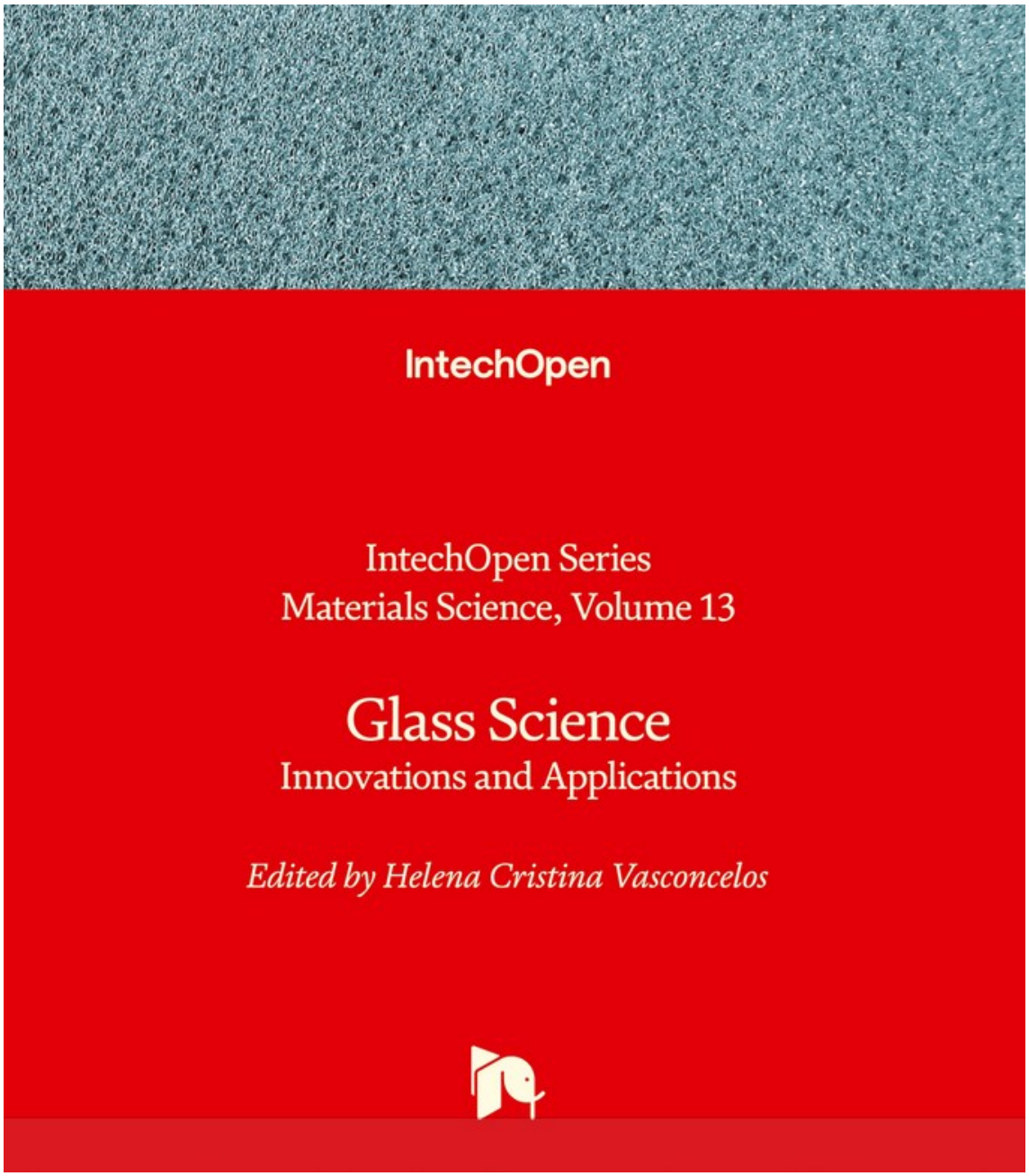
IntechOpen
IntechOpen Series
Materials Science, Volume 13
Glass Science
Innovations and Applications
Edited by Helena Cristina Vasconcelos

Glass Science - Innovations and Applications
http://dx.doi.org/10.5772/intechopen.1005958
Edited by Helena Cristina Vasconcelos

Contributors
Brenno Silva Greatti, Elke Altenburger, Euclydes Marega Junior, Jianwei Li, Jinsheng Jia, José Luis Clabel Huamán, José Yitzhak Aarón Chacaliaza Ricaldi, Kiran D.S., Kiran N., Marcelo Sandrini, Marcos Paulo Belançon, Meilun Zhang, N. Mahendra Reddy, Praveen Kumar R., Rafaela Valcarenghi, Raquel Dosciatti Bini, Robson Ferrari Muniz, Susan R. Trammell, Susheela K. Lenkennavar, Tomasz E. Burghardt, Victor Anthony Garcia Rivera, Vitor Santaella Zanuto, Zhenbo Cao

First published in London, United Kingdom, 2025 by IntechOpen
IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales, registration number: 11086078, 167-169 Great Portland Street, London, W1W 5PF, United Kingdom

For EU product safety concerns: IN TECH d.o.o., Prolaz Marije Krucifikse Kozulić 3, 51000 Rijeka, Croatia, info@intechopen.com or visit our website at intechopen.com.

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Glass Science - Innovations and Applications
Edited by Helena Cristina Vasconcelos
p. cm.

This title is part of the Materials Science Book Series, Volume 13
Topic: Metals and Nonmetals
Series Editor: Chonghe Li
Topic Editor: Joan Josep Roa Rovira

Print ISBN 978-1-83634-098-0
Online ISBN 978-1-83634-097-3
eBook (PDF) ISBN 978-1-83634-099-7
ISSN 3049-8856

If disposing of this product, please recycle the paper responsibly.

Chapter

Glass Thin Films: From Deposition to Integrated Photonic Applications

José Yitzhak Aarón Chacaliaza Ricaldi, Victor Anthony Garcia Rivera, José Luis Clabel Huamán and Euclydes Marega Junior

Abstract

This chapter focuses on the science and technology of glass thin films, emphasizing advanced fabrication techniques such as magnetron sputtering, spin coating, and pulsed laser deposition. It details how these methods produce films with a uniform distribution of rare-earth ions that enhance optical and functional properties. The chapter also explores the underlying mechanisms by which these dopants modify film characteristics to enable the development of photonic devices, emphasizing practical applications that showcase the pivotal role of RE-doped glass thin films in advancing next-generation photonics.

Keywords: glasses, thin films, rare-earth ions, optical spectroscopy, photonic devices

1. Introduction

Glass is one of the most fascinating and versatile materials ever developed by mankind. It has been so essential for the development of modern civilization that Morse and Evenson propose that we are now living in the Glass Age [1], and the United Nations General Assembly named 2022 the International Year of Glass [2].

According to the American Society for Testing and Materials (ASTM) standard of 1945, glass is "an inorganic product of fusion that has been cooled to a level of rigidity without crystallizing" [3]. However, the discovery of organic, polymeric, and metal alloy glasses in the last century invalidated this definition. Furthermore, natural glasses such as obsidian existed long before the emergence of life on Earth [4], and some authors suggest that most of the water in the Universe may be glassy [5].

The conceptual definition of glass remains an open topic of discussion in the scientific community. Modern definitions vary: Mari [6] describes glass as "an amorphous solid obtained by rapid cooling of a molten mass, avoiding crystallization." Zarzycki [7] states that glasses "are non-crystalline solids that exhibit the glass transition phenomenon." Shelby [8] defines it as "an amorphous solid with a complete absence of long-range order and periodicity, exhibiting a glass transition region." Rao [9] describes it as "a solid obtained by overcooling a liquid that is amorphous to X-rays." Varshneya [10] states that glass is "a solid with a noncrystalline structure that continuously turns into a liquid when heated."

Finally, Zanotto and Mauro [11] propose two definitions. The first, aimed at the general public and young researchers, describes glass as "a noncrystalline and nonequilibrium state of matter, which appears solid on a short time scale but continuously relaxes toward the liquid state." The second, more detailed definition states that glass is "a noncrystalline and nonequilibrium condensed state of matter that exhibits a glass transition. The structure of glasses is similar to that of their supercooled liquid (SCL) predecessors, and they spontaneously relax toward this state. Their final destiny, in the limit of infinite time, is to crystallize."

