Measurement of Thin Film Magnetic Characteristics in the Radio Frequency Range

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***Abstract*—The paper presents a method for measuring the ferromagnetic resonance spectrum in the radio frequency range (4 MHz). A high-frequency generator operating in the autodyne mode was used to measure the magnetic characteristics of thin ferromagnetic films. Theoretical equations for ferromagnetic resonance excitations have been presented. Experimental results for the samples of nanocrystalline thin permalloy magnetic films with low magnetostriction and different values of the anisotropy field were obtained. Ferromagnetic resonance in the radio frequency range proved to be an excellent mean for measuring the value and direction of the magnetic anisotropy field in thin magnetic films.**

Keywords— ferromagnetic resonance, thin magnetic film, autodyne detector

I. INTRODUCTION

Recently, thin magnetic films (TMF) based on soft magnetic materials have been widely used in microwave technology. TMF could be sensitive elements in weak magnetic field sensors [1] and other devices [2–4].

The method of ferromagnetic resonance (FMR) is in current use to study TMF. Ferromagnetic resonance excited in the microwave [5] allows measuring the magnetic characteristics of magnetic materials (saturation magnetization, the magnitude and direction of the uniaxial anisotropy field; Hilbert's constant, etc.). Ferromagnetic resonance in the radio frequency (RF) range (from 3 to 30 MHz) also can be used as a tool for studying the magnetic characteristics of TMF [6]. The information from FMR in the radio frequency could be somewhat limited [6].

The FMR measurements running in the RF range are much easier than in the microwave range. Some magnetic characteristics that can be measured in the microwave range can be also measured in the radio frequency range. The frequency of natural ferromagnetic resonance is higher, than the frequency of the exciting high-frequency magnetic field. Therefore, RF measurements allow defining quasi-static magnetic characteristics of TMF.

II. THEORY

In practice, the ferromagnetic resonance is excited by simultaneously affecting on the TMF the constant and high-frequency magnetic fields, directed orthogonally to each other in the film plane.

The main equation connecting the magnetic moment's frequency precession, magnetocrystalline anisotropy and the form anisotropy in TMF was first presented by Kittel [7]. The single domain model of TMF magnetization is shown below.

Suppose the thin magnetic film is positioned in the *Oxy* plane Fig. 1. The external magnetic field H_0 changes from 0 to H_{max}. High-frequency magnetic field h is changing according to the harmonic law with circular frequency ω_{rf}. The angle between the direction H_0 and the X is θ_H. The angle between the h field and the X is $\theta_H + \pi/2$. The uniaxial magnetic anisotropy field H_a is directed by the angularly θ_a, θ_M is equilibrium magnetic moment angle.

Free energy density [8] of the thin magnetic film:

$$W = W_H + W_a + W_M, \tag{1}$$

is the sum of the energies: uniaxial magnetic anisotropy, the energy density of the sample in the external magnetic field (Zeeman energy) and the free energy density of magnetic charges (demagnetization energy). The energy density of uniaxial magnetic anisotropy in the TMF is:

$$W_a = 1/2 H_a M \sin^2 (\theta_M - \theta_a). \tag{2}$$

The Zeeman's energy density leads to the interaction between the vector of magnetization [9] and the applied external constant magnetic field:

$$W_H = H_x \cdot M \cdot \cos \theta_M - H_y \cdot M \cdot \sin \theta_M, \tag{3}$$

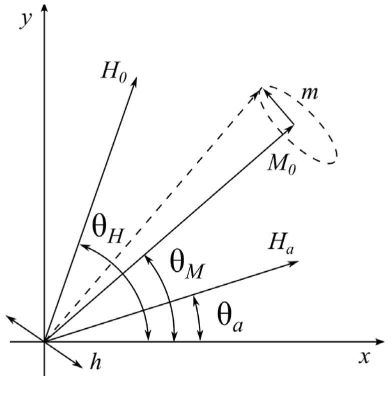

Fig. 1. The model of the thin magnetic film and associated coordinate system (directions of external magnetic fields)

where H_x and H_y are the projection of the applied external magnetic field on the X and Y axes.

The motion of the magnetic moment M, under the influence of a magnetic field, is described by the Landau – Lifshitz – Hilbert equation [10]:

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$$\frac{\partial M}{\partial t} = -\gamma[\mathbf{M} \times \mathbf{H}_{\mathbf{eff}}] + \frac{|\alpha|}{M^2}\left[\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}\right], \tag{4}$$

$$\mathbf{M} = \mathbf{M}_0 + \mathbf{m}, \tag{5}$$

$$\mathbf{H}_{\mathbf{eff}} = -\frac{\partial W}{\partial \mathbf{M}}, \tag{6}$$

where γ – is the gyromagnetic ratio; α – Gilbert damping; $\mathbf{M_0}$ and $\mathbf{m}$ are static and dynamic components of the magnetic moment.

