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## FILMS OF POROUS ALUMINUM OXIDE OBTAINED BY TWO-STAGE ANODIZATION

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**Abstract.** Anodic aluminum oxide films are widely used to obtain many types of organic and inorganic nanomaterials and are of practical importance in studying the optical properties of nanomaterials synthesized from them. This work presents a method of two-sided and two-stage anodization for obtaining anodic aluminum oxide films with periodic and regularly spaced pores. The method of anodic oxidation of aluminum in solutions of acidic electrolytes makes it possible to quite easily vary the parameters of the porous structure of  $Al_2O_3$ . Oxalic acid was used as an electrolyte for “soft” anodizing of the aluminum plate, and ethyl alcohol and a solution of orthophosphoric acid and chromic anhydride were used to pre-clean and polish the aluminum plate. Anodization was carried out at low temperatures, as a result of which it was possible to obtain an aluminum oxide film with a high degree of ordering of pores, the sizes of which ranged from 60 to 110 nm, and the distance between the pores was in the range of 13–27 nm. Absorption and reflection spectra of a porous film of anodized aluminum were obtained, where good absorption of the films is observed in the short-wavelength region of the spectrum, and the maximum value of the refractive index is observed in the short- and long-wavelength regions of the spectrum.

**Keywords:** Transparent anodic aluminum oxide films, double-sided anodizing, porous membranes, anodizing at low temperatures, barrier layer.

### 1. Introduction

Inorganic membranes, including dense membranes (nonporous) and microporous membranes, due to their good thermal and chemical stability, are one of the promising materials for the separation of gaseous  $H_2$  [1-3]. During the last 30 years, many studies have been successfully conducted by various research groups to improve membrane transport/separation properties by modifying porous inorganic membranes using chemical vapor deposition (CVD), sol-gel and other methods [4, 5].

Anodic aluminum oxide (AAO) films with periodic and regularly spaced pores have a wide range of applications [6]. AAO is used to obtain many types of organic and inorganic nanomaterials, which are widely used in optics [7], energy storage [8], sensors [9], molecular sieves for gas separation [10], surface-enhanced Raman scattering [11], ion current rectification [12], biological antibacterial treatment [13], food industry [14] and many other areas. By changing the experimental conditions and preparation processes, it is possible to obtain AAO films with different porous structures [15]. Transparent AAO films are of practical

importance in studying the optical properties of nanomaterials synthesized from them. Transparent AAO films with barrier layers separated from aluminum substrates have nonlinear diode-type current-voltage characteristics and ion rectification properties and are used in biosensing, bioseparation, nanofluidic electronics, etc. [16].

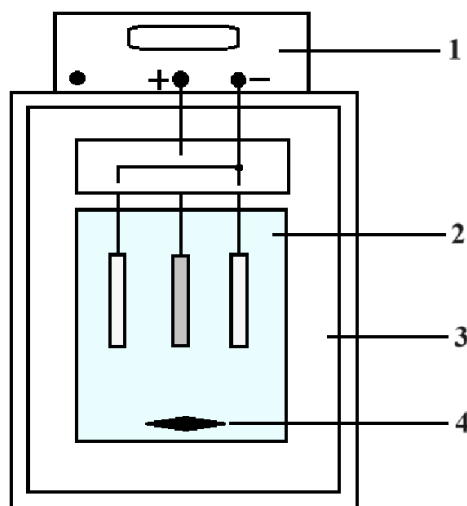
This paper presents the results of the development of technology and studying the properties of anodized aluminum oxide (AAO) films.

## 2. Experimental part

Films of porous aluminum oxide were prepared by two-sided and two-stage anodization. A 0.3 M solution of oxalic acid was used as an electrolyte.