As we move into an era of integrated photonics, where optical systems are becoming more and more miniaturized every day, and incorporated into tiny chips; therefore, the need for new materials that can operate at the nanoscale becomes critical [12–15]. The challenge lies in adapting the remarkable properties of bulk glasses to this new landscape. How do we create glass-based devices that are not only thin enough to be seamlessly integrated into lab-on-chip, but also retain the optical characteristics required for photonic applications? This is where glass thin films come in. These nanometer-thick glass layers, fabricated using advanced cutting-edge techniques, offer a promising solution. By carefully controlling their composition and thickness, researchers can create thin films that take advantage of the properties of RE-doped glasses while also meeting the demands of modern integrated photonic devices.

The annual number of publications on glass thin films has grown significantly in the scientific literature. According to the Scopus database (see **Figure 1a**), the first recorded study on the subject dates back to 1870 by Boettger [16]. However, there was a gap in publications until 1920, when authors Becker and Curttis [17], Frehafer [18], and Curtiss [19] independently published their works in Physical Review. A significant inflection point occurred in the 1980s, marking a steady increase in the number of publications, which peaked at 3000 documents per year in the 2010s. **Figure 1b** presents the 20 countries with the highest publication output in this field. The United States leads with over 9000 published documents, followed by China and India, each exceeding 8000 publications. **Figure 1c** categorizes the research output by field of study, with Materials Science contributing to the largest share (29.3%), followed by Physics (26.7%), Engineering (19.2%), Chemistry (13.9%), and Computer Science (2.6%).

This chapter delves into the realm of glass thin films, beginning with an overview of their advanced fabrication techniques. It then examines methods for precisely tailoring their optical properties and concludes with a discussion of how these materials have the potential to revolutionize integrated photonics, enabling the development of smaller, faster, and more efficient optical devices for the next generation of technological innovation.

2. Fabrication techniques

A thin film is a layer that extends widely in two dimensions but has a limited thickness in the third. Its thickness can range from a few nanometers to several micrometers [20]. The main advantage of thin film technology lies in miniaturization while preserving the properties of the original material. The film's characteristics depend largely on its structure, while its mechanical and thermal properties are closely related to the synthesis conditions and deposition method used.

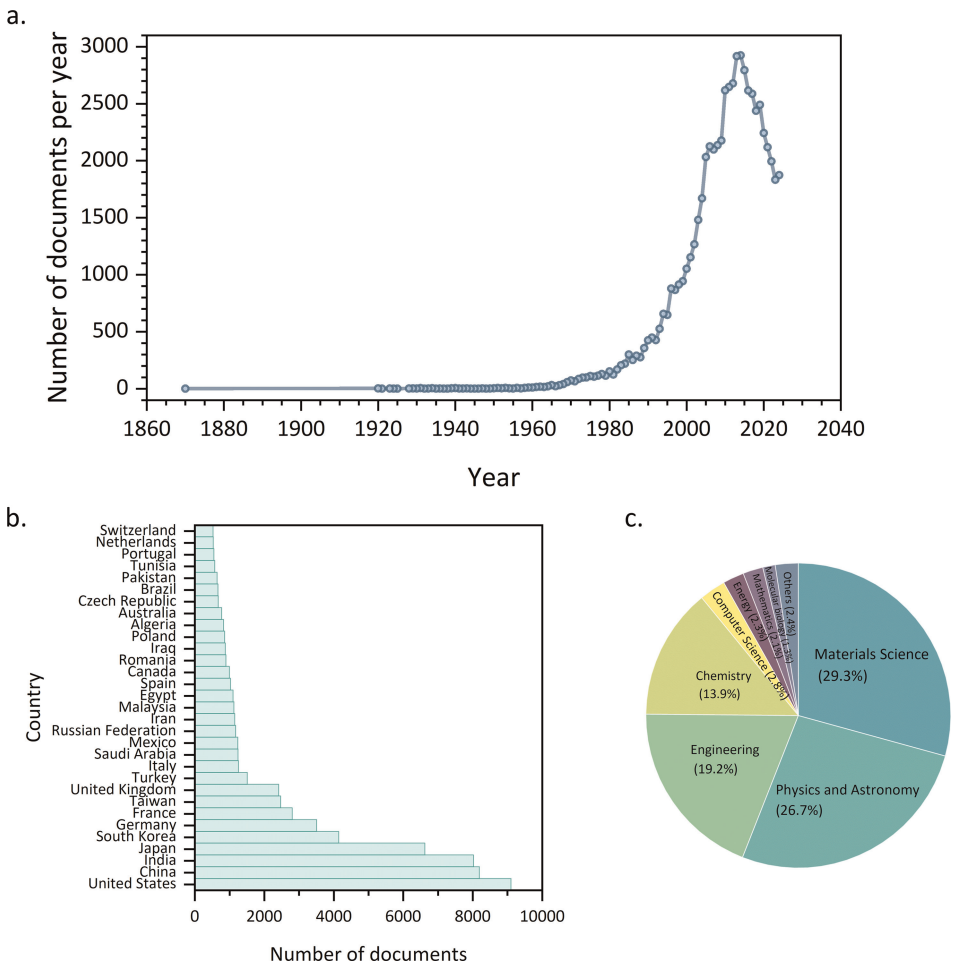

Figure 1.
a. Number of documents per year; b. Number of documents per country; c. Area of knowledge that they publish on glass thin films. Source: Scopus database. Revised 01/02/2025.

Glass thin films are at the forefront of materials science, bridging the extraordinary optical properties of bulk glasses with the demands of integrated photonics at the nanoscale [21, 22]. They preserve the functionality of traditional glasses (such as stoichiometry and optical properties) while enabling seamless integration into modern photonic devices. Their ability to host RE ions and exhibit tailored optical characteristics makes them indispensable for telecommunications, sensing, and quantum technologies [23]. To achieve the precision required for advanced applications, researchers rely on cutting-edge fabrication techniques such as magnetron sputtering, pulsed laser deposition, and spin coating. These techniques enable thin films to meet the stringent requirements of integrated and lab-on-chip photonics [24, 25].

2.1 Magnetron sputtering

One of the most effective techniques for fabricating thin films with high precision and uniformity is radio-frequency magnetron sputtering (RF-MS). This method is

widely used to deposit thin films of complex materials, including glasses, onto various substrates. RF-MS enables the deposition of these materials while preserving their composition, unlocking new functionalities at the nanoscale. Its precise control over film composition, thickness, and microstructure makes RF-MS particularly valuable for applications in biomedicine, optics, and microelectronics [20, 26, 27].

2.1.1 Experimental details

Sputtering is a physical process widely used in materials science and nanotechnology for thin film deposition. It involves the ejection of atoms from a solid material (the target) due to high-energy ion collisions. These ions are generated by ionizing an inert gas, such as argon, under the influence of a strong electric field. Ionization occurs when a high-intensity electric field strips electrons from gas atoms, creating ions and free electrons [28]. These charged particles interact with each other and surrounding gas molecules, forming a plasma—a state of matter consisting of ionized gas with collective electromagnetic properties [29].

The electric field required for plasma generation is produced using a magnetron, a specialized device consisting of two cylindrical electrodes. One of these electrodes is powered by a radio-frequency (RF) source, which establishes an oscillating electric field between them. Additionally, the magnetron contains an array of toroidal-shaped permanent magnets that generate a poloidal magnetic field. This field confines electrons and ions close to the target material, enhancing ionization and prolonging plasma stability, thereby increasing the efficiency of the sputtering process [30].

A schematic of an MS apparatus is shown in **Figure 2**. Typically, deposition occurs in a high-purity inert gas atmosphere (e.g., Ar) at a working pressure of 5×10^{-3} mbar. The targets, which in this case can be glasses, are sputtered using a magnetron power of approximately 200 W.

