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Recent Advances in Borate-Based Glass Nanocomposites: Structural, Dielectric, and Radiation Shielding Properties

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ABSTRACT

Borate-based glass nanocomposites have gained significant attention in recent years due to their unique structural, dielectric, and radiation shielding properties. These materials exhibit excellent thermal stability, tunable optical characteristics, and enhanced mechanical strength, making them suitable for applications in optoelectronics, solid-state batteries, and radiation protection. This comprehensive review provides an in-depth analysis of recent advancements in borate-based glass nanocomposites, with a particular focus on three key aspects: (1) structural modifications induced by different compositional changes, (2) dielectric behavior and their dependence on glass network formers and modifiers, and (3) their effectiveness as radiation shielding materials. The influence of dopants, such as transition metals (e.g., Cu, Fe, Co) and rare-earth elements (e.g., Ce, Eu, Gd), on the optical, electrical, and mechanical properties of these glasses is systematically discussed. These dopants play a crucial role in modifying the glass network, enhancing ionic conductivity, and improving radiation attenuation performance. The influence of dopants, such as transition metals and rare-earth elements, on the physical and chemical properties of these glasses is discussed. Additionally, the role of nanostructuring in improving radiation attenuation is explored, along with future prospects for these advanced materials.

Keywords: Borate glass, Glass-ceramic, Nanocomposite, Dielectric properties, Radiation shielding

1. Introduction

1.1. Overview of Borate Glasses

Borate (B_2O_3)-based glasses have been extensively studied due to their unique structural flexibility, low melting point, and high transparency in the visible and near-infrared regions (Kamitsos, 2025; Shilpa et al, 2025; Eskalen et al, 2025). Unlike silicate and phosphate glasses, borate glasses exhibit a distinctive network structure composed of BO_3 trigonal units and BO_4 tetrahedral units, which can be modified by the addition of various oxides and dopants. This structural adaptability allows for the tailoring of physical, optical, and electrical properties, making borate glasses suitable for a wide range of technological applications, including optical fibers, laser hosts, and solid-state electrolytes (Möncke, 2015 et al; Topper & Möncke, 2022; Yiannopoulos et al 2001; Alderman, 2018).

1.2. Emergence of Borate-Based Glass Nanocomposites

Recent advancements in materials science have led to the development of borate-based glass nanocomposites, where the incorporation of nanoparticles (metallic, ceramic, or rare-earth-doped) into the glass matrix enhances its functional properties. The addition of nanoscale fillers, such as ZnO (Eskalen et al, 2023), Fe_2O_3 (Ivanova et al, 2016), CeO_2 (Ranasinghe et al. 2019), or metallic nanoparticles (Ag (Ande et al, 2021), Au (Jagannath et al, 2018)), introduces novel characteristics, including improved mechanical strength, optical, and superior radiation shielding capabilities. These nanocomposites bridge the gap between traditional glasses and advanced functional materials, offering new possibilities for optoelectronics, energy storage, and radiation protection.

1.3. Importance of Structural, Dielectric, and Radiation Shielding Properties

The structural properties of borate glass nanocomposites are crucial in determining their thermal stability, chemical durability, and optical behavior. By carefully selecting dopants and controlling nanoparticle dispersion, researchers can engineer glasses with tailored properties for specific applications (Deepika et al, 2021).

Dielectric properties are particularly important for electronic and energy storage applications. Borate glass nanocomposites exhibit tunable permittivity and low dielectric loss, making them promising candidates for capacitors, insulators, and solid-state battery components. The presence of nanoparticles can further enhance interfacial polarization, leading to improved dielectric performance (Liu et al, 2019; Chakrabarti et al, 2022; Fan et al, 2018).

Radiation shielding is another critical application, especially in medical imaging, nuclear reactors and space technology (Mortazavi et al, 2024). Traditional shielding materials like lead and concrete have limitations in terms of weight, toxicity, and environmental impact (AbuAlRoos et al, 2019). Borate-based glass nanocomposites, especially those doped with high-Z elements (e.g., Bi, Ba, Gd), offer lightweight, transparent, and efficient alternatives for gamma-ray and neutron attenuation (Alhakami et al, 2025; Al-Buriahi et al, 2020; Intachai et al, 2020).

1.4. Scope of This Review

This review presents a comprehensive analysis of cutting-edge developments in borate-based glass nanocomposites, systematically examining how strategic structural modifications through dopants (alkali/alkaline earth/rare earth elements) and nanoparticle integration fundamentally alter the BO_3/BO_4 network configuration and interface dynamics, enabling unprecedented control over material properties. It explores breakthroughs in dielectric behavior optimization, where interfacial polarization effects from nanofillers (TiO_2, $BaTiO_3$) and ionic conduction pathways in Li-doped systems achieve exceptional permittivity ($\varepsilon' > 100$) with minimal loss ($\tan \delta < 0.01$), revolutionizing capacitor and solid-state battery technologies. The analysis highlights transformative radiation shielding performance, demonstrating how high-Z nanocomposites (Bi_2O_3/Gd_2O_3-B_2O_3) surpass conventional materials in gamma/neutron attenuation while offering transparency and lightweight advantages, supported by Monte Carlo simulations validating their superior mass attenuation coefficients. Addressing critical gaps, the review identifies key future challenges in scalable manufacturing (3D printing, AI-optimized compositions), eco-friendly alternatives (Pb/Cd replacement), and multifunctional integration (luminescent-sensing shields), while projecting their industrial potential in nuclear, aerospace, and medical sectors through advanced glass-ceramic hybrids and smart adaptive designs. By synthesizing these interdisciplinary advances, the review positions borate glass nanocomposites as versatile next-generation materials capable of meeting extreme technological demands through nanoscale-engineered structures and tunable functionalities.

