Light scattering glass material modified by the surface ion exchange for the energy efficient using in the technical and decorative lighting

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Abstract. The research data related to glass surface treatment and new scattering glass material manufacture by the surface modification with the use of the surface ion exchange are given. The special features of the optical properties of the modified soda lime silica glass with/without the thin Au layer are described and compared with that data related to chemical etched glass. The glass modified by surface ion exchange is characterized by more effective simultaneous light transmission and light scattering and by more strongly pronounced spectral and angular dependences of the scattered light. It was found the noticeably greater (up to 16 times) light intensity at light propagating in the full internal reflection regime. Presented optical data may be useful in the technical and decorative illuminating engineering.
Keywords: glass, optical properties, lighting, decoration, ion exchange

1. Introduction

In last decades the development of glasses science have been characterized by the essential accumulation of knowledge about physical and chemical properties of glasses what account for the substantial broadening of the glasses application spectrum and scaled increasing of the glasses production volume. Glasses are now widely used in architecture and building industry as the unique constructive and design material, in automobile industry, solar energy, optics and other fields. In this connection, new tasks of research and controllable change of the glasses are set under scientists including the investigation of glasses' physical and chemical properties determined by their composition, structure and surface state. The present work is devoted to the investigation of optical properties of soda lime silica glass with surface layer modified by ion exchange Na^{+}/Li^{+} with the use of the special Surface Ion Exchange Paste (SIEP) [1]. New optical research data will be compared with that data for the glass treated by the well known method – chemical etching with the composition containing hydrofluoric acid [2]. In authors' opinion, the results of optical measurements may be useful in illuminating engineering for the technical or decorative applications of glasses [3, 4].

2. Experimental

2.1. Glass samples characterization

The soda lime silica glass samples (GOST 111-2001) 4 mm thick have been used. Glass samples modified by SIEP were denoted as GIE (GIE-Au – surface modified glass samples covered by the thin surface Au layer, 10 – 40 nm thick). Na^+/Li^+ ion exchange process with SIEP has included next stages: glass surface degreasing and washing; the SIEP laying on the glass surface; thermal treatment at ~ 300º C for 15 – 20 min.; washing with running water. The surface morphology of glass samples has been observed by the SEM JSM-6460 (Jeol, Japan). The thin Au layer was deposed by the special device JVC-1600 (Jeol, Japan). The surface morphology of the GIE glass samples is characterized by the system of microblocks and microcracks formed due to the mechanical stresses conditioned by the shrinkage taking place during ion exchange process [5-7]. GCE-Au and GCE glass samples were treated by chemical etching with the composition containing hydrofluoric acid [2]; the thickness of the thin surface Au layer was 10 – 40 nm. The surface morphology of these GCE-Au and GCE glass samples is characterized by a number of hills, hollows, steps and kink sites.

2.2. Optical measurements

The measurements of the spectrums of the relative spectral decaying coefficient σ have been carried out with set including light source, collimator, aperture, rotation mechanism, light guide and spectrophotometer connected with computer. The halogen lamp with the intensive blue component up to λ ~ 390 nm has been used as the light source. The collimator has formed the parallel light beam scattered in the modified surface layer of the glass sample. The part of the luminous flux has gotten to light guide on the rotate mechanism. The scattered light has came into spectrometer 7 (S100, SOLAR Laser System). The relative spectral decaying coefficient σ has been determined by the equation $\sigma = I_0 I_s(600)/(I_s I_0(600))$, where I_0 – the light intensity for the halogen lamp; $I_0(600)$ – the light intensity of the halogen lamp at λ = 600 nm; I_s – the scattered light intensity for the glass samples GIE and GCE; $I_s(600)$ – the scattered light intensity for the glass samples GIE and GCE at λ = 600 nm.

During the measurements of the light loss characteristics (extinction) and uniformity of the screen illumination a part of the light flux from the light source (white LED) has been passed through the glass sample and the scattered light has fall onto the white screen. Light spots on the screen have been photographed by the camera CANON D20.

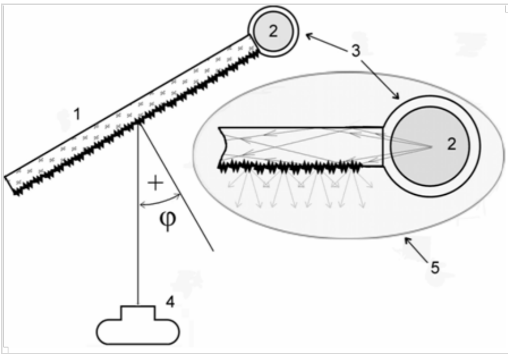


Figure 1. Scheme of the experimental set for the measurements of the light scattering in the full internal reflection regime:
1 – the glass plate with one scattering surface;
2 – light source with the reflector 3;
4 – camera;
5 – schematic diagram of the light scattering.