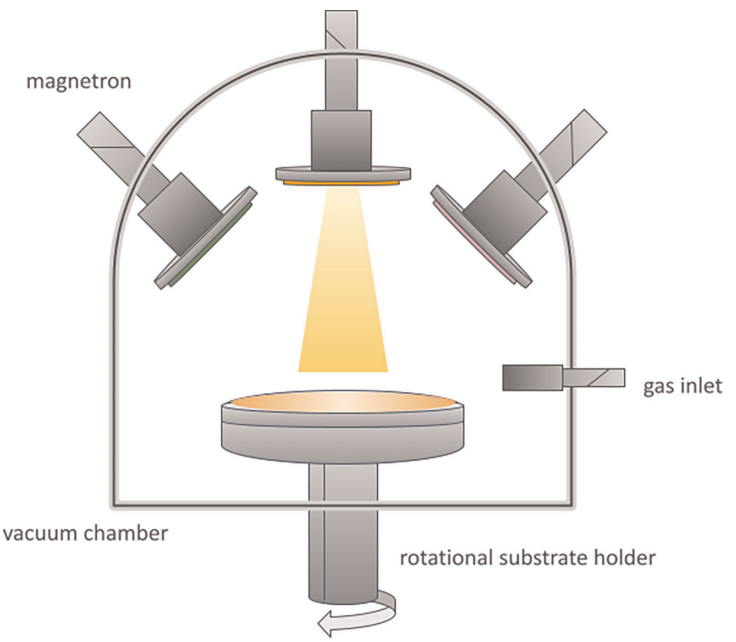

Figure 2.
Graphical scheme of magnetron sputtering chamber.

The deposition process follows these steps:

1. A bulk glass sample doped with RE ions serves as the target material [31].

2. Once the plasma is established, energetic gas ions are accelerated toward the target.

3. Upon collision with the target surface, these ions transfer energy to the material, causing atoms to be ejected (a process known as sputtering).

4. The ejected atoms travel toward a nearby substrate, where they condense to form a uniform thin film.

RF-MS is a fundamental technique in thin film deposition, enabling precise thickness control and high uniformity. It is widely used in the manufacturing of optical coatings, semiconductor devices, and protective layers for various technological applications [32].

2.1.2 Applications

For photonic applications, the literature reports various waveguides based on thin films fabricated by RF-MS. Del Cacho et al. [33] described PbO–GeO_2 rib waveguides deposited *via* RF-MS, followed by plasma etching and lithography. They reported low propagation losses of 0.6 dB/cm for 10 μm rib widths and 2.2 dB/cm for 3–5 μm rib widths.

PbO–GeO_2 glasses have also been used as a matrix for metallic nanoparticles to modify their physical properties. Santos Filho et al. [34] investigated the effects of thermal annealing on the semi-insulating properties of PbO–GeO_2 thin films produced by RF-MS, specifically focusing on PbO–GeO_2 films containing $AgNO_3$. The films were annealed at 420 °C for varying durations, leading to structural changes and the formation of crystalline Ag nanoparticles, which influenced their electrical properties. Key findings included an increase in leakage current, a decrease in the dielectric constant due to nanoparticle incorporation, and the films' potential as passivating materials for power devices. Characterization methods included electron diffraction and electrical measurements (C–V and G–V).

Regarding pedestal waveguides deposited by RF-MS using the glassy PbO–GeO_2 system as a target, studies have explored co-doping with RE ions to enhance optical amplification in the near-infrared (NIR) region [35]. de Assumpção et al. [36] investigated the fabrication and optical characterization of Tm^{3+}/Yb^{3+} co-doped PbO–GeO_2 pedestal waveguides obtained *via* RF-MS. Infrared and infrared-to-visible frequency upconversion luminescence of Tm^{3+} ions was measured under 980-nm continuous wave laser excitation. The waveguides exhibited propagation losses of approximately 11 dB/cm at 630 nm and 9 dB/cm at 1050 nm for widths ranging from 20 to 100 μm.

Further developments were reported by Bomfim et al. [37], who studied the fabrication and optical properties of Yb^{3+}/Er^{3+} co-doped PbO–GeO_2 pedestal waveguides. By optimizing deposition parameters and increasing pedestal height, radiation leakage was minimized, leading to lower propagation losses of around 2.5 dB/cm at 632 nm and 1.0 dB/cm at 1068 nm for waveguides with widths between 12 and 100 μm. These improvements in fabrication also contributed to enhanced internal gain, demonstrating the potential of these waveguides as optical amplifiers in the NIR.

Later, Bomfim et al. [38] incorporated Au nanoparticles into these waveguides using conventional photolithography and plasma etching, avoiding metallic masks that typically introduce roughness. The inclusion of Au nanoparticles resulted in a 180% enhancement in relative gain due to local field amplification near the nanoparticles, increasing the excitation density of RE ions. Additionally, propagation losses were further reduced, and light guiding was achieved in smaller core widths (6 μm) compared to previous studies. These results highlight the advantages of pedestal waveguide amplifiers fabricated *via* RF-MS and emphasize the critical role of deposition parameters in optimizing optical performance.

Beyond PbO–GeO_2, other glassy systems in thin-film form, such as TeO_2-ZnO [39] and TeO_2–WO_3–Bi_2O_3 [40], have been deposited using RF-MS. The effects of RE-ion doping [41] and metallic nanoparticle incorporation [42] have been studied, demonstrating promising results for integrated photonics applications.

Research on thin films fabricated *via* RF-MS from glasses has also shown potential in biomedicine, particularly with bioactive glasses (BGs) as targets. BGs can form strong bonds with tissues and release therapeutic ions. However, their biomechanical compatibility for load-bearing applications remains suboptimal, which may be improved through coatings developed using RF-MS [43]. Stan et al. [44] reviewed the development and application of BG coatings for load-bearing endosseous implants. Several deposition methods, including RF-MS, have been explored to enhance the properties of BG coatings. Studies indicate that BG coatings exhibit good biocompatibility, bioactivity, and antibacterial properties, making them suitable for orthopedic and dental implants.

2.2 Pulsed laser deposition

The nanostructuring of optical devices has driven the rapid advancement of integrated photonics, where compact and efficient light sources, amplifiers, and sensors play a crucial role [45]. In applications such as lab-on-chip technologies, optical communication, and quantum photonics, high-quality thin films with the tailored optical properties are essential [46]. One promising technique for fabricating these films is pulsed laser deposition (PLD), a versatile method capable of transferring complex materials, such as rare-earth-doped glasses, onto various substrates while preserving their composition. These glasses can be transformed through PLD into high-quality thin films, enabling researchers to explore new functionalities at micro- and nanoscale dimensions [47].

PLD emerged as a thin-film synthesis technique shortly after the invention of the pulsed ruby laser in the 1960s. However, it gained significant traction in the late 1980s, particularly for fabricating high-temperature superconducting thin films. While conceptually straightforward, PLD involves highly complex and interrelated physical ablation processes. This method employs a pulsed laser to ablate material from a target, generating a plasma plume that deposits a thin film onto a substrate [48]. The plume, composed of atoms, ions, and clusters, travels toward a substrate positioned 5–10 cm away, where condensation and film growth occur. An image of the plasma plume inside a PLD apparatus during operation is shown in **Figure 3**.

The versatility of PLD offers several advantages, including stoichiometric transfer of the target material, high deposition rates, and the ability to synthesize a wide range of materials. In particular, rare-earth-doped glasses benefit from PLD due to their unique optical properties, making this technique highly relevant for photonic applications.

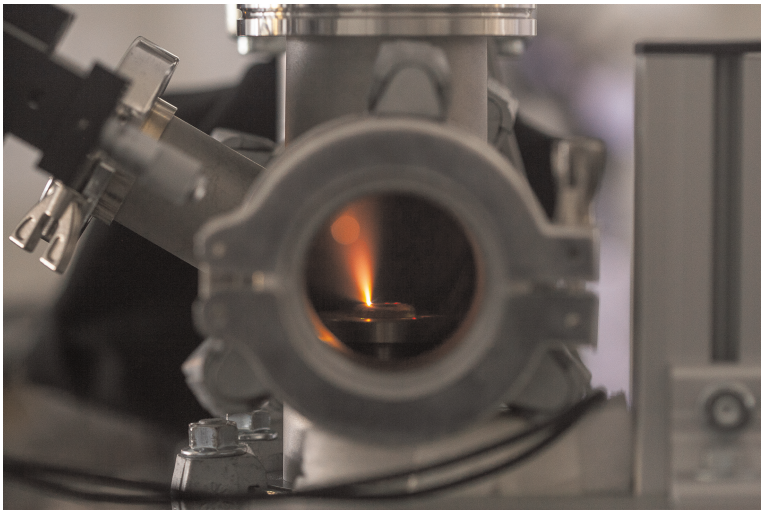

Figure 3.
Plume generated during PLD deposition.

