Optical characterization of thin Al_2O_3 layers deposited by magnetron sputtering technique at industrial conditions for applications in glazing

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In this study, thin Al_2O_3 films (11 nm – 82 nm) were deposited by means of a recently developed pulse gas injection magnetron sputtering method and investigated by means of atomic force microscopy, spectroscopic ellipsometry and spectrophotometry. Quite low values of optical constants (1.581 to 1.648 at $\lambda = 550$ nm) of the alumina films are directly associated with specific growth conditions (pulse injection of the reactive or reactive + inert gas) in the pulse gas injection magnetron sputtering process. The light transmittance of Al_2O_3 /glass systems (86 % to 90 %) is only a few percent lower than that calculated for glass (93 %).

Keywords: Al_2O_3 ; GIMS; refractive index; light transmittance; glazing

1. Introduction

Magnetron sputtering is one of the techniques used to modify properties of large-size glass plates (at industrial conditions) by depositing a functional layer or multi-layered coating. In some applications, mostly based on interference coatings (antireflective [1–4], decorative [5–8] and optical filters), where the thicknesses of particular films should be well defined, the uniformity of thickness as well as optical and microstructural properties of the layers should be carefully controlled and differences in their values should be as small as possible [8]. These important features related to thin films are provided by the pulse gas injection magnetron sputtering technique (GIMS) [8–11].

Šicha et al. [12] reported that the energetic conditions during the formation of layers at relatively low temperatures (below 180 °C) are mainly related to the condensation conditions of particles. In the above mentioned conditions the kinetic energy of condensed particles is the key factor in synthesis of a coating. In standard magnetron sputtering methods, a part of particles energy

is dissipated (as a result of interparticle collisions) before their condensation on the substrate. This feature is important, when coatings are deposited not directly, but some time after the glass production. If a magnetron system is combined with the line used for glass production, the coatings can be deposited directly on the hot substrate. These conditions provide adequate adhesion. Therefore, to obtain a functional coating with adequate adhesion and desirable properties during the layer growth process, in most cases, reheating of glass is necessary. In the GIMS method due to pulsed injection of an inert/reactive gas to the vacuum chamber, the energy of particles is dissipated in a much lesser degree compared to the standard magnetron process [9, 10]. This method of plasma surface engineering technique was successfully adopted in industrial conditions to form hard, nanocrystalline, rutile-like TiO_2 layers on unheated glass directly during the deposition [11] and to produce decorative TiO_2 -based coatings on glass [7, 8, 13], aluminum-coated glass [5], stainless steel [6] and ceramic tiles [9]. Moreover, the investigation of thin dielectric layers (Al_2O_3 , SnO_2 and TiO_2) produced using GIMS have shown their amorphous-like nature [14].

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Recent trends in modern architecture place glass at the forefront of materials commonly used in designing facades and glass walls of contemporary facilities. The attractiveness of glass used worldwide in 21st century architecture results mainly from its aesthetics value and optical properties (transparency). However, restrictive fire protection requirements enforce to use the multi-layered protective glass packages in building windows to ensure impermeable fire barrier. Construction of fireproof composite glass packages bases on a thin strongly alkaline spacer - silica gel, inserted between two float-glass panels. If there is a fire, the gel mass increases its volume forming a hard non-transparent coating protection against fire spreading. One of the problems associated with fireproof glass packages production is the streaks forming, observed on the glass-gel border. Specific streaks are the result of mechanical microdamages, which may occur during the float glass manufacturing process when molten glass is fed into a bath of molten tin. The observed streaks are nothing but corrosion, resulting from point and linear microdefects of glass panels, i.e. stains, seizing and scratches. The corrosion process direction and rapidity are closely dependent on the contact solution type and its pH as well as on the temperature and exposure time [15]. Covering the glass panels with an additional dielectric and transparent in the visible range layer significantly slows down or even completely eliminates the corrosion process. In general, these layers should not affect or affect only slightly the optical properties of the glass-layer system. This paper presents the influence of various magnetron sputtering growth conditions on optical and microstructural properties of glass plates with anticorrosive Al₂O₃ coating. It should be noted that the anticorrosive properties of amorphous Al₂O₃ coatings were described earlier [16]. The findings of this study have a number of important implications for future practice. Thus, the results obtained can be the basis to develop optimal, in terms of cost-effectiveness and technology production process, fire resistant glass packages, free from any defects.

