

Optical properties of Pittsburgh glass subjected to mechanical and chemical treating

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An optical study of satinated Pittsburgh glass wafers was conducted and special attention was paid to their applications in greenhouse industry. They included: specular reflectance spectra in the range 300–1100 nm, using a reflection probe, resolve angle scattering, diffuse reflectance by means of an integrating sphere, *X–Y* optical profile measurements and ellipsometric investigation by means of a spectroscopic ellipsometer. Additionally, a surface topography study of investigated samples was carried out by means of atomic force microscopy (AFM) measurements. The obtained results allowed us to describe surface topography of chemically and mechanically modified surfaces.

Keywords: chemical etching and sanding of glass surface, antireflective properties.

1. Introduction

A fundamental property of glass is transmissibility which is directly associated with reflectance in a glass wafer. A transmissibility increase may be obtained by the deposition of an antireflective thin film on glass or by a chemical or mechanical modification of its surface [1, 2]. For most dielectric materials such as glass with a flat surface, the increase in roughness causes the decrease in total reflectance on the surface, thus increasing the absorption of light due to internal reflections in a studied material.

This property may be applied in the production of glass in greenhouse industry. In many evaluations, the reduction of 1% of total reflectance causes 3% growth of plants vegetation [3]. The total light energy value coming from the sun trapped in a greenhouse depends on topographical parameters of a glass wafer surface. The topography of the surface may be modified by satination (special chemical treatments) or sanding. From the technological point of view, glass with high transmissibility and susceptible to surface modification is needed. These criteria are fulfilled by glasses obtained through old Pittsburgh technology as well as water glasses obtained by means of the newest technologies of glass production. Pittsburgh glass shows very good transmissibility (T is about 91%). The surface of Pittsburgh glass is particularly easy to modify by mechanical and chemical processes. Mechanical sanding or chemical

satination roughen one side of a glass slab and lower the total reflectance on a glass wafer.

2. Reflectance on rough glass surface

Spectral and angular reflectance may be described using the Kirchhoff–Beckman scalar theory [4]. The difference between incident k_1 , and scattered k_2 light vectors, which equals: $\mathbf{v} = k_1 - k_2$, may be presented in Cartesian coordinates according to the following formula:

$$\mathbf{v} = \frac{2\pi}{\lambda} \left\{ \left[\sin(\theta_i) - \sin(\theta_s) \cos(\phi_r) \right] \hat{u}_x - \sin(\theta_s) \sin(\phi_r) \hat{u}_y - \left[\cos(\theta_i) + \cos(\theta_r) \right] \hat{u}_z \right\} \quad (1)$$

where θ and ϕ are angles measured in a polar coordinate system, λ is a light wavelength.

According to the Beckman theory, the scattering coefficient ρ , defined as the ratio of a scattered electric field at an angle θ_s on a rough glass surface to an electric field specularly reflected at an angle θ_i from smooth glass surface. The mean value of the scattering coefficient expressed by topographical terms: the root mean square (rms) roughness σ and autocorrelation length T is given by:

$$\langle |\rho|^2 \rangle = R_F \frac{1}{\pi A} \left[\frac{\lambda T}{4\sigma \cos(\theta_i)} \right]^2 \left[\frac{|\mathbf{v}|}{v_z} \right]^4 \exp\left(-\frac{v_{xy}^2 T^2}{4v_z^2 \sigma^2} \right) \quad (2)$$

where A is the surface area of a light spot, R_F is Fresnel reflection coefficient and

$$|\mathbf{v}| = \sqrt{v_x^2 + v_y^2 + v_z^2} \quad (3)$$

The reflection (R) and scattering (ρ) coefficients are linearly related:

$$R(\theta_s, \phi) = \langle |\rho|^2 \rangle \frac{A^2 \cos^2(\theta_i)}{\lambda^2 r^2} \quad (4)$$

From formulas (2)–(4) it results that if the roughness is large compared to the wavelength, the scattered energy is mainly diffusely scattered and is independent of the light wavelength, which is an important conclusion in reference to greenhouse application.

For simulations of light scattering on rough glass surfaces, a scalar theory has been applied. Figure 1 shows scattered radiation (at normal incidence of light) on surfaces with different roughness.

