natural silicon carbide is known to occur as moissanite. Natural moissanite was first discovered in 1893 as a small component of a meteorite in Arizona by Dr. Ferdinand Henri Moissan, after whom the material was named in 1905. Rare on Earth, silicon carbide is found throughout the universe as stardust around carbon-rich stars [12].

Due to the low prevalence in nature, synthesized silicon carbide is used. The first large-scale production of silicon carbide was started by Edward Goodrich Acheson in 1890. Acheson tried to make artificial diamonds by heating a mixture of clay (aluminum silicate) and powdered coke (carbon) in an iron vessel. He called the blue crystals formed in this case carborundum, believing that this is a new compound of carbon and aluminum, similar to corundum. Acheson patented a process for making silicon carbide powder on February 28, 1893. Perhaps he called the material "carborundum" by analogy with corundum, another very hard substance [1,10]. The Acheson method (synthesis temperature of about 2500°C) is considered the most popular method for the synthesis of silicon carbide.

Today, the synthesis of silicon carbide nanoparticles has become widespread among scientists around the world. There are many developed methods for the synthesis of silicon carbide nanoparticles, for example: sintering [13–19], combustion [20,21], selective method [22], sol-gel method [23–26], hydrothermal acid leaching [27], pyrolysis [28–30], pyrohydrolysis [31], low temperature synthesis [32,33], microwave synthesis [34–37], chemical vapor deposition [38–42], in situ growth [43,44], electric arc synthesis [45,46], etc.

Let us consider in detail the most common methods for the synthesis of silicon carbide nanoparticles.

Currently, the synthesis of nanomaterials using natural resources attracts much attention, since this is an environmentally friendly, less harmful, and economically profitable step towards the "green" synthesis of nanomaterials [47,48]. Many scientists use rice husks in their experiments on the synthesis of silicon carbide nanoparticles. Rice is the staple food of over half of the world's population, and rice husks are the main agricultural by-product of rice production. It is usually disposed of by burning or burying it in the ground, which results in wasted energy, greenhouse gas pollution, etc. Rice husk mainly contains lignin, cellulose, and hydrated silica, so it is a natural reservoir for nanostructured silica and its derivatives [48].

In [49], the synthesis of silicon carbide whiskers by the stacking method was proposed (Fig. 2). The experiment consisted of two groups: using a mixture of graphene and rice husk ash (RHA-G) and using only rice husk ash (RHA). Fig. 2a,e shows the original method of placing the reagents in a graphite crucible. Next, the growth of SiC whiskers on graphene after heat treatment at 1400°C is shown (Fig. 2b,f). Fig. 2c,g shows the separation between the graphene layer (upper part) and the initial silicon layers (lower part). As a result (Fig. 2d,h), SiC samples were obtained after decarbonization of the graphene layer. The diameter of the synthesized whiskers of silicon carbide was 30-120 nm.

In a similar study [50], silicon carbide whiskers were also synthesized using rice husk ash and graphene. For this, rice husk ash and graphene were mixed in a weight ratio of 1:1. 300 mg of the resulting mixture was poured into a graphite crucible with a lid and placed in a tube furnace heated to 1450°C at a heating rate of 5°C/min and held for 2 hours. The resulting samples were decarbonized at 700°C for 2 hours and then treated with hydrofluoric acid to remove residual ions and SiO_2. The synthesized SiC whiskers had a diameter of 50-150 nm and a length of several 10 mm.