To begin with, aluminum plates of 99.99% purity, 3.5x3.5 cm in size and 0.5 mm thick were prepared. Aluminum plates were pre-annealed in a muffle furnace at 500°C for 6 hours. Afterwards, the plate surface was cleaned with ethyl alcohol to degrease it. An important characteristic of metallic aluminum that affects the process of ordering of the porous structure is the roughness of its surface. The aluminum surface was leveled by electrochemical polishing in a pulsed mode. For electrochemical polishing of the aluminum surface, an electrolyte was used, which has the following composition:  $\text{CrO}_3$  (185 g/l) and  $\text{H}_3\text{PO}_4$  (1480 g/l). The solution was poured into a heat-resistant container and placed on a magnetic stirrer at a temperature of 80 °C. An aluminum plate (of the same composition and larger in area) was attached to the negative electrode and an aluminum plate for polishing to the positive electrode, then the aluminum plate was lowered into the solution with a special device and polished for 40 min. The aluminum plate was subjected to electrochemical polishing in a pulsed mode at a maximum voltage of 20 V, current - 11 A, pulse duration - 3 s, interval between pulses - 40 s, number of pulses - 40 pcs. The quality control of electrochemical polishing was assessed by the appearance of the aluminum surface.

A solution of oxalic acid  $(\text{COOH})_2$  with a concentration of 0.3 M was prepared for anodizing aluminum. The electrolyte was poured into a special container, as shown in Figure 1. Two platinum wires were used as a negative electrode. An aluminum plate was placed between the platinum wires and connected to the positive electrode. A stirrer was attached to the container lid to ensure uniform anodization. This entire structure was placed in a refrigerator to ensure anodic oxidation at a temperature of 0 °C.



**Fig.1.** Installation for anodizing aluminum:

1 – power source, 2 – electrochemical cell, 3 – refrigeration chamber, 4 – magnetic stirrer.

The first anodizing stage was carried out at a voltage of 40 V. Then the plate was subjected to electrochemical etching in a solution of orthophosphoric acid (35 ml/l) and chromic anhydride (20 g/l) at 60°C for 15 min. After removing the oxide film, the second stage was carried out according to the same conditions as the first. The resulting transparent aluminum oxide film was washed in deionized water.

The absorption and reflection spectra of the anodic aluminum oxide film were measured on an AvaSpec-ULS2048CL-EVO spectrometer (Avantes). Graphs were built using the obtained data in the OriginPro application.

### 3. Results and discussion

Due to the fact that ordering of the structure occurs during film growth, the upper side of the membrane is characterized by a chaotic arrangement of pores. To obtain films with an ordered structure throughout the entire volume, two-stage anodization of the films was carried out. The method of anodic oxidation of aluminum in solutions of acidic electrolytes makes it possible to quite easily vary the parameters (pore diameter, distance between pores, film thickness) of the  $\text{Al}_2\text{O}_3$  porous structure. The production of aluminum oxide layers was carried out under conditions of “soft” anodization using a two-sided method. The thickness of the films obtained by this method is directly proportional to the duration of electrochemical oxidation, and the rate of formation of the oxide layer varies from 2 to 5  $\mu\text{m}/\text{h}$ . It should be noted that the temperature of the electrolyte is the most important parameter, since at a constant acid concentration it determines the rate of dissolution of the oxide layer at the oxide/electrolyte interface. After preliminary surface preparation, the first anodic oxidation of aluminum was carried out in a solution of 0.3 M  $(\text{COOH})_2$ . After this, subsequent (second) anodic oxidation was carried out under the same conditions as during the first oxidation. In this case, it is possible to obtain an aluminum oxide film with a high degree of pore ordering. Figure 2 shows a chronoamperogram of the process of obtaining anodized aluminum films using a two-stage method.

