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Research and Application of Silicon Nanoscale Heat Dissipation Materials

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Abstract: *In this paper, a review of silicon nanoscale heat dissipation materials is presented. The preparation methods of nano-silicon heat dissipation materials are introduced, including dry preparation (vapor phase method, electric arc method) and wet preparation (sol-gel method, precipitation method, microemulsion method). The factors affecting the heat dissipation efficiency of nano silicon materials are analyzed. The advantages of nano-silicon as a heat dissipation material, such as high heat dissipation efficiency, good stability, processability, and environmental protection and energy saving, are introduced. The applications of nano-silicon heat dissipation materials in various fields in real life are described.*

Keywords: *Nano-silicon, Heat dissipation material, Preparation method, Characteristic, Application field*

1. Introduction

Silicon (Si), the second most abundant element in the earth's crust, is not only inexpensive but also has unique properties. Monolithic silicon is a narrow-band semiconductor with excellent performance, and as one of the most important types of electronic materials in industry, it is widely used in transistors, logic switches, sensors, solar cells, light detectors, and other fields[1-5].

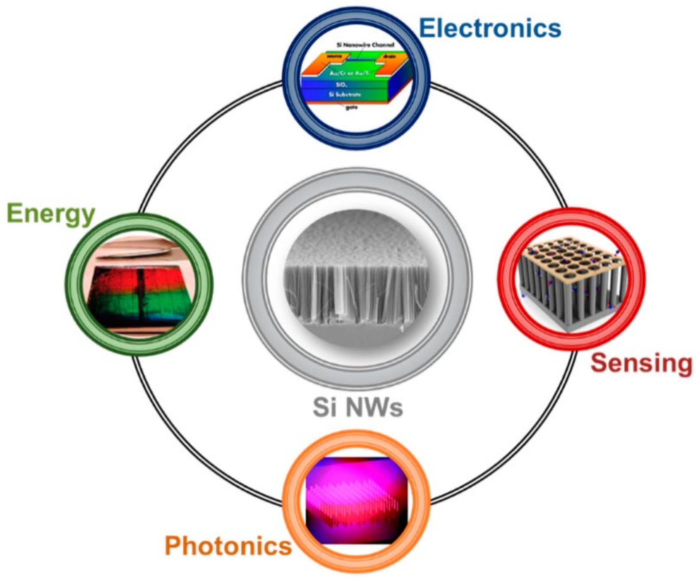

Figure 1: Applications of nanosilicon materials[6].

As a new type of heat dissipation material, nanosilicon heat dissipation material has attracted much attention in recent years. As the integration degree and assembly density of electronic components continue to improve, electronic products provide high functionality and high efficiency, while the operating power consumption and operating temperature of their individual components also increase dramatically. High temperature will have a harmful effect on the stability and reliability of electronic components and shorten the service life of the components. In order to ensure that electronic components

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can operate stably and reliably for a long time, timely and effective heat dissipation has become an urgent problem. Nanosilicon heat dissipation materials provide a new way to solve this problem with their excellent performance and wide application prospects. So far, researchers have developed a number of methods for the preparation of silicon nanomaterials, which can be summarized as vapor deposition, arc discharge, sol-gel, precipitation, and microemulsion methods[7-10].

In this paper, we will review the preparation methods, properties, and application fields of nanosilicon heat dissipation materials, introduce the advantages and disadvantages of different preparation methods, and analyze the factors affecting the heat dissipation efficiency of nanosilicon materials. The advantages of nanosilicon as a heat dissipation material are introduced, and the applications of nanosilicon heat dissipation materials in various fields in real life are described. Finally, the future development direction of nanosilicon heat dissipation materials is further prospected.

2. Preparation Method

2.1. Dry Preparation

2.1.1. Gas Phase Method

The vapor-phase method uses $SiCl_4$ as the raw material and hydrolyzes SiO_2 at high temperatures under a stream of hydroxide gas. The nanosilicon prepared by this method has a number of significant characteristics[11]. Firstly, the high dispersion of nanosilica means that the particles are more evenly distributed in space without local aggregation, which helps to improve the stability of its performance in various applications. Secondly, the product has high purity and very low impurity content, which is important for some areas that require very high material purity, such as electronic device manufacturing. In addition, the particles are fine and spherical, and this spherical particle morphology gives them a small surface area to volume ratio, which reduces reactivity with the external environment and improves the chemical stability of the material.