In [48], β-SiC was synthesized from rice husks by magnesiothermic reduction at a relatively low temperature of 600°C. To do this, rice husks were thoroughly washed with distilled water to remove dirt, and then dried at a temperature of 80°C for 2 hours. After that, it was washed several times with distilled water and dried overnight. Rice husks were annealed in a tube furnace at 600°C for 1 hour in an argon atmosphere to carbonize and remove small organic molecules, then further boiled in HCl (1 mol/L) for 4 hours to remove metal impurities, and then dried at a temperature of 80°C for 3 hours. To synthesize silicon carbide nanoparticles, carbonized rice husk and magnesium powders were mixed at a molar ratio of SiO_2/Mg = 1:2.5, hermetically sealed into a stainless steel container, which was placed in a tube furnace, and heated to 600°C at a heating rate of 5°C/min under a continuous flow of argon for 3 hours. After that, the products were immersed in HCl (1 mol/L) with stirring to remove MgO, washed with distilled water until neutral pH, calcined in air at 700°C for 1 hour to remove residual carbon, and washed with HF to remove residual SiO_2. As a result, a light green powder of SiC nanoparticles with a particle size of 20-30 nm was obtained.

In [51], microsilica particles were obtained by burning rice husks at a temperature of 700°C, acid leaching to remove inorganic impurities, and, finally, mechanical ball milling for 0, 18, 36, and 72 hours to reduce the particle size. The SEM images showed that the particle size decreases with increasing grinding time, resulting in a particle diameter of less than 2.0 mm.

Another "green" precursor for the synthesis of silicon carbide nanoparticles is barley husk, since it is widely available, and its agricultural waste contains a large amount of nanostructured silica. In [52], SiC nanoparticles were obtained by a simple high-temperature synthesis using barley husks (Fig. 3).

Due to its high availability, corn cobs are also used as a raw material for the synthesis of silicon carbide. The

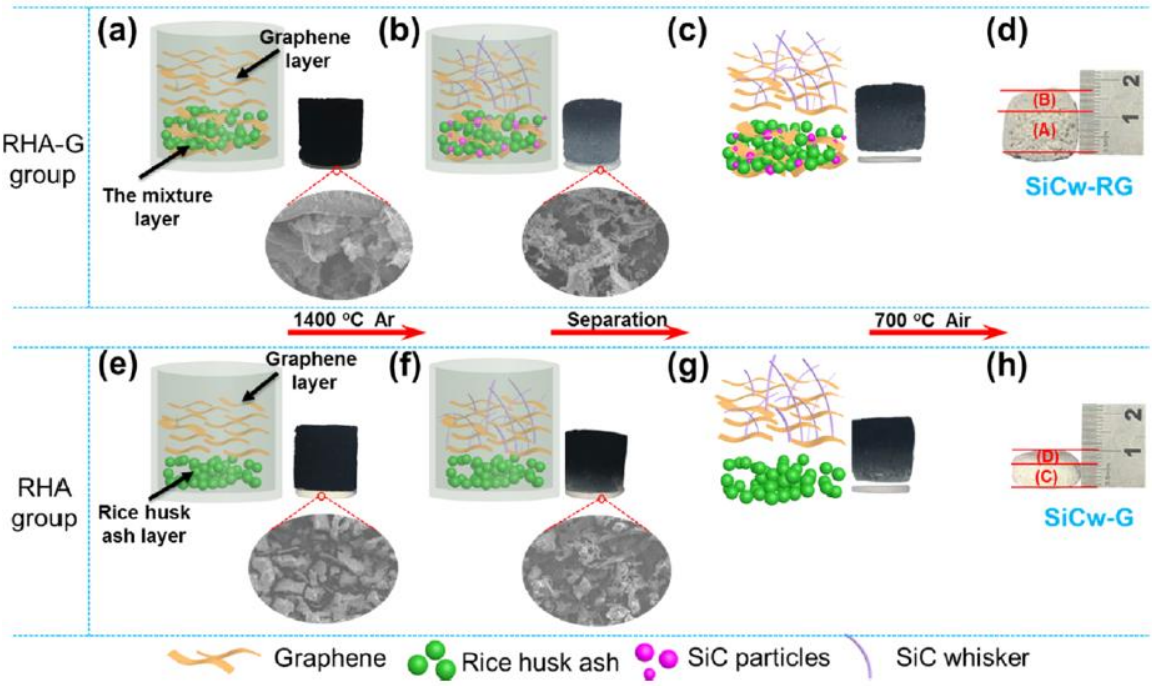

Fig. 2. Scheme for the synthesis of silicon carbide whiskers [49].