2. Structural Properties of Borate-Based Glass Nanocomposites

Borate glasses possess a unique structural framework that distinguishes them from other oxide glasses. The fundamental building blocks of these glasses are triangular BO_3 units and tetrahedral BO_4 units, which form a highly adaptable network structure. This structural flexibility allows for extensive modifications through the incorporation of various modifiers and dopants, making borate glasses particularly attractive for nanocomposite development. Recent advances in characterization techniques and computational modeling have provided deeper insights into the structural evolution of these materials at atomic, nano-, and macro-scales

(Edwards et al, 2014; Stone et al, 2000; Parthé, 2002; Parthé, 2004).

2.1. Fundamental Structural Units and Network Formation

The base B_2O_3 glass features a distinctive structure primarily composed of boroxol rings (B_2O_3) formed by three interconnected BO_3 triangular units linked through bridging oxygen atoms, which creates an open network with low packing density while exhibiting exceptional glass-forming ability and the characteristic "boron anomaly" - a unique phenomenon where physical properties such as density, thermal expansion coefficient, and refractive index vary non-monotonically with composition changes due to the complex interplay between BO_3 trigonal and BO_4 tetrahedral coordination states. This structural peculiarity arises from the ability of boron to readily change its coordination number in response to modifier additions, making the borate network particularly sensitive to compositional variations and enabling precise tuning of material properties through controlled doping or nanostructuring (Fig. 1).

The introduction of network modifiers such as alkali (e.g., Li_2O, Na_2O) or alkaline earth oxides (e.g., CaO, MgO) induces significant structural transformations in borate glasses, initially converting planar BO_3 units into tetrahedral BO_4 units up to a critical modifier concentration (typically around 30-40 mol%), which enhances network connectivity and modifies physical properties, while at higher modifier contents the excess oxygen leads to the formation of non-bridging oxygens (NBOs) that disrupt the network and create more open structures, with these coordination changes (BO_3→BO_4→NBO formation) causing non-linear variations in key physical properties like density, thermal expansion, and mechanical strength, known collectively as the "boron anomaly" that characterizes the unique structure-property relationships in borate glass systems. These structural modifications form the basis for tailoring borate glasses for specific applications through controlled compositional adjustments (Padmaja & Kistaiah, 2009; Kojima, 2020, Lower et al, 2001; Button et al, 1982; Shashikala & Udayashankar, 2016).

Recent studies have demonstrated that strategic doping represents a powerful approach for precisely controlling the borate network structure at multiple length scales, enabling tailored material properties for specific technological applications. Advanced characterization techniques combined with computational modeling have revealed that different dopant categories induce distinct structural modifications: alkali and alkaline earth ions (e.g., Li^{+}, Ca^{2+}) primarily act as network modifiers, systematically converting BO_3 triangles to BO_4 tetrahedra up to characteristic threshold concentrations while simultaneously affecting the overall network connectivity through charge compensation mechanisms (Kamitsos et al, 2020; Pimentel et al, 2018).

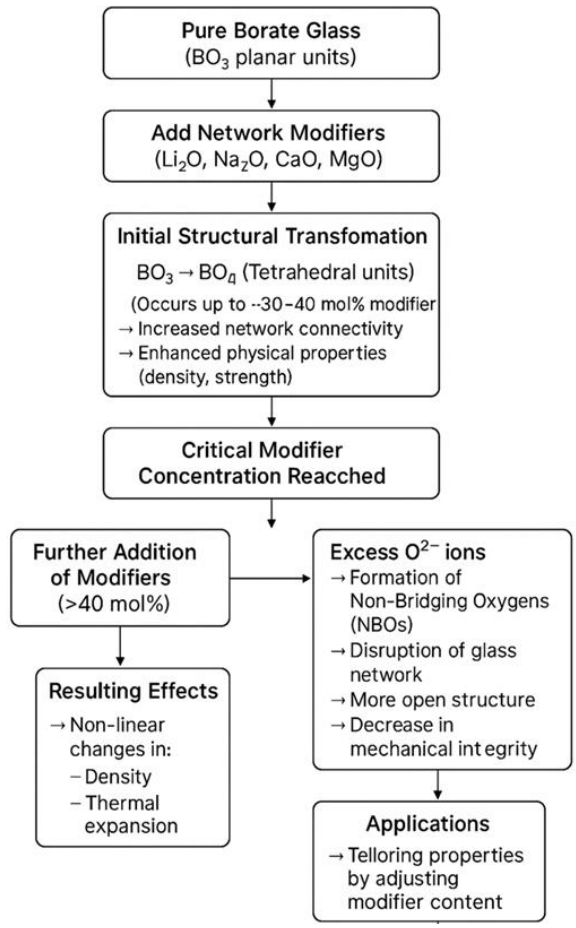

Figure 1: Structural evolution of borate glasses with network modifiers.

Transition metal dopants (e.g., Fe^{3+}, Cu^{2+}) exhibit more complex behavior, functioning as both network modifiers and conditional glass formers, with their multivalent nature introducing additional redox-dependent structural configurations that can be exploited for optoelectronic applications (Wright et al, 2017; Funabiki et al, 2011). Particularly significant are rare earth dopants (e.g., Gd^{3+}, Eu^{3+}) which, despite their large ionic radii, can be incorporated into the borate network through the formation of modified coordination polyhedra that create unique local environments while maintaining glass homogeneity (Wantana et al, 2023; Fayaz et al, 2023; Marimuthu et al, 2009). Recent breakthroughs in in-situ spectroscopy and high-resolution microscopy have shown that these dopant-induced structural changes occur not just at the atomic scale but propagate through medium-range order (2-5 Å) to influence the overall glass network topology. Furthermore, the synergistic effects of mixed dopants have been found to create novel structural motifs that cannot be achieved with single-component doping, opening new possibilities for property engineering. This precise structural control through strategic doping has become particularly valuable in developing advanced glass nanocomposites where the dopants not only modify the base glass structure but also influence nanoparticle-glass matrix interactions, interfacial bonding, and overall composite morphology. The ability to predict and control these structural modifications through machine learning approaches and ab initio calculations represent a significant advancement in glass science, moving from empirical composition-property relationships to rationally designed materials with predetermined characteristics (Rada et al, 2012; Ohkubo, 2016; Kato et al, 2024; Urata et al, 2024; Ahmmad et al; 2022).

