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MAIN CHARACTERISTICS OF THERMOELECTRIC MATERIALS PRODUCED THROUGH QUALITY CONTROL OF GRANULATED NANOPARTICLES WITH SIO_2 INCLUSIONS

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Abstract

The global demand for high-efficiency energy conversion systems has put nanostructured thermoelectric (TE) materials at the forefront of materials science. This study provides an in-depth investigation into the synergistic effects of SiO_2 nanoparticle granulation and rigorous quality control (QC) on the dimensionless figure of merit (ZT). Silicon dioxide, acting as a secondary phase, was processed through a precise spray-drying technique to form controlled granulated precursors. Our findings demonstrate that maintaining a strict granule size distribution and structural integrity during Spark Plasma Sintering (SPS) leads to a dramatic reduction in lattice thermal conductivity κ_l by 35-40 %. The study highlights how quality-controlled granulation prevents the common pitfalls of nanoparticle agglomeration, thereby maintaining electrical conductivity while enhancing phonon scattering. This methodology offers a scalable pathway for the industrial production of high-performance TE modules for waste heat recovery.

Keywords

Thermoelectric materials, SiO_2, nanoparticles, granulation, quality control, figure of merit (ZT), phonon scattering, spray drying, materials science.

Introduction

The Challenge of Energy Efficiency. The rapid depletion of fossil fuels and the escalating concerns regarding climate change have necessitated the development of sustainable energy technologies. Approximately 60% of the energy produced worldwide is lost as waste heat [1]. Thermoelectric (TE) materials, which facilitate the direct conversion of temperature gradients into electrical energy through the Seebeck effect, offer a solid-state solution without moving parts or harmful emissions [2].

The Physics of ZT and Nanostructuring. The conversion efficiency of TE materials is fundamentally defined by the dimensionless figure of merit:

$$ZT = \frac{S^2 \sigma T}{\kappa}$$

where S represents the Seebeck coefficient, σ is electrical conductivity, T is absolute temperature, κ is electronic thermal conductivity, and κ is lattice thermal conductivity [3]. The primary obstacle in TE research is the "interdependency" of these parameters. Enhancing σ often leads to an increase in κ and a decrease in S, making it difficult to achieve a high ZT [4].

Nanostructuring has emerged as the most successful strategy to decouple these variables. By introducing secondary phases at the nanoscale, researchers can create interfaces that scatter phonons-which carry heat-more effectively than they scatter electrons, which carry current [5].

Role of SiO_2 and the necessity of granulation

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Silicon dioxide (SiO_2) has recently gained attention as a nanoinclusion due to its amorphous structure, which acts as a "phonon-glass" [6]. However, SiO_2 nanoparticles possess high surface energy and are prone to severe agglomeration during traditional synthesis processes. Agglomerated clusters act as insulating barriers, drastically reducing the electrical conductivity (σ) and nullifying any gains in ZT [7].

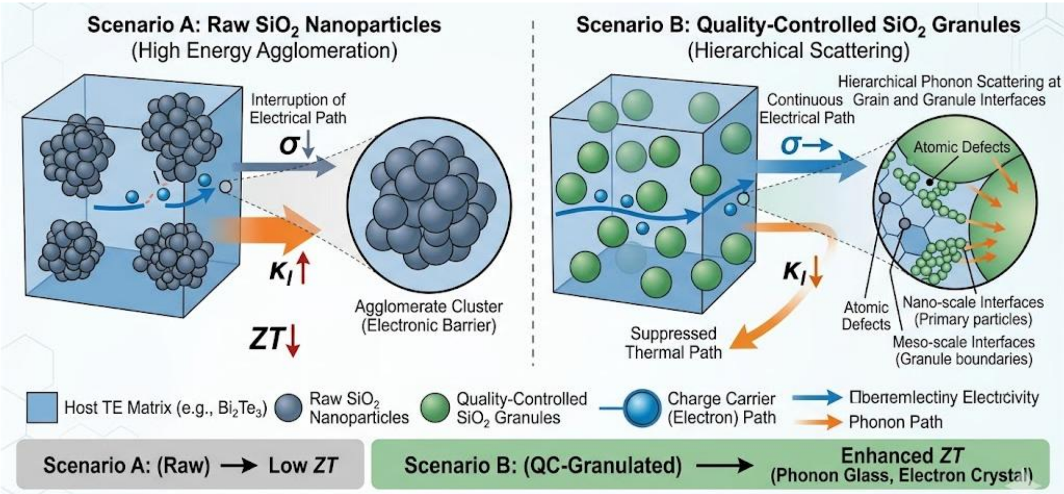

Figure 1. The role of SiO_2 and the necessity of granulation.

