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PHYSICS

Changes in the Microwave Refractive Index Caused by the Giant Magnetoresistive Effect

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Abstract—Studies of the interaction of electromagnetic microwaves with $[Co_{88}Fe_{12}/Cu]_n$ nanostructures, in which the giant magnetoresistive effect (GMR) is observed, have been carried out. The GMR effect was found to contribute to changes in the microwave complex refraction coefficient, including the refractive index.

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INTRODUCTION

Recently, an unsurpassed change in microwave magnetoresistance was discovered in $[Co_{88}Fe_{12}/Cu]_n$ nanostructures [1]. The possibility to obtain the microwave giant magnetoresistive effect μGMR is provided by the technology of preparing $[Co_{1-x}Fe_x/Cu]_n$ nanostructures possessing a giant magnetoresistive effect (GMR) [2]. Papers [3, 4] were of key importance for studies of the μGMR and exchange-coupled multilayered metal nanostructures. The μGMR effect upon the flow of a super-high-frequency (SHF) current across the layer planes of the nanostructure [5] and the μGMR in spin valves [6] were investigated later. The microwave properties of different media can be described by the refraction coefficient; the refractive index is the real part of this coefficient. It is known that the refractive index in metamaterials can be negative [7]. The refractive index in magnetically ordered materials at SHF depends on the magnetic field [8]. It was shown in [9] that the inhomogeneity of the electromagnetic field inside a medium may be characterized by the nonuniformity parameter. The ferromagnetic resonance (FMR) was shown to modify the refractive index due to changes in the magnetic permeability [9]. The refraction coefficient depends also on the complex effective dielectric permittivity $\varepsilon_{ef} = \varepsilon' - i\varepsilon''$. The conductivity of nanostructures changes significantly in the GMR effect, and hence ε_{ef} changes correspondingly. One can expect that the refraction coefficient should vary due to the μGMR effect.

The aim of the present work is to reveal this effect. Superlattices of $[Co_{88}Fe_{12}/Cu]_n$ were chosen as the objects of study. Here we measure the transmission factor of microwaves through the superlattices, and the dependences of the microwave permeability on the magnetic field are obtained based on these measurements. Measurement of the magnetoresistance allows us to determine the field dependence of ε_{ef}. The coefficient of refraction is calculated afterwards, and the contribution of the GMR effect to its changes is revealed.

EXPERIMENTAL

Superlattices of $[Co_{88}Fe_{12}/Cu]_n$ were prepared by magnetron sputtering on an MPS-4000-C6 apparatus (Ulvac). The present investigation was carried out with a sample of Ta(5)/PyCr(5)/$[Co_{88}Fe_{12}(1.3)/Cu(2.05)]_8/Co_{88}Fe_{12}(1.3)$/PyCr(3), where the numbers in parentheses stand for the thickness of the corresponding layer in nanometers. The thickness of the copper spacer was chosen so that the sample showed the second GMR maximum. The number *n* of layer pairs was eight. The sample was grown on a glass substrate with a thickness of 0.3 mm. Small-angle X-ray scattering studies showed a high perfectness of the layered structure of the superlattice.

RESULTS AND DISCUSSION

The relative magnetoresistance as a function of the magnetic field intensity was defined as $r =$

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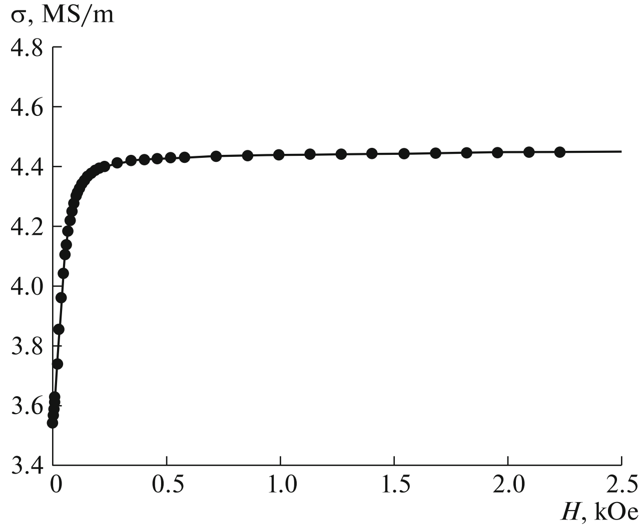

Fig. 1. Dependence of the conductivity of the superlattice on the magnetic field at room temperature.