2.2. Nanostructural Engineering and Characterization

The integration of nanoscale constituents (0D nanoparticles, 1D nanowires/nanotubes, or 2D nanosheets) into borate glass matrices creates complex interfacial regions that profoundly influence bulk material properties through multiple synergistic mechanisms. For metallic nanoparticles (Ag, Au) (Adamiv et al, 2014; Gurushantha et al 2023), the dielectric mismatch between the nanoparticles and glass host generates localized surface plasmon resonance effects, which not only produce vivid plasmonic colors but also enhance nonlinear optical properties and enable surface-enhanced Raman scattering applications (see Fig. 2). Oxide nanoparticles (TiO_2 (Colak, 2017), ZrO_2 (Shearer et al, 2024)) exhibit markedly different behavior, serving as heterogeneous nucleation sites that promote controlled crystallization during thermal processing while simultaneously reinforcing the glass network through a "filler effect" that improves mechanical strength and thermal stability.

Semiconductor quantum dots (CdSe, PbS) introduce quantum confinement effects that enable precise tuning of optoelectronic properties through size-dependent bandgap engineering, making them particularly valuable for luminescent and photovoltaic applications (Hayes et al, 2024; Fan et al, 2014).

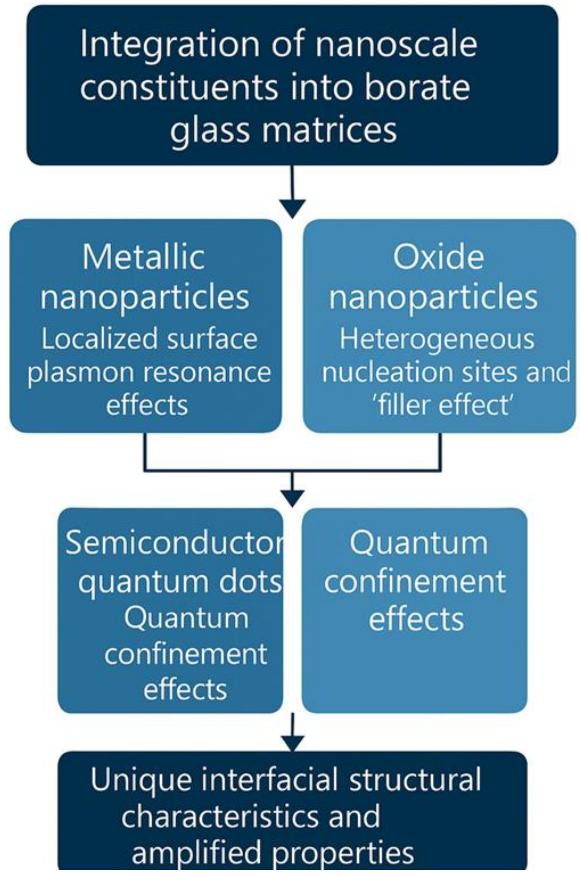

Figure 2: The integration of various nanoscale constituents into borate glass matrices.

The interfacial regions surrounding these nanoscale constituents exhibit unique structural characteristics - typically featuring modified bond angles, altered coordination environments, and strain fields that extend several atomic layers into the glass matrix. These interfacial zones act as "property amplifiers," where small additions of nanomaterials (often <5 vol%) can induce disproportionate improvements in target properties due to the large surface-to-volume ratios and the resulting dominance of interface-mediated phenomena. Recent studies using advanced electron microscopy and spectroscopy techniques have revealed that these interfaces often exhibit graded compositions and distinct short-range ordering that differ substantially from both the nanoparticle cores and bulk glass matrix, creating what are effectively "third phases" with unique characteristics (Moriceau et al, 2019; Svecova et al, 2019). The ability to control nanoparticle dispersion, interface chemistry, and spatial distribution through advanced processing techniques (e.g., laser melting

(Seyfarth, et al, 2018) , sol-gel methods (Lepry & Nazhat, 2015), or field-assisted sintering (Moriceau et al, 2019)) has opened new frontiers in designing borate glass nanocomposites with precisely tailored optical, mechanical, and functional properties for next-generation applications (Vijayakumar et al, 2018; Fonseca, 2022).

2.3. Advanced Characterization Techniques

Modern characterization techniques have revolutionized our understanding of borate glass nanocomposites by providing unprecedented insights into their structural hierarchy across multiple length scales. High-resolution transmission electron microscopy (HR-TEM), particularly when coupled with energy-dispersive X-ray spectroscopy (EDS) and electron energy loss spectroscopy (EELS), enables direct visualization of nanoparticle distribution, crystallographic orientation relationships, and the atomic-scale structure of glass-nano interfaces, revealing critical details about interface bonding, strain fields, and potential reaction layers (Zhao et al, 2023). Synchrotron X-ray diffraction (XRD) techniques leverage the high brilliance and tunable energy of synchrotron sources to probe both the short-range (1-5 Å) and medium-range (5-20 Å) order in these materials, providing pair distribution function (PDF) analysis that can distinguish between different borate structural units and their spatial correlations (Hannon, 2015). Solid-state nuclear magnetic resonance (NMR) spectroscopy, especially ^{11}B magic-angle spinning (MAS) NMR, serves as a quantitative tool for determining the BO_3/BO_4 ratio and characterizing the local coordination environments around boron atoms, while multinuclear NMR (^{23}Na, ^{27}Al, etc.) can track modifier ion distributions and their interactions with the glass network (Wang & Stebbins, 1999; Eckert, 2018) (see Fig. 3).

Raman spectroscopy offers complementary information by identifying specific borate structural units (boroxol rings, pentaborate groups, etc.) through their characteristic vibrational fingerprints, while also monitoring dopant-induced modifications through changes in peak positions, intensities, and bandwidths (Massot et al, 1995; Yano et al, 2003). When these techniques are combined with advanced data analysis methods (multivariate analysis, machine learning-assisted pattern recognition) and in-situ capabilities (high-temperature, pressure, or radiation environments), they provide a comprehensive multiscale understanding of structure-property relationships in these complex materials (George & Brow, 2015; Lu, et al 2021).

