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Entry

Inhomogeneities in Glass: From Defects to Functional Nanostructures

Georgiy Yu. Shakhgildyan ^{1,*}  and Michael I. Ojovan ^{2,3,*} ¹ Department of Glass and Glass-Ceramics, Mendeleev University of Chemical Technology, 125047 Moscow, Russia² School of Chemical, Materials and Biological Engineering, The University of Sheffield, Sheffield S1 3JD, UK³ Department of Radiochemistry, M.V. Lomonosov Moscow State University, 119991 Moscow, Russia

* Correspondence: shakhgildian.g.i@muctr.ru (G.Y.S.); m.ojovan@sheffield.ac.uk (M.I.O.)

Definition

Glass inhomogeneities represent variations in the structural or compositional uniformity of glass, traditionally associated with process-related defects such as striae, bubbles, stones, and inclusions that impair transparency and mechanical stability. These “technological” inhomogeneities emerge during melting, forming, or annealing, and have long been the focus of industrial elimination strategies. However, recent developments in glass science and nanotechnology have reframed inhomogeneity as a potential asset. When precisely engineered at the nanoscale, inhomogeneities, such as nanocrystals, metal or semiconductor nanoparticles, and nanopores, can enhance glass with tailored optical and photonic functionalities, including upconversion luminescence, plasmonic response, nonlinear refractive behavior, and sensing capabilities. This entry provides an integrated perspective on the evolution of glass inhomogeneities, tracing the shift from defect suppression to functional nanostructuring. It discusses both the traditional classification and mitigation of detrimental defects, and the design principles enabling the intentional incorporation of beneficial nanoinhomogeneities, particularly in the context of optics and photonics. The utilization of engineered inhomogeneities in nuclear waste glasses is also discussed.

Keywords: glass inhomogeneity; glass defects; bubbles; nanocrystals; nanopores; nanostructuring

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1. Introduction

Inhomogeneities in glass are any non-uniformities in composition or structure that lead to local variations in properties (especially refractive index) [1]. Traditionally, glassmaking strove for extreme homogeneity: any streaks, bubbles, or inclusions were considered defects to be eliminated because they scatter or distort light [2]. For example, early optical lenses often suffered from striae (“veins” or cords of slightly different refractive index) that blurred images, until the introduction of vigorous stirring in 1805 by P.L. Guinand greatly improved homogeneity. Over the 19th and 20th centuries, techniques like careful batch preparation, controlled melting, and fine annealing were developed to produce glass that was as uniform as possible, free of visible striae, “seeds” (small bubbles), or inclusions. The historical mindset was clear: such inhomogeneities were “faulty” and had to be mitigated for glass to meet technological demands in optics, containers, etc. [3].

Today, however, a new paradigm has emerged. Advances in materials science and nanotechnology have shown that not all inhomogeneity is detrimental. It is now possible to engineer nanoscale inhomogeneities intentionally to impart novel functionalities to glass.

By introducing controlled nanosized second phases or structures (crystals, particles, pores, etc.) into a glass matrix, researchers create composite materials with enhanced optical or photonic properties [4]. The once-“forbidden” heterogeneity is harnessed in a positive way; for example, embedding metallic nanoparticles can produce intense plasmonic absorption and local-field enhancements, and precipitating nanocrystals can enable luminescence or nonlinear optical effects that homogeneous glass lacks [5]. Another example is the utilization of inhomogeneities in the form of crystalline phases embedded in durable glasses aiming to immobilize the radioactive and toxic nuclides of nuclear waste [6].

This article reviews this remarkable transition: from the classical “faulty” inhomogeneities (unwanted process-induced defects) to “desired” inhomogeneities (designed nanostructures that add functionality). We begin by surveying conventional glass defects—their nature, origins, and how they are detected and eliminated—and then discuss the burgeoning field of functional nanoinhomogeneous glasses for optics and photonics.

2. Conventional (“Faulty”) Inhomogeneities in Glass

2.1. Main Types of Defects in Glass

Conventional inhomogeneities refer to flaws introduced during glass manufacturing that degrade the material’s performance or appearance. These include striae (also called cords or veins), swirls, bubbles (or seeds), stones (crystalline inclusions or unmelted batch), and other miscellaneous inclusions [7]. Table 1 summarizes the main types of such defects, their causes, and typical occurrences. All these inhomogeneities are generally detrimental: they can scatter or absorb light (compromising optical clarity), initiate stress concentrations (weakening mechanical strength), or cause failures (e.g., breakage of glass articles). Manufacturers, therefore, employ various detection techniques to identify these defects and implement process controls to minimize them.

Striae and similar refractive index variations are usually detected by optical methods [8]. A classic tool is the striaescope or shadowgraph test, which uses a point light source and a collimator to illuminate a polished glass sample; any streaks of differing index become visible as shadowy lines. Standards such as the MIL-G-174B specify reference “striae grading” samples for comparison [9]; for example, Grade A optical glass has essentially no visible striae. Bubbles and inclusions are often evaluated by visual inspection of samples from each melt or by image analysis, e.g., measuring total cross-sectional area of bubbles per unit volume. Modern production lines use automated optical scanners and cameras to inspect float glass or container glass items, detecting seeds, stones or cords by their visual signatures [10]. The refractive index homogeneity of high-end optical glass blanks is quantified interferometrically; premium lens blanks can achieve index variation $\Delta n < 10^{-6}$ across their aperture [11]. In optical fiber preforms, careful mapping of the refractive index profile ensures uniformity to within 10^{-4} or better, since any micro-fluctuation will contribute to Rayleigh scattering loss. Indeed, the fundamental attenuation floor of silica fiber (~ 0.14 dB/km at $1.55 \mu\text{m}$) is set by frozen-in density micro-fluctuations (on the order of nanometers in size) that scatter light (Rayleigh scattering) [12]. In summary, glass makers have developed an array of techniques to find and quantify inhomogeneities, from simple visual methods to sophisticated interferometry, because understanding the defect content is the first step to eliminating it.

Table 1. Common technological inhomogeneities in glass and their origins.