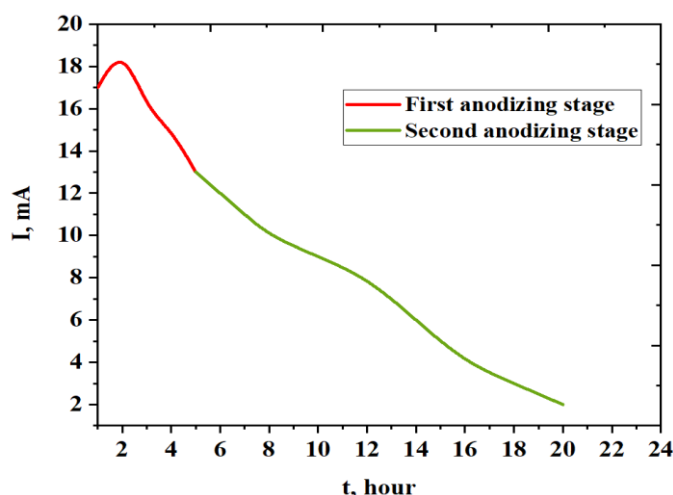
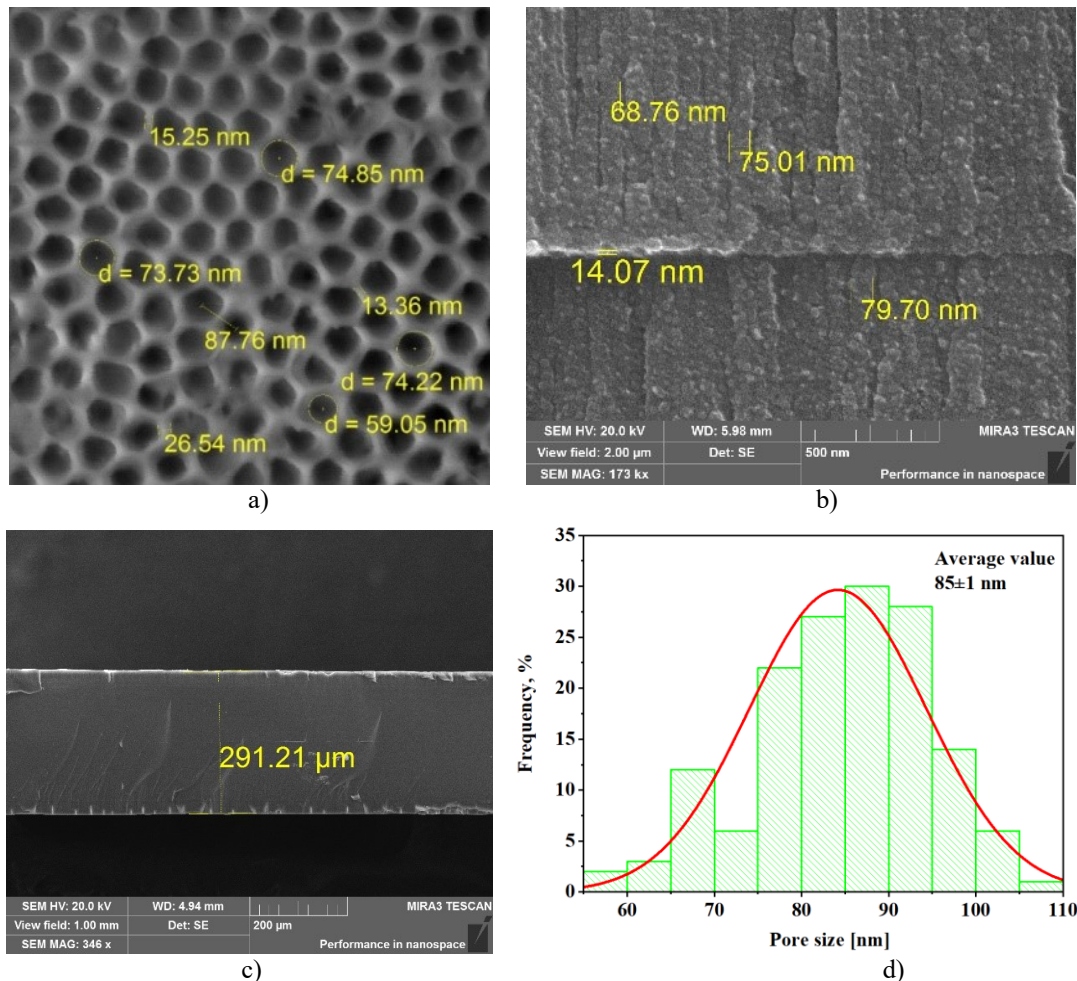


Fig.2. Chronoamperogram of the first and second stages of anodization.

