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TETRAPODAL ZnO: NANOSCALE ARCHITECTURE, MACROSCOPIC IMPACT
ZnO TETRAPODAL: ARHITECTURĂ NANOMETRICĂ ȘI IMPACT MACROSCOPIC

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Rezumat
Oxidul de zinc tetrapodal (t-ZnO) reprezintă unul dintre cele mai avansate și multifuncționale materiale nanostructurate dezvoltate în ultimii ani. Combinând avantajele intrinseci ale oxidului de zinc — bandă interzisă largă, stabilitate chimică, piezoelectricitate, biocompatibilitate și activitate antivirală/antimicrobiană — cu o arhitectură tridimensională distinctă, t-ZnO creează o punte între ingineria la scară nanometrică și aplicațiile industriale sau medicale reale.
Metoda de Transport în Flacără (FTM) permite sinteza scalabilă a ZnO în multiple morfologii, dintre care forma tetrapodală se evidențiază prin capacitatea de interblocare mecanică, suprafața specifică mare și interacțiunea excelentă cu sistemele biologice. Acest articol oferă o prezentare integrată a caracteristicilor nanoscale ale t-ZnO, a procesului de sinteză și a transformării sale din cercetare fundamentală în producție certificată GMP la Phi-Stone AG. Sunt analizate aplicații în compozite polimerice, micro-dispozitive medicale, implanturi pentru glaucom, tratamente antivirale și formulări cosmetice sau pentru protecția suprafețelor. Se acordă o atenție specială mecanismelor antivirale dependente de morfologie împotriva virusului Herpes Simplex (HSV), precum și producerii Microbivac®, un material t-ZnO certificat GMP utilizat în produse comerciale. În ansamblu, t-ZnO ilustrează modul în care morfologiile nanometrice controlate pot genera impact semnificativ în medicină, biotehnologie și ingineria materialelor avansate.
Cuvinte-cheie: *oxid de zinc tetrapodal, nanomateriale, activitate antivirală, producție GMP, aplicații biomedicale*

1. Introduction

Nanostructured materials are central to modern technological development because they allow mechanical, biological, and optical properties to be tailored at the molecular and structural level. Among these materials, zinc oxide (ZnO) occupies a special place due to its multifunctionality, biocompatibility, and broad application potential. ZnO is a wide-bandgap semiconductor (3.37 eV) with a hexagonal wurtzite crystal structure, providing antiviral, antimicrobial, optical, and piezoelectric functionalities that make it one of the most versatile materials in contemporary materials science (Özgür et al., 2005; Janotti & Van de Walle, 2009; Borysiewicz, 2019). Advances in synthesis techniques have enabled ZnO to be engineered into a wide range of morphologies, from nanoparticles and nanowires to complex three-dimensional architectures. One morphology that has attracted scientific and industrial attention is tetrapodal ZnO (t-ZnO). It consists of four elongated single-crystalline arms emerging from a central core, forming a three-dimensional, self-supporting “micro-star” (Fig. 1). This architectural design gives t-ZnO high mechanical stability, a large specific surface area, and strong interactions with polymer matrices, biological tissues, and viral particles.

Phi-Stone AG has played a central role in the technological transfer of t-ZnO, scaling its production from laboratory-scale synthesis to industrial, GMP-certified manufacturing. This transition enables the integration of t-ZnO into medical, pharmaceutical, cosmetic, and advanced material applications, thus turning a scientific concept into concrete products and therapies.

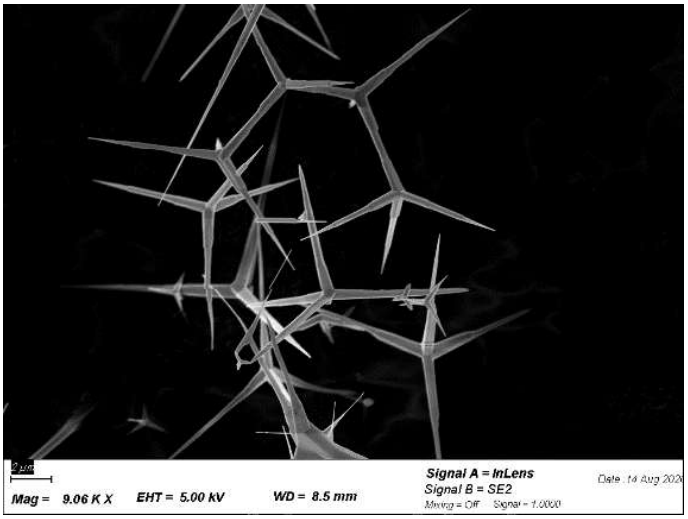


Fig. 1. SEM picture of Tetrapodal ZnO

2. Zinc Oxide as a Functional Material

2.1 Semiconductor properties

Zinc oxide is an II–VI semiconductor with a wide bandgap. Its hexagonal wurtzite crystal structure ensures high robustness and structural integrity (Janotti & Van de Walle, 2009). These properties form the basis for optoelectronic and piezoelectric applications, such as sensors, field-effect transistors, and nanogenerators (Wang et al., 2006).