However, the vapor phase method also has some obvious disadvantages. On the one hand, the preparation cost is expensive. This is mainly due to the high price of $SiCl_4$, the raw material used in this method, and the need to consume a large amount of energy during the preparation process, such as the provision of high-temperature hydrogen-oxygen gas streams requires a large amount of fuel. At the same time, in order to ensure the smoothness of the preparation process, it is also necessary to use advanced equipment and complex process control, which also increases the cost investment. On the other hand, the technology is complex. The preparation process of vapor phase method requires precise control of several parameters, such as temperature, gas flow rate, reaction time, etc. Deviation of any one parameter may lead to a decrease in product quality. In addition, the post-treatment process is also cumbersome, requiring steps such as particle aggregation, separation, and deacidification to obtain high-purity nanosilica.

2.1.2. Arc Method

Arc discharge is an effective method for the preparation of silicon nanomaterials, which has the advantages of easy formation at high temperatures, relatively easy operation, and cheap and readily available raw materials.An arc discharge device usually includes a power supply, electrodes, a reaction chamber, a cooling and vacuum system, and the required medium (gas, gas mixture, or liquid). The basic principle is to generate high temperature by arc discharge between electrodes to evaporate and dissociate the raw materials and thus form nanomaterials[12].

2.2. Wet Preparation

2.2.1. Sol-gel Method

The sol-gel method usually uses metal-alcohol salts or inorganic salts as the initial raw materials, through hydrolysis or precipitation reaction, to prepare a uniform sol, and then undergo the sol-gel transformation, and finally through the aging, drying and heat treatment to obtain the product[13].

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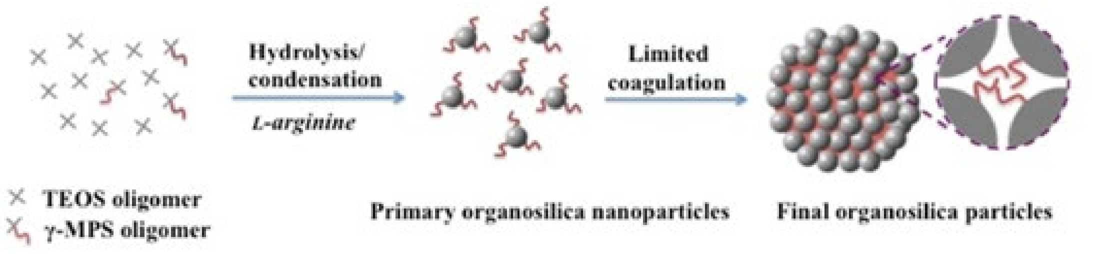

Figure 2: Schematic of the mechanism for the formation of organosilica particles using a one-step liquid-liquid biphasic sol-gel process[14].

The sol-gel method for the preparation of silicon nanothermal materials has the following advantages: first, high purity products can be prepared, because the introduction of impurities can be reduced by controlling the raw materials and reaction conditions during the reaction process; second, nanomaterials with controllable particle sizes can be prepared, and the formation of the sol and the transformation process of the gel can be controlled by adjusting the reaction parameters, so as to control the size of the product particle size; third, nanomaterials with special morphology and structure of nanomaterials, such as microspheres, fibers, etc. These special morphology and structure of nanomaterials may have better heat dissipation properties.

2.2.2. Sedimentation Methods

Precipitation is the acidification of silicates to obtain loose, finely dispersed SiO_2 crystals precipitated in a flocculent structure[15, 16]. For example, SiO_2 ultrafine nanopowder with an average particle size of 40-50 nm was prepared from sodium silicate and CO_2 in a solution of a certain pH value.