Regardless of surface roughness, scattering in this case is symmetrical as far as specular reflection. Interestingly, for very rough surfaces most of the scattered radia-

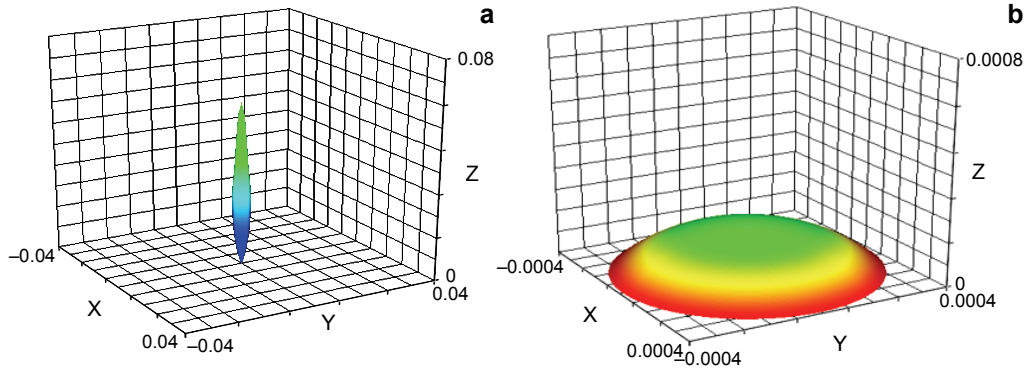


Fig. 1. The modelled light scattering on a glass surface at incident angle $\theta_i = 0$; $\lambda = 633$ nm, $n = 1.5$, autocorrelation length $T = 2000$ nm, roughness $\sigma = 100$ nm (a), and $\sigma = 1400$ nm (b).

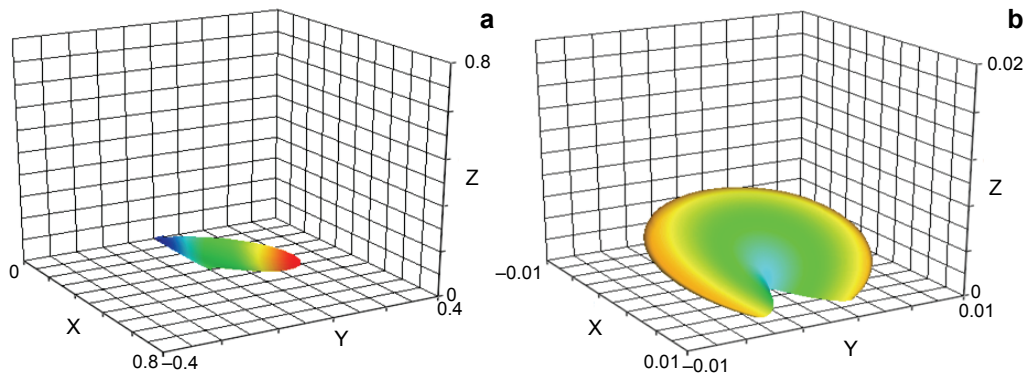


Fig. 2. Simulated light scattering on the same surface as in Fig. 1 at the incident angle $\theta_i = 75^\circ$, $\sigma = 100$ nm (a), and $\sigma = 1400$ nm (b).

tion is parallel to the plane of incidence. Those properties should be taken into account in designing antireflective surfaces.

As it may be noticed for increasing surface roughness, more and more light is scattered into large angles. If roughness is big, then, for greater angles of incidence rear reflection occurs (retroreflection [5]) whose intensity may be greater than the light intensity scattered into a forward direction. This case is shown in Fig. 2. It presents the scattering of radiation on the surface with roughness $\sigma = 10$ nm and 1400 nm, respectively, at an angle of incidence of 75° .

Therefore, in order to avoid strong retroreflection at high angles of incidence, the glass wafer considered to be used in greenhouses should be roughened at the bottom interface. It allows one to decrease total reflection from a glass panel.

Figure 3 shows the reflection from a glass wafer which is used in greenhouse industry and roughened on the bottom substrate. Light is partly reflected from the top

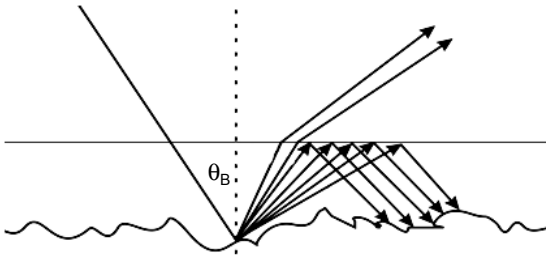


Fig. 3. Propagation of scattered light in a layer with a rough bottom.

surface, partly – after the refraction on the boundary of the media; it traverses the wafer twice and goes out from the sample.