2. Experimental

All the aluminum oxide layers were produced using gas injection magnetron sputtering method (GIMS) [8–11]. The thin Al₂O₃ films were deposited on microscope glass in various growth conditions. Different thicknesses of deposited layers were obtained by changing time of deposition t from 560 s to 4480 s and vacuum conditions, using a commercial production line in BOHAMET Company (Poland) [17]. Dielectric films were deposited in O₂ or Ar+O₂ plasma. The aluminum target (95.5 % Al) was powered by pulsed DPS-type (Dora Power Systems) power supply working at a power of 24 kW [18] which generated 100 kHz sinusoidal pulses grouped in 2 kHz unipolar packets. The distance between the target and substrate was 140 mm. Before the gas injection, the pressure in the magnetron chamber was lower than 0.01 Pa. The sputtering conditions for the films deposition are listed in Table 1.

The ellipsometric azimuths Ψ and Δ were recorded by means of the V-VASE device from J.A. Woollam Co., Inc., for three angles of incidence (65°, 70° and 75°) in the UV-Vis-NIR spectral range (0.6 eV to 4 eV; 310 nm to 2010 nm).

Transmittance and reflectance measurements were performed in the spectral range from 380 nm to 780 nm (1.6 eV to 3.3 eV), using a Cary 5000 spectrophotometer.

Surface topography of the samples was investigated using the atomic force microscope (Innova: Bruker) equipped with a standard Si tip (tapping mode). The roughness parameters R_q and R_a were calculated using the NanoScope Analysis software (v. 1.40) based on the following equations:

$$R_q = \sqrt{\frac{\sum_{j=1}^N Z_j^2}{N}}, \quad (1)$$

$$R_a = \frac{1}{N} \sum_{j=1}^N |Z_j|, \quad (2)$$

Table 1. Time of deposition t (s), partial oxide pressure (p_{O_2}) and partial argon pressure (p_{Ar}) used during deposition of the Al_2O_3 layers.

No.	Sample	t [s]	p_{O_2} [Pa]	p_{Ar} [Pa]
1.	G1a	560	0.09	–
2.	G1b	1120	0.09	–
3.	G1c	2240	0.09	–
4.	G1d	4480	0.09	–
5.	G2a	2240	0.13	–
6.	G2b	2240	0.18	–
7.	G3a	2240	0.09	0.11
8.	G3b	2240	0.18	0.22

where Z_j is the current surface height and N is the number of measured points. Each AFM image size was of $2 \mu m \times 2 \mu m$.

3. Results and discussion

The surface topography of samples deposited in various growth conditions is presented in Fig. 1. All the produced Al_2O_3 layers exhibit nanogranular structure. The lateral size of the grains is in the range of 50 nm to 100 nm. The roughness parameters for the layers are summarized in Table 2. The calculated roughness parameters are in the range from 0.67 nm to 1.74 nm and from 0.84 nm to 2.24 nm for R_a and R_q , respectively. For samples deposited in pure oxygen atmosphere at $p_{O_2} = 0.09$ Pa (samples G1a to G1d) a slight decrease in roughness parameters can be observed. For the other Al_2O_3 layers R_a and R_q values are slightly higher, however, it can be stated that the produced alumina films are relatively smooth.

