

Preparation and Optical Properties of Gelatin-SiO₂ Hybrid Coatings on Glasses for Photovoltaic Applications

Stancho Yordanov^{1*}, Tatyana Ivanova², Shaban Uzun¹, Vladimir Petkov¹, Ina Gospodinova¹

¹ Bulgarian Academy of Sciences, Institute of Metal Science, Equipment, and Technologies "Acad. A. Balevski" with Center for Hydro- and Aerodynamics, 67 "Shipchenski prohod" str., 1574 Sofia, Bulgaria

² Bulgarian Academy of Sciences, Central Laboratory of Solar Energy and New Energy Sources, Sofia, Bulgaria
e-mail: stancho14@abv.bg

Abstract: In this study, gelatin-SiO₂ hybrid coatings were prepared on glass substrates using an acid-catalyzed sol-gel method. The deposited layers were subjected to thermal treatment at 50°C, 150°C, and 250°C to evaluate the effect of temperature on their structure and optical properties. Spectroscopic investigations in the UV-VIS-NIR range show that the hybrid coatings enhance optical transmittance and reduce reflective losses compared to uncoated glass. The best optical performance was observed for the sample thermally treated at 150 °C (GS 150), where an optimal balance between the organic (gelatin) and inorganic (SiO₂) phases was achieved, resulting in maximum transmittance and minimal light reflection. At lower treatment temperatures (50°C), the coating exhibited higher porosity but lower structural stability, whereas at higher temperatures (250°C), partial thermal degradation of the gelatin phase led to layer densification and a slight reduction in the antireflective effect. These results demonstrate that gelatin can be successfully used as a biopolymer component to control the microstructure and optical properties of sol-gel hybrid coatings. Improving optical transmittance and reducing reflective losses of glass surfaces is crucial for enhancing photovoltaic module efficiency, as it allows a greater amount of solar radiation to reach the active layer of solar cells.

Keywords: GELATIN-SiO₂ HYBRID, SOL-GEL METHOD, OPTICAL PROPERTIES, ANTIREFLECTIVE COATINGS

1. Introduction

Photovoltaic (PV) systems are among the fastest-growing renewable energy sources and play a key role in the transition to sustainable energy technologies. The efficiency of photovoltaic panels depends not only on the characteristics of the semiconductor materials but also on the optical properties of the protective glass covering the active layer. Glass serves as mechanical and environmental protection but can cause optical losses due to light reflection at the air-glass interface. For standard glass, reflective losses can reach approximately 4% per surface, reducing the amount of light reaching the photovoltaic cell and, consequently, lowering the module's energy efficiency [1, 2].

One of the most effective approaches to reduce these losses is the application of antireflective (AR) coatings on the glass surface. Such coatings are designed so that their effective refractive index lies between that of air and glass, allowing a reduction in reflection and an increase in light transmittance to the active layer of the photovoltaic cell [1]. In addition to optical performance, coatings for photovoltaic applications must have high transparency over a wide spectral range (UV-VIS-NIR), good mechanical stability, resistance to environmental conditions, and often self-cleaning properties that reduce dust and contamination accumulation on the panel surface [3].

Among the various methods for producing such functional coatings, the sol-gel technique is considered one of the most promising approaches. This low-temperature process allows the synthesis of inorganic and hybrid materials with controlled microstructure and optical properties [4,5]. The sol-gel method is compatible with industrial coating techniques for large surfaces, such as dip-coating, spin-coating, and spray-coating, making it particularly suitable for photovoltaic panel applications [6].

Silicon dioxide (SiO₂) is one of the most commonly used materials for sol-gel optical coatings due to its high transparency, chemical stability, and good adhesion to glass substrates. By controlling the porosity of the silica network, the effective refractive index of the coating can be tuned, enabling the formation of low-refractive-index layers with strong antireflective behavior [7]. Porous silica coatings with very low refractive indices ($n \approx 1.18$) have been reported, while maintaining nearly 100% transmittance at certain wavelengths [8]. Furthermore, multilayer sol-gel silica coatings can provide broadband antireflective performance with transmittance above 98% in the 350-1400 nm spectral range [9].