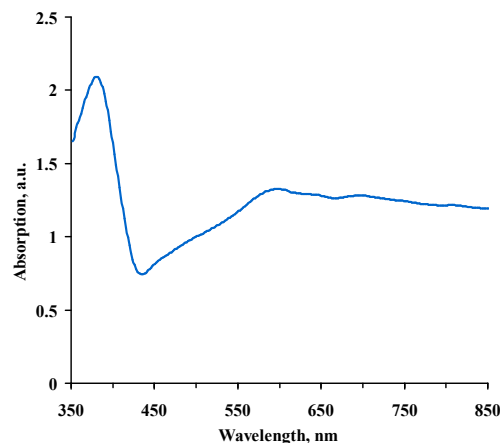
In Figures 3 (a) and (b) are shown SEM images of one of the surfaces of a transparent alumina film. The pictures show a typical ordered porous structure. The size of the ordered pores varies in the range of 60–110 nm, as shown in Figure 3 (d). The distance between the pores was in the range of 13–27 nm. The SEM image of the transverse cleavage of the transparent AAO film is shown in the same Figure 3 c. The film thickness is about 291  $\mu\text{m}$ . The transverse cleavage is divided into upper and lower layers, separated by a barrier layer whose size is on the order of 14 nm (Figure 3 b).

The absorption spectrum of a porous anodized aluminum film is shown in Figure 4. Anodized aluminum films are practically opaque in the spectral range of 400–700 nm. The observed good absorption of anodized aluminum films  $\lambda < 400$  nm in the short-wavelength region of the spectrum with the maximum at 380 nm corresponds to an interband transition from the valence band to the bottom of the conduction band. This region corresponds to transitions from final states of the valence band to broadened states of the conduction band in aluminum oxide [17]. In the long-wavelength part of the absorption spectrum of films at  $\lambda > 450$  nm, a broad band with a maximum at 570 nm is observed, which may be associated with light scattering in porous structures.

The diffuse reflectance coefficient of films is 27% at  $\lambda < 400$  and decreases as the wavelength of light increases. In the spectral range 470–700 nm it is 10%.

