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OPTIC RADIATION OF THIN-FILM STRUCTURE OF FD-RESISTOR WITH ACTIVE $Ni_{0.4}Zn_{0.6}Fe_2O_4$ LAYER

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Abstract- It is shown that the structure of the FD-resistor is a three-layer package of plane-parallel positioned nanofilms, the active layer of which is made of (Ni-Zn) ferrite film. The created structure of the FD-resistor corresponds to the structure of the Fabry-Perot nano resonator. Thin perfect films of $Ni_{0.4}Zn_{0.6}Fe_2O_4$ and SmS with ~20 nm thickness which deposited by thermal method on sapphire or glass substrates were studied by luminescent and optical methods. Atomic force microscope studies have shown that the surface of thin $Ni_{0,4}Zn_{0,6}Fe_2O_4$ ferrite films has a granular structure. It is shown that with the laser (532 nm) excitation in the luminescence spectra and radiation generation in the visible and terahertz ranges in the created nano resonator, with an active layer of (Ni-Zn) ferrite film or samarium monosulphide, a maximum of high intensity is observed.

Keywords: Thin Film, Ferrite, Hyper Resonant Effect, Luminescence of Spinel, FD- Resistor.

1. INTRODUCTION

The practical application of frequency-dependent resistors, which were previously reported in [1-6], revealed a significant problem of their practical use in connection with their luminescence under the influence of solar radiation (especially in hot countries). After the deposition procedure of layers, the structure of the FD-resistor (frequency-dependent) contains, a thin layer (Ni-Zn) of ferrite film deposited on a thin dielectric layer of Al_2O_3 and then on an aluminum wire. Thus, this structure can represent a three-layer Fabry-Perot package that plays the role of a nanoresonator.

This article presents the results of a complex of studies of luminescent effects, as well as the determination of the parameters of the active layer ((Ni-Zn) ferrite film) in FD resistors.

2. EXPERIMENT AND DISCUSSION

The deposition technology of $Ni_{1-x}Zn_xFe_2O_4$ submicron films on the surfaces of sapphire and glass substrates was investigated in previous works. The characteristic features of the obtained films, noted in the control atomic force microscopy experiments, were both the perfection of granular surface, and the presence in the luminescence spectrum (1.2-2.3 eV) excited by laser radiation of a high-intensity maximum (Figure 1) recorded in visible and in terahertz ranges of spectra and likely to generation.

The presence of this maximum in $Ni_{1-x}Zn_xFe_2O_4$ nano powders of ferrites was not observed. Analysis of the effect of the composition of ferrite films on the intensity of this maximum indicated that the high-intensity maximum is observed at concentrations of zinc x=0.6 ($Ni_{1-x}Zn_xFe_2O_4$). As the film thickness increases, the intensity of the maximum decreases.

The decrease or increase in the intensity of the maximum can be seen when the power of the exciting laser radiation changes. Note that the mechanism of stimulated radiation requires efficient radiative interband recombination of optically excited electrons and holes. This is possible only at high, are the centers leading to the loss of inverse population in the film [7, 8].

In publications [9, 10], the registration of laser lasing during optical pumping of polycrystalline ZnO layers deposited on a SiO_2-Si substrate was reported. The authors of the publications [9, 10] pointed out, the low quality of the layers was compensated by selecting the parameters of a three-layer nanoresonator with very different refractive indices, i.e., $n_{air}<n_{ZnO}$ and $n_{ZnO}>n_{SiO2}$, and layer thicknesses.

As our experimental studies have shown, the situation described in the layers of this nanoresonator was confirmed in three-layer resonators: air-(Ni-Zn) ferrite film-SiO_2 (or Al_2O_3); air-SmS-SiO_2 (or Al_2O_3). The emitting properties of the nanoresonator are shown in Figures 1 and 2.