Precipitation method for the preparation of nanosilicon heat dissipation materials has the following advantages: First, low cost, compared with the gas phase method and sol-gel method and other dry preparation methods, the precipitation method requires lower cost of raw materials and equipment; Second, less energy consumption, the preparation process does not require high temperature, high pressure and other harsh reaction conditions, less energy consumption; Third, the preparation process is simple, easy to operate, does not require complex equipment and technology; Fourth, good dispersibility, the preparation of nanosilicon heat dissipation materials by precipitation method has good dispersion, not easy to be agglomerated. Good dispersion, precipitation method prepared by the nano-silicon heat dissipation materials have good dispersion, not easy to agglomerate.

2.2.3. Microemulsion Method

Microemulsions are usually transparent, isotropic, thermodynamically stable systems composed of water, oil, surfactant and co-surfactant. In the preparation of nanosilica by the microemulsion method, the controlled synthesis of nanosilica can be achieved by controlling the composition of the microemulsion and the reaction conditions.

Silicon nanoscale heat dissipation materials prepared by the microemulsion method are usually characterized by a narrow particle size distribution and a controllable particle size. The structure of the microemulsion micelles is in dynamic equilibrium, and by controlling the morphology, structure, polarity and hydrophobicity of the micelles and the “pool”, the size of the nanoparticles can be controlled by the molecular scale, so as to prepare nanosilicon heat dissipation materials with narrow particle size distribution.

3. Factors Affecting Heat Dissipation in Silicon Nanomaterials

3.1. Size

The size of silicon nanoparticles has a significant effect on heat dissipation. In general, the smaller the particle size, the larger the specific surface area and the more pronounced the surface effect. For example, in silica nanofluids, the size of nanoparticles affects the thermal conductivity of the fluid[17]. Smaller sized nanoparticles can increase the contact area between the fluid and its surroundings, thus improving the heat transfer efficiency. However, too small a particle size may also lead to enhanced inter-particle interactions, affecting the stability of the fluid.

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3.2. Shape

The shape of a nanoparticle affects its contact area with the surrounding medium, thermal conduction paths, and heat scattering, among other factors, and thus has an impact on the heat dissipation performance. For example, spherical particles usually have a regular shape and relatively uniform contact with the surrounding medium, but their surface area is relatively small. While other non-spherical particles, such as platelet-shaped , cylindrical, razor blade, etc., may have a larger surface area and more complex heat transfer paths.

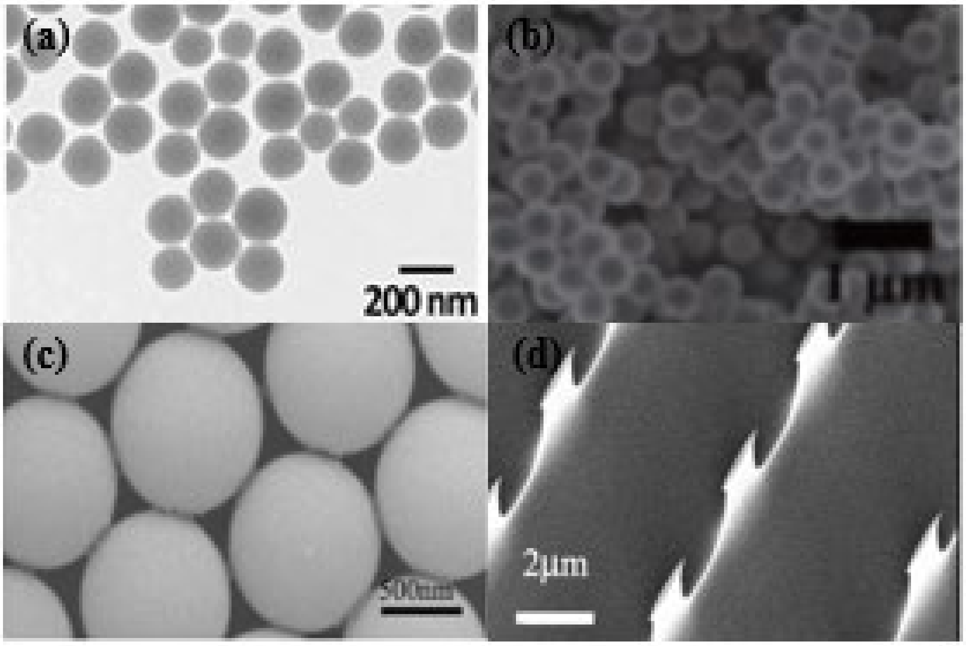

Figure 3 Silicon nanoparticles of various shapes: (a, b) spherical particles, (c) cylindrical particles[18], (d) blade-shaped particles[19].

