

## Calculation of the Membrane Thickness of Magnetite Nanoparticles on the Surface of the Transparent Conductive Electrode in the Electric Field

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We observe and study the reflection and interference in the two-layer thin film composed of a conductive layer of ITO and dispersed particles of magnetic fluid (magnetite). In an electric field the equivalent thickness of the membrane is increased by varying the thickness of the second layer. At a certain value of the electric field the layer becomes unstable, its thickness varies periodically, autowave process leading to the characteristic active centers (pacemakers), spiral waves (reverberators) was observed.

**Keywords:** Magnetic fluid, Electrorreflection, Thin membrane, Reflectance, Reflected light intensity, Instability, Autowaves.

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### 1. INTRODUCTION

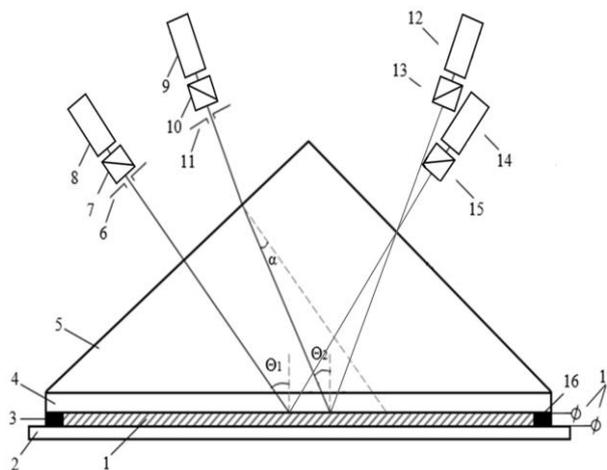
In this paper we investigate the optical properties of a thin membrane consisting of a transparent indium-titanium coating (ITO) and a concentrated layer of solid particles of magnetic fluid – packed magnetite nanoparticles.

Magnetic fluid (MF) is a stable single-domain ferromagnetic colloidal particles (magnetite), dispersed in various liquids (kerosene, water and others) [1]. As a stabilizer for preventing coagulation of the colloidal solution we used surfactants, which are adsorbed on the surface of the solid particles to form a protective coating. In this paper was used for the experiments ferrofluid type «magnetite in kerosene» oleic acid (molecular length of  $\sim 1.5$  nm) as the surfactant. In the absence of an electric field, the magnetic fluid is uniform, but when the field is on, the particles of the solid phase under the effect of the MF electrophoresis and dyppolophoresis start to migrate to the electrodes, and the thin membrane of the solid particles of the magnetic fluid forms on the electrode surface. The approximate time of formation of the film is from 0.2 s. to 1 s., depending on the applied electric field, the thickness is from 10 to 100 nm. Reflection from the surface of the film and variety of the reflection parameters in an electric field, including interference at the border with the electrode has been studied previously in [2-4]. Ability to control the thickness of two-layer thin film «magnetite nanoparticles – ITO» with the help of an external electric field and the possible practical applications of this phenomenon [5] determines the relevance of research carried out in this paper.

### 2. THE EXPERIMENTAL DEVICE AND METHODS OF THE EXPERIMENT

The device for monitoring changes in the intensity of the reflected light in the electric field is a cell (Fig. 1), consisting of two electrodes, one of which – a transparent conductive glass coated ITO (Manufacturer – SPC «Poly-

tech», St. Petersburg). In order to eliminate glare from the surface of the cell it is installed on a glass prism. Optical contact with the glass side of the prism made immersion liquid (epoxy resin without plasticizer  $n = 1,523$ ). With a scanning probe microscope Integra Prima been found that the surface layer of ITO is rough.



**Fig. 1** – Experimental device for observing changes in the intensity of the reflected light. 1 – magnetic fluid; 2 – plate Micarta foil; 3, 16 Isolate pads made of polystyrene; 4 – glass coated with a conductive transparent ITO; 5 – angled isosceles prism; 6, 11 – aperture; 7, 10, 13, 15 – Polaroids; 8, 9 – photo-diodes; 12, 14 – laser pointers; 17 – electrodes;  $\theta_1$ ,  $\theta_2$  – angles of incidence

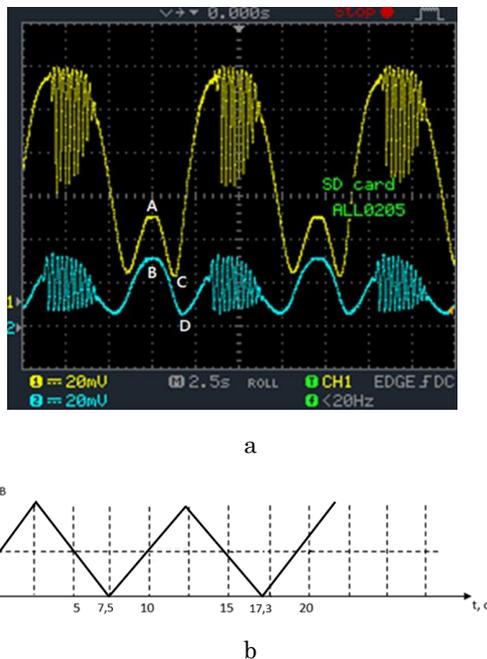
We measured the roughness parameter  $R_a$  – arithmetic mean of the absolute values of the roughness at the «glass-to-air» – is 2 nm, and on the border «ITO-air» is 10-12 nm. Optical parameters of the ITO-film was measured by spectroscopic ellipsometer SE 800 SENTECH ten points at a distance of 5 mm from each other at the wavelength  $\lambda = 650$  nm. The average refractive index was equal to  $1,78 \pm 0,05$ , the absorption coefficient is  $0,08 \pm 0,02$  at a coating thickness of  $200 \pm 10$  nm.