To determine optical constants of Al_2O_3 layers as well as thicknesses of dielectric ($d_{Al_2O_3}$) and rough ($d_{Al_2O_3-rough}$) layers, the four-medium optical model of a sample (ambient/ Al_2O_3 -rough layer/ Al_2O_3 film/substrate) was used. In the spectral range from 0.6 eV to 4.0 eV the aluminum oxide is a non-absorbing material [14, 19–21], therefore, only the real part of the complex refractive index $\tilde{n} = n + ik$ was considered (the extinction coefficient was omitted; $k = 0$). The refractive index ($n_{Al_2O_3}$) of each Al_2O_3 film was

parameterized using the Sellmeier-type dispersion relation of n (a Pole oscillator) [22, 23]:

$$n^2 - 1 = \frac{A_0}{E_0^2 - E^2} \quad (3)$$

where E_0 and A_0 are the Pole oscillator position and magnitude, respectively. Optical constants of the Al_2O_3 rough layer ($n_{Al_2O_3-rough}$) were described by a Bruggeman effective medium approximation (BEMA) [22, 23] with fractions of void (f_{void}) and Al_2O_3 ($f_{Al_2O_3}$) equal 0.5:

$$f_{void} \frac{1 - n_{Al_2O_3-rough}^2}{1 + 2n_{Al_2O_3-rough}^2} + (1 - f_{void}) \frac{n_{Al_2O_3}^2 - n_{Al_2O_3-rough}^2}{n_{Al_2O_3}^2 + 2n_{Al_2O_3-rough}^2} = 0 \quad (4)$$

The optical constants of the glass were established in a separate experiment. For samples deposited in the same vacuum conditions (samples G1a – G1d), the multiple sample analysis approach (MSA) was applied [5–7, 13, 22–24]. In this approach we assumed that optical constants for all layers (G1a – G1d) were the same, whereas the thicknesses of rough ($d_{Al_2O_3-rough}$) and dielectric ($d_{Al_2O_3}$) films were fitted separately. The fitting procedure was performed using WASE32 software [22]. The model parameters were optimized to minimize the reduced mean squared error (χ^2) defined as [22, 23]:

Fig. 1. AFM images of the produced samples.

$$\chi^2 = \frac{1}{N_{\Psi\Delta} - P} \sum_j \left[\left(\frac{\Psi_j^{\text{mod}} - \Psi_j^{\text{exp}}}{\sigma_j^{\Psi}} \right)^2 + \left(\frac{\Delta_j^{\text{mod}} - \Delta_j^{\text{exp}}}{\sigma_j^{\Delta}} \right)^2 \right] \quad (5)$$

where $N_{\Psi\Delta}$ and P are the total number of data points and the number of fitted model parameters, respectively. The quantities $\Psi_j^{\text{exp}}/\Delta_j^{\text{exp}}$ and $\Psi_j^{\text{mod}}/\Delta_j^{\text{mod}}$ are ellipsometric azimuths measured and obtained from the model of the sample, respectively. Quantities σ_j^{Ψ} and σ_j^{Δ} are standard deviations of Ψ and Δ , respectively. An example of a fit (for G1d sample) is presented in Fig. 2.

Fig. 2. Experimental (markers) and calculated (solid lines) Ψ and Δ azimuths for the G1d sample. For experimental data every tenth point is plotted.

For the purpose of individual layers thickness measurements and optical constants determination,

the samples were investigated by means of spectroscopic ellipsometry. Table 2 gives the values of deposition time (t), rough layers thicknesses ($d_{\text{Al}_2\text{O}_3\text{-rough}}$), thicknesses of oxide layers ($d_{\text{Al}_2\text{O}_3}$), deposition rate (D) and (discussed earlier) roughness parameters (R_a and R_q). The thicknesses of the Al₂O₃ films are in the range of 10.6 nm to 82.2 nm and for G1 series of samples, they nicely scale with the deposition time (Table 2). The deposition rate (D) for this set of samples is about 1.2 nm/min. Thicknesses of alumina films synthesized at higher oxygen pressures (G2a, G2b) are slightly lower than that for the G1c sample. The Al₂O₃ layers produced in O₂ + Ar plasma exhibit both higher thickness (66 nm to 69 nm) and higher deposition rate (1.8 nm/min to 1.9 nm/min) compared with films obtained in pure O₂ plasma (for $t = 2240$ s). The thicknesses of rough layer ($d_{\text{Al}_2\text{O}_3\text{-rough}}$) determined from the analysis of ellipsometric data are 2 – 3 times higher than the roughness parameters (R_a and R_q).