authors of [53] synthesized silicon carbide from corn cobs by the sol-gel method. For this, crushed corn cobs were pyrolyzed at a temperature of 600°C to obtain corn cob ash. 10 g of ash was dissolved in 60 ml of 2.5 M NaOH and refluxed at 80°C for 3 hours. The pH of the cooled solution was adjusted to 7.0 with 2.5 M H_2SO_4 to form a silica hydrogel and incubated for 12 hours. The gel was centrifuged at 4000 rpm for 5 minutes. The supernatant was removed, and the resulting silica was washed with deionized water and dried in an oven at 80°C. A mixture of silica, activated carbon and magnesium powder in a ratio of 1:0.2:0.88 was transferred to a crucible, pyrolyzed at 600°C for 8 hours, and reheated to 500°C after cooling at room temperature for 30 minutes. The resulting solid was leached with acid (5 M HCl), and the solution was left to stand for 1 hour. The solution was filtered, the solid was washed several times with deionized water and dried in an oven overnight at 100°C to obtain SiC.

In [54], a technology was developed for using printed circuit board waste as a precursor of silicon and carbon to obtain silicon carbide nanoparticles. The preparation process contained three optimized steps: 1) prewash with 3 mol/L nitric acid at 60°C for 96 hours; 2) low temperature pyrolysis at 500°C to decompose the epoxy resin into carbon; 3) high temperature pyrolysis at a temperature of 1600°C (in situ carbothermal reduction) to obtain pure SiC nanoparticles. Fig. 4 shows the morphology of the obtained SiC using a scanning electron microscope (the pyrolyzed powder was additionally heated to 1500, 1600, and 1700°C). The particle size ranged from several tens to hundreds of nanometers.

In [55], hollow spheres of silicon carbide were synthesized. To do this, SiO_2 was uniformly applied to dry yeast as a biological template by the sol-gel method, and the internal substances of the yeast were removed at a temperature of 700°C to obtain a hollow silicon template. RF aerogel (source of carbon) was then used to wrap the silicone template. After carbonization, a carbon thermal reduction reaction was carried out at a temperature of 1400°C to obtain SiC hollow spheres. And in [36], silicon carbide was synthesized by microwave sintering using graphene as a carbon source and ethyl orthosilicate as a silicon source. First, SiO_2 particles were deposited in situ on the graphene surface by the sol-gel method, and then one-dimensional silicon carbide nanowires were obtained by the thermal reduction reaction. The optimum sintering temperature is 1500°C, holding time is 40 min.

In [56], silicon carbide was obtained by reaction-bonding sintering with the addition of nanosized carbon black and microspherical carbon. Inert carbon particles remained after the process of infiltration of molten silicon and were consumed in reaction with residual silicon at