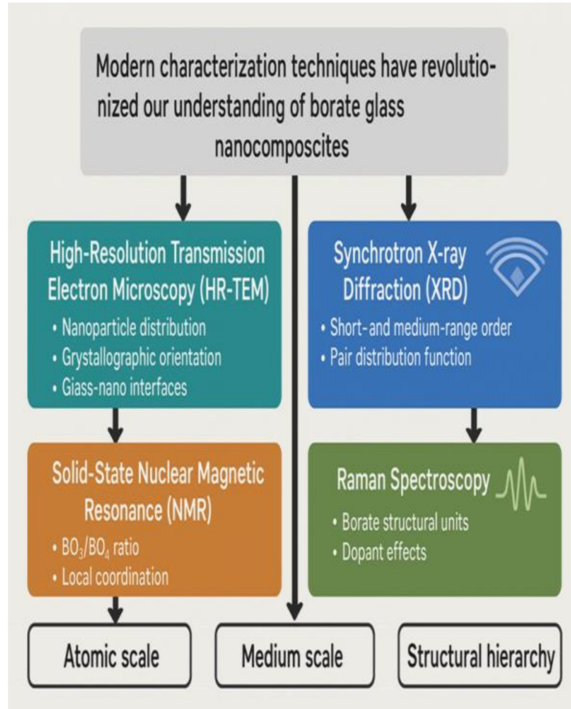

Figure 3: Characterization techniques of borate glass nanocomposites.

Recent developments in correlative microscopy approaches, where multiple techniques are applied to precisely the same sample region, are particularly powerful for bridging the gap between local atomic arrangements and macroscopic material behavior. These advanced characterization methods have become indispensable tools for both fundamental research and industrial development of borate glass nanocomposites, enabling precise quality control and accelerating the discovery of new material compositions with optimized performance characteristics.

2.3. Computational Modeling Approaches

Computational modeling approaches have emerged as indispensable tools for understanding and predicting the complex behavior of borate glass nanocomposites, complementing experimental characterization techniques. Molecular dynamics (MD) simulations, employing either classical force fields or reactive potentials, provide atomic-scale insights into nanoparticle-glass interactions by tracking the temporal evolution of interface formation, structural relaxation processes, and stress distribution patterns during thermal cycling. These simulations reveal how nanoparticle surface chemistry influences the local glass network structure, particularly the BO_3/BO_4 distribution near interfaces, and can predict optimal processing conditions to prevent nanoparticle agglomeration (Liu et al, 2021; Ohkubo et al, 2024). Density functional theory (DFT) calculations enable precise determination of dopant incorporation energies, electronic structure modifications, and the thermodynamic stability of various coordination environments, offering fundamental explanations for experimentally observed phenomena such as the boron anomaly or dopant clustering tendencies (Rada et al, 2008). Advanced DFT approaches, including hybrid functionals and DFT+U methods, are particularly valuable for modeling transition metal and rare earth dopants, accurately capturing their electronic transitions and magnetic properties (Subedi & Tutchton, 2024). Monte Carlo (MC) modeling, especially when combined with machine learning potentials, efficiently simulates nanoparticle dispersion statistics across large length scales, predicting percolation thresholds and spatial distribution patterns that govern properties like electrical conductivity and optical scattering. Recent progress in multiscale modeling frameworks that seamlessly integrate these approaches—combining quantum mechanical accuracy at interfaces with mesoscale particle distribution statistics—has enabled the virtual design of nanocomposites with tailored properties before experimental synthesis (Swenson et al, 1998). These computational tools are increasingly being deployed in high-throughput screening of composition spaces and as digital twins for real manufacturing processes, significantly accelerating the development cycle for advanced borate glass nanocomposites.

2.4. Structure-Property Relationships

The engineered nanostructure of borate glass nanocomposites establishes fundamental structure-property relationships that govern their performance in advanced applications. Thermal properties exhibit marked improvements, with nanoparticle loading typically increasing the glass transition temperature (T_g) depending on filler content and interface quality, as the constrained mobility of polymer-like borate chains near nanoparticle surfaces creates additional energy barriers for structural relaxation (Thakur et al, 2015). Mechanical behavior demonstrates particularly dramatic enhancements, where well-dispersed nanoparticles can simultaneously increase hardness and fracture toughness through multiple reinforcing mechanisms: nanoscale fillers act as obstacles for crack propagation, forcing cracks to bow around particles or follow energetically unfavorable paths, while the residual stress fields surrounding nanoparticles promote crack deflection and branching (Januchta et al, 2019). Optical characteristics become highly tunable through quantum confinement effects in semiconductor nanoparticles and plasmonic interactions in metallic inclusions, enabling precise control over bandgap and refractive index while maintaining excellent transparency in selected wavelength windows (Al–Hadeethi, 2022). Chemical durability improvements stem from nanoparticle-induced modifications to surface chemistry, where fillers either consume reactive non-bridging oxygens or create diffusion barriers that reduce leaching rates by orders of magnitude in corrosive environments (Abodunrin et al, 2023). These property enhancements frequently exhibit nonlinear relationships with nanoparticle content, typically following percolation-like behavior where dramatic improvements occur once a critical interfacial network forms throughout the glass matrix. Recent studies reveal that the most significant property modifications occur not from the nanoparticles themselves, but from the modified glass structure in the 2-5 nm interfacial zones surrounding each particle, where the borate network adapts to minimize interfacial energy through coordination changes and density variations. This understanding has led to the development of "interface-engineered" nanocomposites where surface-functionalized nanoparticles are used to deliberately create specific interfacial structures that optimize multiple properties simultaneously, representing a paradigm shift from conventional composition-based design to interface-controlled material engineering.