Defect Type	Description	Cause	Occurrence	Impact
Striae/Cords	Thread-like streaks of differing refractive index in glass. Visually appear as veins or “cords” in the glass. Essentially regions of abruptly varying density in an otherwise uniform matrix.	Compositional inhomogeneity caused by incomplete mixing or localized evaporation during glass formation.	Found especially in optical glass if the melt is not well-stirred. Also occurs in other glass types with inadequate mixing.	Even slight striae can distort optical wavefronts, making high-end optics require striae-free glass. In less critical applications, may only cause cosmetic issues.
Swirls	Large-scale wavy patterns of refractive index variation. Similar to striae but broader and more diffuse with no sharp edges.	Result from convection currents that are frozen during the cooling process.	Historically seen in old window glass and large cast blocks. Modern float glass processes have largely eliminated these.	Can blur transmitted images or produce distortion (“lens” effects). Modern controlled cooling and flow processes minimize these effects.
Bubbles/Seeds	Gas-filled voids in glass. Seeds refer to small bubbles (<~1 mm) while bubbles refer to larger ones.	Result from gases released during melting (CO ₂ from carbonates, O ₂ from nitrates/sulfates) or air entrapment during insufficient melting.	Can occur in any glass type. More common when melting conditions are inadequate or when using certain raw materials.	In container and float glass, small seeds are usually cosmetic but large bubbles weaken products and can cause leaks or breakage. In optical glass, even tiny bubbles scatter light and must be tightly controlled.
Stones/Inclusions	Solid defects including unmelted raw batch grains, devitrification crystals, or bits of furnace refractory.	Often high-melting particles (e.g., quartz grain or alumina ceramic) that remained undissolved or re-crystallized out of the melt.	More common in commodity glasses (containers, float) due to large-scale production and recycled cullet use.	Act as stress concentrators—hard inclusions can initiate cracks under thermal or mechanical load. In flat glass, tiny stones or NiS inclusions can cause tempered glass to spontaneously shatter.
Unmelt/Cord (chemical)	A subtype of inclusion consisting of streaks of incompletely melted batch, often high-silica threads called cord when they extend in a line.	Essentially a glassy inclusion with different composition (e.g., silica-rich) than the bulk glass due to incomplete melting.	Seen in container glass and some optical glasses produced in pot melts.	Manifest as visible line defects. Chemically different cords can have thermal expansion mismatch, causing internal stresses.
Other Inhomogeneities	Include crizzle (sub-micron phase separation causing cloudiness) and other specialized defects.	Usually secondary effects of composition or furnace environment (e.g., sulfur deposits causing haze). Can result from improper cooling of certain glass compositions.	Generally rare and specific to certain glass compositions or processes. For instance, borosilicate glass can phase-separate if not cooled properly.	Can lead to opalescence, cloudiness, or surface haze. Manufacturers adjust compositions to avoid such effects or apply post-processing like fire-polishing to remove them.

Technological inhomogeneities typically arise from imperfections in the melting, fining (refining), or forming processes. Bubbles often originate from gases released by batch decomposition (CO₂ from carbonates, O₂ from fining agents, etc.) that fail to escape before the melt solidifies. Inadequate refining (insufficient time at high temperature or lack of fining additives like sulfate) will leave an excess of small bubbles (“seeds”) throughout the glass. The remedy is to optimize the melt schedule (time–temperature profile used

during glass melting) and use fining agents that promote bubble coalescence and rise, thereby removing bubbles [13]. Striae and cord defects stem from incomplete mixing or localized composition variations in the melt, for instance, failure to thoroughly stir the melt can leave streaks of higher or lower refractive index [14]. Temperature gradients in large tanks can also “freeze in” convection currents as undulating index bands (sometimes called swirls). The classical cure is vigorous stirring of the molten glass (using mechanical stirrers or convection currents induced by furnace design) to homogenize the melt before cooling [15]. Many optical glass factories use platinum-blade stirrers in the melt for this reason. Composition adjustments also help, e.g., adding refining agents or adjusting viscosity to allow for bubbles to rise and striae to dissipate more easily.

Stones can form if parts of the melt devitrify (crystallize) due to temperature fluctuations or contamination. Certain glass formulas are prone to devitrification within specific temperature ranges, producing crystalline “stones” unless the process strictly avoids holding in those temperature ranges. For example, the high-index optical glass N-SF6 must be cooled or heated through its unstable range quickly to prevent quartz or cryptocrystalline phases from precipitating [16]. Thus, careful thermal profiling and use of additives (nucleating agents or stabilizers) are employed to suppress unwanted crystallization. Stones can also come from unmelted batch grains (if raw materials are not fully dissolved) or from refractory inclusions (tiny bits of the furnace’s ceramic lining that spall off into the melt). These are mitigated by good furnace design and maintenance, e.g., using high-quality refractory materials, employing barrier nets or ceramic filters in the melt, and skimming the melt surface [16]. Raw material purity and grain size control (fine, well-mixed batch) are also crucial to avoid residual “unmelts”.

Inclusions of foreign materials (e.g., metallic impurities) are controlled by strict material handling protocols. A notable example is nickel sulfide (NiS) inclusions in float glass, which form when nickel (from alloy contamination) reacts with sulfur in the melt. NiS inclusions are infrequent and tiny (often <0.5 mm), and thus usually harmless in ordinary annealed glass [17]. However, in tempered glass (which is rapidly cooled), NiS can be trapped in a high-temperature crystal phase that later slowly transforms into a larger low-temperature phase, causing internal stress and spontaneous shattering of the glass pane. To mitigate this, float glass manufacturers implemented rigorous controls in the 1990s, e.g., multi-stage filtration of raw sand to remove nickel-bearing particles and strict avoidance of nickel alloy tools in contact with the melt. Additionally, heat soak testing is used for tempered safety glass: the tempered panes are held at ~290 °C for many hours to force any NiS inclusions to undergo their expansion phase and break the glass before installation, thus culling at-risk pieces [18]. These measures have greatly reduced (though not entirely eliminated) the incidence of NiS-related failures.

In summary, conventional glass technology treats inhomogeneities such as defects to be minimized through careful process control. Figure 1 shows common inhomogeneities in glasses discussed above. With proper melting, refining, and material handling, modern glass (especially optical glass) can be made extremely uniform: large lens blanks are produced with no visible striae and bubble contents under 0.03 mm² per 100 cm³ [16]. Nevertheless, some applications (like containers or architectural glass) tolerate minor inhomogeneities, whereas others (high-precision optics) demand the highest grades of purity and uniformity. The following section presents specific examples of technologically significant inhomogeneities encountered across various glass product sectors, highlighting their origins, manifestations, and impact on performance.