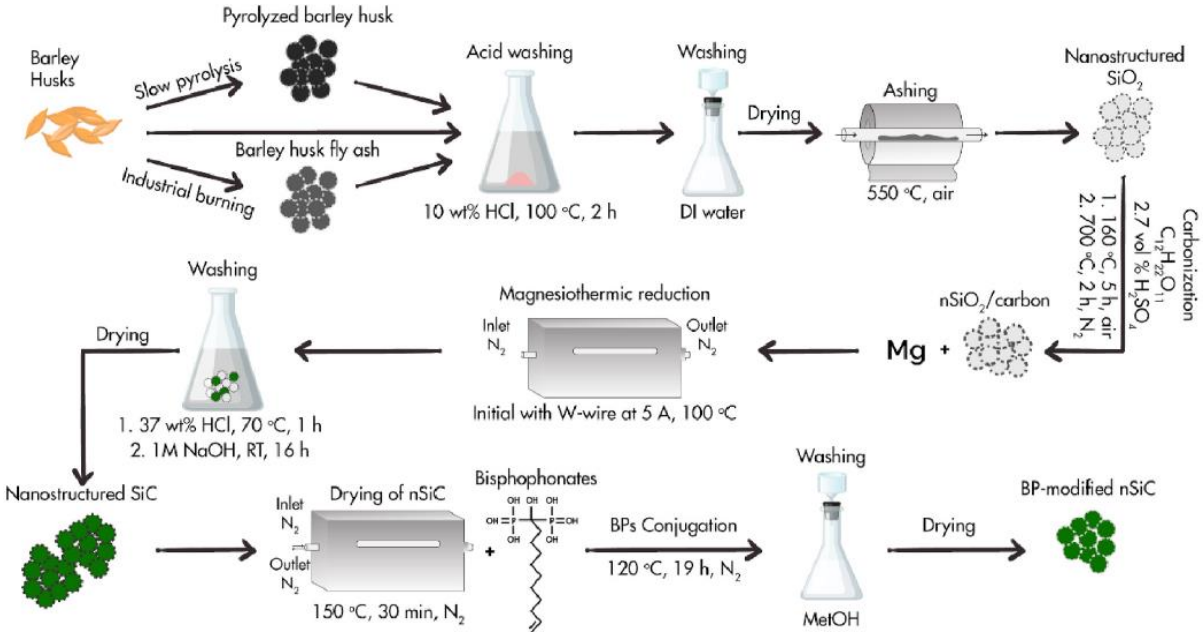

Fig. 3. Graphic scheme for the synthesis of nanostructured silicon carbide [52].

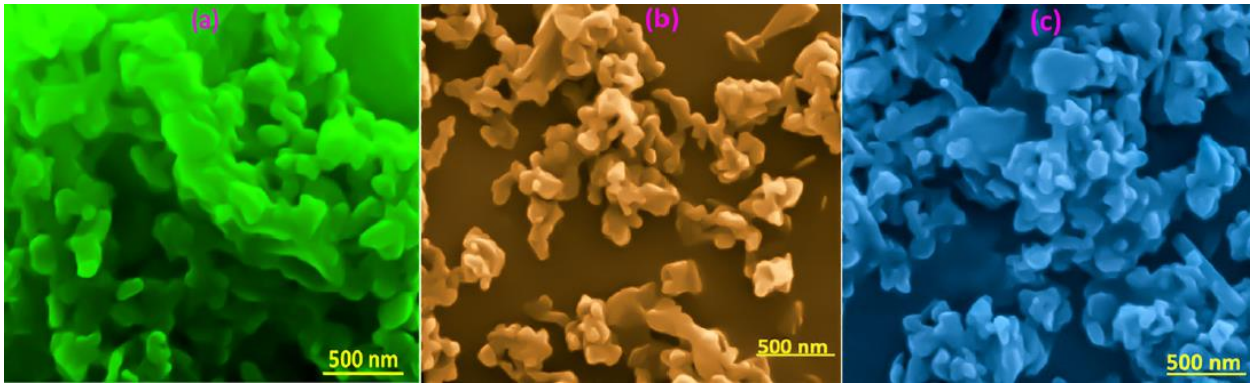

Fig. 4. SEM images of SiC-1500 (a); SiC-1600 (b) and SiC-1700 (c) [54].

high temperature. At a temperature of 1850°C, the residual carbon decreased to almost zero, which was accompanied by 6% Si as a result of continuous infiltration of Si in the second soaking step. A hardness of 25.3 GPa and a Young's modulus of 443 GPa were achieved. It has been found that the sintering process consists of a fast direct reaction by infiltration and a slow reaction by diffusion, potentially resulting in SiC with a very low residual Si content.

