Unit for Measuring the Magnetic Characteristics of Thin Ferromagnetic Films

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***Abstract*—Studying the properties of ferromagnetic films helps in solving the fundamental problems of the physics of magnetic phenomena and in developing the theory of ferromagnetism. Modern software and hardware, along with reliable diagnostic methods are used to research and design thin-film devices. In this regard, the development of devices and methods for measuring the magnetic characteristics of thin ferromagnetic films is an essential task. The aim of the work is to develop an unit for local measurements of the magnetic characteristics of thin ferromagnetic films, which has the ability to change the degree of locality of measurements over a wide range and has high sensitivity at the same time.**

The article reviews a new unit for measuring the magnetic characteristics of thin ferromagnetic films. The unit allows measuring the value and direction of the anisotropy field on a local area of the film. A block diagram and description of a new unit, as well as methods of measurements are shown in the article. The experimentally obtained distribution of the anisotropy field over the area of the studied sample of $Ni_{80}Fe_{20}$ film is shown in this work. The experimental results confirm the compliance of the new unit with the declared characteristics. The unit can be used for non-destructive quality control and for measuring uniformity of thin ferromagnetic films magnetic characteristics.

Keywords—thin magnetic films, measuring unit, magnetic characteristics, ferromagnetic resonance.

I. Introduction

Thin magnetic films (TMF) are being studied all over the world. Many devices are developed based on them, for example, sensitive sensors [1], microwave attenuators and phase shifters, which are controlled by magnetic fields, frequency-selective elements of communication and radar systems, various effective protective and absorbing coatings. The characteristics and the reliability of devices based on TMF determined by the degree of magnetic homogeneity. As is known, the heterogeneity is due to the imperfect technology for manufacturing TMF [2, 3]. The analysis of existing methods [2] and devices [4–6] for the study of TMF revealed such shortcomings, such as a low measurement accuracy, low sensitivity and limited degree of locality of the measurements. These shortcomings do not allow measuring the distribution of magnetic characteristics over the film area with high detail. Therefore, the development of devices and methods for measuring the magnetic characteristics on local areas of TMF is an essential task. This is essential for testing the technology of producing films, for controlling their quality during the production process and, as a result, for improving the characteristics and reliability of devices based on TMF. There is well known device [7] for measuring magnetic characteristics of TMF: a ferromagnetic resonance (FMR) spectrometer for investigations on local areas of magnetic films. The authors use a microstrip resonator as a sensitive element of spectrometer because it has high sensitivity and is technologically advanced to manufacture. The block diagram of the FMR spectrometer is shown in Fig. 1.

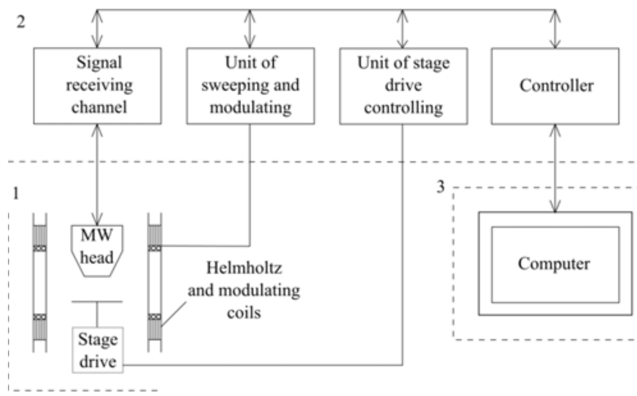

Fig. 1. FMR spectrometer block diagram: 1 – sensor block, 2 – signal forming block, 3 – spectrometer control and data processing block

The technical characteristics of the FMR spectrometer are shown in table I.

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TABLE I. TECHNICAL CHARACTERISTICS OF THE FMR SPECTROMETER [7]

Parameter	Value
SNR at the locality of measurements 1.0 mm for permalloy film with thickness 100 Å	not less than 10
Sweeping magnetic field	from 0 to 500 Oe
Locality of the measurements	from 0.3 to 2.5 mm
Operating frequency range	0.1-6.0 GHz
Dimensions of the scanned area	45×45 mm
Minimum film thickness (for permalloy)	50 Å
Axes of movement and rotation	sample RXY+ sensitive element ZR
Sample rotation angle	360°
Sensitive element rotation angle	90°

The FMR spectrometer [7] has high sensitivity and can be used for investigation of small TMF local area. But it is difficult to use it for quick estimation of TMF homogeneity, because main magnetic properties of TMF local area are obtained by recalculation of FMR spectrum angular dependencies. In this article the authors proposed a new unit for local measurements of the TMF magnetic characteristics. It allows direct measuring the value and direction of the anisotropy field and can be used for quick estimation of TMF homogeneity, for example, in a factory condition.

II. THE DESIGN OF THE MEASURING UNIT

The structural diagram (Fig. 2) presents the design of the new unit for local measurements of the magnetic characteristics of thin ferromagnetic films.