Despite these advantages, purely inorganic sol-gel silica films may exhibit limitations, such as cracking, internal stress, and limited mechanical durability during operation. One approach to

overcome these issues is the development of organic-inorganic hybrid materials, where the organic component is integrated into the inorganic silica network. Such hybrid systems combine the mechanical and chemical stability of the silica phase with the flexibility and film-forming properties of the organic components [10, 11].

Biopolymers are an especially interesting class of organic additives for producing such hybrid coatings. Gelatin, obtained by partial hydrolysis of collagen, is widely used due to its biocompatibility, biodegradability, and excellent film-forming properties. The presence of functional groups such as amino (-NH₂), carboxyl (-COOH), and hydroxyl (-OH) allows interaction with hydrolyzed silicate species and participation in the formation of organic-inorganic hybrid structures [12]. Moreover, gelatin can influence the viscosity of the sol system, hydrolysis and condensation kinetics, and thin-film formation, facilitating the preparation of uniform coatings [13].

Previous studies have shown that silica-gelatin hybrid materials can form transparent coatings on glass substrates. For instance, Smitha et al. reported transparent SiO₂-gelatin coatings with a thickness of about 300 nm and optical transparency above 90% [14]. Other studies have obtained silica-gelatin nanohybrid coatings with nearly 100% optical transmittance, indicating that proper control of nanostructure and component dispersion can preserve high optical transparency [15].

Despite these promising results, the relationship between synthesis conditions, hybrid network structure, and optical properties of gelatin-SiO₂ coatings on glass is not yet fully understood. The optical characteristics of these materials depend on several factors, including porosity, film uniformity, particle size, and the degree of interaction between the organic and inorganic phases [16].

Therefore, the aim of this work is to prepare gelatin-SiO₂ hybrid coatings on glass substrates using the sol-gel method and to investigate their optical properties through UV-Vis spectroscopy. Particular attention is paid to the influence of synthesis parameters and thermal treatment on the transparency and antireflective performance of the coatings, with a view to their potential application in photovoltaic panels.

2. Experimental procedure

The gelatin-SiO₂ hybrid coatings were prepared via an acid-catalyzed sol-gel process using tetraethyl orthosilicate (TEOS, ≥98%), absolute ethanol, 0.1 M HCl, distilled water, and commercial gelatin, all used without further purification. Standard soda-lime glass slides were used as substrates.

The initial silica sol was prepared by mixing 19 mL TEOS (17.73 g, 0.085 mol), 30 mL ethanol (23.67 g, 0.514 mol), 2.7 mL water (2.70 g, 0.150 mol), and 0.5 mL of 0.1 M HCl. The resulting initial molar ratio of TEOS:H₂O:EtOH was 1:1.76:6.05. In a separate vessel, 2 g of gelatin was dissolved in 60 mL of distilled water at 45 °C under magnetic stirring until fully dissolved. The gelatin solution, containing an additional 60 g water (3.33 mol H₂O), was slowly added to the silica sol under continuous stirring. After addition, the total water content reached 62.7 g (3.48 mol), resulting in a final molar ratio of TEOS:H₂O:EtOH = 1:40.9:6.05 and a hydrolysis ratio $R \approx 41$, characteristic of highly hydrolyzed silica systems.

For a more complete description of the composition, all components were also calculated in mass percentages. The final sol contained 59.1 wt% water, 22.3 wt% ethanol, 16.7 wt% TEOS, and 1.9 wt% gelatin. This high water fraction facilitates complete hydrolysis of TEOS and the formation of a hydroxyl-rich Si-O-Si network capable of interacting with the functional groups of gelatin. The resulting sol was stirred for 60 min and left to rest for 24 h at room temperature to stabilize the hydrolysis-condensation processes.

The glass substrates were cleaned ultrasonically in sequence with ethanol and distilled water and then dried at 100 °C. The coatings were applied via dip coating at a withdrawal speed of 72.9 mm/min under ambient conditions. After deposition, the films were allowed to dry for 2 h at 25 °C and subsequently thermally treated in air at 50 °C (GS 50), 150 °C (GS 150), and 250 °C (GS 250). These temperatures were selected to investigate the effect of partial or complete degradation of the organic phase on the optical properties and microstructure of the hybrid layers.