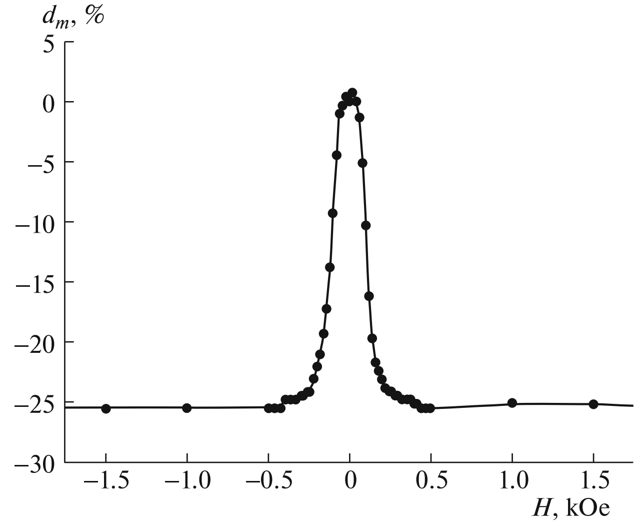

Fig. 2. Dependence of the transmittance coefficient on the magnetic field, measured at $f = 38$ GHz.

$\left[\frac{(R(H) - Rs)}{Rs}\right] \times 100\%$, where $R(H)$ is the resistance in the field H and Rs is the resistance in the saturation field. The superlattice sample has a rather high magnetoresistance of 28% in the saturation state, which is achieved in the field of about 0.4 kOe. Figure 1 presents the dependence of the resistance σ on the magnetic field.

Studies of propagation of electromagnetic waves were performed in the frequency range from 26 to 38 GHz as described in [4]. The superlattice sample was placed in the cross section of the rectangular waveguide. The relative change in the absolute value of the transmission factor $d_m = \left[\frac{|D(H)| - |D(0)|}{|D(0)|}\right]$ was measured, where $|D(H)|$ is the transmission factor modulus in the field H. The field was applied in the superlattice plane parallel to the narrow side of the waveguide, so that the vectors **H** of the constant and $\mathbf{H}_\sim$ of the alternating magnetic fields were perpendicular to each other. Measurements without the magnetic field and measurements of the magnetoresistance allowed estimating the effective complex permittivity $\varepsilon_{ef} = \varepsilon' - i\varepsilon'' = \varepsilon' - i\frac{4\pi\pi}{\omega}$ of the superlattice. Here, $\omega = 2\pi f$ is the angular frequency.

The results on the field dependence of the microwave transmission factor through the superlattice at the frequency of $f = 38$ GHz are shown in Fig. 2. The monotonic decay in the transmission coefficient is due to the change in the electric conductivity of the sample; the relative change in the transmission coefficient is nearly the same as the relative magnetoresistance. The proof of this equality for $[Co_{88}Fe_{12}/Cu]_n$ superlattices is given in [1]. The FMR linewidth allows estimating the dimensionless damping constant in the magnetic system, which turned out to be $\alpha = 0.03$.

The high-frequency permeability can be derived using known relations from [10] provided that we know the saturation magnetization of the superlattice layers $M_S = 1200$ G (from the magnetic measurements [2]), the constant α, and assume that the FMR line has a Lorentzian shape. First, the diagonal μ and off-diagonal μ_a components of the permeability tensor are calculated, and then the effective permeability is calculated as [10]

$$\mu_{ef} = \mu - \frac{\mu_a^2}{\mu}. \quad (1)$$

The real part of μ_{ef} is negative in fields smaller than the FMR field. The imaginary part is positive and attains its maximum in the FMR field. The complex coefficient of refraction $n_{ef} = n' - in''$ can be calculated using the known dynamic permittivity ε_{ef} and dynamic permeability μ_{ef}:

$$n_{ef} = n' - in'' = \sqrt{\varepsilon_{ef}\mu_{ef}}. \quad (2)$$

The real part of the refraction coefficient n' is the refractive index. The dependences of the complex refraction coefficient on the field at 38 GHz are plotted in Fig. 3. The figure shows the dependences for both the real and imaginary components of n_{ef}. Calculation of the coefficient of refraction n_{ef} allowing for the magnetoresistance effect is presented on the dependences labelled as $\sigma = \sigma(H)$. It is evident from Fig. 3 that the field dependences of n_{ef} have a resonance character. The position of the resonance of n_{ef} coincides with the resonance in the magnetic permeability. To reveal the contribution from the GMR, calculation for the case of constant conductivity σ =