3. Preparation Techniques

Several techniques exist for fabricating glass nanocomposites. Melt-quenching is widely used for its simplicity, followed by controlled heat treatment to induce crystallization. Other methods include Sol-Gel, Chemical Vapor Deposition (CVD), Physical Vapor Deposition (PVD), and Hot Pressing. Each technique offers distinct advantages in tailoring the microstructure and performance of the resulting materials.

3.1 Melt Quenching

It is a simple way for glass nanocomposites preparation, and the most popular for its simplicity. The chemical ingredients weighted and mixed in an Aluminum crucible that withstand high temperatures. Components may be heated at low temperature before melting for good mixing and to ensure that some components do not evaporate during melting. Then the mixture melts by using electric furnace at high temperature for a specific period of time. During melting the glass in liquid state so the melt poured into the mold that shapes the samples in the required shape for different measurements (See Fig. 5). Annealing at temperature near the glass transition temperature may be needed for remove residual thermal stress (Kashif et al, 2012; Taha et al, 2024). Sometimes heat treatment is required for growing nanocrystals in glass matrix, where the samples reheated for a specific time at temperature above Tg and blow Tm. Samples may be reheated at low temperature below Tg for a period of time to remove the undesirable mechanical stresses, and to ensure that the physical properties are uniform throughout the glass (El-Rabaie et al, 2014a; 2014b). Fig. 4 shows ischemic diagram of melt quenching technique.

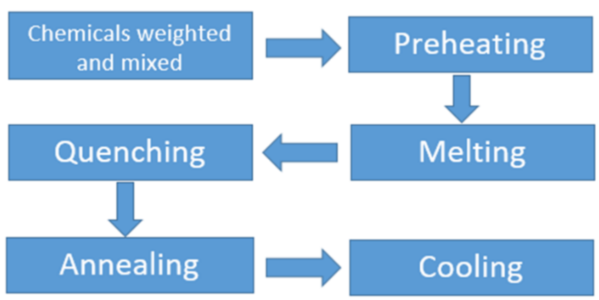

Figure 4: Schematic diagram of melt-quenching technique.

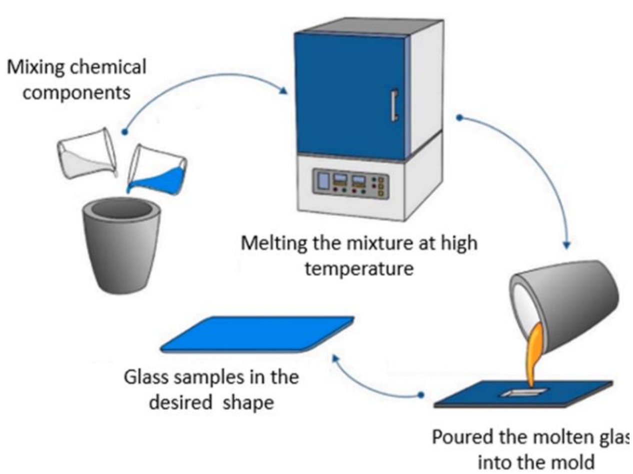

Figure 5: Melt-quenching technique.

4.2 Sol-Gel Method

Sol-Gel process based on the hydrolysis and polymerization of metal alkoxide precursors of alumina, silica, titania, zirconia, as well as other oxides to form a solution. The solution stirred well by using magnetic stirrer to form high viscosity solution, the solutions of precursors are reacted to form irreversible gels (ageing), that dry for water and other solvents removing by continuous heating at specific temperature for a certain. The last step is annealing at high temperature (calcining) to form a dense glass (see Fig. 6). This method can be carried out at low temperatures as compared melt-quenching technique, which makes it compatible with organic polymers. This method results in high purity materials, and allows fine control over the composition and microstructure. Can be applied for optical devises, electronics, and catalysis (Mukherjee, 1980; Zheng & Boccaccini, 2017; Roman et al, 2003).

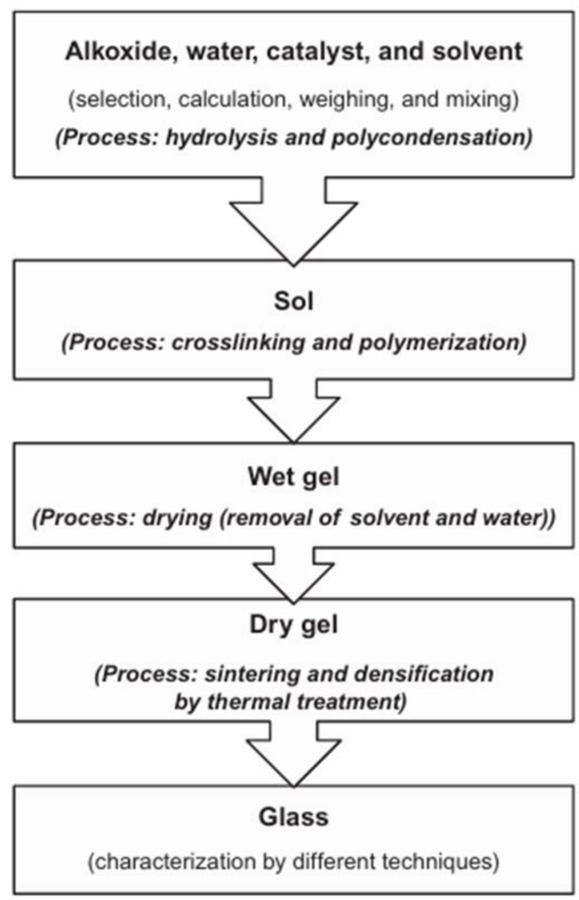

Figure 6: Schematic diagram of glass preparation by sol-gel technique.

4.3 Chemical Vaporization Deposition (CVD)

This method uses chemical reaction for solid material deposition from a vapor on heated substrate surface. The procedures are shown in the figure 7. High purity, uniform properties, thin film with controlled thickness can be produced because CVD has excellent throwing power. CVD can localize or select the deposition pattern. CVD with cold-wall reactors reduce contaminations on the wall than hot-wall reactors. CVD use for thin film production in different fields (microelectronics, optical fibers, solar energy conversion, and semiconductor lasers), for amorphous, glassy thin film fabrication (Gordon, 1997; Karches et al, 2002). CVD has three main components as shown in the figure 8.