In [57], silicon carbide was synthesized by calcining tissue and glass microspheres at high temperature. The results show that a higher synthesis temperature can improve SiC crystallinity, form more whiskers, and reduce the content of impurities. The synthesized products at 1600°C have excellent microwave absorption properties. Also a good material for microwave absorption is porous silicon carbide foams synthesized in [58] as a result of the reaction of phenolic resin and silicon powder by the replica method using polyurethane foam followed by sintering. SiC foams have also been modified by adding various microwave absorbing additives such as ZrO_2, Fe_3O_4, and NiO.

In [59], cubic 3C-SiC was synthesized at different temperatures (1600°C, 1650°C, and 1700°C) using graphite flakes and microfine silica by the carbothermal reduction method. The grown SiC structures were observed in two different morphologies, namely ribbon-type (diameter 2-5 μm) and rod-type (diameter ≤ 2 μm). The ribbon-type morphology was formed on the surface of the graphite flakes at a relatively low temperature (1600°C), and the rod-type morphology was formed at a higher temperature (≥ 1650°C) between the interlamellar spaces of the graphite flakes.

In [60], amorphous and crystalline SiC nanoparticles were synthesized by laser ablation (wavelength 1064 nm) of microsized SiC powder in water and ethanol. The analysis showed the amorphous nature of SiC nanoparticles with an average particle size of 44 nm in water and crystalline nature of 6H-SiC nanoparticles with an average particle size of 18 nm in ethanol. The direct and indirect bandgaps for SiC nanoparticles according to absorption spectra in the UV-visible range in water were 5.3 and 3.03 eV, respectively, and in ethanol, 4.9 and 3.05 eV, respectively.

In [46], an AC multi-arc plasma device was developed for continuous gas-phase synthesis of ultra-small silicon carbide nanoparticles (Fig. 5). SiC nanoparticles with an average size of 7-10 nm were obtained by decomposition of triethylsilane in an AC multi-arc plasma (Ar, H_2, and N_2 were used as buffer gases).

In [61], the detonation synthesis of silicon carbide is presented. Simulation of detonation on a continuum scale showed that the detonation wave energy transfer is completed within 2-9 μs, depending on the location of the measurement within the detonating explosive charge. Carbon and added elemental silicon in the detonation products remained chemically reactive up to 500 ns after the passage of the detonation wave, indicating that carbonaceous detonation products can participate in the synthesis of silicon carbide with sufficient carbon-silicon interaction. Controlled charge detonation with 3.2 wt% of elemental silicon, carried out in an argon environment, leads to the formation of ~3.1 wt% of β-SiC in the condensed detonation products. In a similar study [62], the same scientists added polycarbosilane to a mixture of 1,3,5-trinitro-1,3,5-triazinane and 2,4,6-trinitrotoluene, which was then detonated in a closed chamber filled with an inert gas. X-ray diffraction analysis of detonation soot showed the presence of crystalline silicon with a diamond cubic structure and cubic silicon carbide along with amorphous material.

In [63], SiC membranes were synthesized by additive sintering using NaA zeolite residues (sodium, aluminum, and silicon oxides) as additives. Zeolites are among the largest cation exchangers [64]. With such additives, the particles are more tightly connected due to the formation of new phases. The SiC powder was ground in a ball mill with NaA residues (NaA content: 6, 8, 10, 12, and 14 wt%) and activated carbon powder (activated carbon content: 0, 5, 10, 15, and 20 wt%) for 2 hours. After sieving, an 8 wt% polyvinyl alcohol solution was added to the mixture. Next, the samples were sintered in an atmospheric air from 850°C to 1050°C and gradually cooled to room temperature. The use of NaA zeolite residues has effectively reduced the cost of production and improved the performance of ceramic membranes. SiC membranes have shown high resistance to cyclic thermal shock, strong long-term acidity, and caustic corrosion [63].