2.2.1 Experimental details

PLD is a physical vapor deposition technique that relies on the interaction between a high-power laser and a solid target material. The general working principle involves the following steps:

1. A bulk glass sample doped with RE ions serves as the target material.

2. A high-energy pulsed laser, typically an excimer laser (KrF, 248 nm; ArF, 193 nm) or a Nd:YAG laser (1064, 532 nm), is directed onto the target surface inside a vacuum chamber.

3. The laser pulse ablates the material, generating a highly energetic plasma plume composed of atoms, ions, and molecular fragments.

4. The ejected species travel through the chamber and condense onto a substrate (e.g., Si, quartz, or sapphire), forming a thin film.

5. By tuning parameters such as laser fluence, repetition rate, ambient gas pressure (e.g., oxygen or argon), and substrate temperature, the properties of the deposited film can be precisely controlled. A schematic representation is presented in **Figure 4**.

By adjusting parameters such as laser energy, pulse duration, and substrate temperature, researchers can fine-tune the structural and optical properties of the resulting films. PLD is particularly advantageous for fabricating films from complex materials, as it preserves the stoichiometry of the target, which is crucial for maintaining the optical characteristics of RE-doped glasses. Moreover, PLD enables the deposition of multilayer structures and the integration of different materials on a single substrate, facilitating the development of advanced photonic devices.

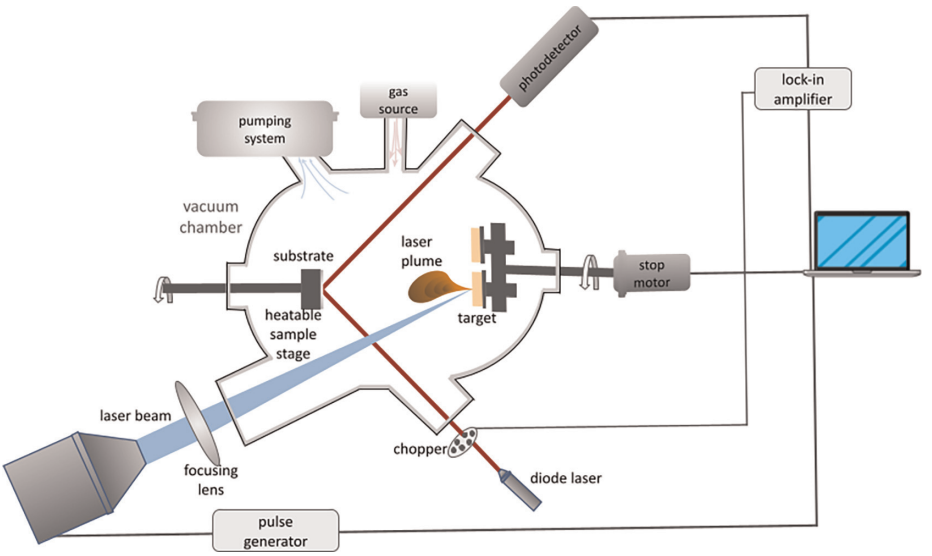

Figure 4.
Schematic representation of the PLD process.

2.2.2 Applications

PLD has emerged as a versatile and powerful technique for fabricating high-quality glass thin films, enabling precise control over composition, structure, and functionality [49].

Recent advancements in PLD have broadened its applications to bioactive glass-ceramics for medical implants [50], transparent conductive oxides for optoelectronics [51], and radiation-sensitive materials for imaging technologies [52]. By optimizing parameters such as laser fluence, background gas pressure, and substrate temperature, researchers have achieved films with the tailored optical properties [53]. The technique's ability to preserve target stoichiometry while accommodating complex multilayer architectures establishes it as a critical tool in advancing glass-based technologies [54].

Substrate heating during deposition enhances surface diffusion, promoting the formation of crystalline phases within otherwise amorphous glass matrices [55]. For instance, in fluorochlorozirconate films deposited on fused silica, substrate temperatures below 300 °C resulted in amorphous layers, whereas post-deposition annealing at 870 °C induced the crystallization of barium chloride nanocrystals within the glass network [56]. The interplay between thermal energy and the glass transition temperature (T_g) dictates whether the films retain their amorphous structure or develop controlled crystallinity [57]. Adhesion mechanisms vary significantly between metallic and dielectric substrates—titanium implants require surface pre-treatment with HNO_3/HF solutions to create micromechanical interlocking sites for bioactive glass coatings [58], whereas oxide substrates such as silica rely on chemical bonding through oxygen bridges [59].

Several glassy systems have been explored in thin-film form using PLD, including fluoride [55], sulfide [60], fluorozirconate [56], and chalcogenide glasses [61], all demonstrating promising results for integrated photonics applications.

PLD has also been extensively used to fabricate high-quality RE-doped glass thin films. Morea et al. [62] reported the production of Er^{3+}-doped fluorotellurite (TeO_2–

$ZnO–ZnF_2$) thin films with high refractive index, low absorption, and broad optical transmission, focusing on the effects of processing parameters. Their findings indicate that oxygen pressure (5–10 Pa), laser energy density (~2 J/cm^2), and substrate-target distance are crucial for achieving transparent films with $n \approx 2$ at 630 nm. In a subsequent study on the same glass system, Morea et al. [63] investigated the Er^{3+} emissions in the NIR region (1530 nm). Their results demonstrated that thermal annealing at 300–315 °C significantly enhanced photoluminescence (PL) performance, increasing emission intensity by over an order of magnitude and extending the PL lifetime to approximately 3.3 ms. This improvement was attributed to a reduction in OH^- concentration during annealing. However, residual OH^- content still contributed to non-negligible nonradiative relaxation. The study concluded that PLD is an effective method for producing high-quality Er^{3+}-doped glass thin films suitable for optical applications, such as integrated lasers and amplifiers, while suggesting further optimization of the PLD process and thermal treatments to improve film properties.

An intriguing application of PLD was reported by Barimah et al. [64], who explored the fabrication and characterization of Er^{3+}-doped sodium zinc tellurite glass nanoparticles embedded in polymeric siloxane thin films. Their study demonstrated the successful integration of glass nanoparticles into polymer layers, with an average size of 12–21 nm and broad PL emission at 1530 nm. These findings highlight the potential of PLD for creating hybrid polymer-glass waveguide amplifiers, opening new possibilities for the development of low-cost integrated optical amplifiers.

2.3 Spin coating

One of the primary limitations of thin-film deposition *via* high-vacuum methods is the high production cost [65]. However, spin coating offers significant advantages, including simplicity, lower equipment costs, and reduced material waste compared to vapor deposition techniques [66]. This method enables the rapid and efficient fabrication of thin films while yielding novel and reproducible results. Spin coating involves depositing a liquid solution onto a substrate that is rapidly rotating at a high angular velocity. As the substrate spins, centrifugal forces distribute the solution evenly across its surface while counteracting adhesive interactions between the liquid and the substrate [67]. The final film thickness is primarily governed by the solution's viscosity, rotation speed, and the acceleration of the spinning platform [68].

Despite its advantages, spin coating presents challenges, such as controlling film uniformity on larger substrates and limitations regarding substrate compatibility. Variations in process parameters can significantly affect the film's final quality, potentially leading to issues with thickness consistency and surface defects [70, 71]. Furthermore, while the method is highly reproducible under controlled conditions, scaling up the process or adapting it to different material systems may require careful optimization.

Building on the general overview of the spin-coating process presented above, the following section focuses on the key parameters that govern film formation.

2.3.1 Key parameters in the film formation process

Spin coating differentiates itself from drop-casting and dip-coating by incorporating a stage where the substrate undergoes radial acceleration. Initially, the precursor

solution is deposited at the center of the substrate, either while the substrate is stationary (static deposition) or rotating slowly (dynamic deposition). Once the substrate rotates, the increasing centrifugal force eventually overcomes the liquid's surface tension, causing the material to spread uniformly across the surface and expelling the excess liquid [72–75]. Key parameters include the following:

- *Centrifugal force vs. surface tension:* The balance between these forces is crucial. The centrifugal force, which depends on the angular speed of the substrate, must exceed the liquid's surface tension, determined by its viscosity and molecular interactions, to achieve uniform spreading.