The scattered light intensity in the full internal reflection regime has been measured with set shown in figure 1. One site of the glass plate 1 had the scattering surface in the form of the surface areas modified by SIEP or chemical etching. Light from the luminescent lamp 2 with the reflector 3 has passed into the glass plate through its side surface and has reflected from the plate surface as it is shown in the part 5. The light scattering has occurred from the modified surface areas. The image of the glass sample at various angles φ has been registered by the camera 4.

Degree of the depolarization during the light scattering forward has been determined for the linearly polarized light (λ = 488 nm) by the measurement of the intensity dependence of the light passed through the polaroid at the definite φ of the polaroid rotation. The light beam was absorbed by the polaroid completely at the crossed polaroid position with the angle 90º. In the case of the linearly polarized light, the angle dependence graph of the light intensity is a half period of the function $(1 - \sin^2\varphi)$. For the no polarized light the light intensity has not depend on the polaroid angle φ. The degree of the depolarization is equal $\eta = I_n/I_p$, where I_n and I_p are the intensities of the normally and parallel polarized light, respectively.

3. Results and discussion

The morphology of the glass surface layer modified by SIEP has important special features: it is characterized by the system of microblocks and microcracks, penetrate deep into the glass in the considerable thickness (tens or more microns). But the chemical etching process occurs only on the glass surface forming hills, hollows, steps and kink sites and does not penetrate deep into the glass. These morphological special features may influence on the optical properties of the surface modified glass. The scheme of the light scattering in the modified glass layer is shown in figure 2.

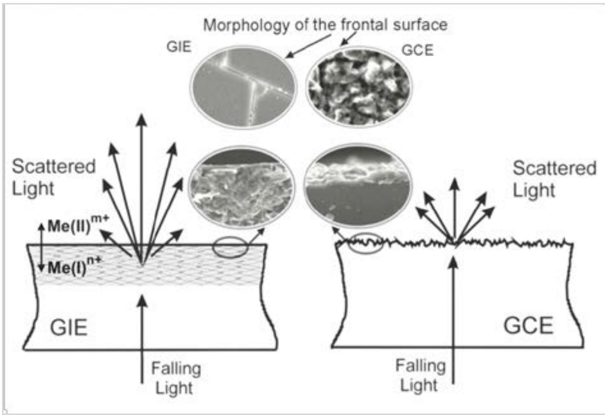


Figure 2. Schematic diagram of light scattering in the glass surface layer modified by the surface ion exchange process (on the left, GIE) and by the surface chemical etching (on the right, GCE).

Spectrums of the relative spectral decaying coefficient σ are presented in the figure 3. It can be seen that the spectral dependence of σ (λ) for the GIE glass sample is more strongly pronounced (especially at minor angles) than that dependence for the GCE sample. Analogously, the spectral dependence σ (λ) for the GIE-Au glass sample is also sufficiently strong. The increase of the Au layer thickness (10 – 40 nm) leads to the increase of σ (λ) due to the partial local overgrowth of microcracks with the deposed Au and to the increase of light reflection from the Au layer. The observed dependence σ (λ) for the GCE-Au glass is very weak; σ (λ) varies in the range 0.8 – 1.2.

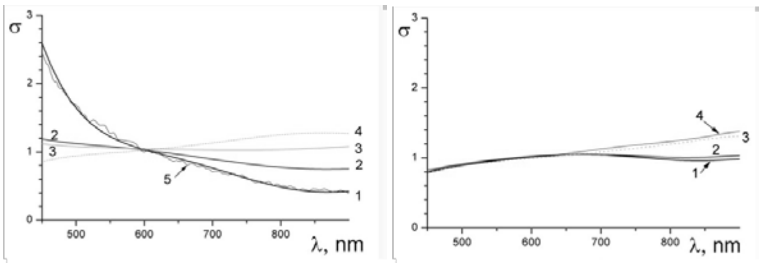


Figure 3. Spectrums of the relative spectral decaying coefficient σ: a - for the glass sample GIE measured at angles φ 0º (1), 5º (2), 20º (3), 45º (4); b - for the glass sample GCE measured at angles φ 0º (1), 20º (2), 50º (3).

The Light loss characteristics (extinction) and uniformity of the screen illumination by the light passed through the modified glass samples has been measured as described above. The curves of the angular distribution of the screen illumination along the spot diameter are shown in figure 4. The measured values of the half-width $\varphi_{1/2}$; the relative total luminous flux, S_i, defined as the areas under the curves of the angular distribution; the factor of the reduction of the initial total luminous flux, S_1/S_i and the fractional light losses $(S_1 - S_i)/S_1$ are presented in the table 1 for all four types of the investigated glass samples. The thickness of the Au layer on the glass samples GIE-Au and GCE-Au was ~10 nm.