3.3. Structure

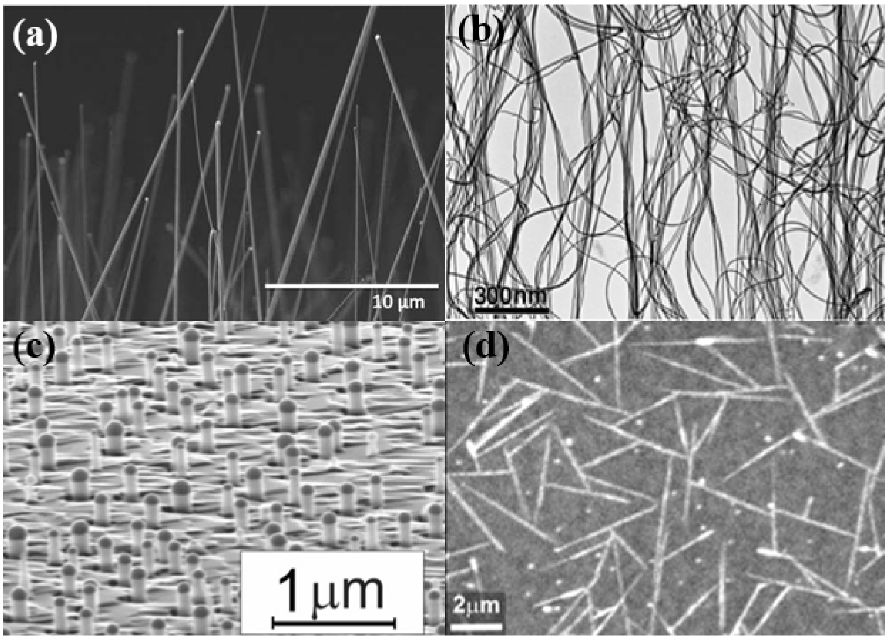

Figure 4 Silicon nanowires grown by different processes:(a) Chemical vapor deposition[26], (b) Pulsed laser deposition[27], (c) Molecular beam epitaxy[28], (d) RF magnetron sputtering[29].

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The structure of one-dimensional nanostructured materials such as silicon nanowires and silicon nanotubes also affects heat dissipation. Silicon nanowires, as a typical representative of one-dimensional silicon nanomaterials, have been widely studied due to their easy synthesis, fascinating properties, and applications in a wide range of fields. In the past decades, several research groups around the world have prepared various types of 1D silicon nanostructures using various methods such as chemical vapor deposition (CVD), pulsed laser deposition (PLD), thermal evaporation, template-assisted growth, molecular beam epitaxy (MBE), reactive ion etching (RIE), and metal-assisted chemical etching (MACE), etc[20-25]. Figure 4 illustrates FESEM images of Si NWs grown by various fabrication techniques. The top-down approach is to form Si nanowire arrays by RIE and MACE selective reduction of bulk Si wafers. Among the conventional methods, CVD and MACE methods are the most widely used due to their versatility, controllability, reproducibility, high quality, relatively low cost and mass production.

4. Characteristics of Nano-silicon Heat Dissipation Materials

4.1. High Thermal Efficiency

4.1.1. High Thermal Conductivity

The relatively high thermal conductivity of nanosilicon can quickly conduct heat away and reduce the accumulation of heat inside the material, thus effectively lowering the temperature of the object. For example, in some high-performance electronic devices, the use of nanosilicon heat dissipation materials can quickly conduct the heat generated by the chip to the heat sink, preventing the chip from overheating performance degradation[30].