- *Solvent evaporation:* The solvents vapor pressure, combined with environmental conditions such as temperature, humidity, and gas flow, directly impacts the drying rate and, ultimately, the film quality. A rotation period of 30–90 seconds is a good starting point for many solvents, whereas higher boiling-point solvents may require longer drying times or additional drying steps.

- *Solution properties:* The concentration and viscosity of the polymer solution are essential factors, as they determine the final film thickness and uniformity. These properties depend on the polymer's chain length and the nature of intermolecular interactions.

- *Additional parameter—substrate surface energy:* The substrates surface energy affects wetting behavior and adhesion. A substrate with higher surface energy can improve film uniformity and durability by promoting better adhesion between the film and the substrate.

By carefully controlling these parameters, the spin-coating process can be optimized to produce high-quality films with desired structural and functional properties.

2.3.2 Er^{3+}-doped nanoglasses embedded in polymeric matrix

This section presents unpublished results on glass thin films deposited *via* spin coating, using a solution of Er^{3+}-doped tellurite nanoglass embedded in a polymethyl methacrylate (PMMA) matrix. The films were deposited on a pure silicon (Si (001)) substrate, selected for its non-luminescent properties under 980-nm excitation. The deposition methodology was adapted from previous studies on nanoceramic-based thin films [76–78].

Thin film deposition was conducted in a cleanroom under controlled airflow, temperature, and humidity conditions. The fabrication process consisted of the following steps:

1. Er^{3+}-doped tellurite glass was initially ground in an agate mortar to obtain a fine powder, which was further nanostructured using rotational mechanical milling with yttrium-stabilized zirconia grinding spheres. **Figure 5a** provides a schematic representation of the mechanical milling equipment.

2. The resulting nanoglass powder was dispersed in a PMMA matrix dissolved in anisole.

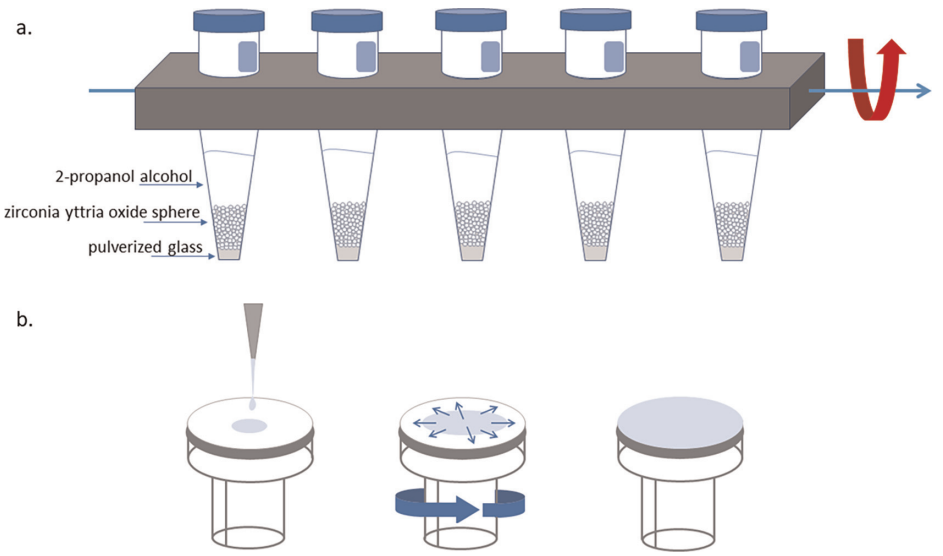

Figure 5.
Graphical representation of (a) rotational mechanical grinding and (b) spin-coating deposition. Adapted from Ref. [69].

3. The solution was deposited onto the Si substrate using a micropipette (60 μL) and spin-coated in two sequential steps:

   a. 1000 rpm for 10 s to spread the solution,

   b. 2000 rpm for 60 s to homogenize the film and achieve the desired thickness.

Figure 5b illustrates the spin coating process.

The thin film morphology was analyzed using scanning electron microscopy (SEM) (see **Figure 6a**. The embedded nanoglass particles within the PMMA matrix exhibited an average size of approximately 218 nm (see **Figure 6b**). Additionally, **Figure 6c** shows the surface profile obtained *via* atomic force microscopy (AFM) along the indicated black solid line. Based on this analysis, the PMMA film thickness was determined to be approximately 140 nm (see **Figure 6d**).

Figure 7a presents hyperspectral confocal microscopy measurements of the thin film across different regions, revealing the embedded nanoglasses within the PMMA matrix. The corresponding luminescence hyperspectra, shown in **Figure 7b**, exhibit the characteristic transitions of Er^{3+}, confirming the optical activity of the thin films. Moreover, the hyperspectral images demonstrate a nanoglass distribution and homogeneity consistent with the SEM and AFM results discussed in the previous section.

3. The effect of production methods on glass thin film properties

As presented in the previous sections, glass thin films play a crucial role in various integrated photonics applications, and their properties are strongly influenced by the deposition technique employed. Factors such as surface roughness, stoichiometry retention, amorphousness, and optical characteristics relative to the bulk can vary

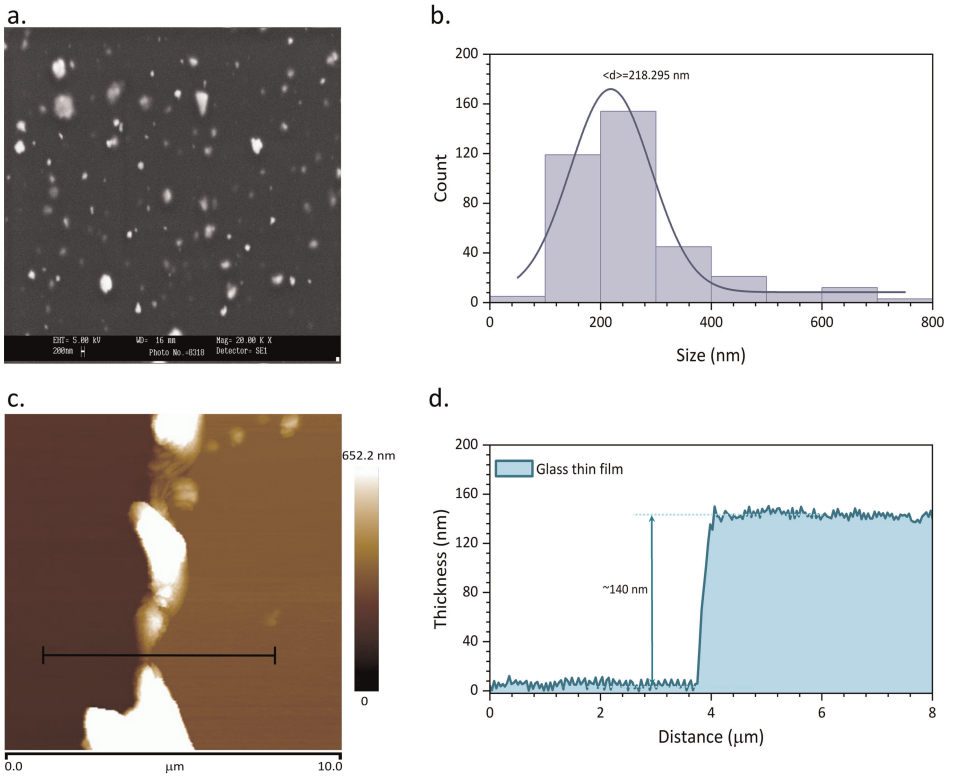

Figure 6.
(a) SEM image, (b) nanoglass size distribution, (c) AFM surface profile, and (d) thin film thickness measurement.