This occurs for specular reflection for any angle of incidence. If, however, the bottom surface is rough, the part radiation is scattered into angles θ_s that are larger than Brewster's angle θ_B . If $\theta_s > \theta_B$ all the radiation is internally reflected.

This means that the reflected light at suitably great angles comes only from the scattering from the upper interface of a glass wafer which substantially decreases the total reflection from glass panels [6].

3. Results and discussions

Glass obtained through Pittsburgh technology was chosen as a subject of our investigation. Before saturation we performed ellipsometric measurements of Pittsburgh glass for spectral dispersion of refractive index determination by means of the Wollam M-2000 spectroscopic ellipsometer [7]. The $n(\lambda)$ dependence in a wavelength range 400 to 900 nm is shown in Fig. 4.

Pittsburgh glass surfaces are soft and particularly susceptible to damage. These properties may be applied in chemical etching or mechanical dullness in order to reduce

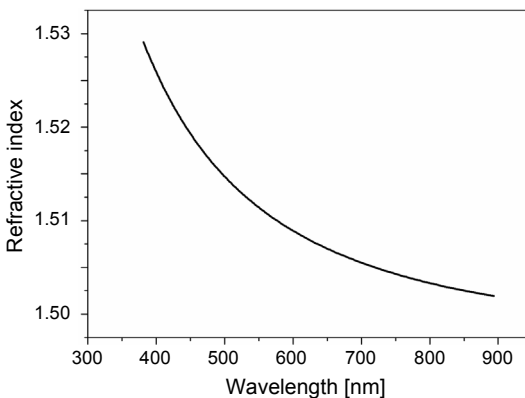


Fig. 4. Refractive index dispersion for Pittsburgh glass.

gloss from the bottom surface of a glass panel. The satination of the surface using the etching process in hydrofluoric acid (HF) solution (25%) in time 60 s is presented.

Figure 5 shows AFM images performed for flat (Fig. 5a) and satinated (Fig. 5b) glass surfaces.

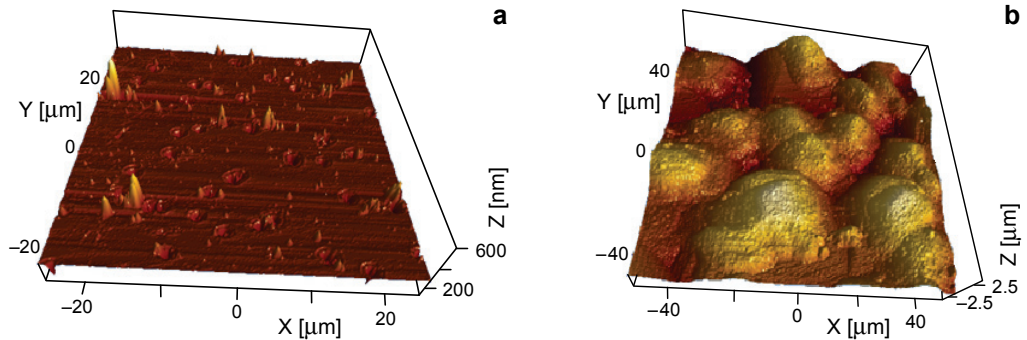


Fig. 5. AFM profiles for flat (a), and satinated (b) Pittsburgh glass surfaces.

Caves visible in Fig. 5a were created on the glass surface before the satination process. The morphology of the types of glass subjected to sanding or satination processes was similar. The average roughness at several measured points has been determined. It has been estimated as $1.2 \mu\text{m}$.

In Figure 6 the height distribution function (HDF) obtained from the AFM image of a Pittsburgh glass surface is presented.

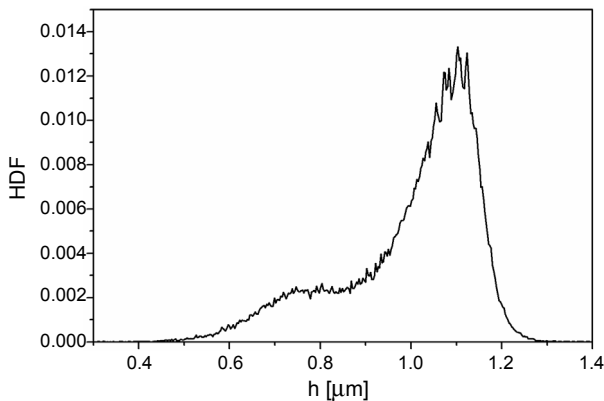


Fig. 6. Histogram of surface heights for Pittsburgh glass determined from AFM study.