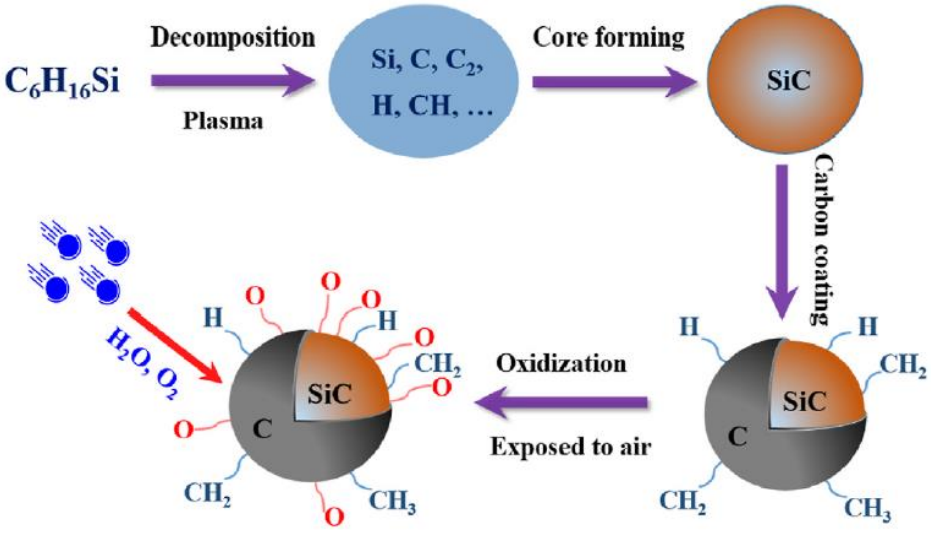

Fig. 5. Formation of SiC nanoparticles in an AC multi-arc plasma [46].

The authors of [65] studied the effect of the addition of TiO_2 nanoparticles [66,67] on the physicomechanical properties of a silicon carbide composite. The samples were made without pressure at a temperature of 1900°C. The results have shown that the addition of TiO_2 nanoparticles up to 4.5 wt% inhibits excessive growth of SiC grains. According to research data, composites were affected by density, synthesized phases, as well as their distribution in the matrix, and grain size. The highest density was 98.7%, Young's modulus was 401.2 GPa and hardness was 27.1 GPa.

In [68], SiC/SiO_2 nanowires were synthesized from silica fume [69] and sucrose by carbothermal reduction. To do this, silica fume (as a source of silicon) and sucrose (as a source of carbon) were mixed in a molar ratio of 1:4. NaCl and NaF were used as the molten salt medium. Silica and sucrose were mixed with salt and placed in a graphite crucible covered with a lid, and then kept at a temperature of 1300-1500°C for 4 hours in an argon flow. After cooling in a furnace to room temperature, the reacted mass was washed several times with hot distilled water and filtered to leach out the remaining salts. After drying at 100°C for 12 hours, the obtained samples were heated at 700°C for 3 hours in air to remove residual carbon. The resulting nanowires were a heterostructure composed of a 3C-SiC core 100 nm in diameter and a 5-10 nm thick amorphous SiO_2 shell layer.

Many studies of methods for obtaining silicon carbide are devoted to synthesis by chemical vapor deposition.

In [70], β-SiC nanowires were synthesized by catalyst-free chemical vapor deposition using silicon, trace nanoscale SiO_2 particles, and phenolic resin powders. To do this, the SiO_2 nanopowder was ultrasonically dispersed in ethanol to obtain a SiO_2-alcohol suspension. The suspension was then added to the Si powder and then stirred for 30 minutes, resulting in a Si- SiO_2 mixture. Thereafter, the phenolic resin powder and the dried Si- SiO_2 mixture were blended for 30 minutes. The final mixture was heated at 1400°C for 3 hours in a small corundum crucible with a lid embedded in a large closed corundum crucible filled with graphite powder. The synthesized β-SiC nanowires were well crystallized, had different morphology (chain, bamboo-shaped, and linear), lengths up to tens of microns, and diameters of 80-650 nm.

