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Shielding properties of optically transparent thin-film sandwich structures $In_2O_3/Ag/In_2O_3$

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The paper presents a synthesis and comprehensive study of the optoelectric and shielding properties of optically transparent conductive sandwich structures $In_2O_3/Ag/In_2O_3$ on a flexible polyethylene terephthalate (PET) substrate. The relationship between the silver layer thickness and the optoelectric parameters of the sandwich structures $In_2O_3/Ag/In_2O_3$ was studied. Measurement of the transmittance and reflection coefficients in the range of 0.01−7 GHz showed a clear correlation between the sheet resistance and the transmittance coefficient. It is shown that the obtained results can be described by the thin layer model in the entire range considered.

Keywords: Transparent conductive coatings, shielding, radio waves, flexible electronics.

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Transparent conducting coatings are key materials of optoelectronics [1]. Apart from optoelectronics, one of the important applications of transparent conducting coatings is screening of transparent objects, which is relevant for metrology and information protection [2,3]. Screening of windows, inspection holes in metrological premises and information display devices helps to reduce the impact of noise at the operation of the precision metering equipment and prevents theft of confidential information.

The main class of materials used in practice are the transparent conducting oxides (TCO) [4]. However, TCO films have high operating parameters on glass substrates only. One of the alternatives to TCO are thin-film structures of oxide/metal/oxide (OMO) [5]. OMO-coatings combine low sheet resistance, high transmission in the visible range and high screening coefficient, and are also compatible with polymer substrates in contrast to TCO films. However, their potential in solving the radio-emission screening tasks is not sufficient, which provides for the relevance of this paper.

Sandwich structures $In_2O_3/Ag/In_2O_3$ (hereinafter referred to as IAI structures) were formed by the method of subsequent magnetron sputtering at DC in pulse mode. The substrate of polyethylene terephthalate (PET) with thickness of 50 μm was sputtered with a sublayer and a closing layer made of indium oxide (thickness of 20 nm), and the central layer was silver (thickness of 9, 13 and 17 nm). Indium oxide was applied by reactive method from a metal target of indium at capacity of 100 W in the atmosphere of argon and oxygen gases with the ratio of 79/21 [%] accordingly, the residual pressure was $4.4 \cdot 10^{-3}$ Torr. Silver was sputtered in the argon atmosphere at capacity of 50 W and residual pressure of $4.4 \cdot 10^{-3}$ Torr. Estimated speed of silver sputtering was 1.1 Å/s, indium oxide — 1.7 Å/s. The thickness of each layer was determined using a quartz resonant cavity.

Morphology of the indium oxide layer (fig. 1, *a*) and silver layer on the indium oxide layer was studied by the method of scanning electron microscopy S 5500 (SEM, Hitachi, Japan). The silver film with thickness of both 9 nm (fig. 1, *b*) and 17 nm (fig. 1, *c*) has stable percolation between individual grains, however, the grain size increases as the film thickness increases. Nevertheless, the structure of the silver layer to a large extent depends on the sublayer and in general follows the specific dimensions of the indium oxide sublayer grains. Roughness of the surface of IAI sandwich structures was studied by the method of atomic-force microscopy (AFM, Ntegra Prima, NT-MDT SI, Russia), the probe rounding radius was 10 nm. Fig. 1, *d* shows the surface profiles, the mean square roughness of IAI sandwich structures increases with the increase of the silver layer thickness and is 2 ± 1, 3 ± 1 and 4 ± 1 nm accordingly. This behavior is not typical for ultrathin films of metals on glass and silicon, whose roughness decreases as the thickness increases. We assume that such behavior is related to the response of the PET-substrate to the thermal impact in process of IAI sandwich structures sputtering.