The TMF magnetization vector is in equilibrium, when:

$$\frac{\partial W}{\partial \theta_M} = 0 \text{ and } \frac{\partial^2 W}{\partial \theta_M^2} > 0, \tag{7}$$

the free energy density of the film is minimal [9].

The equation considering the FMR frequency of TMF, the magnitude and direction of the constant magnetic field was given by Smith and Beljers [11]:

$$\omega = \gamma\sqrt{4\pi M[H_0\cos(\theta_M - \theta_H) + H_a\cos 2(\theta_a - \theta_M)]}. \tag{8}$$

The solution (8) at different angles θ_H and $\theta_a = 0$ is shown in Fig. 2 (saturation magnetization $M = 1500$ G, $H_a = 5$ Oe, $\alpha = 0.005$).

III. MEASURING UNIT

The absorption of the alternating magnetic field energy in the TMF was measured by an autodyne detector The high-frequency magnetic field was created by Helmholtz coils. The Helmholtz coils were included to the inductive part of the RF generator circuit, which operated in autodyne mode [12, 13]. The oscillator was developed according to the Clapp circuit design. The constant magnetic field H_0 was produced by the second pair of Helmholtz coils. It was directed orthogonally to the high-frequency magnetic field. The block diagram of the measuring unit is shown in Fig. 3.

To determine the direction of the film hard magnetization axis the TMF sample was placed in the center of small Helmholtz coils and rotated around self-axis Fig. 4. The constant magnetic field (the field magnitude was chosen in the range from 0 to ~ $2H_a$) and the high-frequency excitation field affected TMF simultaneously. The detector output voltage amplitude was measured by voltmeter. The minimum amplitude signal corresponded to the direction of the external magnetic field, directed along TMF hard magnetization axis.

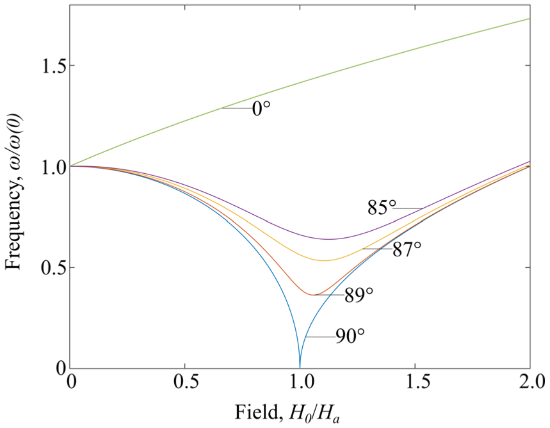

Fig. 4. The dependence of the ferromagnetic resonace frequency on the value of the constant magnetic field applied in the film plane, with different angles to the easy magnetization axis (blue curve is the direction of H_0 along the TMF hard magnetization axis)

The main requirement for measurements is the orthogonality between the direction of the constant magnetic field and the TMF easy magnetization axis Fig. 3.

Note, that the measuring system has a strong dependence on the ambient temperature. Semiconductor circuit elements have the greatest impact on temperature drift. The depth of generator positive feedback in the autodyne mode [14, 15] is very low, but it's enough to provide minimum amplitude at the generator output. Thermal fluctuations can change the positive feedback depth or shift the transistor operating point. This results in either generation amplification or its disruption. Therefore, the measuring system is placed in a thermostating shield.

The measuring unit amplitude detector is designed according to the signal doubling scheme. The output of the amplitude detector is connected to the input of the operational amplifier follower. A second-order active low-pass filter is used to filter the signal from the detector. After

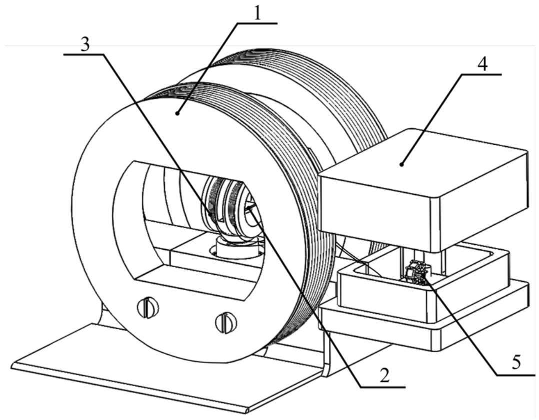

Fig. 2. Measuring system of the unit (1 – the Helmholtz coils, inducing the constant magnetic field; 2 – the TMF; 3 – the Helmholtz coils, inducing the high-frequency magnetic field; 4 – thermostating shield; 5 – the RF generator with the amplitude detector)