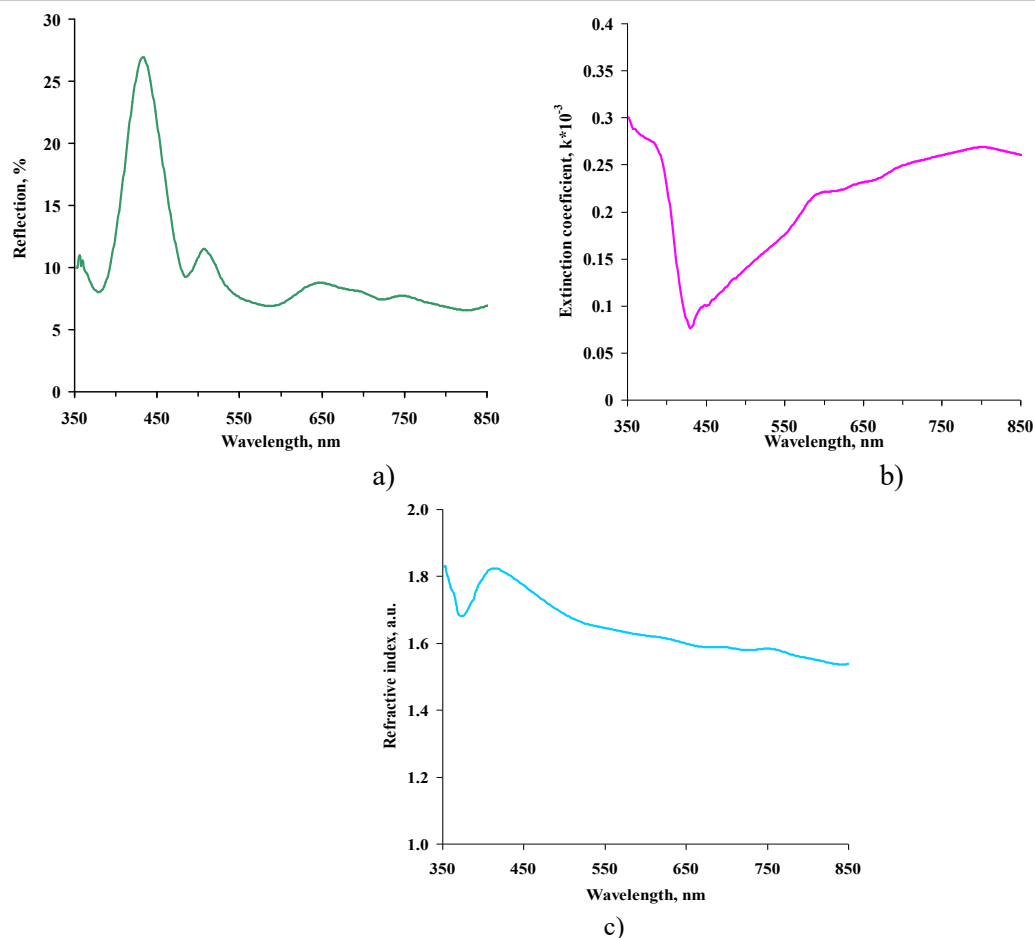


**Fig.3.** (a) SEM image of the surface of an aluminum oxide film; (b) SEM image of a transverse cleavage of a transparent AAO film; (c) size of a transverse cleavage; (d) histogram of pore size distribution.



**Fig.4.** Absorption spectrum of a porous film of anodized aluminum.

The diffuse reflectance coefficient of films is 27% at 430 nm and decreases as the wavelength of light increases (Figure 5a). Such pronounced peaks are observed in thin AAO films, the thickness of which is comparable to the wavelength [18]. The appearance of such a peak in a thick AAO film is apparently associated with the presence of a barrier layer in the center of the oxide structure. In the range of 550-850 nm, the reflection is on average no more than 10%. The optical constants of thin films of anodized aluminum ( $k$  – extinction coefficient and  $n$  – refractive index) were determined according to the method [3]. As expected, the extinction coefficient given in Figure 5b for the resulting structure generally follows the absorption spectrum corrected for the reflection and refractive index.



**Fig.5.** (a) Reflection spectrum; (b) dependence of the extinction coefficient on the wavelength; (c) dependence of the refractive index on the wavelength of anodized aluminum films.

The refractive index is one of the fundamental properties of an optical material, since it is closely related to the electronic polarization of ions and the local field within the material. The Figure 5 c shows that the maximum value of the refractive index ( $n=1.82$ ) is observed in the short-wavelength  $\lambda=412$  nm and gradually decreases in the long-wave part of the spectrum. These results are in good agreement with data obtained by other authors [19-21].

#### 4. Conclusion

Using the method of two-sided and two-stage anodization, AAO films with periodic and regularly spaced pores were obtained. Anodization was carried out in oxalic acid at a voltage of 40 V at low temperatures. The aluminum plate was subjected to electrochemical polishing in orthophosphoric acid. As a result, an aluminum oxide film with a high degree of pore ordering was obtained, which is confirmed by the surface patterns of the transparent aluminum oxide film. The absorption and reflection spectra of a porous film of anodized aluminum were obtained. The ability to regulate the time of first and secondary anodization allows precise control of the thickness of the transparent AAO film, and the prepared film is a two-sided porous layer separated by a barrier layer, with subsequent use as molecular sieves in ion transport for photocatalytic reactions and hydrogen fuel cells. The proposed method is very easy to operate and does not require complex preparation processes. The advantage of the method we propose is that we have obtained a two-stage anodizing technology with through channels with adjustable dimensions formed towards each other. This method will allow the production of membranes and various types of filters for various applications. The results of the proposed solutions will allow developing technologies related to the development of new types of nanomaterials used as hydrogen fuel cells, which will expand the range of technologies in the field of “green energy”.