4.1.2. Large Specific Surface Area

Nanosilicon has a large specific surface area, which means it has more contact area with its surroundings and is able to exchange heat more efficiently. During the heat dissipation process, heat can be quickly emitted to the surrounding medium through the surface of the silicon nanomaterials to improve the heat dissipation effect[31]. For example, in porous silicon nanomaterials, their spongy structure provides a large number of nanoscale pores and channels, which increase the surface area for heat conduction and thus improve the heat conduction efficiency.

4.2. Good Stability

Nanosilicon can still maintain good performance in high temperature environment, not easy to deformation, melting or decomposition and other phenomena. Nanosilicon has good chemical stability and is not easy to react with other substances, thus ensuring that its heat dissipation performance in different chemical environments is not affected. In some complex chemical media, such as acid and alkali solutions, organic solvents, etc., nanosilicon heat dissipation materials can still maintain good heat dissipation effect, which broadens the scope of its application.

4.3. Environmental Protection and Energy Saving

4.3.1. Non-toxic and Harmless

Nano-silicon itself is non-toxic and harmless, will not cause harm to the human body and the environment, in line with environmental requirements. In the process of use, there is no need to worry about its impact on the environment and human health, has a good environmental friendliness.

4.3.2. Remarkable Energy-saving Effect

As nano-silicon can effectively improve the heat dissipation efficiency and reduce the working temperature of the equipment, thus reducing the energy loss of the equipment due to overheating, improving the energy utilization efficiency and achieving the purpose of energy saving. In some large data centers, the use of nanosilicon cooling technology can reduce the energy consumption of servers, reduce operating costs, but also help to reduce greenhouse gas emissions, to achieve the goal of energy saving and emission reduction.

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5. Application of Silicon Nanoscale Heat Dissipation Materials

5.1. Silicon Nanofluids

Nanofluids are dispersions of nano-sized particles dispersed in a base fluid[32]. First proposed by Choi in 1995, it has attracted a great deal of attention in the last few decades due to its excellent thermal properties[33, 34], extensive and in-depth studies have been conducted on nanofluids[35].

Among them, nanosilicon fluid cooling, as a cutting-edge cooling technology, combines the advantages of nanotechnology and fluid cooling[36]. Silica nanoparticles were utilized to have high thermal conductivity, much higher than that of conventional coolants. When they are uniformly dispersed in the base fluid, they can significantly improve the overall thermal conductivity of the fluid and accelerate the transfer of heat from the heat source to the coolant.Yan et al. investigated the relationship between the thermal conductivity of nanosilica fluids and mass fraction as well as temperature, and found that the nanosilica fluids can achieve a thermal conductivity efficiency of 0.75 at 65°C and 5% nanosilica content[17]. Darvanjooghi et al. pointed out that the size of silicon nanoparticles for nanofluids is not as small as possible, and that an increase in the diameter of the nanoparticles, within a certain range, rather improves the thermal conductivity of the silicon nanofluids[37]. Pang et al. showed that the thermal conductivity of SiO_2 nanofluids was enhanced to a greater extent than that of Al_2O_3 nanofluids[38].