The distribution of irregularities cannot be described using the Gaussian curve. It appears that the etching process is a superposition of two independent stochastic processes with different maxima. For surface characterization in longer spatial wavelengths (from $50 \mu\text{m}$ to 100mm) optical profilometry [8] measurements were performed.

The measurements performed by means of integrating sphere and standard reflectometry give a rather average reflectance over a larger scale reflected samples. In order to study the reflection from small surface areas, an optical profilometer (OP) [9] was applied. The scattered radiation measured by OP is a function of heights of irregularities and slopes of microfacets, but the sensitivity of this method derives mainly from the detection of the slope change. The long spatial wavelength irregularities detected in OP investigations may contribute substantially to the total roughness. Optical profilometry measurements complete the topography description in long spatial wavelengths [10].

The optical profilometer used in glass surface topography studies is applied for surface topography research. It works in a specular mode. It employs the He-Ne laser as a light source with a collimating system enabling us to achieve the light beam with a 12 μm diameter. OP measurements have been normalized through the calibration sphere method [11]. A lead screw stepper motor actuated device may scan a 30 mm \times 30 mm surface with the step of 0.025 mm. It allows one to obtain optical profiles of the surface with 25 μm lateral resolution.

Figure 7a shows the Fourier transform (FT) of an optical profile of satinated glass texture. In Figure 7b the calculated power spectral density (PSD) function [12] from surface profile is presented.

As results from Fig. 7b, the PSDs for x and y directions are nearly the same. Thus, one may conclude that a satinated glass surface exhibits very good isotropy. It is also an important property for glass used in greenhouses.

Also for the samples the total reflectance in wavelength ranges from 250 to 2500 nm using the Perkin–Elmer 490 integrating sphere [13] was measured. The results are presented in Fig. 8.

For sanded and satinated glass, the specular reflectance from the upper surface is the same as in the case of a smooth surface, but the reflection from the bottom plane is reduced. As a result of total internal reflection, most scattering inside the wafer is absorbed. Therefore the total reflection is smaller. This also applies to diffused light

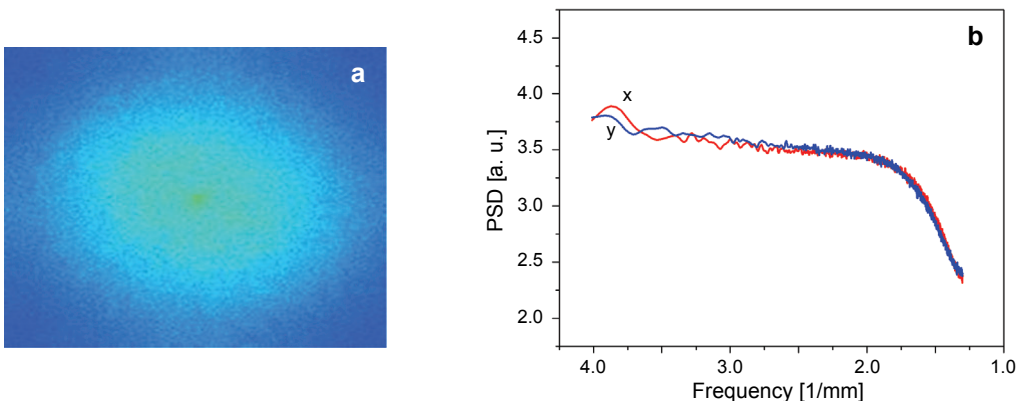


Fig. 7. FT of satinated glass surface (a) and arbitrary one-dimensional PSD for x and y direction (b)

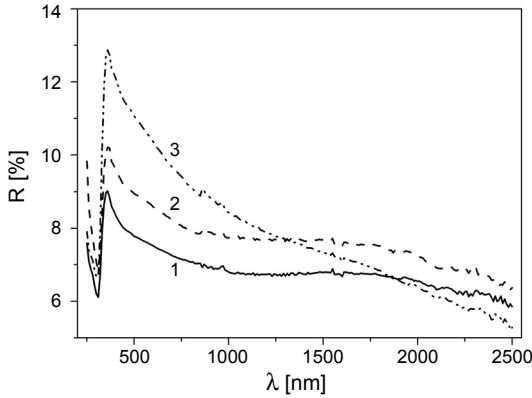


Fig. 8. Total reflectance spectra for flat, sanded, and satinated glass surfaces curves 1, 2, 3, respectively.

coming from the clouds. As one may notice from Fig. 8, the total reflection from satinated glass is more than three percent lower than from smooth glass in a visible spectral range.