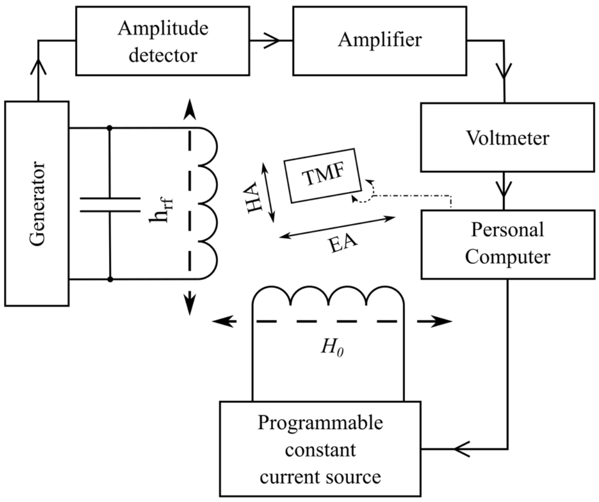

Fig. 3. Block diagram of the measuring unit (HA – direction of the hard axis of magnetization; EA – direction of the easy axis of magnetization; h_{rf} – high-frequency magnetic field)

compensating the output signal constant component the signal is transmitted to the amplifier input and is measured with the voltmeter. The Helmholtz coils inducing the HF magnetic field are part of generator resonance system [16] and are placed very close to the generator. The electronic components of RF generator should be non-magnetic as the constant magnetic field can influence the unit measuring system. Before the measurements, the constant magnetic field was formed without TMF and the effect of H_0 on the operation of the unit measuring system was estimated.

IV. MEASUREMENTS

1. The TMF was placed inside the small Helmholtz coils, with the fixed constant magnetic field and the high-frequency excitation field.

2. By rotating TMF on the measuring desk we got minimum signal at the amplitude detector output.

3. Voltmeter was connected to the PC. The software processed voltmeter readings about the signal amplitude and determined the value of field minimum at which absorption occurred. For the search of the absorption minimum the software changed the value of the constant magnetic field (using a programmable current source). The minimum of the field was determined by the golden ratio and the inverse parabolic interpolation methods.

4. The constant magnetic field sweep was created with a step of 1 Oe (near minimum of the field, which was found at 3-th stage, step was 0.1 Oe).

5. Based on the voltmeter readings the software showed the absorption spectrum.

The value of the minimum constant magnetic field determined by the software is equal to the value of the anisotropy field H_a.

V. MEASUREMENT RESULTS

In this work, thin permalloy magnetic films of peramlloy were investigated. Fig. 5 shows the absorption spectrum of the HF magnetic field energy in TMF at the ferromagnetic resonance. The detector output voltage amplitude (which is proportional to FMR absorption in TMF) was normalized in the range from 0 to 1 Oe. The TMF had one layer, 100 nm thick (composition $Ni_{80}Fe_{20}$).

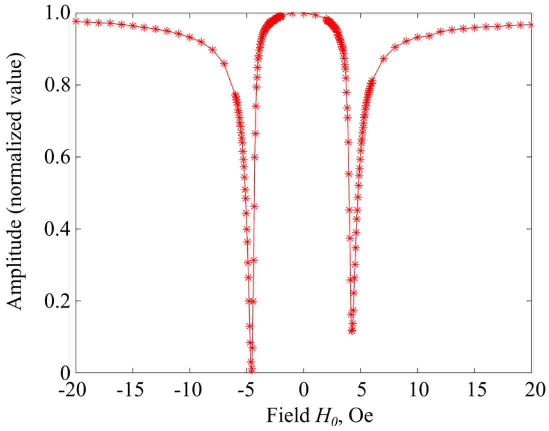

Fig. 5. The FMR absorption spectrum of a single-layer film with the layer thickness of 100 nm (sweep of the constant magnetic field from -20 to 20 Oe)

To provide high accuracy measuring H_a in the absorption spectrum shown in Fig. 5 was measured with different field sweep. In the range from -20 to -7 Oe with a step of 1 Oe and similarly in the range from 0 to 20 Oe. Near the anisotropy field (± 1 Oe from H_a) with a step of 0.1 Oe.

The asymmetry of the absorption line on the graph Fig. 5 associated with the influence of the uncompensated magnetic field of the Earth. The value of the absorption minimum for this sample corresponds to the anisotropy field $H_a = 4.8$ Oe.