The optical properties of the coatings were examined using UV-VIS-NIR spectroscopy in the 300-1100 nm range in both transmittance and reflectance modes. Uncoated glass was used as a reference sample, allowing direct comparison of the effect of the hybrid layer on optical behavior.

3. Results and Discussion

The transmittance spectra of the hybrid coatings, measured with a Shimadzu UV 3600 UV-VIS-NIR spectrophotometer in the 240-1800 nm range, show a pronounced increase in optical transparency compared to uncoated glass. The spectra were recorded relative to air, with the spectrum of bare glass used as a reference. All samples exhibit higher transmittance in the 400-800 nm range, which can be attributed to the formation of a low-refractive-index porous silica layer modified by the organic gelatin phase. The highest transmittance is observed for the GS 150 sample, indicating optimal structuring of the SiO₂ network at this thermal treatment temperature. At 250 °C, partial degradation of the gelatin leads to densification of the layer and a slight increase in the refractive index, reducing the antireflective effect (Figures 1, 2, 3, and 4).

Reflectance spectra, measured using an aluminum mirror as the reference standard, confirm a reduction in surface reflection for all hybrid coatings. The minimum reflectance is observed for the GS 150 sample, corresponding to the best match of the effective refractive index between air and the glass substrate. The reduced reflection indicates the presence of nanometer-scale porosity in the hybrid SiO₂ structure, induced by the organic component. At higher temperature (250 °C), partial breakdown of the organic matrix results in a denser structure and, consequently, a slight increase in reflectance.

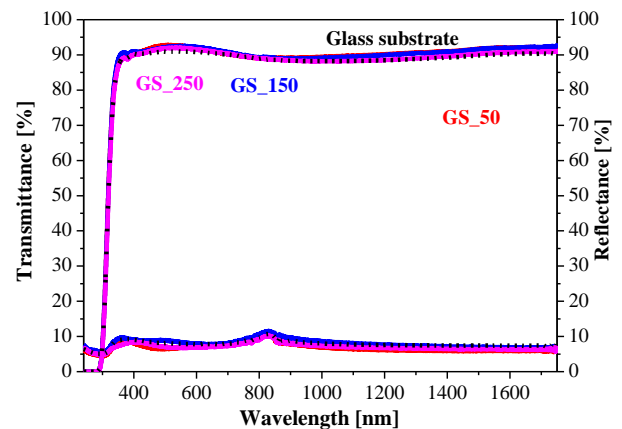


Figure 1. Transmittance and reflectance of gelatin-SiO₂ coatings after thermal treatment at 50 °C, 150 °C and 250 °C in the region 240-1800 nm range.

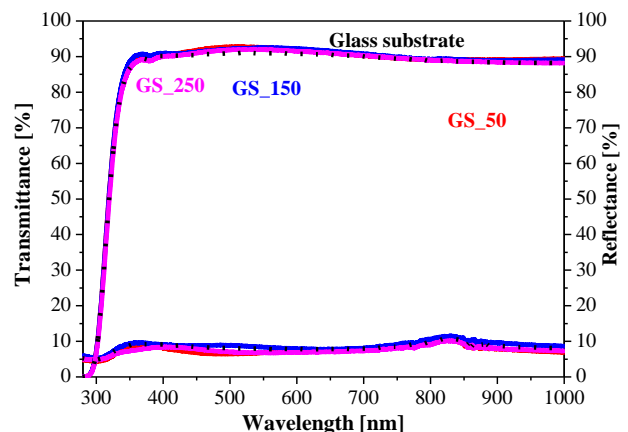


Figure 2. UV-VIS-NIR transmittance and reflectance of gelatin-SiO₂ coatings after thermal treatment at 50 °C, 150 °C and 250 °C in the 240-1000 nm spectral range

The spectra are recorded against air, with bare glass used as reference. The GS 150 sample shows the highest transmittance due to optimal stabilization of the hybrid silica network.