The crucial information about optical properties of glass surfaces may be obtained from the bidirectional transmission distribution function (BTDF) [14] measurements. The BTDF measures the differential power of a transmitted beam dP per solid

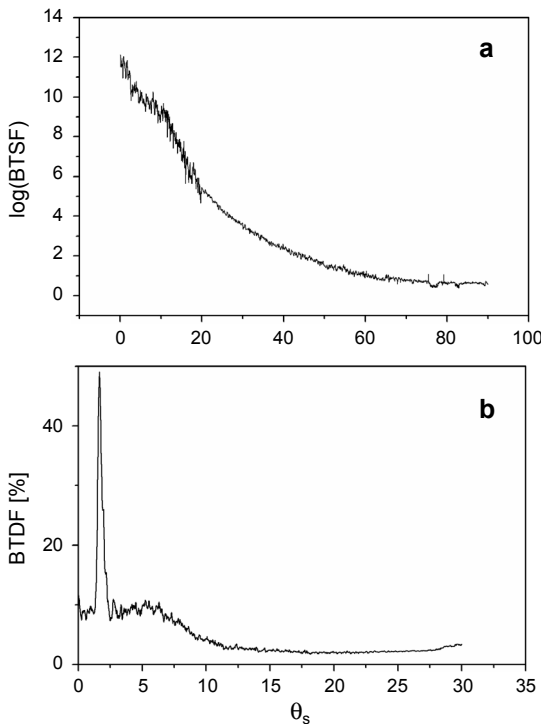


Fig. 9. Angular dependence of scattered light intensity (BTDF) for satinated (a), and flat glass wafer (b).

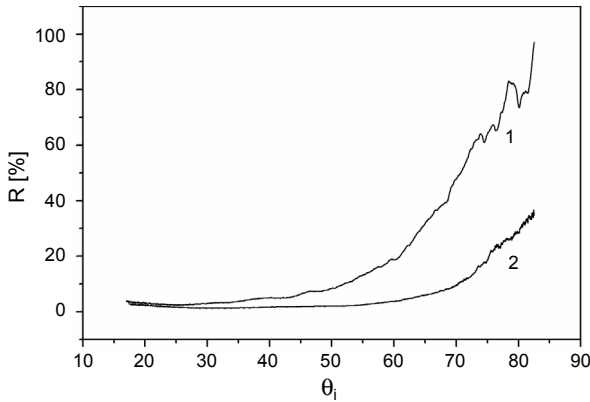


Fig. 10. Specular reflection coefficient versus angle of incidence for s polarized light. Curves 1, 2 denote reflection from smooth and satinated glass, respectively.

angle of a receiver aperture $d\Omega$ in the θ_s direction and per incident power P_i coming from the incident direction. As an example, in Fig. 9 the BTDF for wavelength $\lambda = 650$ nm of used light source is shown.

As it may be noticed, transmitted radiation for satinated panels is scattered into wide solid angles. Moreover the knowledge of the reflection coefficient as a function of an incidence angle is important with a view to optimizing the absorption of radiation in glass panels. Figure 10 shows the specular reflection coefficient for s polarization versus the angle of incidence for smooth and satinated glass wafers.

As it is seen in Fig. 10 the specular reflection from satinated glass panels is lower than from flat ones for all incidence angles.

4. Conclusions

Pittsburgh glasses may be effectively applied in greenhouses due to their high transmissibility. Their surfaces are easily susceptible to chemical and mechanical modification. These properties cause the decrease in reflectance by more than 3%. The topography of glass surfaces was modified by chemical etching of glass panels in a HF solution. The saturation process enables one to achieve more than $1.2 \mu\text{m}$ roughness. It causes the effective decrease in scattered radiation from glass panels. Also, the diffusive properties of satinated Pittsburgh slabs may be used for some kind of cultures. The theoretical model of optical scattering based on a scalar theory enables us to simulate the scattering from a one-side roughened glass panel. Further studies on other glass surfaces will allow us to effectively optimize the etching process applied in greenhouse glass production.

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