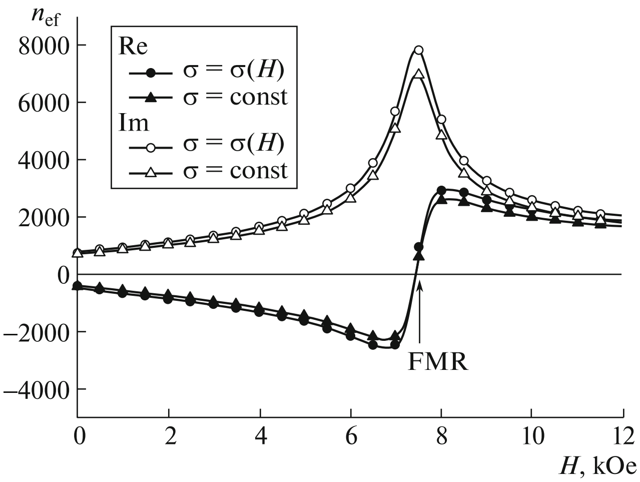

Fig. 3. Field dependences of the imaginary and real parts of the refraction coefficient at the frequency of $f = 38$ GHz.

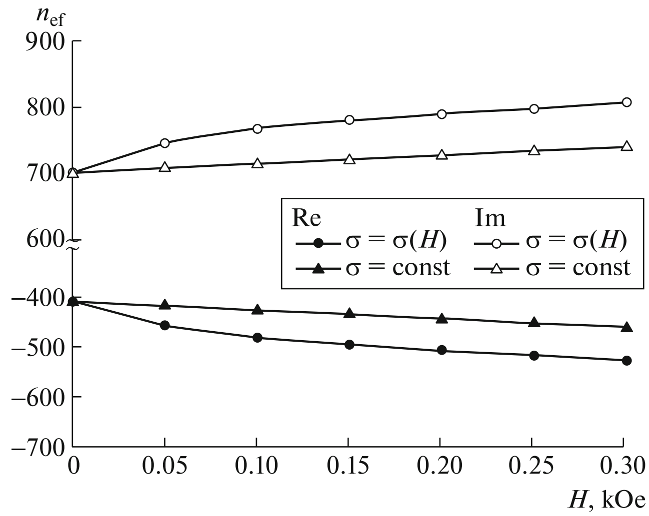

Fig. 4. Field dependences of the imaginary and real parts of the refraction coefficient in weak magnetic fields.

const was made. The assumed value of $\sigma = 3.5 \times 10^6$ S/m corresponds to the conductivity of the sample in the zero field. Evidently, the shapes of the dependences at $\sigma = \sigma(H)$ and $\sigma = $ const are similar, but there is a difference caused by the influence of the GMR on the refraction coefficient.

It is evident from Fig. 3 that the real part of the refraction coefficient (i.e., refractive index n') in fields below the FMR point is negative, as defined by the following inequality [7]:

$$(\varepsilon' + |\varepsilon_{ef}|)(\mu' + |\mu_{ef}|) < \varepsilon''\mu''. \quad (3)$$

For a metal object $|\varepsilon_{ef}| \approx \varepsilon''$, and Eq. (3) yields a simple inequality $\mu' < 0$.

CONCLUSIONS

Most of the conductivity variations occurred in fields up to 0.3–0.4 kOe, so it is worth investigating this field region more closely (see Fig. 4). Indeed, the difference between the dependences $\sigma = \sigma(H)$ and $\sigma =$ const in this range increases as the field intensity grows. Thus, the contribution of the GMR effect to the changes in the microwave refraction coefficient can be taken for granted.

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