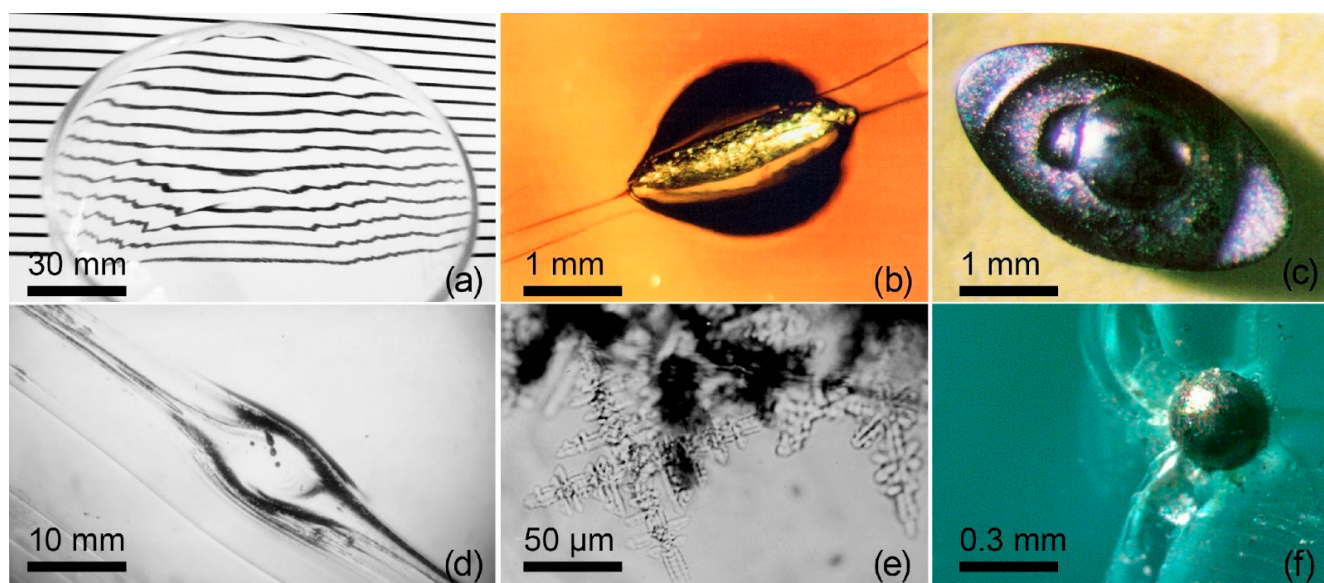


Figure 1. Common inhomogeneities in glasses: (a) optical distortions due to cords; (b) an elongated metal inclusion in glass; (c) a metallic bubble in bottle glass; (d) striae and cords in glass; (e) cristobalite crystals in glass; (f) a NiS inclusion as a cause of breakage in flat glass. Adapted from ref. [18].

2.2. Container Glass (Bottles and Jars)

Container glass (typical soda–lime–silica compositions for bottles, jars, etc.) is manufactured in huge volumes by continuous melting. Inhomogeneities in containers primarily include stones, cords, and bubbles. Because containers are relatively thick-walled and not designed as optical components, the presence of a few small bubbles or faint cords is generally acceptable, as long as they do not affect structural integrity or visual appearance [19]. However, larger defects can be critical. Stones (unmelted sand grain or refractory chip) embedded in a bottle wall can create a stress concentration; under impact or thermal shock, cracks may initiate at that inclusion, causing bottle failure. If the inclusion has a different thermal expansion (for example, a bit of ceramic), it can generate internal stress on cooling. Thus, glass companies pay close attention to stone defects; their presence in a batch of containers often triggers investigation of the furnace condition (e.g., checking for damaged refractories or batch quality issues).

Cords in container glass appear as faint streaks or ripples. These usually indicate minor chemical inhomogeneity but can also be caused by imperfect mixing of cullet and raw materials. While cords do not typically cause breakage, they are cosmetic defects and can distort the appearance of the product (important for high-end cosmetics or spirits bottles). To control cords and stones, container glass makers use good batch pre-heating (to ensure full melting), maintain steady tank temperatures (to avoid devitrification zones), and may install ceramic screens in the forehearth “to catch unmelted particles”. Bubbles (or “blisters”) in bottles are common at some level; small bubbles under 1 mm (seeds) are often tolerated, but larger bubbles can weaken the container or cause leakage if they intersect the surface. Insufficient refining or overly fast pulls can lead to bubbly glass. Consequently, tanks are designed with a refining zone where glass resides at a high temperature long enough for most bubbles to rise and escape.

Refining agents (like Sb_2O_3 or sulfate) produce fining gas that helps “float” bubbles out. Overall, container glass processes accept a low level of inhomogeneities, as long as safety and functionality are not impaired. Automated inspection machines examine each bottle with cameras and light sources, rejecting items with stones or large bubbles. The trend over time has improved quality, e.g., modern glass bottles rarely have visible stones or blisters, whereas a century ago, such defects were more common.

2.3. Flat Glass (Window/Architectural Glass)

Flat glass, typically made by the float process, is drawn in large continuous ribbons for windows, facades, etc. Float glass is very homogeneous in thickness and has few bulk defects; the process (floating on molten tin) naturally allows bubbles to rise out and yields a uniform sheet. Nonetheless, some inhomogeneities can occur. A notorious defect in float glass is the nickel sulfide inclusion discussed earlier. NiS inclusions are extremely small (often <0.2 mm) and not visible to the naked eye in raw glass. In annealed window glass, they pose no issue, but if that glass is later tempered (for safety glass), the NiS can cause spontaneous breakage months or years later. This is a serious concern for architectural glazing. To reduce risk, major float glass manufacturers implemented strict controls on raw materials and furnace upkeep to eliminate nickel contamination. They also typically heat-soak tempered glass panels destined for high-rise building use. NiS defects are relatively rare (perhaps a few per hundred tons of glass), but when they do cause breakage, the effect is dramatic (the tempered pane explodes into shards) [20].