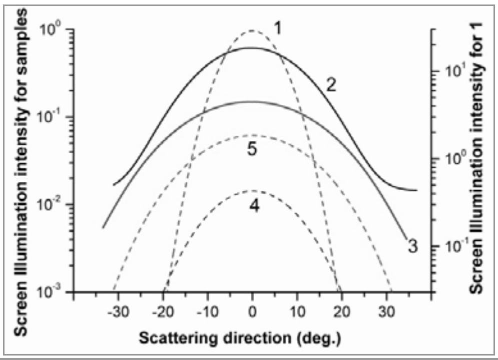


Figure 4. The angular distribution of the screen illumination intensity:
1 – the initial total luminous flux, S_1 = 1.0;
2 - glass sample GIE, S_2 = 0.48;
3 - glass sample GCE, S_3 = 0.16;
4 – glass sample GIE-Au, Au layer 10 nm thick, S_4 = 0.012;
5 – glass sample GCE-Au, Au layer 10 nm thick, S_5 = 0.089

Table 1.

Type of sample	**$\varphi_{½}$ (i)**	**S_i**	**S_1/S_i**	**$(S_1-S_i)/S_1$**
light has not passed through the glass sample (curve 1);	*5.7º*	*1.00*	*1.00*	*0*
the glass sample GIE (curve 2)	*8.7º*	*0.48*	*2.08*	*0.52*
the glass sample GCE (curve 3)	*11.9º*	*0.16*	*6.25*	*0.84*
the glass sample GIE-Au (curve 4)	*8.8º*	*0.012*	*83.33*	*0.99*
the glass sample GCE-Au (curve 5)	*11.8º*	*0.089*	*11.24*	*0.91*

$\varphi_{1/2}$ – half-width of the screen illumination distribution; S_i - the relative total luminous flux; S_1/S_i – the factor of the reduction of the initial total luminous flux; $(S_1-S_i)/S_1$ – the fractional light losses

As can be seen in figure 4 and table 1, the simultaneous light transmission and scattering occur more effective for the glass sample GIE with least fractional light losses and factor of the reduction of the initial total luminous flux 0.52 and 2.08, respectively. At the same time, the values of the half-width $\varphi_{1/2}$ for glass samples GIE and GCE differ from each other not so much 8.7º and 11.9º. It may be concluded that the glass modification by the surface ion exchange is more preferable than chemical etching, as it is characterized by lower light absorption and has very important advantage – it allows avoid the use of very hazardous compositions containing hydrofluoric acid. The glass samples with the thin surface Au layer (GIE-Au and GCE-Au) are characterized by small values of the relative total luminous flux: 0.012 and 0.089, respectively, what may be connected with the light absorption and reflection by the thin Au layer.

It was interesting to compare the light scattering in the full internal reflection regime for the modified glass samples GIE and GCE. In this regime the light propagating in a medium with the index of refraction n_1 (the glass medium) falls on the boundary with medium, which has the index of refraction n_2 (air), where $n_2 < n_1$. The full internal reflection regime may be realized by lighting of a glass plate through a lateral surface at the angle of incidence $\theta_f > 41º48'$, i.e. at $\sin\theta_f > n_2/n_1$ (Shubnikov [8]). This means that the no modified glass areas will be dark and the modified glass areas with rough surface will be bright, see figure 5.

A view of the glass plate with images at the scattering angle $\varphi = 0$ is shown in this figure 5 a. The more bright images were made by surface ion exchange (as stars' image 1, GIE); the other images correspond to glass surface areas modified by chemical etching (as stars' image 2, GCE). Images 1 and 2 indicated in the rectangles are shown also in the nine small photos below at $-70º < \varphi < 70º$. Quantitative comparison of the effectiveness of light scattering for images 1 (GIE) and 2 (GCE) have been carried out by photometry method. The curves of the intensities I_1 and I_2 for images 1 and 2 normalized to the maximum values of their brightness are shown in figure 5 b. The curve I_1 is practically constant at any measurable angles. The curve I_2 has had broad minimum at the range -45º < φ < 45º and has achieved I_{2min} ~ 0.03. There has been observed the maximum of the angle dependence I_1/I_2 and $(I_1/I_2)_{max}$ has achieved substantial value 16. These results confirm the conclusion that the light scattering in the full internal reflection regime occurs substantially more effective for the glass with the surface areas modified by the surface ion exchange than by chemical etching.