2.2 Environmental and techno-economic advantages

From a practical perspective, ZnO is environmentally safe, relatively low-cost, and suitable for large-scale production, which is crucial for translational applications beyond the laboratory (Kołodziejczak-Radzimska & Jesionowski, 2014).

2.3 Biological and antiviral activity

ZnO also exhibits significant biological activity, including antiviral and antimicrobial effects. These arise from direct interactions at the particle surface and from the release of zinc ions (Zn^{2+}), which influence cellular pathways, modulate inflammation, and inhibit bacterial proliferation (Rasmussen et al., 2010; Sirelkhatim et al., 2015). Due to its inherent biocompatibility and capacity to interact with skin and tissue, ZnO is widely explored for wound healing, tissue regeneration, antiviral formulations, and drug delivery systems (Pasquet et al., 2014).

At the nanoscale, ZnO benefits from increased surface area, enhanced reactivity, and more efficient interactions with biological membranes and microorganisms (Mishra & Adelung, 2018; Wang, 2004). These features make nanoscale ZnO a strong candidate for next-generation biomedical technologies and multifunctional materials.

3. ZnO Morphologies and the Flame Transport Method

One of the main challenges in nanomaterials engineering is controlling morphology while maintaining scalability and reproducibility. The Flame Transport Method (FTM) offers a scalable, energy-efficient route to obtain diverse ZnO morphologies (Mishra et al., 2013; Kaps et al., 2014).

In FTM, metallic zinc is oxidized in a high-temperature, oxygen-rich flame, leading to the formation of structures such as:

- nanoparticles,
- nanowires,
- plates and multipods,
- tetrapods,
- complex hierarchical 3D architectures (Fig. 2).

Originally developed in the Functional Nanomaterials Group at Kiel University and later transferred to Phi-Stone AG, the FTM has been successfully upscaled from laboratory to industrial levels. By adjusting parameters such as temperature, oxygen concentration, partial pressure and growth duration, FTM enables the controlled formation of t-ZnO and high purity—conditions essential for medical and GMP-grade applications.

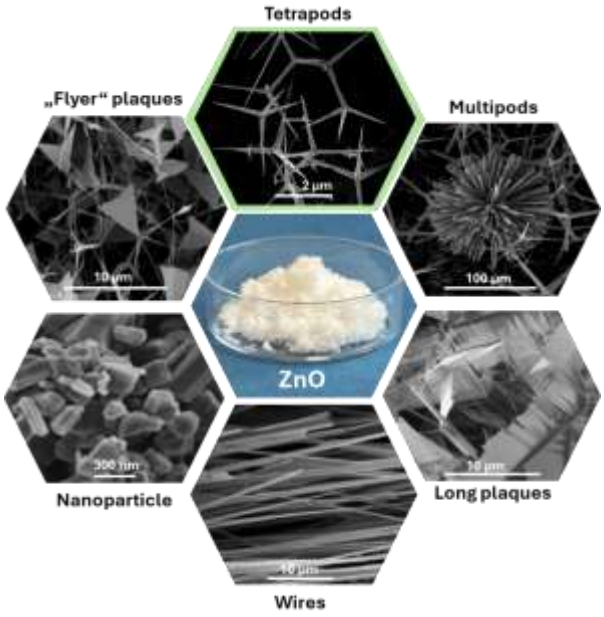


Fig.2 Different ZnO Morphologies

4. Architecture and Core Characteristics of Tetrapodal ZnO

Tetrapodal zinc oxide (t-ZnO) is built around a central nucleation point from which four monocrystalline arms extend in a tetrahedral arrangement (Fig. 1) (Willander et al., 2006/2007; Mishra & Adelung, 2018). This deterministic, anisotropic architecture produces structural, mechanical, and functional attributes that clearly differ from those of conventional ZnO morphologies such as spherical nanoparticles, rods, or platelets. When many tetrapods interpenetrate, they form self-supporting three-dimensional networks. Each arm acts as a robust wurtzite ZnO crystal capable of efficiently redistributing mechanical stresses across the interconnected architecture. As a result, these networks show:

- exceptional mechanical resilience,
- high porosity combined with structural stability,
- large accessible surface area for chemical or biological functionalization.

This open architecture makes t-ZnO suitable for applications ranging from mechanical reinforcement in composites to drug delivery, surface coatings, catalysis, and biomedical devices.