Aside from NiS, float glass can contain occasional refractory inclusions (stones from the tank), sulfate blisters (bubbles from fining agent reboil, usually near the top surface of the ribbon), or minor striations from uneven mixing. These are kept to minimal levels through advanced process control. Float glass lines use electro-magnetic stirring in the melt and carefully controlled cooling to prevent striae or devitrification. The result is that modern float glass has optical homogeneity sufficient for window use; any remaining distortion (e.g., the waviness seen in old drawn sheet glass) is virtually eliminated. For very demanding optical applications (like telescope mirror substrates or lithography scanner plates), special polished float or fused silica glasses are used, as they offer higher homogeneity. In summary, the “faulty” inhomogeneities in flat glass are rare events; the industry’s experience with NiS has been a key driver in maintaining material purity.

2.4. Optical Fibers

Optical fibers are a unique case: they are drawn from preforms that are fabricated with extremely high purity and control (often by vapor deposition processes) to achieve minimal inhomogeneity. Even minute fluctuations in composition or density in an optical fiber’s core can cause light scattering or mode perturbations, contributing to attenuation and dispersion. In fact, after eliminating impurity absorption (by reducing transition metal and OH^- content to parts-per-billion), the dominant loss in telecom fibers is Rayleigh scattering from intrinsic microscopic density fluctuations “frozen in” as the silica glass cools. These fluctuations are on the nanoscale (~ 1 nm) and lead to the 0.14 dB/km fundamental loss limit at 1550 nm in pure silica core fiber [21].

Fiber manufacturers strive to push inhomogeneity even lower by optimizing the fictive temperature and reducing frozen-in stress, but this is a physical limit of glass structure. Larger-scale inhomogeneities, like striae or bubbles, are essentially not tolerated in fiber preforms; any such defect would cause excessive scattering or even break the fiber during draw. By making fiber preforms with the modified chemical vapor deposition (MCVD) or related vapor processes, doping concentrations are very uniform and the material is free of stones or seeds. Occasionally, a preform may have a tiny bubble or inclusion; fiber drawn from that segment would show a spike of loss or a scattering point. Thus, preforms are inspected (e.g., via laser interferometry or by slicing and microscopy) to ensure no macroscopic defects. The drawing process itself can introduce some microscopic inhomogeneity: as the fiber cools from the draw tower, slight concentric compositional variation might occur (especially in fibers with doped cores, like Ge-doped silica) [22]. Fiber specifications often include an index profile tolerance on the order of 1% or better. High-bandwidth fibers also must avoid any striations that could cause mode coupling.

In practice, modern fibers have exquisitely uniform core glass; the proof is their low attenuation (0.15–0.2 dB/km) and the fact that Rayleigh scattering (an intrinsic micro-inhomogeneity) is the main loss.

For specialty fibers (e.g., laser-doped fibers or photonic crystal fibers), any “defect” like a bubble in a cladding hole or a refractive index inconsistency can dramatically affect performance. Manufacturers, therefore, use techniques like pressure-assisted MCVD (to prevent bubble entrapment in hollow-core fibers) and inspect each preform segment. In short, optical fiber technology has mastered the elimination of classical inhomogeneities to an extraordinary degree, turning glass into arguably the purest, most homogeneous medium ever made in large volume [23]. This perfection is necessary for fibers to guide light over tens of kilometers with minimal loss.

2.5. Optical Glasses (Precision Optics)

Optical glasses (such as those used for lenses, prisms, high-end optics) demand the highest levels of homogeneity. Customers like telescope makers or semiconductor lithography companies set stringent specifications: e.g., refractive index uniformity $\Delta n < 1 \times 10^{-6}$, no striae of Grade B or worse in the clear aperture, bubble content below 0.03 mm² per 100 cm³, etc. [24]. To achieve this, optical glass is typically melted in relatively small batches (a few hundred kg) in platinum crucibles, with careful stirring and slow cooling (fine annealing) to relieve stress. As noted, companies like Schott and Ohara classify striae quality; “A” grade optical glass has no visible striae under the standard test. If a piece of glass shows any cord-like stria, it may be relegated to a lower grade or removed from the blank’s usable area. Large optical blanks (for lenses 300 mm across or laser glass slabs, etc.) are often cast as blocks and then inspected interferometrically. If needed, manufacturers will selectively remove inhomogeneous regions (for example, discarding the top and bottom of a casting where convection currents might have caused striae). In some cases, a block with a mild striation at the periphery can be reshaped (slumped) so that the stria lies outside the optical aperture.

Optical glass makers also take great care with raw materials (to avoid stones), i.e., high-purity sand, nitrates instead of sulfates (to reduce blistering), and continuous filtering of the melt are common. The result is that today’s optical glasses are superbly uniform. For instance, Ohara’s “Grade Special A1” homogeneity is $\Delta n \leq 1 \times 10^{-6}$ in a 100 mm path, and their highest quality melts have virtually no inclusions >0.1 mm. Such glass can produce diffraction-limited lenses with no image degradation from the glass itself. In extreme applications like large telescope mirrors made of low-expansion glass–ceramic (ZERODUR[®], which has nanocrystals but is treated as homogeneous on optical scales), the residual inhomogeneity of the material is on the order of 10^{-8} in the refractive index, negligible compared to atmospheric distortions [25,26].

Having reduced deleterious inhomogeneities to the point that bulk optical glass now contributes only a negligible share of an instrument’s aberration budget or stray-light loss, we can turn to a contrasting paradigm. The next section examines how intentionally engineered nanoscale heterogeneities, introduced in a controlled manner, can endow glass with new functional properties while preserving its macroscopic transparency.

3. Functional (“Desired”) Nano-Inhomogeneities in Glass

While traditional glass science treats inhomogeneity as a problem, modern research shows that embedding nanometer-scale secondary phases in glass can be highly beneficial [27]. By carefully designing the size, volume fraction, and chemistry of these nanoinclusions, one can produce glass-based nanocomposites that retain the overall transparency, yet exhibit new optical, thermal, or mechanical functionalities. The key distinction from

the “defects” discussed earlier is scale and control: “desired” inhomogeneities are typically 10^{-9} – 10^{-7} m in size (much smaller than the wavelength of light) and are introduced in a controlled fashion (often via heat treatments that precipitate a uniform dispersion of nanocrystals or via doping during fabrication). At this scale, the inclusions do not cause the unwanted scattering or image distortion that larger defects do [28]. Instead, they can interact with light quantum mechanics (e.g., quantum confinement in semiconductor nanocrystals, or surface plasmon resonance in metal nanoparticles) to produce effects impossible in a homogeneous glass. Figure 2 summarizes the main functional (“desired”) nano-inhomogeneities in glass. Below, we reviewed several important classes of functional nanoinhomogeneities in glass, and highlighted their material examples and the optical/photonic enhancements they provide.