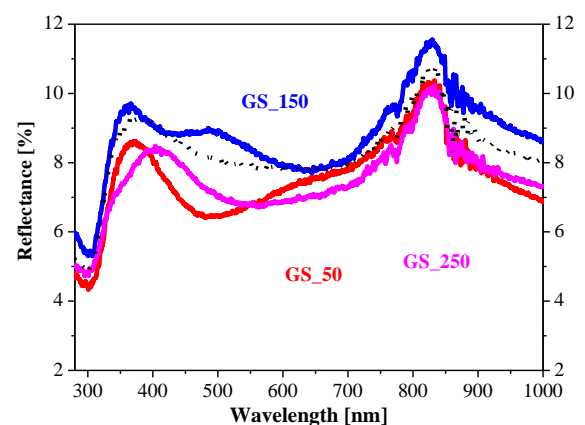


Figure 3. Reflectance in the range 2-12 % of gelatin-SiO₂ coatings after thermal treatment at 50 °C, 150 °C and 250 °C in the region 240-1800 nm range.

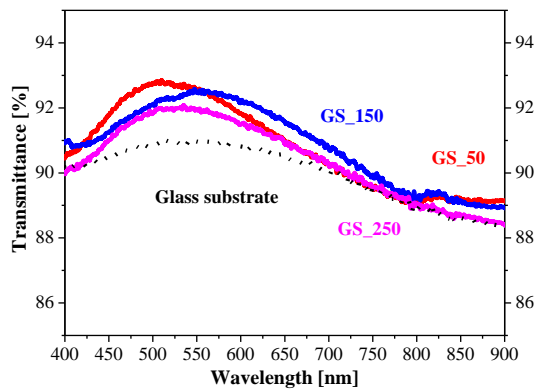


Figure 4. Transmittance in the range 86–94 % of gelatin-SiO₂ coatings after thermal treatment at 50°C, 150°C and 250°C in the region 240-1800 nm range.

Figure Summary

- GS 50: High organic phase → higher porosity, but lower structural stability.
- GS 150: Optimal balance between organic and inorganic phases → highest transmittance and lowest reflectance.
- GS 250: Partial gelatin degradation → densification of the layer, higher refractive index, reduced antireflective effect.

The results clearly demonstrate the influence of thermal treatment on the structure and optical properties of gelatin-SiO₂ hybrid coatings. At low temperature (50°C), the high organic content leads to increased porosity and lower structural stability, resulting in slightly reduced transmittance and higher reflectance. The optimal performance is observed for GS 150, where the interaction between gelatin and the SiO₂ network promotes the formation of a compact yet porous structure, which minimizes surface reflection and maximizes transmittance. This indicates that the organic phase not only facilitates the formation of a porous network but also stabilizes the hybrid structure, enhancing the optical properties.

At 250°C, partial degradation of gelatin results in densification of the layer, an increase in refractive index, and a slight rise in reflectance, confirming the role of the organic component in controlling porosity and the antireflective effect. These observations are consistent with previous studies on SiO₂-organic hybrid systems, where the balance between the organic and inorganic phases determines the optical characteristics and mechanical stability [9, 11].

Overall, the results demonstrate that by precisely controlling the thermal treatment temperature and sol composition, functional coatings with tailored optical properties can be obtained, suitable for applications such as antireflective layers on glass and potentially for photovoltaic panels.

4. Conclusion

1. Gelatin can be effectively integrated into the SiO₂ sol-gel network, providing structural adaptability and control over the porosity of the layer.
2. Gelatin-SiO₂ hybrid coatings exhibit enhanced transparency and reduced reflectance compared to uncoated glass, with optimal optical properties achieved at a thermal treatment of 150°C.
3. At lower temperature (50°C), the layer is porous but structurally less stable, whereas at higher temperature (250°C), partial gelatin degradation leads to densification and a slight reduction in the antireflective effect.
4. The results highlight the potential of gelatin-SiO₂ hybrid coatings for applications requiring transparent, antireflective, and functional glass layers, such as optical devices and photovoltaic panels.

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