As the experiments showed, an increase in the film thickness led to the disappearance of generation, thereby refuting the assumption of the presence of hyper resonance. On the other hand, spinels, which include $Ni_{0.4}Zn_{0.6}Fe_2O_4$ ferrites, have a defective structure. As it turned out, the presence of a granular surface increased the amplitude of the luminescence maximum if the size of the granules decreased [5, 6].

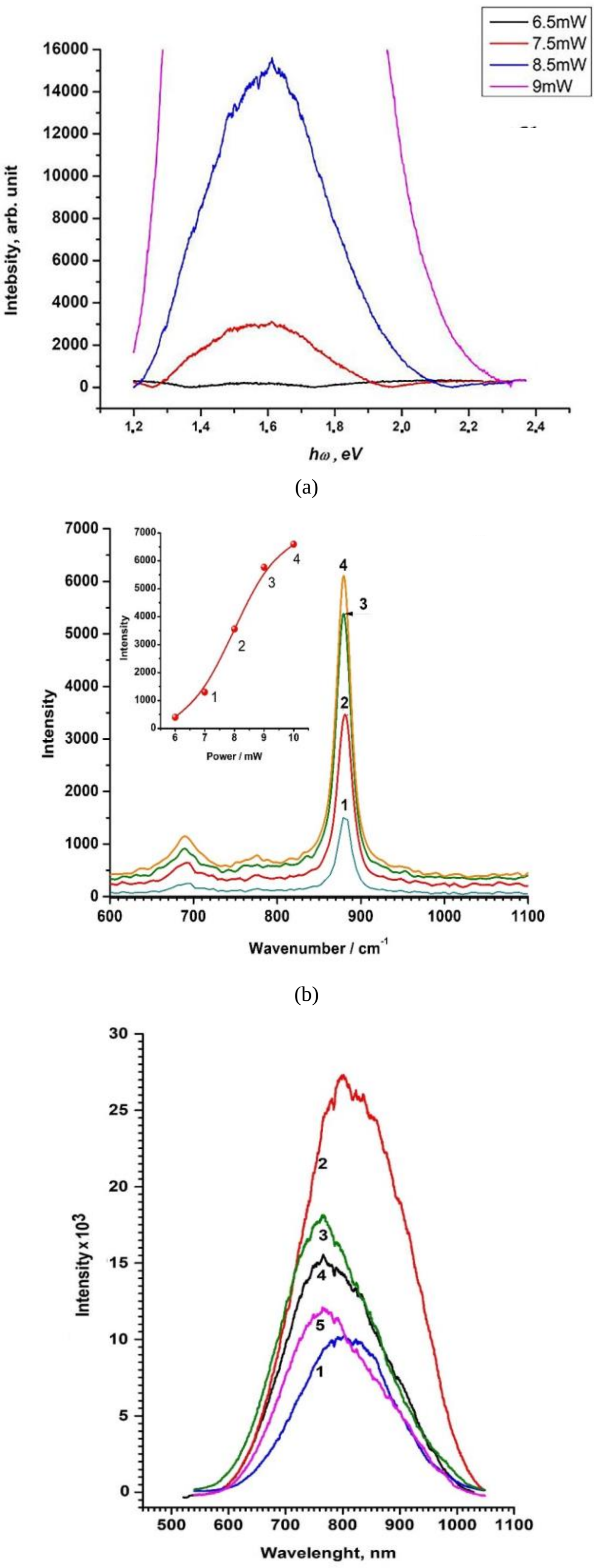

Figure 1. (a) Photoluminescence, (b) Raman scattering, spectra of the nanoresonator of $N_{i0.4}Zn_{0.6}Fe_2O_4$ at different laser pump power 1- 7 mW; 2- 8 mW; 3- 9 mW; 4-10 mW [5, 6]; (c) Photoluminescence spectra of nanoresonators with (Ni-Zn) ferrite films of various compositions, at a laser pumping power of 8/5mW and T=300 K: 1- $Ni_{0.25}Zn_{0.75}Fe_2O_4$; 2- $Ni_{0.4}Zn_{0.6}Fe_2O_4$; 3- $Ni_{0.5}Zn_{0.5}Fe_2O_4$; 4- $Ni_{0.6}Zn_{0.4}Fe_2O_4$; 5- $Ni_{0.75}Zn_{0.25}Fe_2O_4$