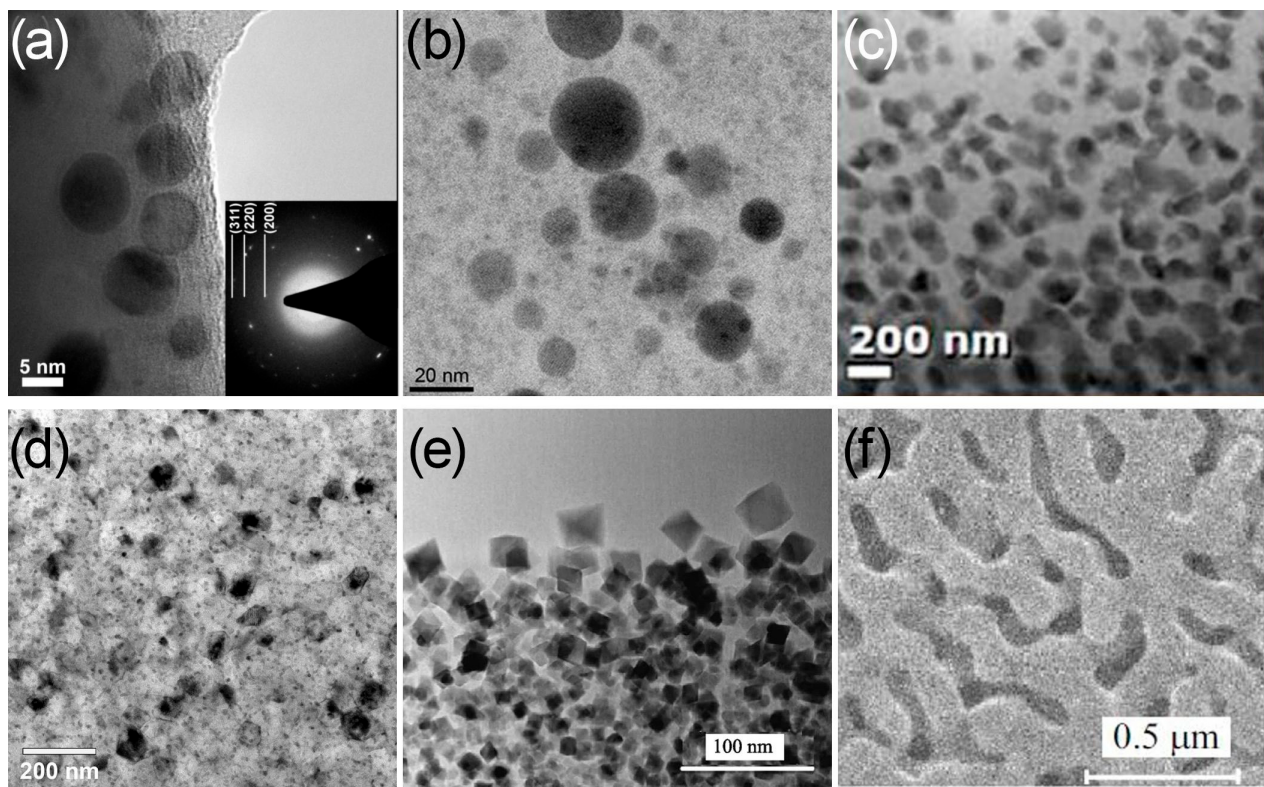


Figure 2. The main functional (“desired”) nano-inhomogeneities in glass visualized by electron microscopy: (a) plasmonic gold nanoparticles in phosphate glass precipitated after the heat treatment (Reprinted with permission from ref. [29], Copyright 2025 IOP Publishing); (b) plasmonic silver nanoparticles in zinc—phosphate glass precipitated after laser irradiation (Reprinted with permission from ref. [30], Copyright 2018 Elsevier); (c) CdS quantum dots precipitated in silicate glass after the laser irradiation (Reprinted with permission from ref. [31], Copyright 2022 Elsevier); (d) microstructure of LAS transparent glass-ceramics with near-zero CTE reprinted from ref. [27]; (e) microstructure of ZMAS transparent glass-ceramics after the laser amorphization (Reprinted with permission from ref. [32], Copyright 2023 Springer Nature); (f) microstructure of nanoporous glass used for the synthesis of oligonucleotides (Reprinted with permission from ref. [33], Copyright 2019 Springer Nature).

3.1. Nanocrystals in Glass (Transparent Glass–Ceramics)

One major avenue is the development of transparent glass–ceramics materials, wherein a glass matrix contains a dispersed nanocrystalline phase, typically produced by the controlled heat treatment of a precursor glass. Unlike conventional glass–ceramics (which often have micron-size crystals and are opaque or translucent), the goal here is to keep crystal size so small (tens of nanometers) that visible light is not scattered and the material

remains clear [34]. Such nanocrystal-in-glass composites combine the ordered structure of a crystal (which can impart advantageous properties like second harmonic generation, or efficient luminescence from dopant ions) with the disordered matrix of glass (which provides shapeability and robustness) [35]. As a result, glass–ceramics can exhibit improved mechanical, thermal, or optical properties relative to the original glass. For example, the precipitated nanocrystals often have higher hardness or elastic modulus, so the composite is mechanically tougher [35]. The classic demonstration is Corning’s photothermal glass–ceramics (used for cooktops and telescope mirrors) which achieve nearly zero thermal expansion by incorporating nanocrystals with negative expansion; the composite outperforms homogeneous glass in thermal stability. In photonics, however, the most exciting developments have been with optically functional nanocrystals, especially fluoride or oxynitride nanocrystals doped with rare earth ions for lasers and phosphors.