Spectral transmission was measured using spectrophotometer Shimadzu UV-3600i plus (Shimadzu, Japan) with the integrating sphere. Fig. 2, *a* shows transmission in the range of 300−2600 nm for the reference PET-substrate

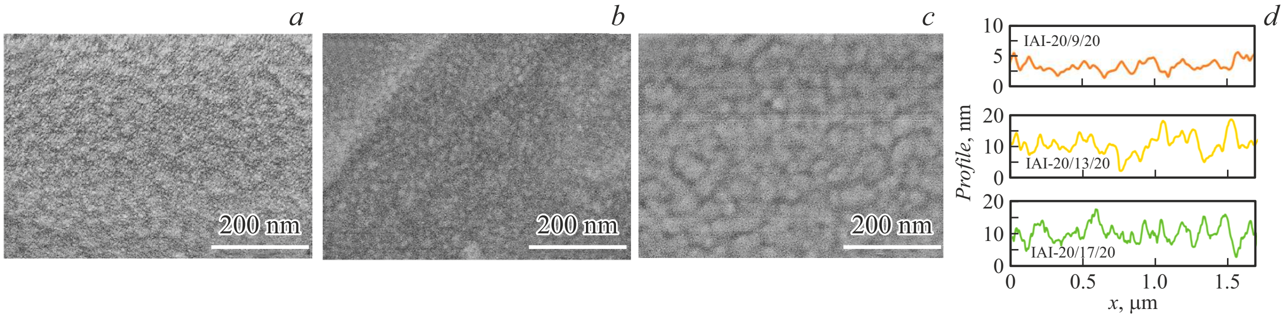

Figure 1. SEM-images of morphology of indium oxide initial layer films on PET (a) and silver films with thickness of 9 (b) and 17 nm (c) on indium oxide sublayer (magnification of 200 k). d — roughness profiles of IAI sandwich structures surface with different thickness of silver.

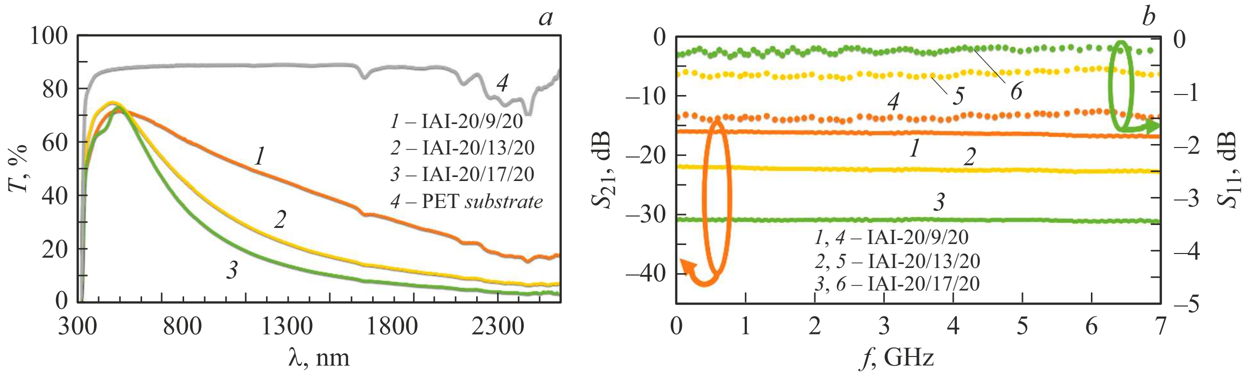

Figure 2. a — transmission in the visible and near IR-ranges; b — transmission and reflection coefficients of IAI sandwich structures in the range of 0.01–7 GHz.

and IAI sandwich structures. As a rule, thin metal films have low transmission due to losses in the thin layer of the metal. Since the losses for absorption in the thin film of the metal are insignificant, one of the loss mechanisms is reflection of radiation at the interface of metal–air. Application of the transparent oxide layer above the metal film makes it possible to reduce the losses for reflection, thus clarifying the whole structure [6]. The upper layer of the indium oxide serves as an anti-reflection coating. It should be noted that competing processes are observed between increased transmission due to anti-reflecting properties of the indium oxide film and lower transmission due to the increase in the thickness of the silver layer, which provides for the unambiguity of the spectra behavior in the visible area. Transmission at wavelength of 500 nm for the structures with silver layer of 9, 13 and 17 nm thickness is 71.46, 73.35 and 72.28 % accordingly. However, the integral transmission in the visible range decreases significantly with the increase of the silver layer thickness, which correlates with the literature data [7]. In the near IR-range (780–2600 nm) the even reduction of transmission for all IAI sandwich structures was observed. There is a clear interconnection between the thickness of the silver layer and the transmission coefficient.