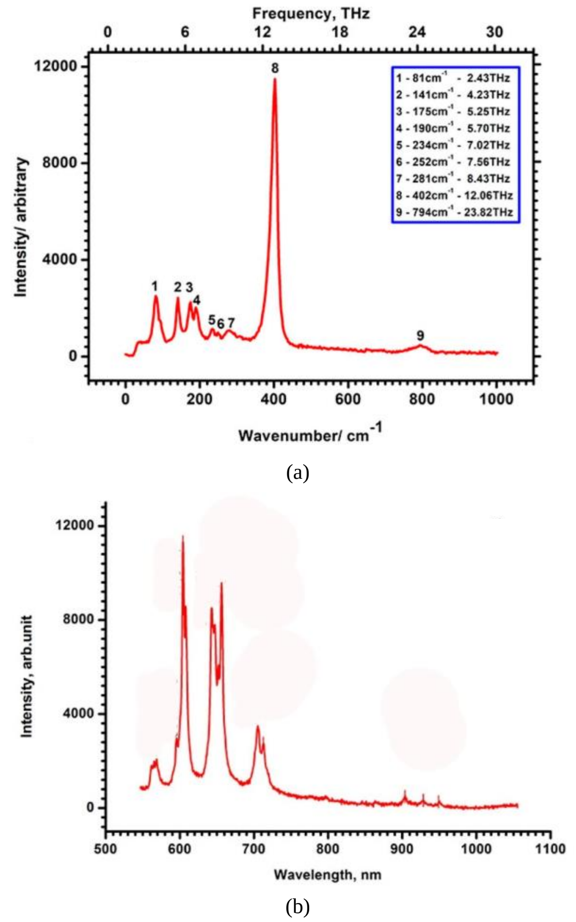

Figure 2. Raman spectrum (*a*) and photoluminescence spectrum (*b*) of the semiconductor SmS thin film on a sapphire substrate 50 nm thick at a temperature of 300 K in the range 500-1100 nm with excitation by a titanium-sapphire laser, λ = 532 nm

In Figure 3b represents fractions that make up large blocks of particles, while fractions in Figure 3a are smaller blocks by 100%, since the volume of fractions Figure 3a and Figure 3b calculated from experimental data: the particle diameter of the fraction Figure 3a is 2-20 nm, and fractions Figure 3b are 22-30 nm. For example, it is known that the magnetic characteristics of bulk nickel ferrite ($NiFe_2O_4$) differ significantly from the nanosized one [11]. $NiFe_2O_4$ nanoparticles give small values of magnetization and high values of coercive force compared to bulk material, and, depending on their size, demonstrate various possibilities for the manifestation of ferrimagnetism, super Para magnetism or Para magnetism.

The characteristics of the second layer, no less important component of the optical structure of the FD-resistor - thin films of Al_2O_3 - were studied primarily for surface quality and optical properties. The film thicknesses were determined by an interference microscope, and the surface quality was determined by an atomic force microscope. The typical thickness of ultrathin films was 150 nm. The observed surface roughness did not exceed 2 nm. The dispersion of the refractive index was determined by the reflection spectrum from the Al_2O_3 film, which has an interference character, for several angles of light incidence.