**Conflict of interest statement**

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

**CRedit author statement**

**Zhangbyrbay Ye.R.:** Writing – original draft, Investigation; **Aimukhanov A.K.:** Supervision, Methodology; **Zeinidenov A.K.:** Resources, Project administration, Conceptualization; **Gadirov R.M., Abeuov D.R.:** Formal analysis, Visualization; **Zhakanova A.M.:** Data curation. The final manuscript was read and approved by all authors.

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**References**

- 1 Ismail A.F., Khulbe K.C., Matsuura T. (2015) Gas Separation Membranes, *Switz. Springer, New York*, 10, 973–978. <https://doi.org/10.1007/978-3-319-01095-3>
- 2 Chiu W.V., Park I.S., Shqau K., White J.C., Schillo M.C., Ho W.S.W., Dutta P.K., Verweij H. (2011) Post-synthesis defect abatement of inorganic membranes for gas separation. *J. Membr. Sci.*, 377, 182–190. <https://doi.org/10.1016/j.memsci.2011.04.047>
- 3 Poelman D., Smet P.F. (2003) Methods for the determination of the optical constants of thin films from single transmission measurements: a critical review. *J. Phys. D: Appl. Phys.*, 36, 1850–1857. <https://doi.org/10.1088/0022-3727/36/15/316>
- 4 Cooper C.A., Lin Y.S. (2002) Microstructural and gas separation properties of CVD modified mesoporous  $\gamma$ -alumina membranes. *J. Membr. Sci.*, 195, 35–50. [https://doi.org/10.1016/S0376-7388\(01\)00508-7](https://doi.org/10.1016/S0376-7388(01)00508-7)
- 5 Wang H., Zhang L., Gavalas G.R. (2000) Preparation of supported carbon membranes from furfuryl alcohol by vapor deposition polymerization. *J. Membr. Sci.*, 177, 25–31. [https://doi.org/10.1016/S0376-7388\(00\)00444-0](https://doi.org/10.1016/S0376-7388(00)00444-0)
- 6 Lee W., Park S.J. (2014) Porous anodic aluminum oxide: anodization and templated synthesis of functional nanostructures. *Chem. Rev.*, 114, 7487–7556. <https://doi.org/10.1021/cr500002z>
- 7 Irvani S. (2023) Surfactant-free synthesis of metal and metal oxide nanomaterials: a perspective. *RSC Sustainability*, 1, 72–82. <https://doi.org/10.1039/d2su00088a>
- 8 Li Z., Wei H., Chen D., Chang M., Hu H., Ye X., Zhang Y., Wen W., Wang M. (2021) Optical properties of multicolor, hierarchical nanocomposite films based on anodized aluminum oxide. *Opt. Mater.*, 111, 110557. <https://doi.org/10.1016/j.optmat.2020.110557>
- 9 Wei H., Xu Q., Chen D., Chen M., Chang M., Ye X. (2022) Lowered infrared emittance and enhanced thermal stability of solar selective absorption properties of anodic aluminum oxide photonic crystal coatings. *Sol. Energy*, 241, 592–600. <https://doi.org/10.1016/j.solener.2022.06.041>
- 10 Roslyakov I.V., Kolesnik I.V., Evdokimov P.V., Skryabina O.V., Garshev A.V., Mironov S.M., Stolyarov V.S., Baranchikov A.E., Napolskii K.S. (2021) Microhotplate catalytic sensors based on porous anodic alumina: operando study of methane response hysteresis. *Sensor. Actuator. B Chem.*, 330, 129307. <https://doi.org/10.1016/j.snb.2020.129307>
- 11 Pan M., Cooper C., Lin Y.S., Meng G.Y. (1999) CVD modification and vapor/gas separation properties of nanoporous alumina membranes. *J. Membr. Sci.*, 158, 235–241. [https://doi.org/10.1016/S0376-7388\(99\)00016-2](https://doi.org/10.1016/S0376-7388(99)00016-2)
- 12 Wang X., Wang J., Jiang Z., Tao D., Zhang X., Wang C. (2021) Silver loaded anodic aluminum oxide dual-bandgap heterostructure photonic crystals and their application for surface enhanced Raman scattering. *Appl. Surf. Sci.*, 544, 148881. <https://doi.org/10.1016/j.apsusc.2020.148881>
- 13 Shi L., Jia F., Wang L., Jalalah M., Al-Assiri M.S., Gao T., Harraz F.A., Li G. (2021) Fabrication of an artificial ionic gate inspired by mercury-resistant bacteria for simple and sensitive detection of mercury ion. *Sensor. Actuator. B Chem.*, 326, 128976. <https://doi.org/10.1016/j.snb.2020.128976>
- 14 Zhang X., Zhang J., Han X., Wang S., Hao L., Zhang C., Fan Y., Zhao J., Jiang R., Ren L. (2023) A photothermal therapy enhanced mechano-bactericidal hybrid nanostructured surface. *J. Colloid Interface Sci.*, 645, 380–390. <https://doi.org/10.1016/j.jcis.2023.04.148>
- 15 Thao D.T.V., Weng W.T., Hieu N.V., Chang C.C., Wang G.J. (2022) A flexible and stretchable photonic crystal film with sensitive structural color-changing properties for spoiled milk detection. *Food Chem. X*, 16, 100526. <https://doi.org/10.1016/j.fochx.2022.100526>
- 16 Ruiz-Clavijo A., Caballero-Calero O., Martin-Gonzalez M. (2021) Revisiting anodic alumina templates: from fabrication to applications. *Nanoscale*, 13, 2227–2265. <https://doi.org/10.1039/D0NR07582E>