The sheet resistance of IAI sandwich structures was measured by the four-probe method using ST2258C installation (Jingge Electronics Co., China), it was 31 ± 6, 14 ± 3 and $6 \pm 2\,\Omega$/sq accordingly. Electrical transport may be described within the model of three resistors connected in parallel. According to this model, the main contribution to the electric conductivity of the IAI sandwich structure is made by the layer with minimum resistance, i. e. silver layer. For the silver films sputtered on the indium oxide layer and described above, the sheet resistance was 15 ± 6, 10 ± 3 and $5 \pm 1\,\Omega$/sq accordingly. You can see that the values differ from the values specific for the end IAI sandwich structures. Note that the sheet resistance for the IAI structure with the silver layer of 9 nm thickness has the highest deviation, which is due to the partial oxidation of the silver nanocrystallite surface in process of reactive sputtering of the indium oxide layer closing the sandwich structure, besides, for the film with thickness of 9 nm this effect is more pronounced since the average size of the crystallite is considerably smaller.

Transmission (S_{21}) and reflection (S_{11}) coefficients in the range of 0.01–7 GHz were measured using a coaxial cell, the detailed description of the experiment is provided in our previous paper [8]. Fig. 2, b shows the results of transmission coefficient measurement for three types of

Averaged energy balance of IAI sandwich structures

Sample	S_{11}, %	S_{21}, %	A, %	SE, dB	SE_{calc}, dB
IAI-20/9/20	70.6	2.28	27.12	16.42	16.91
IAI-20/13/20	84.9	0.56	14.54	22.55	23.03
IAI-20/17/20	94.2	0.077	5.72	31.12	29.67

IAI sandwich structures. The transmission coefficient of IAI sandwich structures is permanent in the entire studied range. IAI sandwich structures may be characterized by the averaged transmission coefficient in the entire studied range. Increased thickness of the silver layer causes serial reduction of the transmission coefficient. Increase of the silver thickness from 9 to 17 nm causes decrease in the transmission coefficient from -16.42 to -31.12 dB.

The screening coefficient (SE) of solid structures of OMO type is related to the transmission coefficient by dependence $SE = -10\lg S_{21}$ and may be assessed using the thin layer model [9]:

$$SE = 20\lg\left(1 + \frac{Z_0}{2R}\right), \qquad (1)$$

where R — sheet resistance, $Z_0 = 377\,\Omega$ — vacuum impedance. This simple model makes it possible to compare the experimental and model results.

Reflection spectra of IAI sandwich structures in the range of 0.01–7 GHz are shown in fig. 2, *b*. The reflection is even in the entire studied range. Increase of the silver layer thickness increases the share of the reflected radiation. The full energy balance of IAI sandwich structures in the range of 0.01–7 GHz, calculated using formula $S_{11} + S_{21} + A = 1$ (A — absorption coefficient), is given in the table.

Therefore, the paper describes the production of thin-film sandwich structures In_2O_3/Ag/In_2O_3, which are promising optically transparent screens of electromagnet radiation. Spectral transmission in the range of 0.01–7 GHz is constant and correlates with the thin film layer. The maximum screening coefficient in the range of 0.01–7 GHz was obtained for the IAI sandwich structure with the thickness of the silver layer of 17 nm and made 31.12 dB. High screening coefficient at high transmission in the visible range demonstrates the promising outlook of IAI sandwich structures for practical use.

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Conflict of interest

The authors declare that they have no conflict of interest.

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