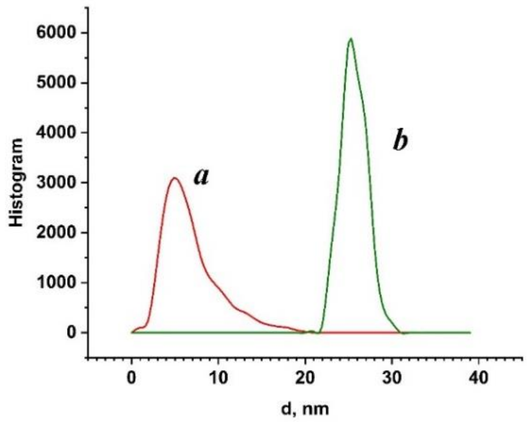

Figure 3. Histogram of the surface topography of the SmS: a- before annealing; b- after annealing at 600 ºC

This technique was previously described in [12]. The ratio between the film thickness d and the refractive index *n* has the form:

$$n = \sqrt{\sin^2 \alpha + \left(\frac{N \lambda_1 \lambda_2}{2d(\lambda_1 - \lambda_2)} \right)^2} \quad (1)$$

where, λ_1 and λ_2 are the wavelengths of the maxima/minima of interference in the spectrum, *N* is the order of interference, *n* is the refractive index of the film, and α is the angle of incidence of radiation on the film.

For the $Ni_{0.4}Zn_{0.6}Fe_2O_4$ film, in which the grain size was minimal, the intensity of the luminescence maximum was maximum.

As follows from Figure 4, the ferrite film is surrounded by dielectric (non-absorbing) layers: silicon oxide (refractive index is 1.5) and air (refractive index is 1.0). The refractive index for the ferrite film *n*=2.7. The thicknesses of the ferrite and SiO_2 layers are 100nm and 150 nm, respectively.

Note that, depending on the emission angle, there can be three types of output light from the resonator (Figure 4) [9,10]:

I. The emitted light comes out from the front side.

II. The light is fully reflected on the air / $Ni_{0.4}Zn_{0.6}Fe_2O_4$ interface, but not on the $Ni_{0.4}Zn_{0.6}Fe_2O_4$ / SiO_2 (or Al_2O_3) interface;

III. The emitted light represents 75% of the light inside the layer with an angle higher than θ_2, total reflection at two interfaces.

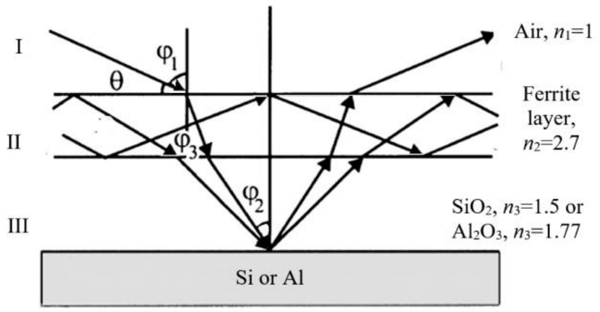

Figure 4. Block diagram of the nanoresonator (the notation is the same as in [9, 10])

This part of the resonator structure will act as a dielectric planar wave guide structure for some discrete propagation angles. The thickness of the ferrite layer, below which the controlled *m* as mode of a given polarization ceases to exist, is given by the following expressions:

$$\left(\frac{d}{\lambda}\right)_{TE} = \frac{1}{2\pi\sqrt{n_2^2 - n_3^2}} \times \left(m\pi + \tan^{-1}\left(\frac{n_3^2 - n_1^2}{n_2^2 - n_3^2}\right)^{1/2} \right) \quad (2)$$

$$\left(\frac{d}{\lambda}\right)_{TE} = \frac{1}{2\pi\sqrt{n_2^2 - n_3^2}} \times \left(m\pi + \tan^{-1}\frac{n_2^2}{n_1^2}\left(\frac{n_3^2 - n_1^2}{n_2^2 - n_3^2}\right)^{1/2} \right) \quad (3)$$

where, *m* is the order of the mode; and *d* is the thickness of the ferrite layer. The calculation results for the minimum thicknesses of the $Ni_{0.4}Zn_{0.6}Fe_2O_4$ ferrite film are shown in Table 1.

Hence, it follows that for 100-150 nm thicknesses for the ferrite layer there will be only one mode of each polarization instead of two for 250 nm thicknesses.