A prime example is lanthanide-doped fluoride nanocrystals in a silicate glass matrix. Oxyfluoride glass compositions can be heat-treated to precipitate Ln-doped fluoride crystals (like NaYF_4 or LaF_3) on the order of 10–20 nm, yielding a transparent glass–ceramic that greatly enhances rare earth emission efficiency. The rare earth ions (Er^{3+} , Yb^{3+} , Eu^{3+} , etc.) preferentially enter the crystalline phase where they have a lower phonon-energy environment than in amorphous glass, which reduces non-radiative relaxations. Intense upconversion luminescence has been demonstrated this way: for instance, an $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped glass–ceramic containing LiYF_4 nanocrystals showed markedly stronger upconverted emission (green and red luminescence under 980 nm excitation) than equivalent ions in a pure glass. In one study, Yb/Er-doped transparent glass–ceramic achieved intense upconversion and even enabled optical temperature sensing via the fluorescence intensity ratio of Er^{3+} levels thanks to the partitioning of Er^{3+} into the precipitated nanocrystals. Such materials are promising for upconversion lasers, phosphor converters for LED lighting, and optical thermometry [36]. Similarly, Eu-doped nanocrystal glass–ceramics can exhibit enhanced down-conversion (e.g., converting UV to visible with higher quantum yield) compared to Eu-doped glass [37]. Another application is transparent scintillators: heavy metal halide nanocrystals (like $\text{BaCl}_2:\text{Eu}^{2+}$ or perovskites discussed below) embedded in glass can provide high light yield and fast decay for radiation detection, while the glass matrix offers mechanical strength and shaping. An example is a transparent glass–ceramic with ultra-fine $\text{BaCl}_2:\text{Eu}$ nanocrystals which showed improved scintillation performance (fast response and decent light output) relative to a single-phase glass [38].

Control of nanocrystal size and index is crucial to maintain transparency. Typically, for visible-light transparency, the crystals should be smaller than 50 nm, and the refractive index difference between the crystal and glass phases must be less than 0.1 to minimize scattering and maintain optical clarity. These conditions suppress Mie scattering [39]. Researchers achieve this through careful composition design (choosing a crystal phase of which the index is near that of the base glass) and by using nucleating agents to get a high density of very fine crystals rather than a few large ones [35]. For example, adding TiO_2 or ZrO_2 as nucleators can induce dense, uniform nucleation of nanocrystals. One work designed a fluoroborosilicate glass that, upon heating, precipitated 10–20 nm BaGdF_5 nanocrystals doped with Tb^{3+} ; the resulting glass–ceramic had higher green luminescence and remained ~90% transparent [40]. Beyond luminescence, nanocrystals in glass can also impart nonlinear optical properties. Ferroelectric or birefringent nanocrystals (like $\beta\text{-BaB}_2\text{O}_4$ or LiNbO_3) could enable frequency doubling (second harmonic generation) in an originally centrosymmetric glass if polar order can be achieved. While making an oriented nanocrystal glass–ceramic is challenging, progress is being made using electric field poling or laser-induced crystallization to create regionally oriented nanocrystals for quadratic nonlinear optics. Another avenue is mechanical functionality: some glass–

ceramics with nanocrystalline phases (e.g., spinel or high-quartz) exhibit greater toughness, scratch resistance, low CTE or radiative cooling ability than the base glass [41], which is already used commercially as transparent glass–ceramics such as CLEARCERAM® [25] and ZERODUR® [26].

In summary, by transforming a fraction of a glass into nanocrystals, one can engineer a material that still looks like a glass (transparent, monolithic) but behaves partly like a crystal (utilizing the optically active lattice of the nanophase). Compositional and thermal design is key: the glass composition must be tuned to allow for the desired nanocrystal to form at a convenient heat treatment, and the treatment schedule (time/temperature) controls the size and volume of crystals. This ability to “tune” the internal nanoscale structure is a powerful new tool in glass science, leading to products like photonic upconversion fibers, transparent laser ceramics, and advanced luminescent displays.

3.2. Metal Nanoparticles (Plasmonic Glasses)

Dispersing metal nanoparticles (NPs) in glass gives rise to vivid optical effects due to surface plasmon resonances. When a metal NP (such as gold or silver) is much smaller than the wavelength of light (about 5–50 nm), it can support collective oscillations of its conduction electrons, i.e., a localized surface plasmon. This leads to a strong absorption band at the plasmon resonance frequency (and associated scattering), as well as greatly enhanced electromagnetic fields in the immediate vicinity of the particle. Glasses containing metal NPs have been prized for their colors since antiquity (e.g., the ruby red of Au⁰-doped glass, or the yellow of Ag⁰-doped glass), but in modern photonics, these plasmonic glasses are attracting interest for advanced functionalities beyond coloration [41].

One well-known example is gold nanoparticle glass (“gold ruby” glass) [42]. Colloidal gold in glass (~10 nm particles) produces a deep red color due to a localized surface plasmon resonance (LSPR) absorption around 520–540 nm [43]. Beyond the color, this plasmon band can be exploited for optical filtering and sensing [44]. Similarly, silver nanoparticles (~40 nm) in glass have an SPR around 400 nm, imparting a yellow tint, and have been used in photochromic glasses and antibacterial coatings [41]. The local field near resonant-metal NPs can be huge; the intensity can be enhanced by orders of magnitude at the particle surface. This is the basis for surface-enhanced Raman scattering (SERS): a glass substrate doped with Ag NPs can serve as a SERS-active surface to detect trace molecules, as the Ag plasmon amplifies the Raman signals [30]. Likewise, the plasmon near field can boost the emission of nearby luminescent centers (plasmon-enhanced fluorescence) [45]. In glass, one can co-dope a luminescent ion (or quantum dot) along with metal NPs to create a plexcitonic system (plasmon + exciton). A recent study demonstrated this with CdTe quantum dots and Ag NPs co-embedded in a sodium–borate glass: under blue excitation, the composite showed ultra-narrow (13 nm FWHM) and ultrafast (90 ps decay) photoluminescence at ~503 nm, thanks to strong coupling between excitons in the QDs and plasmons in the Ag dimer cavities [46]. The Ag NPs amplified the QD emission and shortened its lifetime by three orders of magnitude (from ~30 ns to <0.1 ns). Such plasmonic enhancement is promising for making fast light-emitting devices and even achieving laser-like spasing (surface plasmon amplification by stimulated emission) in bulk media.