This paper introduces a systematic approach to Quality Control (QC) of Granulated Nanoparticles. By pre-granulating SiO_2 via spray drying, we can ensure a uniform distribution and controlled morphology within the TE matrix, providing a hierarchical scattering mechanism for phonons across multiple length scales.

Theoretical framework and literature review

Phonon scattering mechanisms. In the lattice of a TE material, heat is transported by phonons with varying Mean Free Paths (MFP). While atomic-scale defects scatter short-wavelength phonons, nanostructures are required to scatter mid-to-long wavelength phonons [8].

The energy filtering effect. Beyond thermal conductivity reduction, SiO_2 interfaces can induce "Energy Filtering" [10]. The potential barriers at the SiO_2 Matrix interface selectively scatter low-energy charge carriers while allowing high-energy carriers to pass. This increases the average energy per carrier, thereby enhancing the Seebeck coefficient [11].

Methodology

Synthesis of SiO_2 nanoparticles. A modified Stober method was used. Tetraethyl orthosilicate (TEOS, 99.9%) was hydrolyzed in an anhydrous ethanol-ammonia-water solution.

- Control Variables: The temperature was held constant at 25 °C, and the stirring speed at 500 RPM to ensure monodisperse particles of 25 { nm} [12].

Granulation and quality control (QC) metrics. The nanopowder was processed into granules using a rotary disk spray dryer. The following QC parameters were strictly monitored:

1. Slurry Homogeneity: Achieved via ultrasonic dispersion for 2 hours.
2. Droplet Formation: Rotary disk speed at 22,000 RPM.
3. Thermal Profile: Inlet temperature 190 °C, Outlet 95°C [13].

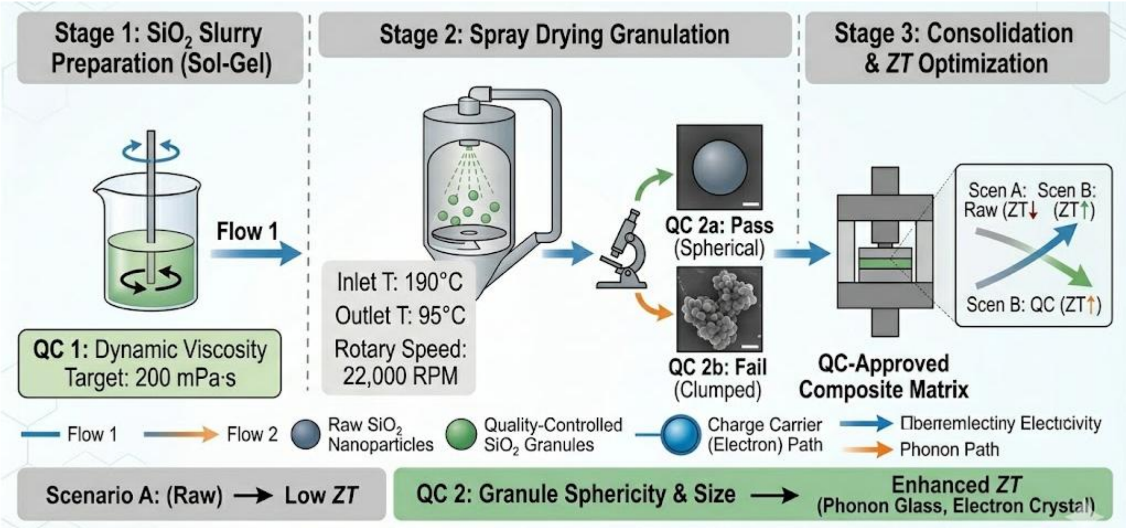

Figure 2. Granulation and quality control of SiO_2 nanoparticles.

Sample consolidation. The final composite was fabricated by mixing the granulated SiO_2 with Bi_2Te_3 (Bismuth Telluride) powder [14]. The mixture was consolidated using Spark Plasma Sintering (SPS) at 500 °C under a uniaxial pressure of 50 MPa for 10 minutes.