Several samples of thin magnetic films with the thickness of 50 nm were also measured. All samples were obtained by magnetron sputtering in the constant magnetic field. This field formed the easy direction in the TMF. The composition and numbers of the samples are shown in Table 1.

TABLE I. EXPERIMENTALSAMPLES OF THE TMF

Samples	**Characteristics**			
	Composition	***Layer thickness, nm***	***H_a, Oe***	***H'_a, Oe***
1	$Ni_{80}Fe_{20}$	50	4.75	4.81±0.1
2	$Ni_{75}Fe_{25}$	50	5.61	5.88±0.21
3	$Ni_{70}Fe_{30}$	50	7.55	7.73±0.4

The measurements were carried out with a constant magnetic field sweep in the range from -20 to 20 Oe (Fig. 6). The obtained values of H_a are shown in Table 1.

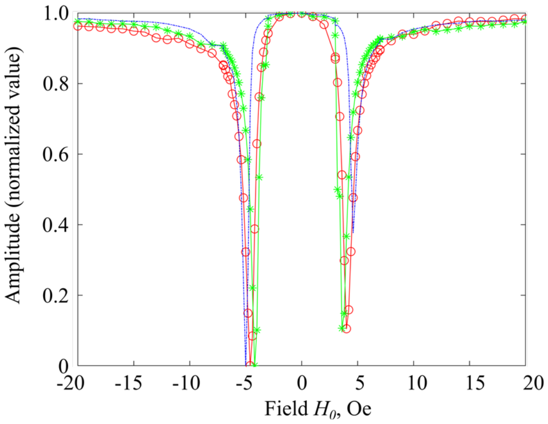

Fig. 6. There are absorption spectra for 3 TMF samples (red – $Ni_{80}Fe_{20}$; green – $Ni_{75}Fe_{25}$; blue – $Ni_{70}Fe_{30}$)

Distribution of H'_a at the surface film was obtained by the local FMR spectrometer [8]. Table 1 shows the average value of H'_a ($\pm H'_a$ dispersion field). The obtained values of H_a are consistent with the values determined using a local FMR spectrometer.

The accuracy of determining the magnetic characteristics of samples from the ferromagnetic resonance spectra obtained using this method depends on several factors: percentage of magnetic material in the sample, the thickness (volume) of the sample and the quality of the samples. The fewer defects are there in the sample, the less is the number of internal demagnetizing fields [17, 18]. Accordingly, the smaller dispersion value, the narrower absorption peak is observed in the spectrum of FMR.

VI. CONCLUSION

Today, the most widespread method for measuring the magnetic characteristics of thin films is the broadband method using a vector network analyzer [19–21]. This method differs by the simple design of the measuring cell. But it has many drawbacks: the external factors influencing the measurements, expensive equipment, the constant calibration and adjustment of the measuring system.

Another method uses a local ferromagnetic resonance spectrometer [8]. This method allows measuring the magnetic characteristics only from local areas of the TMF. Its advantage is high accuracy and the ability to determine many magnetic characteristics of the TMF: saturation magnetization, uniaxial anisotropy field, FMR linewidth, dispersion of magnetic anisotropy on the field and angle, the magnitude of the unidirectional anisotropy field and etc. The disadvantage of these methods is the difficulty of determining the magnetic characteristics at frequencies below the of the natural ferromagnetic resonance frequency.

The method for studying thin magnetic films presented in this work differs from others in its simplicity. There is no need to calibrate and to adjust the measuring system. Measuring system of the unit registers the absorption spectrum, produced only by the influence of the TMF. Since the film in the inductive part of the RF generator, the system has a high sensitivity. The disadvantage of this method is strong temperature dependence. These disadvantages can be avoided by using measurement automation methods (automatic adjustment of the regenerative feedback depth and shift of the operating point).

By numerically approximating the obtained TMF absorption spectra it becomes possible to determine many magnetic characteristics (e.g. saturation magnetization, Hilbert constant, dispersion on angle and field, transverse magnetic susceptibility). As the measurements are carried out in the low-frequency area more accurate determination of the magnitude (direction) of the anisotropy field are possible.

Received values of the magnetic field H_a in the RF range correspond to the values determined by a local ferromagnetic resonance spectrometer.

The magnetic characteristics of TMF strongly depend on the quality and the technology used in the deposition, which heavily affect the finished devices, e.g. sensors for weak magnetic fields [4]. In such sensors it is essential to provide a high value of the sensor conversion factor (V/Oe). The conversion factor is determined by the width of the absorption line, anisotropy field magnitude, dispersion and etc. Thus, methods for determining the TMF magnetic characteristics are very essential as the TMF quality influences the finished device.

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