From a materials perspective, creating metal NPs in glass can be achieved by ion exchange and reduction (e.g., exchanging Ag⁺ into a glass then thermally reducing to Ag⁰) [47], adding metal compounds to the melt (e.g., AuCl₃) and heat-treating nucleate particles [48], or the ion implantation of metals into glass [49]. The size and dispersion of nanoparticles are controlled via time–temperature profiles (longer heat treatments grow larger particles, shifting the SPR peak) [29]. A challenge is to avoid aggregation or phase separation that would cause light scattering; ideally the particles remain well-dispersed

and sub-wavelength [50]. When carried out properly, one obtains a uniformly tinted yet transparent glass. Because the plasmon resonance is highly sensitive to particle size, shape, and refractive surroundings, tunable optical filters can be made; e.g., a glass with a mix of spherical and rod-like Au nanoparticles could show two absorption bands (transverse and longitudinal plasmon modes) [51]. Furthermore, the plasmon frequency can be tuned by changing particle size or composition (e.g., alloying Ag–Au or tuning the refractive index of the media) [52,53]. Researchers have even developed photosensitive plasmonic glasses, where femtosecond laser writing in a Ag⁺-doped glass can precipitate Ag NPs along the beam path, “drawing” plasmonic structures inside the bulk [54]. These have potential in 3D optical memory or photonic microcircuits [55].

In summary, metal nanoparticle inhomogeneities represent a “desired” use of what would traditionally be an impurity. By embedding a controlled population of nanometer-scale metals in glass, one adds plasmonic functionality, enabling applications in sensing, light modulation, enhanced emission, nonlinear optics, and even solar energy (plasmonic particles can act as nanoheaters or spectral converters for photovoltaics). The field of plasmonic glass is rapidly growing, with ongoing research exploring new metals (like aluminum or transparent conducting oxide NPs for UV or IR plasmons) and new techniques to spatially pattern these nanoparticles within a glass for gradient-index or metamaterial-like effects.

3.3. Semiconductor and Perovskite Nanoparticles

Another exciting class of nanoinclusions are semiconductor nanocrystals (quantum dots) and perovskite nanocrystals embedded in glass [56]. These bring quantum-confined electronic states into the glass, enabling size-tunable optical properties (bandgap absorption, photoluminescence) and strong nonlinearities, while the glass matrix provides physical protection and thermal stability that colloidal nanocrystals alone often lack [57].

Semiconductor quantum dots (QDs) such as CdSe, CdS, PbS, or ZnO have been incorporated into glasses via various techniques (melting, sol–gel, ion implantation) for decades [58]. Today, research focuses on making these nanocrystals smaller and more uniform to exploit true quantum confinement [59]. When quantum dot diameters are only a few nanometers, the electron–hole pair is confined, raising the effective bandgap. Thus, by controlling QD size, one can tune the absorption and emission wavelength. A glass doped with, say, 4 nm CdSe QDs will absorb and emit at shorter wavelengths (e.g., orange), whereas 6 nm QDs might give red, covering a range continuously. This size tunability is highly useful for photonics (e.g., broadband sources, tunable lasers, etc.) [31]. Embedding QDs in a glass host protects them from oxidation and agglomeration, allowing for high-power or high-temperature operation that colloidal QDs in polymer could not withstand [60].

One demonstration of the synergy is in nonlinear optical switching. Glasses containing PbS or CdSe QDs have shown absorption saturation and optical limiting behavior [61]. Under intense light, QDs can bleach (empty state filling) or exhibit two-photon absorption, useful for passive Q-switches. A seminal result involved PbS quantum dots in a phosphate glass used as a saturable absorber for a 1.54 μm Er:glass laser, achieving mode-locking [62].

A very hot topic in recent years is the encapsulation of lead–halide perovskite nanocrystals (such as CsPbX₃, where X = Cl, Br, I) inside glass [63,64]. Halide perovskite QDs are renowned for their outstanding photoluminescence (quantum yields 50–90%) and color purity, making them ideal for LEDs and lasers; but in colloidal form, they are chemically and thermally unstable (decomposing with moisture or heat) [65]. Encapsulating these perovskite NCs in a robust inorganic glass addresses the stability issue. Researchers have developed special glass compositions (often all-inorganic oxides or halide-containing

glasses) where, upon heat treatment, CsPbX_3 nanocrystals precipitate in situ [66]. The resulting perovskite–glass nanocomposite can be handled like a regular piece of glass but emits brightly in the desired wavelength. For instance, a transparent aluminosilicate glass was used to precipitate CsPbBr_3 nanocrystals ($\sim 8\text{--}10\text{ nm}$) uniformly throughout the matrix. The composite showed a strong green photoluminescence at $\sim 520\text{ nm}$ (characteristic of CsPbBr_3) with high stability: it withstood water immersion and $250\text{ }^\circ\text{C}$ heating in air with no degradation of emission [67]. Moreover, the refractive index of the glass (~ 1.7) was close to that of the NCs, enhancing radiative emission rates by increasing the photonic density of states. As a result, the scintillation performance was impressive: under X-ray excitation, the perovskite-NC glass generated about half the light of a standard $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) crystal scintillator, but with a decay time of only 15 ns (compared to BGO's $\sim 300\text{ ns}$) [68]. This combination of decent light yield and very fast response is extremely attractive for X-ray imaging screens and high-frame-rate radiation detectors. It underscores how a “nanoinhomogeneity”—here, perovskite crystals—turns a passive glass into an active scintillator.

Another merit of perovskite–NC glasses is tunable emission: by adjusting halide ratio (Cl/Br/I) or NC size, one can span the whole visible spectrum with high color purity [69]. These could serve as down-conversion phosphors in LED backlights (replacing less stable organic phosphors). The glass encapsulation prevents anion exchange and Ostwald ripening that plagues colloidal perovskites, thus preserving the intended emission color over time.

In summary, embedding semiconductor or perovskite nanoparticles in glass imparts to the glass the optoelectronic functionalities of semiconductors (light emission, nonlinear absorption, etc.) while leveraging the glass's advantages (thermal stability, rigidity, transparency). It represents a convergence of glass science with nanocrystal chemistry, sometimes termed glass nanocomposites [35].