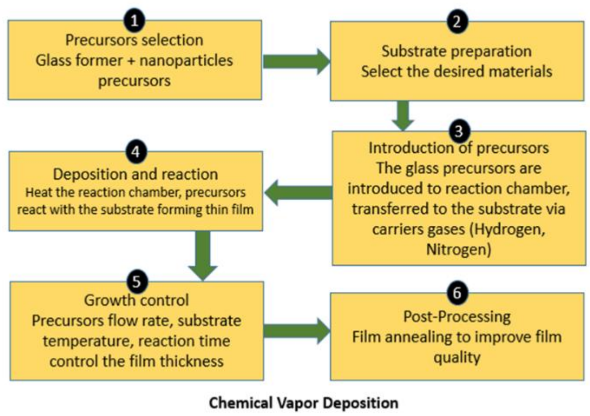

Figure 7: Schematic diagram of chemical vapor deposition procedures.

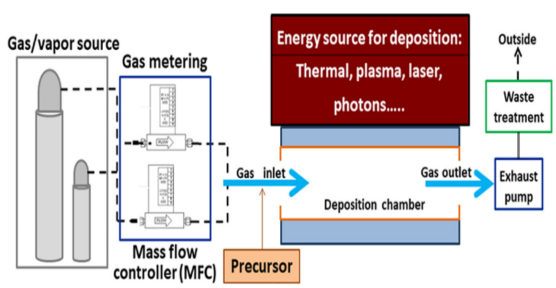

Figure 8: Chemical vapor deposition main components.

3.4 Physical Vaporization Deposition (PVD)

Thin film glass nanocomposites formation by physical transfer of materials from the source to the substrate, as shown in the diagram. Crystalline, or amorphous structure can be produced, this method proceeds under vacuum or low gas pressure, where the film formation based on pure physical condensation, or chemical reactions. This method is the gold standard for the preparation of multilayered structures, graded films, free-standing structures, etc. PVD is used for the improvement of wear resistance, oxidation resistance, lubricity, surface roughness, cutting tools, and sliding characteristics, so it used for coating tools (See Fig. 9). The nano-layer thickness and composition can be precisely controlled by this method. Different processes can by used such as thermal, electron beam, pulsed laser, direct current, and radiofrequency magnetron sputtering in this method (Mohri et al, 2017; Cué-Sampedro et al, 2019).

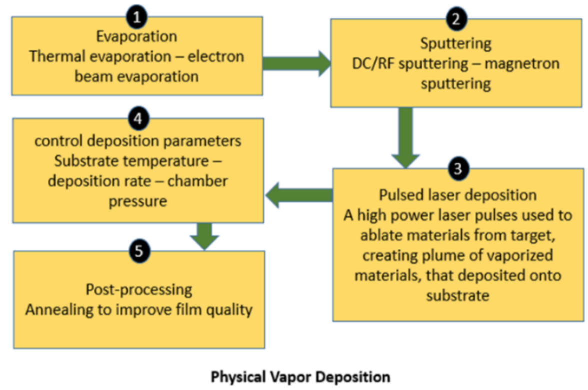

Figure 9: Schematic diagram of physical vapor deposition procedures.

3.5 Hot Pressing

Hot pressing method used for glass nanocomposites fabrication, based on the application of high temperature and high pressure to form high dense materials. This method produces high mechanical properties material, controls microstructure, and has uniform disruption of nanoparticles. This method can be used for densification glass ceramic products. Hot pressing method used for optoelectronics, energy storage, and biomedical devices (Decottignies et al, 1978; Matamoros-Veloza et al 2008). Figure 10 shows the details of glass ceramic preparation via hot pressing method.

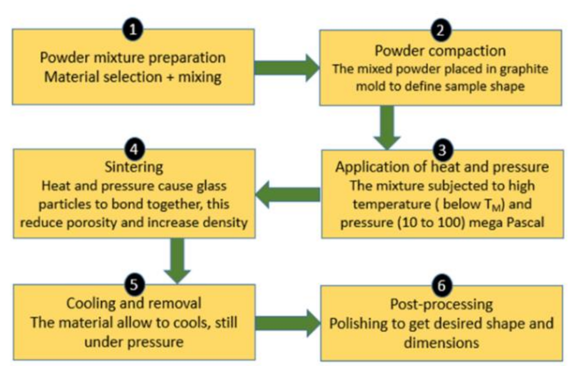

Figure 10: Schematic diagram of Hot-pressing procedures.

4. Dielectric Properties of Borate Glasses

Borate glass nanocomposites exhibit highly tunable dielectric properties, making them promising candidates for advanced electronic applications; including high-energy-density capacitors, microwave substrates, and solid-state electrolytes. The dielectric behavior of these materials is governed by complex interactions between the borate glass matrix and embedded nanoparticles, leading to several key phenomena (Heikal et al, 2025; Biswas et al, 2024).

4.1 Interfacial Polarization and Enhanced Permittivity

The incorporation of metal oxides (e.g., TiO_2, $BaTiO_3$, or conductive fillers) introduces interfacial polarization (Maxwell-Wagner-Sillars effect), where charge carriers accumulate at the glass-nanoparticle boundaries under an applied electric field. This effect significantly increases the effective dielectric constant (ε'), with some nanocomposites achieving ε' values exceeding 100 at low frequencies—orders of magnitude higher than undoped borate glasses. The magnitude of this enhancement depends on nanoparticle conductivity, volume fraction, and dispersion quality, with percolation effects playing a critical role near conductive filler thresholds (Paramesh & Varma, 2013; Li et al, 2018; Salem et al, 2011).