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Between the electrodes there is a magnetic fluid (MF). The experiments used magnetic fluid type «magnetite in kerosene». Bulk solids concentration was calculated from the density of the magnetic fluid. For MF density  $\rho = 930 \text{ kg/m}^3$  the concentration of the solid phase was about 3.2 %. The refractive index of MF in the amount of cell  $n_3 = 1,47$  refractive index MF concentration of 27 % (near-electrode layer)  $n_2 = 1,78 \pm 0,05$ , the absorption coefficient – 0.07.

On the face of the prism (Fig. 1) fall rays from a 2 mm diameter laser pointers ( $\lambda = 650 \text{ nm}$ ) with angles  $\alpha_1$  and  $\alpha_2$ , so that the angles of incidence on the surface of ITO are 30 and 45 degrees (Fig. 2). The rays are reflected from the surface of the «glass film ITO» and «film ITO – magnetic fluid» and interfere. Reflect rays enter through the diaphragm – 6, 11 and Polaroids – 7, 10 in the photodiodes PD-256. The photodiodes are connected to the input of a two-beam oscilloscope GDS-71022. The rays reflected from the boundaries of the «prism-glass» and from the layer «ITO – magnetic fluid» spatially separated  $\sim 4 \text{ mm}$ . In order to avoid stray light photodiodes front polarizers 7 and 10 diaphragms about 1 mm were placed. Lasers and polaroids can rotate relative to the rays. The plane of polarization of the polarizers 13 and 14 coincides with the plane of polarization of the laser beams. Polaroids serve to reduce the depolarized component of laser light. Turning lasers polaroids we make the s-component (TE-wave) perpendicular to the plane of incidence. Turning polaroids 7, 10 we weaken light to photodiodes operated in the linear mode. The surface area of the electrodes  $S = 36 \times 30 \text{ mm}^2$ , the layer thickness l MF – 250 microns.



**Fig. 2** – Waveform of voltage time changes on photodiodes (a), type of voltage applied to the electrodes of the cell with a magnetic fluid (b)

On the electrode is applied slowly varying voltage of 0-20 V – (Fig. 2b). Voltage change period – 9.8 seconds. Curve 1 – change in reflectance  $R$  on the surface of «ITO – a layer of solid particles of magnetic fluid» in

the fall of the laser beam at an angle of 30 degrees, curve 2-45 degrees. In the early period of zero voltage (the points A and B on the curve 1 and 2) fixed to the optical response. Then, with the increase in voltage, the reflectance decreases (portion on the curve AC 1 and BD portion of the curve 2) to a minimum, which is typical for interference in thin films.

Measurements of spectroscopic ellipsometer SE 800 SENTECH showed that the values of the refractive indices of ITO-coating and concentrated particle layer MF are close in value, and therefore can be considered as ITO layer and concentrated MFs optically equivalent to the incident light wave. With the increase of the electric field an increase in the thickness of the layer of optically equivalent «particle MF + layer ITO» can be stated.

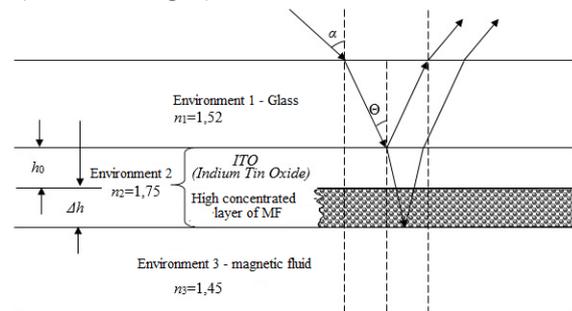
Please note that in the ITO-coating a transition layer whose properties, including refractive index change (1.8-1.7 – data SE 800 SENTECH). Roughness is comparable with the size of «trapped» MF particle layer (layer thickness about 200 nm and an average particle diameter of 10 nm). Speaking of optically equivalent to the total thickness of the layer (ITO + MF particles), we mean a layer of flat geometric borders and the average refractive index.

### 3. DISCUSSION OF THE RESULTS

We calculate the dependence of  $R$  on the thickness of the two-layer film «ITO + layer concentrated MF» at angles of incidence of  $30^\circ$  and  $45^\circ$  for the s-components by the method described in [6].