In a similar study [42], SiC nanowires were also synthesized by simple chemical vapor deposition at high temperatures using silicon, phenolic resin, and ZrB_2 powder. A mixture of phenol formaldehyde resin powder, Si powder, and ZrB_2 powder was stirred at 310 rpm for 30 minutes using a QM-3SP4 ball mill. The well-blended mixture was placed in a small corundum crucible and covered with a lid. The small crucible was then placed in the larger crucible and coated with graphite powder. A large crucible containing the mixture was fired at 1400°C for 3 hours. Since a large corundum crucible with an excess of graphite powder was sealed, the gases in the crucibles mainly consisted of CO and N_2 (from a protective atmosphere), which contributed to the formation of SiC nanowires.

The authors of [71] proposed a new chemical vapor deposition process in which gaseous SiO and toluene vapor react to form SiC in the presence of iron oxide as a catalytic component. One side of the alumina plate used as the substrate was wetted with an iron (III) nitrate aqueous solution, then dried and heated to 800°C in air. Thus, a layer of iron oxide with a thickness of about 5 μm was deposited as a catalytic component. Next, 300 mg of granular SiO was poured into an alumina crucible with an internal volume of 15 mL, and an alumina support plate and the above-mentioned iron oxide deposited alumina plate were placed on granular SiO, which were then placed on the support plate (Fig. 6). The crucible in this state was placed in an electric furnace, and the air in the furnace was replaced with argon. Then, the crucible was heated to a temperature of 1450°C for a given time, while toluene vapor was continuously fed into the crucible. Thus, various SiC coatings along with fibrous materials were formed at those places on the alumina plates where iron oxide was deposited. The fibrous material is composed of fibrous SiC as well as a spherical substance containing Fe and can be easily removed mechanically from the SiC coating.

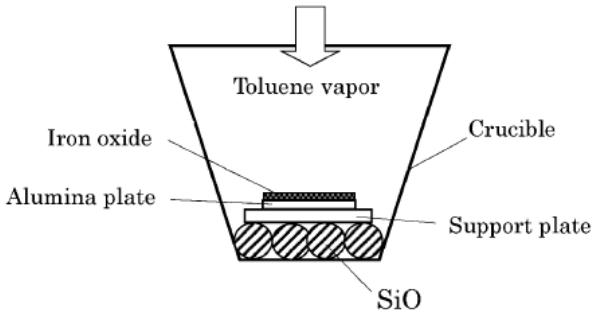

Fig. 6. Scheme for the SiC coating [71].

In [39], a SiC fiber was synthesized at atmospheric pressure in a horizontal hot wire CVD reactor (Fig. 7). A coil of tungsten wire with a diameter of 17.8 ± 0.1 μm was used as a heating element and a substrate for SiC deposition. CH_3SiCl_3 (purity > 98%) was used as a precursor, the flow rate of which was controlled by supplying a diluent gas through a thermostatic bubbler. H_2 and Ar were used as diluent gases. The substrate temperature was measured through a viewing window inside the reactor using a SYG WGG2–201 optical pyrometer with an error of ±20°C, and the corresponding temperature of the reactor wall was measured with a Lutron TM902C digital thermometer with an error of ±1°C. Before introducing CH_3SiCl_3 into the reactor, an external heating jacket was used to preheat the reactor wall to 150°C, and a dilution gas was used to purge the reactor for 30 minutes at a flow rate of 400 sccm. During SiC deposition, the W wire speed and the flow rate of CH_3SiCl_3 were separately maintained at 2 cm/s and 600 sccm, while the diluent gas flow rate varied from 800 to 1600 sccm. By controlling the input power, all deposition processes were carried out at a substrate temperature of 1000°C.