4.2 Low Dielectric Loss for High-Frequency Applications

Optimized nanocomposites demonstrate remarkably low dielectric loss (tan $\delta < 0.01$ at MHz-GHz frequencies), a crucial requirement for 5G/6G communication devices and high-speed electronics. This is achieved through precise control of nanoparticle composition (e.g., using high-purity oxides) and glass network stabilization (e.g., reducing OH^- content). Recent studies show that core-shell nanoparticle architectures can further suppress loss mechanisms by preventing direct current leakage paths while maintaining high permittivity (Tripathi et al, 2019).

4.3 Ionic Conductivity in Solid-State Battery Applications

Lithium-doped borate glass nanocomposites (e.g., Li_2O-B_2O_3 with LLZO or LATP nanoparticles) exhibit exceptional ionic conductivity (>10^{-3} S/cm at room temperature) due to synergistic effects: the borate glass provides a percolating Li^+ conduction pathway, while embedded nanoparticles create space-charge regions that enhance ion mobility along interfaces. Advanced nanocomposite designs now incorporate 3D-connected ceramic nano frameworks to achieve both high conductivity and mechanical stability for next-generation solid-state batteries (Graça et al, 2008; Rai & Kundu, 2023; Dongare 2017).

4.4 Frequency-Dependent Behavior and Temperature Stability

The dielectric response of these materials shows strong frequency dispersion, transitioning from interfacial polarization dominance at low frequencies to dipolar/ionic relaxation at higher frequencies. Carefully engineered compositions maintain stable dielectric properties across broad temperature ranges (-50 °C to 300 °C), enabling applications in harsh environments. Emerging research focuses on nanocomposites with negative permittivity for metamaterials and on-demand dielectric switching behavior for adaptive electronics (Tretyakov, 2001; Tallman, 2020).

5. Radiation Shielding Applications

Borate-based glass-ceramics are emerging as alternatives to lead and concrete for gamma-ray shielding due to their non-toxic, transparent, and thermally stable nature. The shielding efficiency is evaluated using parameters like linear attenuation coefficient, HVL, Zeff, and RPE. Adding heavy metal oxides enhances these properties, making them suitable for medical and nuclear safety applications. Today ionization radiation is used for many applications such as radiation thereby, medical imaging, agriculture, and sterilization. And the exposure to ionization radiation causes health risks. The need to reduce exposure to radiation becomes a very important role occupational health safety and radiation protection (Al-Buriahi, 2023; Al-Hadeethi, 2022; Al-Buriahi, 2025, Bagheri & Shirmardi, 2021).

One of the most important issues in radiation safety is radiation shielding, where the distance, time, and shielding are the basic of ALARA principle for radiation protection. In medicine, radiation thereby, sterilization, and space application radiation shielding material is needed. The most essential requirements for radiation shielding material are high atomic number, high density, and proper thickness to be easy reconstructed and low cost in addition to must be environmentally safe (Mansouri et al, 2020). The most common radiation shielding materials are lead and concrete, but lead has low mechanical properties in addition to toxicity, and concrete is heavy, opaque, and losses water content when exposed to radiation. So, using glasses for radiation shielding material become widespread due to its important feature such as transparency, chemical stability, thermal stability, easy manufacture and features manipulating, low cost, low weight, and biocompatible (Al-Buriahi, 2025).

Glass in contrast other radiation shielding materials characterized by transparency and water resistance than heavy, opaque, and hazard materials (lead, and concrete) (Saudi et al, 2020). Concrete is used as a radiation shielding, but concrete losses its water content when exposed to nuclear radiation. Some applications need the transparency of the glasses such as nuclear medicine laps, X-ray and computed tomography scanner's windows, moreover its ability of glasses to absorb neutrons and gamma rays, so glasses regarded as new generation of radiation shielding applications (Abdullah et al, 2022; Azreen et al, 2018).

Borate-based glass nanocomposites have emerged as highly promising materials for advanced radiation shielding applications due to their structural flexibility, compositional tunability, and ability to incorporate high-Z dopants and nanofillers. The integration of heavy metal oxides such as Bi_2O_3 (Biradar et al, 2024; Mhareb, 2023) and Gd_2O_3 (Kilic, 2023) significantly enhances gamma and neutron attenuation by increasing the mass attenuation coefficient while maintaining advantages like low toxicity, transparency, and lightweight nature compared to conventional lead-based shields. Nanoparticles further improve shielding through interface-driven effects, including enhanced scattering, bond rearrangements, and densification at the glass-nanoparticle boundaries. Monte Carlo simulations have been widely employed to validate and optimize the shielding performance of these composites. Future directions emphasize the development of multifunctional materials that combine radiation shielding with smart features such as real-time monitoring via scintillation from rare-earth dopants (Eu^{3+} (Kilic et al, 2021; Katubi et al, 2024), Tb^{3+}), and adaptive shielding using photochromic or piezoelectric components for on-demand protection and sensing. Additionally, the review highlights the importance of sustainable design, promoting eco-friendly, recyclable borate glass systems, which offer excellent shielding efficiency without relying on hazardous substances. Together, these advances establish borate glass nanocomposites as next-generation candidates for protective technologies in medical, nuclear, and aerospace environments.

6. Challenges and Future Perspectives

Despite the remarkable progress in borate-based glass nanocomposites, several critical challenges must be addressed to facilitate their widespread industrial adoption. One of the most persistent issues is achieving uniform nanoparticle dispersion without agglomeration, which currently requires precise control over synthesis parameters (temperature, viscosity, cooling rates) and often leads to batch-to-batch inconsistencies. Additionally, high production costs associated with rare-earth dopants (e.g., Gd_2O_3) and specialized nano-processing techniques (e.g., spark plasma sintering) limit large-scale commercialization. Scaling up laboratory synthesis methods while maintaining nanostructural precision remains a significant hurdle, particularly for glasses requiring controlled crystallization or hybrid organic-inorganic phases.