The refractive index ($n_{\text{Al}_2\text{O}_3}$) of the produced Al₂O₃ films was parameterized using the Sellmeier-type dispersion relation (equation 3). The Pole oscillator magnitude (A_0) and energy (E_0) as well as the value of $n_{\text{Al}_2\text{O}_3}$ at 550 nm for the synthesized Al₂O₃ layers are summarized in Table 3. Value of the magnitude ranges from 175.9 eV² to 198.8 eV². Higher values of A_0 mean higher n values for the same wavelength. The value of E_0 was fixed at 11 eV because of a strong correlation between A_0 and E_0 . Optical constants of the Al₂O₃

Table 2. Thicknesses of the rough ($d_{\text{Al}_2\text{O}_3\text{--rough}}$) and oxide ($d_{\text{Al}_2\text{O}_3}$) layers, deposition rate (D), roughness parameters (R_q and R_a) determined for the investigated samples.

No.	Sample	$d_{\text{Al}_2\text{O}_3\text{--rough}}$ [nm]	$d_{\text{Al}_2\text{O}_3}$ [nm]	D [nm/min]	R_q [nm]	R_a [nm]
1.	G1a	3.7 ± 0.1	10.6 ± 0.1	1.33 ± 0.01	1.15	0.92
2.	G1b	2.6 ± 0.1	19.3 ± 0.1	1.10 ± 0.01	1.06	0.83
3.	G1c	2.1 ± 0.1	38.3 ± 0.1	1.07 ± 0.01	0.84	0.67
4.	G1d	1.7 ± 0.1	82.2 ± 0.1	1.11 ± 0.01	0.89	0.71
5.	G2a	4.0 ± 0.3	34.9 ± 0.8	0.98 ± 0.03	1.59	1.27
6.	G2b	4.5 ± 0.3	32.3 ± 1.0	0.93 ± 0.03	1.94	1.62
7.	G3a	1.0 ± 0.2	66.3 ± 0.3	1.82 ± 0.01	1.70	0.97
8.	G3b	4.3 ± 0.4	69.2 ± 0.6	1.90 ± 0.02	2.24	1.74

Table 3. Dispersion parameters (A_0 , E_0), refractive index of aluminum oxide layer at 550 nm ($n_{\text{Al}_2\text{O}_3@550\text{nm}}$) and light transmittance (τ_v) for the produced samples. The data for glass are added as complementary information.

No.	Sample	A_0 [eV ²]	E_0 [eV]	$n_{\text{Al}_2\text{O}_3@550\text{ nm}}$	τ_v [%]
1.	G1a	$198.9 \pm 0.1^{(1)}$	11 ⁽²⁾	$1.648 \pm 0.001^{(1)}$	90.0
2.	G1b	$198.9 \pm 0.1^{(1)}$	11 ⁽²⁾	$1.648 \pm 0.001^{(1)}$	89.4
3.	G1c	$198.9 \pm 0.1^{(1)}$	11 ⁽²⁾	$1.648 \pm 0.001^{(1)}$	88.3
4.	G1d	$198.9 \pm 0.1^{(1)}$	11 ⁽²⁾	$1.648 \pm 0.001^{(1)}$	86.5
5.	G2a	193.4 ± 1.1	11 ⁽²⁾	1.634 ± 0.003	88.5
6.	G2b	193.0 ± 1.6	11 ⁽²⁾	1.633 ± 0.004	89.8
7.	G3a	175.9 ± 0.1	11 ⁽²⁾	1.581 ± 0.001	88.5
8.	G3b	182.5 ± 0.3	11 ⁽²⁾	1.605 ± 0.001	85.6
9.	Glass	-	-	1.518 ± 0.001	93.0