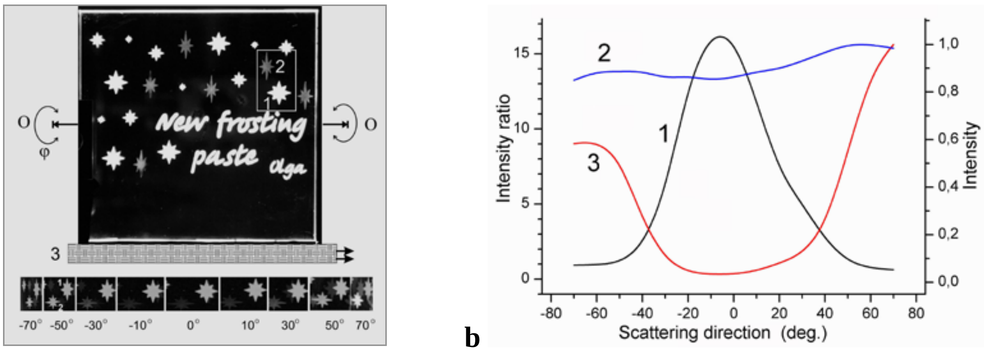
a b


Figure 5. Light scattering in the glass in the full internal reflection regime:

a. 1 – the star's image 1 made by surface ion exchange (GIE area); 2 – the star's image 2 made by chemical etching (GCE area); 3 – the light source with the reflector. Low stars' images are indicated at angle -70º < φ < 70º.
b. The light dependences of the stars' images with the angle of the scattering direction: 1 – the normalized intensity I_1 of the image 1; 2 – the normalized intensity I_2 of the image 2; 3 – the
dependence I_1/I_2 with the angle of the scattering direction.

Depolarization of the scattered light. The partial depolarization of the linearly polarized light may occur owing to light scattering in medium with small dielectric particles. In the authors' opinion, such light depolarization process may take place also in the modified rough surface layer of samples GIE, GCE, GIE-Au and GCE-Au. Experimental data on the dependence of the depolarization parameter η on the coating thickness δ are presented in figure 6 including data for glass samples GIE and GCE published early in [9]. The depolarization parameter η is substantially smaller for the glass samples GIE-Au and GCE-Au than for the glass samples GIE and GCE.

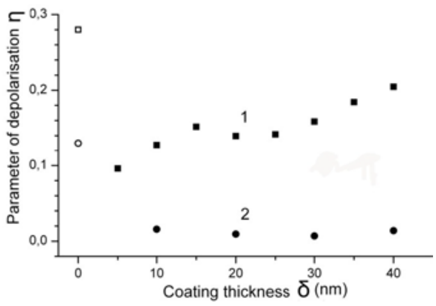


Figure 6. Dependence of the scattered light depolarisation parameter η on the thin Au layer thickness δ: curve 1 – for the glass sample GIE-Au; curve 2 – for the glass sample GCE-Au; no filled square and circle are concerned to the glass samples without the thin Au layer (GIE and GCE, respectively).

This difference may be explained by the weak change of the electromagnetic wave's polarization during the reflection from the conducting metal surface in contrast to the reflection from the dielectric glass surface [10].

CONCLUSIONS

The presented results allow conclude that the investigated optical properties depend considerably on the type of glass treatment (by the surface ion exchange process and by chemical etching). Thus, glass sample modified by the surface ion exchange is characterized

- by the more effective (in tree times) simultaneous light transmission and light scattering;
- by the more strongly pronounced spectral dependence of the scattered light;
- by the stronger dependence of the scattered light with an angle.

Figure 7. The glass sample decorated with the surface ion exchange paste (SIEP) and illuminated by coloured LEDs (a gold medal on the fair SIBPOLYTECH-2009, ITE Siberian Fair, Novosibirsk, Russia).

The light intensity of the scattered light in the full internal reflection regime is noticeably greater (up to 16 times!) in comparison with the chemical etched glass sample. Therefore, in authors' opinion, the use of the surface ion exchange process for the glass surface treatment is very attractive for the lighting technology with the technical, decorative and artistic purposes for the manufacture of the glass production: luminariers; light screens and indicator panels, displays; decorative or technical images on glass; souvenirs and elements of furniture design; elements of architectural design; glass sculptures and others. As example, there is presented the glass sample decorated by the surface ion exchange and illuminated by coloured LEDs (figure 7) exhibited in the Fair SIBPOLYTECH-2009 (ITE Siberian Fair, Novosibirsk, Russia); the development was awarded with a gold medal. It is also very important that the surface ion exchange process is preferable in ecological point of view because the used SIEP composition doesn't contain such hazardous substance as hydrofluoric acid (see also [11].

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