Future research on borate glass nanocomposites should prioritize the development of multifunctional materials that synergistically combine radiation shielding with smart responsive properties, opening new possibilities for advanced applications. A key direction involves integrating luminescent rare-earth dopants (Eu^{3+}, Tb^{3+}, Dy^{3+}) to create self-diagnostic shields capable of real-time radiation monitoring through scintillation effects, where the intensity and wavelength of emitted light correlate directly with radiation dose and type. Simultaneously, incorporating photochromic (e.g., AgCl-doped) or electrochromic (e.g., WO_3-based) components could enable adaptive shielding systems that dynamically modulate their opacity and attenuation properties in response to changing radiation fields or electrical stimuli, particularly valuable for spacecraft and variable-intensity medical imaging environments. Furthermore, embedding piezoelectric nanoparticles (e.g., ZnO, $BaTiO_3$) within the glass matrix presents an innovative approach to self-powered radiation detection, where the energy from incident radiation generates measurable electrical signals through the piezoelectric effect, eliminating the need for external power sources in detector applications. These multifunctional designs require precise nanoscale engineering to prevent property interference - for instance, ensuring scintillation centers don't quench piezoelectric responses - potentially achieved through core-shell nanoparticle architectures or spatially graded compositions. Such advanced materials could revolutionize radiation protection by merging shielding, sensing, and adaptive response into single, compact systems for nuclear facilities, space habitats, and portable medical devices.

The development of eco-friendly and sustainable borate glass nanocomposites represents a critical research direction, focusing on replacing conventional toxic heavy metals (Pb, Cd) with high-performance, environmentally benign alternatives while maintaining superior shielding capabilities. Lead-free gamma shielding compositions based on

Bi_2O_3-WO_3-TeO_2 systems have shown particular promise, as bismuth's high atomic number (Z=83) provides excellent photon attenuation comparable to lead, while tungsten oxide (WO_3) enhances mechanical stability and tellurium oxide (TeO_2) improves glass-forming ability, creating a balanced ternary system suitable for medical and nuclear applications. For neutron absorption, innovative boron-rich polymers and bio-glasses derived from sustainable precursors (e.g., borosilicate waste or biologically compatible compounds) offer lightweight, non-toxic alternatives to traditional cadmium-based shields, with the added advantage of tunable hydrogen content for enhanced moderation capabilities. A crucial parallel effort involves designing fully recyclable nanocomposites through strategic selection of components with similar melting points and chemical compatibility, enabling closed-loop material reprocessing without property degradation; this includes developing nanoparticle coatings that prevent agglomeration during remelting and optimizing glass matrices for easy separation of constituent materials. These sustainable approaches not only address environmental and health concerns but also open new opportunities for cost-effective production and end-of-life material management, making radiation shielding technologies more accessible for large-scale civil applications while meeting increasingly stringent global regulations on hazardous substances.

Recent advances in manufacturing techniques are revolutionizing the production of borate glass nanocomposites, enabling unprecedented control over material properties and structure. Sol-gel processing has emerged as a powerful low-temperature (300-600 °C) alternative to conventional melt-quenching, allowing superior nanoparticle homogeneity through molecular-level mixing of precursors while minimizing agglomeration risks. For consolidation, field-assisted sintering techniques (FAST/SPS) combine high heating rates with uniaxial pressure to achieve >99% theoretical density at reduced temperatures, preserving nanoscale features that would degrade in conventional furnaces and enabling unique glass-ceramic nanocomposites with tailored crystallinity. Additive manufacturing (3D printing) of borate glasses, particularly via direct ink writing or selective laser melting, permits the fabrication of functionally graded shields with spatially varying compositions optimized for multi-spectral radiation attenuation - an impossibility with traditional forming methods. Most transformatively, AI-driven materials design is accelerating development cycles, where machine learning algorithms trained on vast datasets of composition-structure-property relationships can predict optimal dopant combinations and processing parameters, potentially identifying novel nanocomposite formulations with exceptional shielding efficiency, mechanical robustness, and optical clarity. These advanced manufacturing approaches collectively address longstanding challenges in scalability, reproducibility, and performance optimization, transitioning borate glass nanocomposites from laboratory curiosities to industrially viable next-generation materials.

Future advancements in borate glass nanocomposites must prioritize enhanced performance metrics to meet the rigorous demands of cutting-edge applications. A critical focus lies in improving mechanical toughness through nanoscale reinforcement strategies, such as incorporating carbon nanotubes or graphene oxide platelets to create crack-bridging networks that resist embrittlement under prolonged radiation exposure, while maintaining the composite's attenuation capabilities. Simultaneously, extending thermal stability to 1000 °C requires innovative approaches like refractory nanoparticle additions (ZrO_2, HfO_3) and controlled crystallization to develop stable glass-ceramic nanocomposites capable of withstanding extreme nuclear reactor environments without devitrification or property degradation. For medical imaging applications, optimizing optical clarity demands precise engineering of nanoparticle size (<20 nm) and interfacial chemistry to minimize light scattering while preserving shielding efficacy, potentially through advanced polishing techniques and resonant plasmonic nanostructures that selectively block ionizing radiation while transmitting visible wavelengths. These performance enhancements must be achieved synergistically, requiring fundamental advances in understanding radiation-induced structural changes, high-temperature phase stability, and light-matter interactions at the nanoscale - challenges that will drive the next generation of multifunctional shielding materials for aerospace, energy, and healthcare technologies.

The future of borate glass nanocomposites lies in smart, adaptive materials that respond to radiation flux, self-monitor damage, and even self-heal microcracks. Advances in nanoscale interface engineering and multi-material integration (e.g., glass-ceramic hybrids) could unlock unprecedented performance, making these composites viable for space exploration, fusion reactors, and next-gen medical therapy systems. Collaborative efforts between material scientists, engineers, and industry stakeholders will be crucial to transition these materials from lab-scale breakthroughs to real-world solutions.

7. Conclusions

Borate-based glass nanocomposites represent a versatile class of materials with significant potential in dielectric and radiation shielding applications. Recent advancements in nanostructuring and doping strategies have enhanced their structural, electrical, and protective properties. Further research is needed to optimize these materials for commercial use, particularly in medical imaging, nuclear safety, and optoelectronic devices.

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