- 17 Wangkasem P., Rojananan S. (2015) Mechanical and Electrical Properties of Aluminium Alloy by Cryorolling Process. *The International Journal of Advanced Culture Technology*, 3(1), 46-51. <https://doi.org/10.17703/IJACT.2015.3.1.46>
- 18 Liu Y., Wang H.H., Indacochea J.E., Wang M.L. (2011) A colorimetric sensor based on anodized aluminum oxide (AAO) substrate for the detection of nitroaromatics. *Sensors and Actuators B: Chemical*, 160(1), 1149-1158. <https://doi.org/10.1016/j.snb.2011.09.040>
- 19 Hierro-Rodriguez A., Rocha-Rodrigues P., Valdés-Bango F., Alameda J.M., Jorge P.A.S., Santos J.L., Araujo J.P., Teixeira J.M., Guerreiro A. (2015) On the anodic aluminium oxide refractive index of nanoporous templates. *Journal of Physics D: Applied Physics*, 48(45), 455105. <https://doi.org/10.1088/0022-3727/48/45/455105>.
- 20 Koushki E., Mousavi S.H., Jafari Mohammadi S.A., Majles Ara M.H., Oliveira P.W. (2015) Optical properties of aluminum oxide thin films and colloidal nanostructures. *Thin solid films*, 592, 81-87. <https://doi.org/10.1016/j.tsf.2015.09.003>
- 21 Seredin P.V., Lenshin A.S., Kashkarov V.M., Lukin A.N., Arsentiev I.N., Bondarev A.D., Tarasov I.S. (2015) Ultrathin nano-sized Al<sub>2</sub>O<sub>3</sub> strips on the surface of por-Si. *Materials Science in Semiconductor Processing*, 39, 551-558. <https://doi.org/10.1016/j.mssp.2015.05.067>

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