3.4. Nanopores in Glass (Nanoporous Glasses)

Not all useful inhomogeneities are separate phases; some are in the form of nanometer-scale pores or voids introduced in glass. Nanoporous glasses—typified by Vycor[®], which is made by leaching phase-separated borosilicate glass to remove one phase and leave a porous silica skeleton—have long been used for filtration and catalyst supports [70]. However, they are increasingly viewed as tunable optical materials in their own right [56]. A nanoporous glass (porosity of 30–50%, pore size 2–20 nm) maintains transparency if the pores are much smaller than visible wavelengths, yet the presence of pores yields a high specific surface area (up to $\sim 100\text{ m}^2/\text{g}$) that can be exploited for surface functionalization and infiltration. In essence, one creates an all-glass sponge that can be filled or coated with various substances to impart new properties [71].

One advantage is the ability to adsorb or load molecules into the pore network. For example, luminescent dyes or quantum dots can be infiltrated into a nanoporous glass, creating a hybrid material where the guest species is held in a rigid glass matrix [72]. Unlike doping a melt (where high temperatures might destroy an organic dye), nanoporous glass allows for the introduction of temperature-sensitive functional molecules at room temperature by soaking in solution and then drying [73]. Researchers have demonstrated making a luminescent device by loading Eu^{3+} complexes into nanoporous glass; the resulting material showed the expected red emission of Eu^{3+} , but with the inorganic glass protecting the complex from photochemical degradation [74]. Similarly, laser dyes have been incorporated in porous glass to make solid-state dye lasers (the glass prevents dye aggregation and improves thermal stability compared to polymer hosts). Nanoporous structure also allows for the tuning of optical properties via filling of the pores [75]. Since

the effective refractive index of a porous glass is lower than solid glass (a mix of glass and air), filling the pores with a liquid or polymer of a certain refractive index will change the composite's index. One can, thus, make tunable index materials or sensors: for instance, a porous glass waveguide's guiding property will change when pores fill with an analyte, enabling refractometric sensing of solvents or vapors. An all-optical example is using nanoporous glass in a photonic crystal fiber: researchers have drawn porous core fiber and then infiltrated the core with nonlinear liquids to achieve modulatable guided-wave optics. The nanoporous glass in the fiber provided a stable scaffold that could be infiltrated on-demand [76]. Moreover, the internal structure of nanoporous glass can be exploited for high-density optical data storage: a recent study demonstrated that just three femtosecond laser pulses per bit are sufficient to record information within nanoporous high-silica glass, enabling multilayer data storage with a capacity of 25 GB per disc and exceptional thermal stability up to 700 °C [77].

From a fabrication standpoint, nanoporous glasses are usually made by phase separation of a multi-component glass, followed by leaching. The classic Na_2O – B_2O_3 – SiO_2 system, when heat-treated, separates into a silica-rich phase and a borate-rich phase; acid leaching dissolves the borate, leaving a nanoporous silica skeleton [78]. Recent advances employ the sol–gel method to fabricate 3D-printable porous glass gels, enabling the creation of complex, functional structures. This approach allows for the production of nanoporous glass components that can be post-functionalized by infiltrating functional molecules. In one study, printed porous glass was infused with perylene dye for luminescence and with fluorosilane to achieve superhydrophobicity, demonstrating the versatility of this method for multifunctional optical devices [79].

In essence, nanopores are “inhomogeneities” that can be viewed as an empty second phase. While air inclusions of micron size would scatter light (like in foam glass), nanometer-size pores do not, so the material stays transparent [80]. The porous topology allows for things that solid glass cannot do, such as rapid diffusion of fluids (leading to applications in chromatography and microfluidics) and dynamic tuning (by filling or emptying pores). One can even do chemistry inside the glass: nanoporous glass can act as a nanoreactor to synthesize other nanomaterials in situ [33]. For example, by soaking porous glass in a gold salt and then reducing it, one can grow Au nanoparticles inside the pores, yielding a composite of Au NP + porous glass [81]. This is a way to stabilize otherwise aggregation-prone particles. Similarly, semiconductor QDs like CdS have been grown within nanoporous glass, essentially using the pores to confine the particle size [82].

Overall, nanoporous glasses represent a versatile form of functional inhomogeneous glass. They leverage the concept that a glass can be deliberately made two-phase on the nanoscale (solid + void) to gain new abilities. The field is seeing convergence with electronics and chemistry, e.g., porous glass membranes in sensors, or optical fibers with nanoporous cladding for tunable dispersion. As with nanocrystal composites, the challenge is controlling the structure (pore size distribution, connectivity) to achieve the desired effect without compromising transparency or strength.

3.5. Nuclear Waste Glasses

The immobilization of high-level nuclear waste nowadays fully relies on vitrification using durable glasses [83], extending this technological approach to much larger volumes of low- and intermediate-level waste [84]. These commonly contain relatively large amounts of crystalline particles within the body of durable vitreous wasteform [85]. Moreover, within nuclear waste immobilisation sector there is an evident trend of deliberate use of inhomogeneities in nuclear waste glasses aiming to increase the waste loading in the final wasteform at vitrification plants, as well as to use suitable crystalline species as matrices

for most toxic and long-lived waste components such as those containing minor actinides. The composition of crystalline inhomogeneities within the glass can be tailored both via composition designs and thermal processing schedules which enable the synthesis of durable glass crystalline (composite) materials (GCM) as final wasteforms characterized by high chemical, mechanical, and radiation durability [86].

4. Conclusions

The evolution of glass materials has transformed the concept of inhomogeneity: from a detrimental flaw to a functional design feature. Historically, striae, bubbles, and inclusions were defects to be eliminated. Today, with advances in nanotechnology and glass science, controlled nanoscale inhomogeneities, such as nanocrystals, metal nanoparticles, and nanopores, are deliberately introduced to impart optical, mechanical, or thermal functionalities.

This shift from “defects to features” reflects deep advances in compositional design and thermal processing. As 19th-century glassmakers refined techniques to eliminate striae, modern researchers now optimize doping, nucleation, and heat treatment to engineer nanostructured glasses. Such materials retain the advantages of glass: transparency, durability, processability, while gaining new capabilities, from upconversion luminescence to plasmonic enhancement and nonlinear optical behavior.

Looking forward, nanoscale inhomogeneities will continue to define the next generation of functional glasses for photonics and beyond. What was once a liability is now a design strategy: glass has become not just a medium, but a tunable, multifunctional nanocomposite.

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