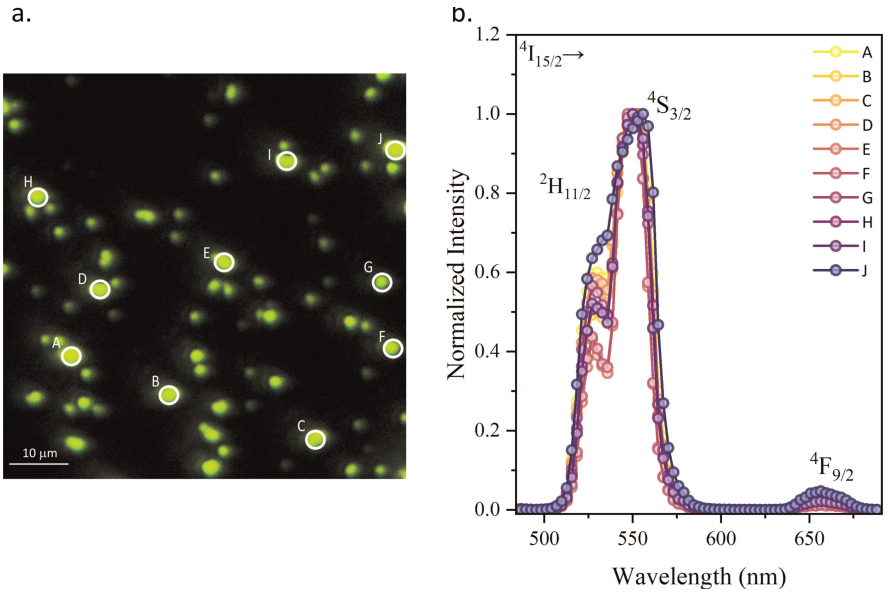

Figure 7.
(a) Hyperspectral image and (b) normalized luminescence spectra of the nanoglass thin film.

Property	RF-MS	PLD	Spin coating
Roughness	Low, but depends on working pressure and atom energy during deposition	Low, precisely controlled by laser energy and oxygen pressure	Can be high if the solution is not well dispersed or if aggregates are present
Stoichiometry retention	May vary due to preferential sputtering of lighter elements	High, as it faithfully transfers the bulk material composition	May vary due to differential solvent evaporation or phase segregation
Amorphicity	Depends on substrate temperature and working pressure; at low temperatures, amorphous films can be obtained	Can remain amorphous, but high temperatures may induce partial crystallization	Generally amorphous if dried properly without inducing crystallization
Optical properties	May differ from bulk glass due to changes in density and lattice defects	Similar to bulk material if deposition is homogeneous and free of optical defects	Refractive index and optical dispersion may change due to porosity or non-uniformity

Table 1.
Influence of the type of deposition on physical properties.

significantly depending on the deposition technique used (see **Table 1**). Understanding these differences is essential for optimizing the fabrication of thin films for specific applications. The following table summarizes the key characteristics of glass thin films deposited using these three methods. The information presented is based on the literature review presented in Section 2.

The selection of the appropriate technique depends on the intended application, whether prioritizing smooth surfaces, precise retention of stoichiometry, or ease of fabrication.

4. Conclusions

This study explores the fabrication of glass thin films using three complementary deposition techniques: pulsed laser deposition, magnetron sputtering, and spin coating. Each method presents unique advantages in terms of film quality, processing conditions, and potential applications in integrated photonics.

Magnetron sputtering, in contrast, provides a scalable and uniform deposition method suitable for producing high-quality dielectric films with controlled thickness and surface morphology. The technique allows for the precise tuning of film composition and microstructure by adjusting the sputtering power, gas pressure, and substrate temperature. While it is typically employed for depositing oxide-based optical coatings, its potential in RE-doped glass films is promising, particularly for applications requiring highly homogeneous layers with the excellent adhesion properties.

PLD has demonstrated its ability to produce high-quality thin films while preserving the stoichiometry of complex glass compositions. By optimizing deposition parameters such as laser fluence, background gas pressure, and substrate temperature, researchers have achieved films with tailored optical properties. Studies on glass thin films have shown that post-deposition thermal annealing significantly enhances PL by reducing OH^- impurities, leading to improved emission intensity and prolonged lifetimes. Furthermore, the ability of PLD to integrate multilayer structures opens new possibilities for optical amplifiers and photonic devices.

Spin coating offers a cost-effective and straightforward alternative for thin film fabrication, particularly for polymer-based hybrid materials. In this study, Er^{3+}-doped tellurite nanoglass thin films embedded in a PMMA matrix were successfully deposited on Si (001) substrates. SEM and AFM analyses confirmed a uniform nanoglass distribution within the PMMA matrix, with an average nanoparticle size of approximately 218 nm and a film thickness of 140 nm. Hyperspectral confocal microscopy validated the optical activity of the embedded nanoglass, revealing the characteristic luminescence emissions of Er^{3+}.

Overall, these three deposition techniques offer complementary advantages: PLD ensures precise compositional control and enables multilayer integration, magnetron sputtering provides scalability, uniformity, and excellent control over film microstructure, and spin coating presents a cost-effective and efficient method for fabricating polymer-based hybrid films.

Each method is highly relevant for different photonic applications, including integrated optics, optical amplifiers, and hybrid waveguide structures. Finally, the versatility of glass thin films, especially when doped with rare-earth ions, positions them as key materials in this evolving field. Future research directions include the development of hybrid integration platforms combining glass thin films with semiconductor and polymer photonics, advanced patterning techniques for precise light confinement, and the incorporation of plasmonic nanostructures to enhance light-matter interactions at the nanoscale. More broadly, integrated photonics is poised to revolutionize optical technologies by enabling compact, energy-efficient, and high-speed devices for telecommunications, quantum information processing, sensing, and biomedical diagnostics. Continued progress in deposition control, materials engineering, and device architecture will be crucial to fully realize the potential of glass thin films in next-generation integrated photonic systems.

Acknowledgements

This research was supported by the São Paulo Research Foundation (FAPESP) under the grants 2013/07276–1, 2021/11484-5 and 23/12143-2, 2023/08401-6, and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under the grant 174213/2023-9 and through the Centro de Pesquisas em Óptica e Fotônica (CePOF) - São Paulo - Brazil (processes 314505/2021-0 and 386305/2024-2). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

ASTM	American Society for Testing and Materials
BG	bioactive glasses
PLD	pulsed laser deposition

PMMA	polimetyl-metacrilate
RE	rare earths
RF	radio frequency
RF-MS	radio frequency magnetron sputtering
SCL	supercooled liquid
PL	photoluminescence
NIR	near infrared
SEM	scanning electron microscopy
AFM	atomic force microscopy

Author details

José Yitzhak Aarón Chacaliaza Ricaldi*, Victor Anthony Garcia Rivera,
José Luis Clabel Huamán and Euclydes Marega Junior
Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brazil

*Address all correspondence to: jchacaliaza@usp.br

IntechOpen

References

[1] Morse DL, Evenson JW. Welcome to the glass age. International Journal of Applied Glass Science. 2016;**7**(4):409-412. ISSN: 2041-1294. DOI: 10.1111/IJAG.12242

[2] Duran A. International Year of Glass Conference (10-11 February 2022): Overview Indico.UN. 2022. Available from: https://indico.un. org/event/37050/overview [Accessed: June 13, 2025]

[3] Yamane M, Asahara Y. Glasses for Photonics. Cambridge University Press; 2000. ISBN: 9780521580533. DOI: 10.1017/CBO9780511541308

[4] Mauro JC, Zanotto ED. Two centuries of glass research: Historical trends, current status, and grand challenges for the future. International Journal of Applied Glass Science. 2014;**5**(3):313-327. ISSN: 2041-1294. DOI: 10.1111/IJAG.12087

[5] Jenniskens P, Blake DF. Structural transitions in amorphous water ice and astrophysical implications. Science. 1994;**265**(5173):753-756. ISSN: 00368075. DOI: 10.1126/SCIENCE.11539186

[6] Mari EA. Los vidrios: Propiedades, tecnologías de fabricación y aplicaciones. Editorial Américalee; 1982. ISBN: 9500066173

[7] Zarzycki J. Les verres et l'état vitreux. Elsevier; 1982

[8] Shelby J. Introduction to Glass Science and Technology. Royal Society of Chemistry; 1997

[9] Rao KJ. Structural Chemistry of Glasses. Elsevier; 2002

[10] Varshneya AK. Fundamentals of Inorganic Glasses. Elsevier: Society of Glass Technology; 2012

[11] Zanotto ED, Mauro JC. The glassy state of matter: Its definition and ultimate fate. Journal of Non-Crystalline Solids. 2017;**471**:490-495. ISSN: 00223093. DOI: 10.1016/J.JNONCRYSOL.2017.05.019

[12] Crespi A et al. Integrated photonic quantum gates for polarization qubits. Nature Communications. 2011;**2**:566. ISSN: 2041-1723. DOI: 10.1038/ncomms1570