5. Morphology-Driven Functionality

A defining feature of t-ZnO is that its geometry—not only its composition—drives performance across multiple scales. The tetrapodal shape dramatically improves dispersion in polymer melts, liquid formulations, and elastomeric matrices by reducing the tendency to agglomerate. The rigid arms act as natural mechanical anchors within polymer networks, penetrating and interlocking with the host phase. This leads to:

- enhanced interfacial adhesion,
- improved load transfer,
- significant increases in tensile strength and fracture resistance.

Silicone–polythiourethane and thiourethane-based composites modified with t-ZnO show improved mechanical robustness, abrasion resistance, long-term flexibility, and stability under cyclic loading (Qiu et al., 2018; Feng et al., 2023). In comparison, spherical ZnO or short fibers are less effective at forming continuous, percolating networks.

In flexible ceramics and porous 3D semiconductor networks, interpenetrating t-ZnO structures enable lightweight, mechanically resilient morphologies (Mishra et al., 2013; Gröttrup et al., 2016). These networks efficiently distribute stresses and help prevent crack initiation and propagation.

5.2 Advanced interfacial adhesion and joining "un-joinable" materials

Because tetrapodal arms can penetrate multiple phases, t-ZnO can act as a three-dimensional "stitching" element between otherwise incompatible materials. When embedded at interfaces between low-surface-energy polymers, the tetrapods form mechanical bridges that enable strong adhesion without aggressive surface treatments (Jin et al., 2012; Jin et al., 2014).

This concept extends to polymer–metal and polymer–shape memory alloy (SMA) interfaces, where t-ZnO improves bonding, load transfer, and long-term stability (Gapeeva et al., 2023). Such interfacial engineering is particularly important for flexible electronics, smart implants, and mechanically demanding medical devices.

5.3 Biological and antiviral functionality enhanced by geometry

The tetrapodal morphology also has profound consequences for biological performance. t-ZnO shows higher antiviral and antimicrobial efficacy than spherical or rod-shaped ZnO due to:

- its accessible surface area,
- enhanced surface reactivity,
- favorable geometric interactions with cells and viral particles.

Antoine et al. (2012, 2016) demonstrated strong prophylactic, therapeutic, and neutralizing effects of t-ZnO against Herpes Simplex Virus type 2 (HSV-2). The proposed mechanism is morphology-driven: the tetrapods can trap viral particles on their surface and contribute to their inactivation before they infect host cells. In minimally invasive glaucoma stents, t-ZnO improves tissue integration, structural reliability, and resistance to microbial contamination (Gapeeva et al., 2023). In marine antifouling systems, tetrapods act both as physical anti-adhesion structures and as synergistic enhancers of the antimicrobial properties of polythiourethane and hybrid elastomeric matrices (Qiu et al., 2018; Feng et al., 2023).

Collectively, these examples show that geometry is a key driver of function:

- each arm acts simultaneously as a load-bearing element, an anchoring point, and a reactive surface.
- the interconnected 3D network prevents structural collapse.
- porosity and shape enable selective interactions with cells, microorganisms, and biomolecules.
- compatibility with diverse polymer matrices arises intrinsically from morphology rather than requiring extensive chemical modification.

6. From Laboratory Concept to GMP Production and Commercial Products

The translation of t-ZnO from fundamental research to industrial reality required not only materials innovation but also robust process engineering and quality control. Through the upscaling of the Flame Transport Method and the implementation of Good Manufacturing Practice (GMP) standards, Phi-Stone AG established a production route for highly pure, well-defined tetrapodal ZnO suitable for biomedical use. Within this framework, Microbivac® was developed as a GMP-certified t-ZnO material (www.phi-stone.de). It is used as an active component in commercial products, particularly in formulations targeting antiviral and antimicrobial performance. These activities illustrate how nanomaterial development can progress from university laboratories to regulated production environments and, ultimately, to end-user medical and consumer products.

7. Conclusions

Tetrapodal ZnO is a clear demonstration of how nanoscale architecture can be engineered to deliver macroscopic impact. By shaping ZnO into three-dimensional tetrapods:

- the mechanical behavior of composites and porous networks is dramatically improved through mechanical interlocking and efficient stress distribution;
- interfacial adhesion challenges between otherwise incompatible materials can be overcome by using t-ZnO as a three-dimensional mechanical linker;
- biological and antiviral functionalities are enhanced, enabling viral trapping, antimicrobial action, and improved tissue interaction in medical devices;
- industrial relevance is ensured through scalable synthesis by the Flame Transport Method and GMP-certified production, culminating in products such as Microbivac®.

The tetrapodal ZnO structure creates bridges—between soft and hard materials, between laboratory and industry, and ultimately between nanoscale design and real-world impact in medicine, biotechnology, and advanced materials engineering.

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