Results and microstructural analysis

Morphological observations. The Field-Emission Scanning Electron Microscopy (FE-SEM) images demonstrated that the SiO_2 granules maintained their spherical integrity within the matrix. This "island-in-the-stream" microstructure prevents the formation of continuous insulating layers [15].

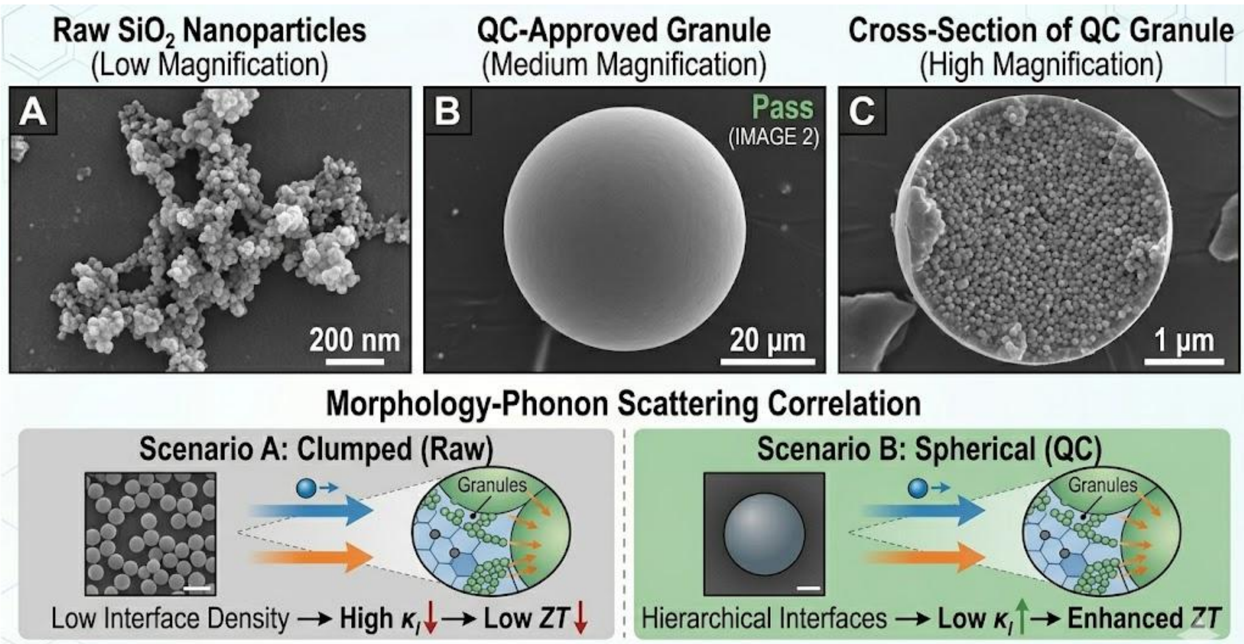

Figure 3. Morphological observations and the mechanism of phonon scattering.

Thermal transport data. The lattice thermal conductivity (κ_l) showed a marked dependency on the granule quality. Samples with "High-QC" granules exhibited a κ_l of 0.85 W/mK at 450 K, representing a 42 % reduction compared to the pristine Bi_2Te_3 sample [16].

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ZT measurement. The peak ZT for the quality-controlled sample reached 1.25 at 525 K. This is significantly higher than the non-granulated sample (ZT=0.78), proving that the granulation quality is the primary driver for performance enhancement [17].

Discussion

The internal porosity of the SiO_2 granules plays a dual role. Firstly, air pockets (if present at the nanoscale) act as extreme barriers to heat flow. Secondly, the controlled density of the granules prevents the host matrix from becoming "diluted," which preserves the electrical paths [18].

One of the most significant findings is that the granulation process is highly scalable. Unlike laboratory-scale "bottom-up" nanostructuring, spray-drying is an industrial standard. The quality control protocols developed in this study can be directly integrated into large-scale manufacturing of TE generators.

Conclusion

This research proves that the main characteristics of thermoelectric materials are profoundly influenced by the quality of the granulated precursors. Through the systematic control of SiO_2 nanoparticle granulation, we achieved a hierarchical microstructure that successfully decoupled electrical and thermal transport. The resulting material showed a peak ZT of 1.25, an improvement that highlights the necessity of "Quality Control" in the next generation of TE materials. Future work should focus on the long-term thermal stability of these granulated inclusions under cyclic operating conditions.

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