[13] Crespi A et al. Integrated multimode interferometers with arbitrary designs for photonic boson sampling. Nature Photonics. 2013;**7**:545-549. ISSN: 1749-4885. DOI: 10.1038/nphoton.2013.112

[14] Dyakonov IV et al. Reconfigurable photonics on a glass chip. Physical Review Applied. 2018;**10**:044048. ISSN: 2331-7019. DOI: 10.1103/PhysRevApplied.10.044048

[15] Pentangelo C et al. High-fidelity and polarization-insensitive universal photonic processors fabricated by femtosecond laser writing. Nano. 2024;**13**:2259-2270. ISSN: 2192-8614. DOI: 10.1515/nanoph-2023-0636

[16] Boettger. Coating of glass, porcelain or earthenware with a thin film of lustrous metallic platinum. Journal of the Franklin Institute. 1870;**89**:360. ISSN: 00160032. DOI: 10.1016/0016-0032(70)90158-4

[17] Becker JA, Curtiss LF. Physical properties of thin metallic films. I. Magneto-resistance effects in thin films of bismuth. Physical Review. 1920;**15**:

457-464. ISSN: 0031-899X. DOI: 10.1103/PhysRev.15.457

[18] Frehafer MK. Reflection and transmission of ultra-violet light by sodium and potassium. Physical Review. 1920;**15**:110-125. ISSN: 0031-899X. DOI: 10.1103/PhysRev.15.110

[19] Richtmyer FK, Curtiss LF. Physical properties of thin metallic films. II. Magneto-resistance effects in films of bismuth. Physical Review. 1920;**15**:465-475. ISSN: 0031-899X. DOI: 10.1103/PhysRev.15.465

[20] Garg R et al. Sputtering thin films: Materials, applications, challenges and future directions. Advances in Colloid and Interface Science. 2024;**330**:103203. ISSN: 00018686. DOI: 10.1016/j.cis.2024.103203

[21] Chu JP et al. Thin film metallic glasses: Unique properties and potential applications. Thin Solid Films. 2012;**520**:5097-5122. ISSN: 00406090. DOI: 10.1016/j.tsf.2012.03.092

[22] Hammi M, Maaroufi A. On optical properties of phosphate glass thin films. Materials Letters. 2016;**182**:227-230. ISSN: 0167577X. DOI: 10.1016/j.matlet.2016.06.094

[23] Diyatmika W et al. Thin film metallic glasses in optoelectronic, magnetic, and electronic applications: A recent update. Current Opinion in Solid State and Materials Science. 2015;**19**:95-106. ISSN: 13590286. DOI: 10.1016/j.cossms.2015.01.001

[24] Xian HJ et al. Flexible strain sensors with high performance based on metallic glass thin film. Applied Physics Letters. 2017;**111**:121906. ISSN: 0003-6951. DOI: 10.1063/1.4993560

[25] Kawata R et al. High-Q two-dimensional photonic crystal nanocavity on glass with an upper glass thin film. Optics Letters. 2024;**49**:2345. ISSN: 0146-9592. DOI: 10.1364/OL.522068

[26] Tite T et al. Phosphate bioglass thin-films: Cross-area uniformity, structure and biological performance tailored by the simple modification of magnetron sputtering gas pressure. Applied Surface Science. 2021;**541**:148640. ISSN: 01694332. DOI: 10.1016/j.apsusc.2020.148640

[27] Ma Y et al. Materials and structure engineering by magnetron sputtering for advanced lithium batteries. Energy Storage Materials. 2021;**39**:203-224. ISSN: 24058297. DOI: 10.1016/j.ensm.2021.04.012

[28] Braun M. Magnetron Sputtering Technique. Springer; 2015. pp. 2929-2957. DOI: 10.1007/978-1-4471-4670-4 28

[29] Chen FF. Introduction to Plasma Physics and Controlled Fusion. Springer; 2016. ISBN: 978-3-319-22308-7. DOI: 10.1007/978-3-319-22309-4

[30] Houska J. Design and reactive magnetron sputtering of thermochromic coatings. Journal of Applied Physics. 2022;**131**:110901. ISSN: 0021-8979. DOI: 10.1063/5.0084792

[31] Carvalho DO et al. A review on pedestal waveguides for low loss optical guiding, optical amplifiers and nonlinear optics applications. Journal of Luminescence. 2018;**203**:135-144. ISSN: 00222313. DOI: 10.1016/j.jlumin.2018.06.037

[32] Depla D, Mahieu S, Greene JE. Sputter deposition processes. In: Handbook of Deposition Technologies for Films and Coatings. Elsevier; 2010. pp. 253-296. DOI: 10.1016/B978-0-8155-2031-3.00005-3

[33] Del Cacho VD et al. PbO–GeO2 rib waveguides for photonic applications. Journal of Alloys and Compounds. 2011; **509**:S434-S437. ISSN: 09258388. DOI: 10.1016/j.jallcom.2011.01.141

[34] dos Santos Filho SG et al. Effects of thermal annealing on the semi-insulating properties of radio frequency magnetron sputtering-produced germanate thin films. Thin Solid Films. 2012;**520**:2695-2700. ISSN: 00406090. DOI: 10.1016/j.tsf.2011.11.043

[35] Kassab LRP, da Silva DM. Pedestal doped waveguides for infrared light amplification. In: Metal Nanostructures for Photonics. Amsterdam; 2019. pp. 303-326. DOI: 10.1016/B978-0-08-102378-5.00012-X

[36] de Assumpção TAA et al. Production and characterization of Tm3+/Yb3+ codoped waveguides based on PbO–GeO2 thin films. Journal of Alloys and Compounds. 2014;**586**:S368-S372. ISSN: 09258388. DOI: 10.1016/j.jallcom.2013.01.133

[37] Bomfim FA et al. Advances on the fabrication process of Er3+/Yb3+:GeO2–PbO pedestal waveguides for integrated photonics. Optical Materials. 2015;**49**: 196-200. ISSN: 09253467. DOI: 10.1016/j.optmat.2015.09.010

[38] Bomfim FA et al. A new fabrication process of pedestal waveguides based on metal dielectric composites of Yb3+/Er3 + codoped PbO-GeO2 thin films with gold nanoparticles. Optical Materials. 2018;**86**:433-440. ISSN: 09253467. DOI: 10.1016/j.optmat.2018.10.044

[39] Bontempo L, dos Santos Filho SG, Kassab LRP. Conduction and reversible memory phenomena in Au-nanoparticles-incorporated TeO 2 –ZnO films. Thin Solid Films. 2016;**611**:21-26. ISSN: 00406090. DOI: 10.1016/j.tsf.2016.04.046

[40] Camilo ME et al. Fabrication and characterization of pedestal optical waveguides using TeO2–WO3–Bi2O3 thin film as core layer. Thin Solid Films. 2014;**571**:225-229. ISSN: 00406090. DOI: 10.1016/j.tsf.2014.07.050

[41] Del Cacho VD et al. Fabrication of Yb3+/Er3+ codoped Bi2O3–WO3–TeO2 pedestal type waveguide for optical amplifiers. Optical Materials. 2014;**38**: 198-203. ISSN: 09253467. DOI: 10.1016/j.optmat.2014.10.027

[42] Kumada DK et al. Enhanced optical gain assisted by the plasmonic effects of Au nanoparticles in Nd^3 doped TeO-ZnO waveguides produced with the pedestal architecture. Journal of Luminescence. 2024;**276**:120865. ISSN: 00222313. DOI: 10.1016/j.jlumin.2024.120865

[43] Mesquita-Guimarães J, Henriques B, Silva FS. Bioactive glass coatings. In: Bioactive Glasses. Elsevier; 2018. pp. 103-118. DOI: 10.1016/B978-0-08-100936-9.00007-1

[44] Stan GE et al. Critical advances in the field of magnetron sputtered bioactive glass thin-films: An analytical review. Applied Surface Science. 2024; **646**:158760. ISSN: 01694332. DOI: 10.1016/j.apsusc.2023.158760

[45] Yang Z, Hao J. Progress in pulsed laser deposited two-dimensional layered materials for device applications. Journal of Materials Chemistry C. 2016;**4**(38): 8859-8878. ISSN: 2050-7526. DOI: 10.1039/C6TC01602B

[46] Masood KB et al. A comprehensive tutorial on the pulsed laser deposition technique and developments in the fabrication of low dimensional systems and nanostructures. Emergent Materials.