⁽¹⁾ the same value for G1a-G1d samples (MSA approach)

⁽²⁾ a fixed parameter

films calculated based on A_0 and E_0 and equation 3 are presented in Fig. 3. For all wavelengths, the values of refractive indexes are lower than those taken from the database of optical constants [22]. The samples synthesized in a pure oxygen plasma (1.633 for $p_{\text{O}_2} = 0.18$ Pa, 1.634 for $p_{\text{O}_2} = 0.13$ Pa and 1.648 for $p_{\text{O}_2} = 0.09$ Pa) exhibit the highest value of $n_{\text{Al}_2\text{O}_3@550\text{ nm}}$, while for the layers obtained in a mixed plasma ($\text{O}_2 + \text{Ar}$) these values are definitely lower (1.605 Pa for $p_{\text{O}_2} = 0.18$ Pa and $p_{\text{Ar}} = 0.22$ Pa and 1.581 for $p_{\text{O}_2} = 0.09$ Pa and $p_{\text{Ar}} = 0.11$ Pa). It should be noted that the reported values of n for Al_2O_3 strongly depend on the method of synthesis and are in the range from 1.3 to 1.8 [25, 27, 28]. These relatively low values of the refractive index of alumina films described in this publication result from the specific method of

synthesis and are the most probably associated with nanoporosity of these layers. This fact (lower values of n) was observed earlier for Al_2O_3 , SnO_2 and, first of all, TiO_2 coatings deposited using GIMS [5–7, 11, 13, 14] and was described in detail in the literature [11].

Transmittance spectra (T) of the alumina layers deposited on float glass substrates are shown in Fig. 4. The T values of $\text{Al}_2\text{O}_3/\text{glass}$ samples in the visible spectral range are at the level of 83 % to 91 %. The transmittance value for glass is about 93 %. The decrease in T with the decrease in the light wavelength is directly associated with the increase in the refractive index of alumina layer and glass for $\text{Al}_2\text{O}_3/\text{glass}$ samples (Fig. 3) and only with n of glass for substrate (the reference sample). The refractive index of the G1 series of samples is

Fig. 3. Refractive index ($n_{\text{Al}_2\text{O}_3}$) of Al₂O₃ layers deposited at different vacuum conditions.

the same, so lower values of T were recorded for specimens with thicker dielectric layer (Fig. 4a). For the other samples (Fig. 4b), two competitive processes related to the transmittance behavior take place. Higher transmittance values are observed for samples with thinner Al₂O₃ films, however this statement is correct only for the same shape of n (and values for particular wavelengths). The other process is associated directly with values of n . According to the relation (no absorption in the considered spectral range; $k = 0$ for alumina layer and glass):

$$T = 1 - R = 1 - \frac{(n - 1)^2}{(n + 1)^2} \quad (6)$$

where R is reflectance. Higher n values lead to lower R and, thus, to higher T .

Aluminum oxide films exhibit protective properties. They are excellent barrier to diffusion of sodium out of soda-lime glass [16]. In general, the Al₂O₃ layer used as a diffusion barrier should not introduce any color. This requirement is satisfied by a quite flat shape of T in the visible spectral range. Moreover, the additional layer deposited on the glass should not drastically change the transparency of the coating-substrate system. To test this

Fig. 4. Transmittance spectra of (a) G1a to G1d; (b) G2a, G2b, G3a and G3d samples. The transmittance spectrum for glass is added for comparison.

feature the light transmittance (τ_v) of the produced samples was calculated using the following equation [29]:

$$\tau_v = \frac{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} D_\lambda T(\lambda) V(\lambda) \Delta\lambda}{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} D_\lambda V(\lambda) \Delta\lambda} \quad (7)$$