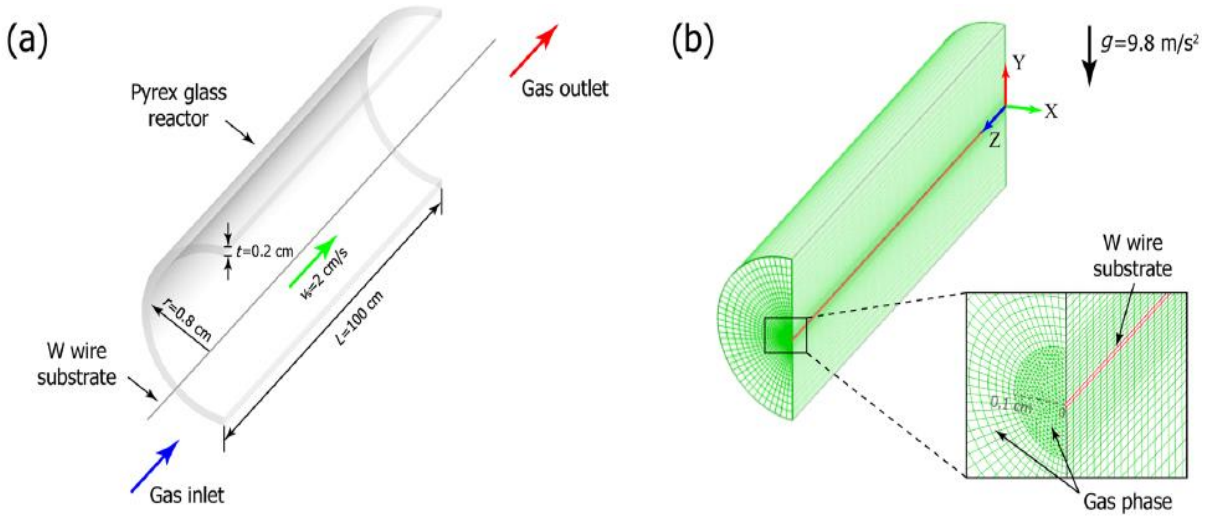

Fig. 7. Schematic diagrams of the CVD reactor [39].

Conclusions

Silicon carbide is a widely used material with unique physical and chemical properties. In particular, high hardness (~25 GPa), high compressive strength (~3.5 GPa), and low density make SiC an attractive option for many applications at high temperatures and in corrosive environments. The most important problems in the synthesis of silicon carbide are the low sinterability of SiC due to the presence of covalent bonds and its low self-diffusion. Therefore, the sintering of silicon carbide must be carried out at a very high temperature. New modern heating technologies such as microwave, plasma and laser heating allow the reaction to be carried out at a low temperature, which reduces preparation costs and significantly reduces reaction time. Today, the concept of "green" synthesis is very popular, involving the development of renewable, non-toxic and environmentally friendly materials based on silicon carbide. Therefore, scientists actively study ways to synthesize SiC nanoparticles using biomass. Due to their excellent characteristics, silicon carbide nanoparticles have a high potential for application in many aspects, in particular, use in structural and functional composites, catalysts, fluorescent biomarkers, bioadhesives, etc.

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Синтез та властивості силіцій карбіду (огляд)

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Силіцій карбід надзвичайно твердий матеріал, який проявляє виняткову корозійну стійкість, а також стійкість до теплових ударів. Його високі механічні характеристики визначають підвищену роботоздатність матеріалів на його основі. Поєднання великої теплопровідності та низького коефіцієнта термічного розширення зумовлюють стійкість силіцій карбіду при великих швидкостях нагріву та в умовах стаціонарного теплового режиму. На сьогодні існує значний прогрес у розвитку методів синтезу різноманітних матеріалів на основі силіцій карбіду. Основними методами синтезу, які використовують науковці у своїх дослідженнях, є золь-гель метод, спікання, піроліз, мікрохвильовий синтез, хімічне осадження з парової фази тощо. Широкої популярності набуло використання «зелених» методик у синтезі SiC, через екологічність, відновлюваність та простоту виконання. У даному огляді зроблено аналіз сучасних досліджень у галузі синтезу силіцій карбіду, які опубліковані у рецензованих фахових виданнях.

Ключові слова: силіцій карбід, політип, «зелений» синтез, керамічні наноматеріали.