2021;**4**:737-754. ISSN: 2522-5731. DOI: 10.1007/s42247-020-00155-5

[47] Haider AJ et al., editors. A comprehensive review on pulsed laser deposition technique to effective nanostructure production: Trends and challenges. Optical and Quantum Electronics. 2022;**54**:488. ISSN: 0306-8919. DOI: 10.1007/s11082-022-03786-6

[48] Alejandro O-G-P, Döbeli M, Lippert T. Influence of plume properties on thin film composition in pulsed laser deposition. Advanced Materials Interfaces. 2018;**5**:1701062. ISSN: 2196-7350. DOI: 10.1002/admi.201701062

[49] Ganser D et al. Pulsed laser deposition of fluoride glass thin films. Applied Surface Science. 2010;**257**:954-959. ISSN: 01694332. DOI: 10.1016/j.apsusc.2010.07.100

[50] Teghil R, Curcio M, De Bonis A. Substituted hydroxyapatite, glass, and glass-ceramic thin films deposited by nanosecond pulsed laser deposition (PLD) for biomedical applications: A systematic review. Coatings. 2021;**11**:811. ISSN: 2079-6412. DOI: 10.3390/coatings11070811

[51] Ismail RA et al. Preparation and characterization of carbon nanotubes by pulsed laser ablation in water for optoelectronic application. Physica E: Low-dimensional Systems and Nanostructures. 2020;**119**:113997. ISSN: 13869477. DOI: 10.1016/j.physe.2020.113997

[52] Wang B et al. Recent progress in high-performance photo-detectors enabled by the pulsed laser deposition technology. Journal of Materials Chemistry. 2020;**C8**:4988-5014. ISSN: 2050-7526. DOI: 10.1039/C9TC07098B

[53] Ogugua SN, Ntwaeaborwa OM, Swart HC. Latest development on pulsed laser deposited thin films for advanced luminescence applications. Coatings. 2020;**10**:1078. ISSN: 2079-6412. DOI: 10.3390/coatings10111078

[54] Shepelin NA et al. A practical guide to pulsed laser deposition. Chemical Society Reviews. 2023;**52**:2294-2321. ISSN: 0306-0012. DOI: 10.1039/D2CS00938B

[55] Bond CW et al. Pulsed laser deposition of transparent fluoride glass. Journal of Non-Crystalline Solids. 2018;**488**:19-23. ISSN: 00223093. DOI: 10.1016/j.jnoncrysol.2018.03.005

[56] Jin Y et al. The effect of annealing on optical transmittance and structure of ZLANI fluorozirconate glass thin films. Micron. 2021;**140**:102977. ISSN: 09684328. DOI: 10.1016/j.micron.2020.102977

[57] Yu J et al. The correlation of optical transmittance with structural evolution in Fluorozirconate glass (ZLANI) thin films as a function of thermal annealing. Microscopy and Microanalysis. 2019;**25**(S2):2070-2071. ISSN: 1431-9276. DOI: 10.1017/S1431927619011085

[58] Joanni E et al. Pulsed laser deposition of SiO2 - P2O5 – CaO - MgO glass coatings on titanium substrates. Materials Research. 2004;**7**:431-436. ISSN: 1516-1439. DOI: 10.1590/S1516-14392004000300010

[59] Socol M et al. Pulsed laser deposition of indium tin oxide thin films on Nanopatterned glass substrates. Coatings. 2018;**9**:19. ISSN: 2079-6412. DOI: 10.3390/coatings9010019

[60] Normani S et al. Comparative study of Er3+—doped Ga-Ge-Sb-S thin films fabricated by sputtering and pulsed laser

deposition. Scientific Reports. 2020;**10**: 7997. ISSN: 2045-2322. DOI: 10.1038/s41598-020-64092-3

[61] Albarkaty KS et al. Erbium-doped chalcogenide glass thin film on silicon using femtosecond pulsed laser with different deposition temperatures. Applied Physics A. 2019;**125**:1. ISSN: 0947-8396. DOI: 10.1007/s00339-018-2286-x

[62] Morea R et al. Pulsed laser deposition of rare-earth-doped glasses: A step toward lightwave circuits. In: SPIE Opto 9744. 2016. p. 974402. ISSN: 1996756X. DOI: 10.1117/12.2208859

[63] Morea R et al. Er3+−doped fluorotellurite thin film glasses with improved photoluminescence emission at 1.53 μm. Journal of Luminescence. 2016;**170**:778-784. ISSN: 00222313. DOI: 10.1016/j.jlumin.2015.08.031

[64] Barimah EK et al. Erbium-doped glass nanoparticle embedded polymer thin films using femtosecond pulsed laser deposition. Optical Materials Express. 2018;**8**:1997. ISSN: 2159-3930. DOI: 10.1364/OME.8.001997

[65] Mammeri F. Nanostructured flexible PVDF and fluoropolymer-based hybrid films. Frontiers of Nanoscience. 2019;**14**: 67-101. ISSN: 1876-2778. DOI: 10.1016/B978-0-08-102572-7.00003-9

[66] Yilbas BS, Al-Sharafi A, Ali H. Surfaces for Self-Cleaning. Amsterdam: Elsevier; 2019. DOI: 10.1016/B978-0-12-814776-4.00003-3

[67] Boudrioua A, Chakaroun M, Fischer A. Organic light-emitting diodes. In: Organic Lasers. Elsevier; 2017. pp. 49-93. ISBN: 978-1-78548-158-1. DOI: 10.1016/B978-1-78548-158-1.50002-X

[68] Zhang JXJ, Hoshino K. Fundamentals of Nano/Microfabrication and Scale Effect. New York: Academic Press; 2019

[69] Ricaldi JYAC. Thin films based on Er^{3+} doped germanate-tellurite nanoglasses for plasmonics [MA thesis]. Universidade de São Paulo; 2023. DOI: 10.11606/D.76.2023.tde-18082023-093815

[70] Clabel JLH et al. Understanding the electronic properties of BaTiO 3 and Er 3 + doped BaTiO 3 films through confocal scanning microscopy and XPS: The role of oxygen vacancies. Physical Chemistry Chemical Physics. 2020;**22**:15022-15034. ISSN: 1463-9076. DOI: 10.1039/D0CP01010C

[71] Clabel JLH et al. Fabrication of micro patterns on BaTiO3:Er3+/Yb3+ perovskite films by femtosecond laser micromachining. Applied Surface Science. 2023;**634**:157658. ISSN: 01694332. DOI: 10.1016/j.apsusc.2023.157658

[72] Mokarian-Tabari P et al. Quantitative evaluation of evaporation rate during spin-coating of polymer blend films: Control of film structure through defined-atmosphere solvent-casting. The European Physical Journal E. 2010;**33**:283-289. ISSN: 1292-8941. DOI: 10.1140/epje/i2010-10670-7

[73] Münch A, Please CP, Wagner B. Spin coating of an evaporating polymer solution. Physics of Fluids. 2011;**23**: 102101. ISSN: 1070-6631. DOI: 10.1063/1.3643692

[74] Nguyen AN et al. Spin coating and micro-patterning optimization of composite thin films based on PVDF. Materials. 2020;**13**:1342. ISSN: 1996-1944. DOI: 10.3390/ma13061342

[75] Yin Y. Advances and perspectives of spin coating techniques. Applied and

Computational Engineering. 2023;**7**:291-301. ISSN: 2755-2721. DOI: 10.54254/2755-2721/7/20230495

[76] Clabel JL et al. Near-infrared light emission of Er3+—doped zirconium oxide thin films: An optical, structural and XPS study. Journal of Alloys and Compounds. 2015;**619**:800-806. ISSN: 09258388. DOI: 10.1016/j.jallcom.2014.09.007

[77] Clabel JL et al. Insights on the mechanism of solid state reaction between TiO_2 and BaCO3 to produce BaTiO3 powders: The role of calcination, milling, and mixing solvent. Ceramics International. 2020;**46**:2987-3001. ISSN: 02728842. DOI: 10.1016/j.ceramint.2019.09.296

[78] Clabel JL et al. Activation energy and its fluctuations at grain boundaries of Er3+:BaTiO3 perovskite thin films: Effect of doping concentration and annealing temperature. Vacuum. 2021;**194**:110562. ISSN: 0042207X. DOI: 10.1016/j.vacuum.2021.110562