In equation 7, D_λ is the relative spectral distribution of illuminant D65, $V(\lambda)$ is the spectral luminous efficiency for the photopic vision defining the

standard observer for photometry and $T(\lambda)$ is the transmittance spectrum of the sample. The value of τ_v can be treated as an average value of T weighted arithmetic mean where the weight is a multiplication of the relative spectral distribution of illuminant D65 and the spectral luminous efficiency for the photopic vision. The values of τ_v calculated for the prepared samples are summarized in Table 3. For the reference sample, the value of τ_v is equal to 93 %. For systems with Al_2O_3 film, the light transmittance is in the range of 88 % to 90 %, and only for samples with the thickest alumina layer (G1d and G3b) the τ_v value is slightly lower (86 % to 87 %). It should be noted that the G3a sample exhibits high light transmittance (88.5 %) with relatively thick dielectric layer ($d_{\text{Al}_2\text{O}_3} = 66$ nm). This fact can be explained by the relatively low values of the refractive index for the G3a layer. A slight decrease in the τ_v value of $\text{Al}_2\text{O}_3/\text{glass}$ systems produced by GIMS indicates that they can be used as protective coatings.

4. Conclusions

Thin Al_2O_3 layers prepared at the industrial production conditions using the GIMS method were investigated by means of atomic force microscopy, spectroscopic ellipsometry and spectrophotometry. The examined layers were deposited in oxygen and oxygen + argon plasma environment. The influence of growth conditions on topography, optical constants, transmittance as well as on thickness of the produced coatings was examined. It was shown that all the layers exhibit nanogranular structure. Their optical constants are lower than those reported earlier and, for $\lambda = 550$ nm, are in the range of 1.581 to 1.648. These quite low values of the refractive index provide a low optical contrast between the substrate and the Al_2O_3 film which causes that the value of the light transmittance calculated for the $\text{Al}_2\text{O}_3/\text{glass}$ systems is only a few percent lower than that estimated for the pure glass, so the alumina layers can be used as anticorrosion coatings.

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References

- [1] MARSZAŁEK K., WINKOWSKI P., MARSZAŁEK M., *Mater. Sci.-Poland*, 33 (1) (2015), 6.
- [2] DOBRZAŃSKI L.A., SZINDLER M., DRYGAŁA A., SZINDLER M.M., *Cent. Eur. J. Phys.*, 12 (9) (2014), 666.
- [3] KANDA H., UZUM A., HARANO N., YOSHINAGA S., ISHIKAWA Y., URAOKA Y., FUKUI H., HARADA T., ITO S., *Energy Sci. Eng.*, 4 (4) (2016), 269.
- [4] PERKINS C.K., MANSENGH R.H., RAMOS J.C., NANAYAKKARA C.H.E., PARK D.-H., GOBERNA-FERRÓN S., FULLMER L.B., ARENS J.T., GUTIERREZ-HIGGINS M.T., JONES Y.R., LOPEZ J.I., ROWE T.M., WHITEHURST D.M., NYMAN M., CHABAL Y.J., KESZLER D.A., *Opt. Mater. Express*, 7 (2017), 273.
- [5] SKOWRONSKI L., WACHOWIAK A.A., WACHOWIAK W.W., *Appl. Surf. Sci.*, 421 (2017), 794.
- [6] SKOWRONSKI L., WACHOWIAK A.A., ZDUNEK K., TRZCINSKI M., NAPARTY M.K., *Thin Solid Films*, 627 (2017), 1.
- [7] SKOWRONSKI L., WACHOWIAK A.A., GRABOWSKI A., *Appl. Surf. Sci.*, 338 (2016), 731.
- [8] ZDUNEK K., SKOWRONSKI L., CHODUN R., NOWAKOWSKA-LANGIER K., GRABOWSKI A., WACHOWIAK W., OKRASA S., WACHOWIAK A.A., STRAUSS O., WRONKOWSKI A., DOMANOWSKI P., *Mater. Sci.-Poland*, 34 (1) (2016), 137.
- [9] ZDUNEK K., NOWAKOWSKA-LANGIER K., CHODUN R., OKRASA S., RABIŃSKI M., DORA J., DOMANOWSKI P., HALAREWICZ J., *J. Phys.: Conf. Ser.*, 564 (2014), 012007.
- [10] ZDUNEK K., NOWAKOWSKA-LANGIER K., DORA J., CHODUN R., *Surf. Coat. Technol.*, 228 (2013), 367.
- [11] SKOWRONSKI L., ZDUNEK K., NOWAKOWSKA-LANGIER K., CHODUN R., TRZCINSKI M., KOBIERSKI M., KUSTRA M.K., WACHOWIAK A.A., WACHOWIAK W., HILLER T., GRABOWSKI A., KURPASKA L., NAPARTY M.K., *Surf. Coat. Technol.*, 282 (2015), 16.
- [12] ŠIČHA J., MUSIL J., MEISSNER M., ČERSTVÝ R., *Appl. Surf. Sci.*, 254 (2008), 3793.
- [13] SKOWROŃSKI Ł., TRZCINSKI M., ANTOŃCZAK A.J., DOMANOWSKI P., KUSTRA M., WACHOWIAK W., NAPARTY M.K., HILLER T., BUKALUK A., WRONKOWSKA A.A., *Appl. Surf. Sci.*, 322 (2014), 209.
- [14] SKOWRONSKI L., SZCZESNY R., ZDUNEK K., *Thin Solid Films*, 632 (2017), 112.