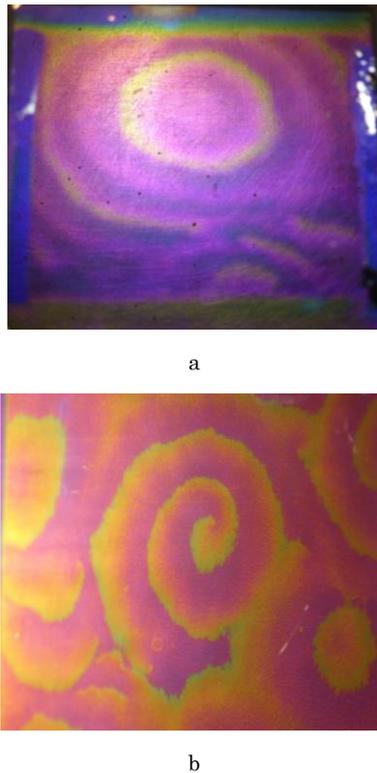
The scheme of multilayer structure with two boundaries is shown in Fig. 3. The first medium – glass with a refractive index  $n_1 = 1,52$ , medium 2 – two-layer film «ITO – concentrated MF» variable thickness  $h_0$  of no electric field to  $h = \Delta h + h_0$  in electrical field having a refractive index  $n_2 = 1.78 \pm 0.05$ . Third environment – magnetic fluid with a refractive index  $n_3 = 1,45$  (without taking into account the absorption coefficient).

Voltage proportional to the intensity of the oscilloscope reflected from the surface of the beam which strikes the photo diodes 8 and 9, is equal to  $U_1 (V)$ , where  $V = V(t)$  – the voltage applied to the electrodes 17 (curve b in Fig. 2).



**Fig. 3** – The circuit of the multilayer structure with two boundaries

Since the photodiode operates in the linear mode, the voltage on the oscilloscope is directly proportional to the intensity of reflected rays. It was possible to calculate the index and film thickness on the intensity of the reflected beams at different angles of incidence as described in [4].



**Fig. 4** – Autowaves with characteristic leading centers (pacemakers) (a). Spiral waves (reverberators) (b)

After calculations, we obtained the following values: film thickness  $h = h_0 + \Delta h$  at the maximum value of the electric field above which the instability surface approximates  $200 + 300 = 100$  nm, the refractive index of the two-layer film  $n_2 = 1,78$ , which meaning is close to the refractive index of the ITO.

By adjusting the value supplied to the electrodes of the electric field, it is possible to control the thickness

«adhering» to the electrode layer of the solid particles. Given the equality of the refractive index and absorption of the ITO layer of the particles of the magnetic fluid, we get electrically increase in optical thickness bilayer film «ITO-magnetite nanoparticles».

With further increase in voltage observed fluctuations in the intensity of the reflected light. Apparently, a layer of solid particles of the magnetic fluid becomes unstable; its thickness varies periodically, as shown by the oscillograms of the voltage on reaching  $\sim 15$  V. Replacing a source of visible laser light in the experimental device (Fig. 1) at a certain critical value of the voltage with typical autowave leading centers – pacemakers, spiral waves – reverberators were observed (Fig. 4). A thin layer of the magnetic fluid in the electric field represents a unique active environment, where in the laboratory conditions we can investigate and easily reproduce the autowave process. Its uniqueness lies in the fact that commonly autowave processes are difficult to reproduce (population dynamics), or too short-lived, or proceed with a limited number of repeats (Belousov-Zhabotinsky reaction).

#### 4. CONCLUSIONS

We have investigated the optical properties of a thin membrane composed of a conductive coating (Indium tin oxide – ITO) and a layer of densely packed particles of magnetite. It was found that the refractive index of the conductive coating (ITO) layer and the magnetite particles are close in value, so the thin film bilayer «ITO - magnetite particles» can be regarded as an optically homogenous to incident light. An increase in the thickness of the two-layer membrane depending on the applied electric field. Membrane thickness  $h$  was calculated. Given equality of the refractive indices of layers of thin membrane, it is shown that the magnitude of  $h$  may be controlled by varying the electric field.

#### REFERENCES

1. V.E. Fertman, *Magnetic Fluids: A Reference Guide* (Minsk: High school: 1988).
2. V.V. Chekanov, A.A. Butenko, Y.L. Larionov, L.V. Nikitin, A.A. Tulinov, *Bull. Russ. Academy Sci.: Phys.* **55** No 6, 1141 (1999).
3. V.V. Chekanov, N.V. Kandaurova, V.S. Chekanov, *Tech. Phys.* **59** No 9, 1286 (2014).
4. V.V. Chekanov, N.V. Kandaurova, V.S. Chekanov, V.V. Romantsev, *J. Opt. Technol.* **82** No 1, 43 (2015).
5. V.V. Chekanov, N.V. Kandaurova, Yu.A. Rachmanina, V.S. Chekanov, Pat. 2449382, Russian Federation, IPC G09F 9/30 G02F 1/167, publ. 27.04.2012 bull. №12.
6. M. Born, E. Wolf. *Principles of Optics* (M.: Nauka: 1973).