Table 1. Minimum thicknesses of the $Ni_{0.4}Zn_{0.6}Fe_2O_4$ ferrite film

Mod number (type II) N	0	1	2	3	4
d_2, nm (TE)	48.43	182.22	316.01	449.79	583.38
d_2, nm (TM)	41.96	175.75	309.533	443.32	577.103

Compliance with this condition can be seen in Figure 1, on the layer thickness of about 100 nm. The observation was carried out at an angle of 0 deg. to the layer surface. Let us consider in more detail the condition for the existence of one coupled mode (type II) in the generating layer. In this case, the phase incursion in one pass in the reflected beam should be equal to an integer number of, that is

$$N\pi = \frac{1}{2\pi\sqrt{n_2^2 - n_3^2}} \left(m\pi + \tan^{-1}\left(\frac{n_3^2 - n_1^2}{n_2^2 - n_3^2}\right)^{1/2} \right) \quad (4)$$

$$N\pi = \left(\frac{2\pi}{\lambda}\right) n_2 d_2 \cos\varphi_3 + \chi_{21} + \chi_{23} \quad (5)$$

where, $\chi_{21} + \chi_{23}$ is phase shifts due to total internal reflection at the film interfaces. The critical angle of total internal reflection is determined from the condition:

$$\sin\varphi_3^0 = \frac{n_3}{n_2} = 0.658 \quad (6)$$

Similar calculations for the air as ferrite film interface already show the presence of two coupled modes at thicknesses over 200 nm. In our case, the second coupled mode (type III) penetrates into the sapphire layer. However, due to the absence of resonance conditions for the perpendicular projection of the wave vector simultaneously in two sapphire and ferrite layers, the intensity of this mode is significantly lower than the intensity of the first mode (type II), which propagates only in the ferrite layer.

The extinguishing of the intensity of the emitting modes (type I) can be achieved by calculating a minimum interference of light. The wavelength of this light is

532 nm and spread perpendicular to the boundaries of the section, along the axis Z. In this case, the doubled sum of the optical lengths of the sapphire and ferrite layers must equal an odd number of half-waves:

$$n_3 d_3 + n_1 d_1 = \frac{(2N+1)\lambda}{2} \quad (7)$$

For the first time, laser generation was obtained by optical pumping of nonepitaxial $Ni_{0.4}Zn_{0.6}Fe_2O_4$ layers obtained by high-temperature spraying on sapphire and glass substrates. The low crystalline quality of the ferrite layer was compensated by the selection of parameters of the three-layer nano-resonator.

3. CONCLUSIONS

A mathematical model of a three-layer Fabry-Perot nanoresonator with active $Ni_{0.4}Zn_{0.6}Fe_2O_4$ ferrite or SmS element is presented. Radiation E=1.6 eV and γ=26.4 THs was observed in the three-layer Fabry-Perot nanoresonator width d_2=40 nm. It is shown that in the structure of thin (nanotollen) layers of the FD-resistor, representing the Fabry-Perot resonator, at a high intensity of optical (solar) pumping, choosing the appropriate thickness and the observance of ratios of the refractive indexes: $\arcsin\left(\frac{n_1}{n_2}\right) = 21.75°$, $\arcsin\left(\frac{n_3}{n_2}\right) = 40.96°$ are the effect of generation in the (Ni-Zn) ferrite film or in the SmS layer should be observed. Thus, the emitted light exits the nanoresonator into the air at an angle between 0-90°. Note that in the nanoresonator of the FD resistor, the internal reflection angle has a value close to 41°.

In this case, all the photoexcitation can be transmitted in the mode of radiation of the type (ferrite layer-air), which is nothing but optical losses for generation in the frequency binding mode. Then most of the photoexcitation will switch to the binding mode and with optical pumping, it is easier to obtain inverse population and generation. The obtained results are well commented and match with the results of [9] work on ZnO nanoresonators. Note that ZnO is one of the components of (Ni-Zn) ferrispinels.

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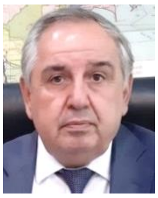

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