- [15] BUNKER B.C., *J. Non-Cryst. Solids*, 179 (1997), 300.
- [16] GORDON R., *J. Non-Cryst. Solids*, 218 (1997) 81.
- [17] DOMANOWSKI P., WAWRZAK A., *J. Mach. Eng.*, 2 (2012), 111.
- [18] POSADOWSKI W.M., WIATROWSKI A., DORA J., RADZIMSKI Z.J., *Thin Solid Films*, 516 (2008), 4478.
- [19] FILATOVA E.O., KONASHUK A.S., *J. Phys. Chem. C*, 119 (2015), 20755.
- [20] TAHIR D., KWON H.L., SHIN H.CH., OH S.K., KANG H.J., HEO S., CHUNG J.G., LEE J.CH., TOUGAARD S., *J. Phys. D Appl. Phys.*, 43 (2010), 255301.
- [21] COSTINA I., FRANCHY R., COSTINA I., FRANCHY R., *Appl. Phys. Lett.*, 78 (2001), 4139.
- [22] WOOLLAM J.A., Co., Inc., *Guide to Using WVASE32®*, Wextech Systems Inc., 310 Madison Avenue, Suite 905, New York, NY 10017, 2010.
- [23] FUJIWARA H., *Spectroscopic Ellipsometry. Principles and Applications*, John Wiley & Sons Ltd, UK, 2009.
- [24] JÄRRENDahl K., ARWIN H., *Thin Solid Films*, 313 – 314 (1998), 114.
- [25] HOUSKA J., BLAZEK J., REZEK J., PROKSOVA S., *Thin Solid Films*, 520 (2012), 5405.
- [26] KUMAR P., WIEDMANN M.K., WINTER C.H., AVRUTSKY I., *Appl. Optics*, 48 (2009), 5407.
- [27] GOTTMANN J., HUSMANN A., KLOTZBÜCHER T., KREUTZ E.W., *Surf. Coat. Technol.*, 100 – 101 (1998), 415.
- [28] BALAKRISHNAN G., KUPPUSAMI P., TRIPURA SUNDARI S., THIRUMURUGESAN R., GANESAN V., MOHANDAS E., SASTIKUMAR D., *Thin Solid Films*, 518 (2010), 3898.
- [29] EN 410:2011 Glass in building – *Determination of luminous and solar characteristics of glazing*.

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