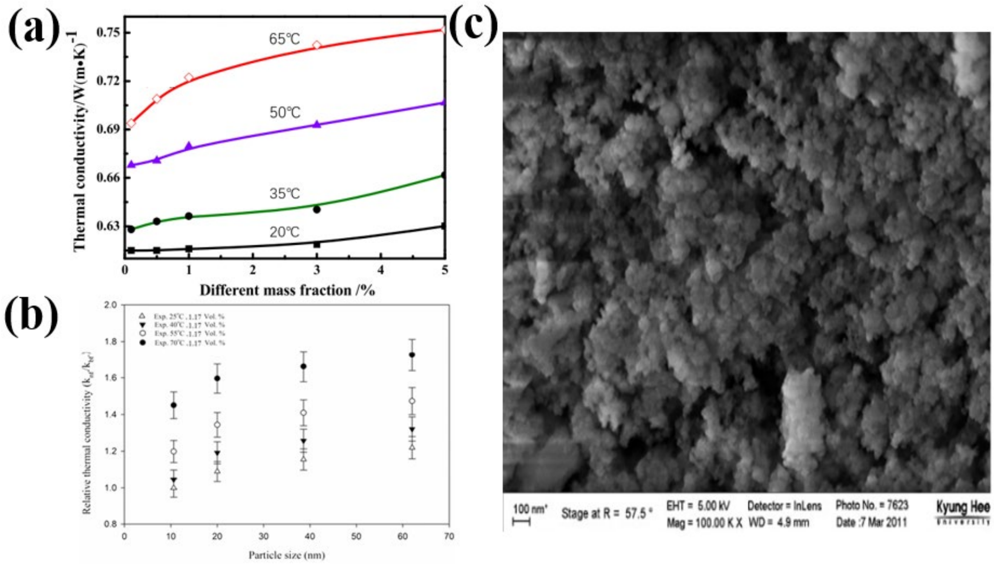

Figure 5 (a) Variation of thermal conductivity of silica nanofluids at different mass fractions as well as at different temperatures[17], (b) Relative thermal conductivity of silica nanofluid at 1.17 vol.% versus nanoparticle diameter[37], (c) Electron microscope image of silica nanoparticles[38].

5.2. Electronic Devices

As the performance of smartphones, tablet PCs, laptops and other electronic devices continues to improve, their heat dissipation problems are becoming more and more prominent[39]. Nano-silicon heat dissipation materials can be applied to the chips, batteries and other components of these electronic devices to effectively reduce the temperature of the device and improve the stability and reliability of the device[40].

5.3. Biomedical Field

In the biomedical field, the thermal efficiency of silicon nanothermal materials is mainly reflected in the control of thermal effects on biological tissues[41]. For example, optical nano-heating platforms based on silicon nanocubes, which are capable of efficiently localizing thermal energy to the nanoscale, are crucial for applications such as nanosurgery, photochemistry, and nanofabrication[42, 43]. Currently, optical nano-heating platforms based on silicon nanocubes can increase the temperature up to 300 K at an incident power density of 2.9 mW/μm².

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5.4. LED Field

LED lighting products generate a lot of heat during the working process, which will affect their life and performance if they cannot dissipate heat in time. Nano-silicon heat dissipation materials can be applied to the heat sinks of LED lighting products to improve the heat dissipation efficiency and prolong the product life[44].

5.5. New Energy Vehicle Sector

Batteries of new energy vehicles generate a large amount of heat during charging and discharging, which will affect the performance and life of the batteries if they cannot dissipate heat in time. Nano-silicon heat dissipation materials can be used in the heat dissipation system of the battery pack to improve the heat dissipation efficiency and ensure the safe operation of the battery. In addition, nano-silicon heat dissipation materials can be applied to the battery management system, motor controller and other components of new energy vehicles to improve heat dissipation efficiency and safeguard the safety performance of automobiles.

6. Conclusion

Silicon nanoscale heat dissipation materials have become a hotspot of current research due to their unique preparation method, excellent properties and wide range of applications. With the continuous progress of technology, its performance will be continuously improved and the application scope will be further expanded.

In the future research, the development of nanosilicon heat dissipation materials can be further explored in the following aspects. First, in the preparation method, the dry and wet preparation processes are continuously optimized to reduce cost, improve yield and quality stability. For example, for the gas-phase method, more economical raw materials and more efficient process control can be explored to reduce the problems of expensive and technically complex preparation costs; for the electric arc method, equipment and process parameters can be further improved to enhance energy utilization efficiency and particle quality. For the sol-gel, precipitation and microemulsion methods of wet preparation, more precise particle size control, higher purity and better morphology can be achieved through in-depth study of the reaction mechanism and control conditions.

Secondly, in terms of characterization, the intrinsic mechanism of quantum size effect, compatibility with microstructures and other properties of nanosilicon heat dissipation materials are deeply explored to provide theoretical basis for further improvement of heat dissipation performance. At the same time, the stability of nanosilicon heat dissipation materials in different environments should be strengthened to improve their reliability in complex application scenarios.

In terms of application fields, we will continue to expand the application of nanosilicon heat dissipation materials in electronic devices, biomedicine, LED, new energy vehicles and other fields.

In conclusion, nano-silicon heat dissipation materials have a broad development prospect, through continuous technological innovation and application expansion, will bring more opportunities and challenges for the development of various fields.

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