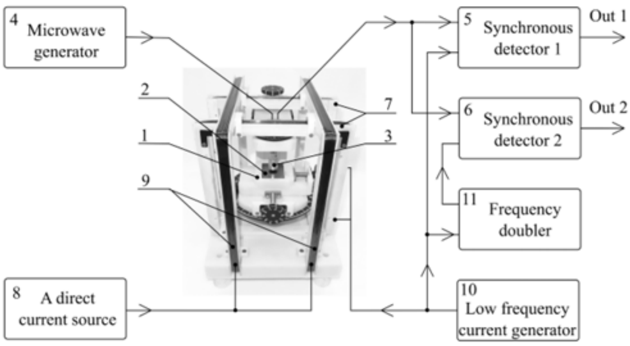

Fig. 2. Structural diagram of the measuring unit: 1 – subject table; 2 – test sample; 3 – sensitive element; 4 – microwave generator; 5, 6 – synchronous detectors; 7, 9 – orthogonal Fanselau coils; 8 – a direct current source; 10 – low frequency current generator; 11 – frequency doubler

The test sample is placed on a subject table. The sensitive element is located above the test sample. The input of the sensitive element is connected to the microwave generator, and the output is connected to two synchronous detectors (SD) at the same time. The first Fanselau coils are connected to a direct current source. They are used to create an offset field H_{offset} (given constant magnetic field) in the sample. The second Fanselau coils are connected to a low frequency current generator. They are used to create an alternating modulating magnetic field H_{mod}. The output signal from the low-frequency current generator is supplied to the second synchronous detector through a doubler and is used as a reference signal for the first synchronous detector. The external appearance of the unit is shown in Fig. 3.

The design of the sensitive element is shown in Fig. 4, a, its electric circuit is shown in Fig. 5. The inductive part of the microwave resonator is located on the bottom layer of the printed circuit board. The length of the inductive part determines the size of the studied area of the sample. It can vary from 1 to 25 mm. This allows changing the degree of measurements locality. A number of removable sensitive elements with different lengths (2 mm, 3 mm, 4 mm) of the inductive part are manufactured. Fig. 4, b shows the manufactured printed circuit boards for the sensitive element with different inductance lengths.

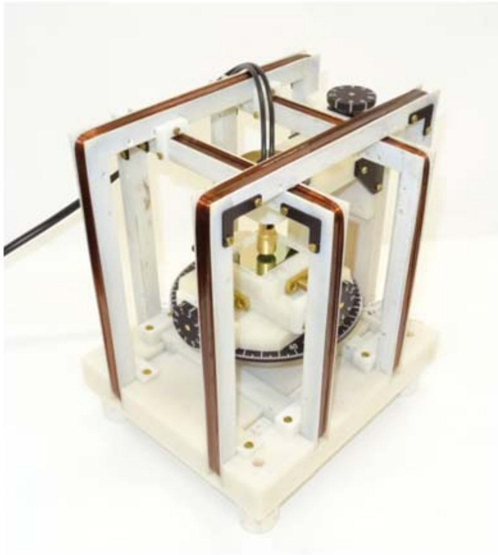

Fig. 3. The external appearance of the unit for local measurements of the magnetic characteristics of thin ferromagnetic films

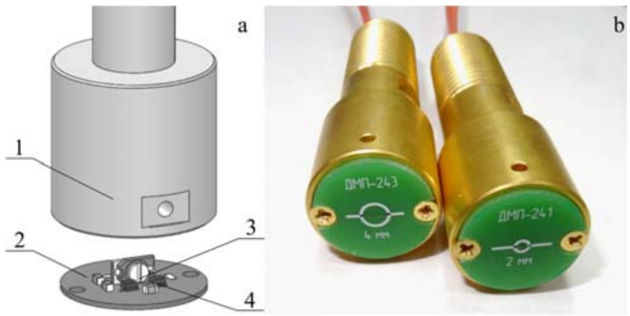

Fig. 4. The sensitive element of unit: a – the design of the sensitive element: 1 – housing with a hole for adjusting the tuning capacitor; 2 – a printed circuit board with elements of a microwave resonator; 3 – tuning capacitor; 4 – amplitude detector; b – the sensitive elements with different inductance lengths

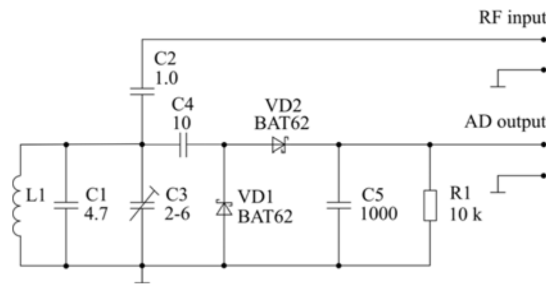

Fig. 5. Electric circuit of the sensitive element

The technical characteristics of the new unit for local measurements of the magnetic characteristics of TMF are presented in table II.

TABLE II. TECHNICAL CHARACTERISTICS OF THE UNIT FOR LOCAL MEASUREMENTS OF THE MAGNETIC CHARACTERISTICS OF TMF

Parameter	Value
SNR at the locality of measurements 5.0 mm for permalloy film with thickness 100 Å	not less than 10
Sweeping magnetic field	from 0 to 50 Oe
Locality of the measurements	from 1.0 to 25 mm
Operating frequency range	0.01-1.0 GHz
Dimensions of the scanned area	60×60 mm
Minimum film thickness (for permalloy)	100 Å
Axes of movement and rotation	sample RXY+ sensitive element ZR
Sample rotation angle	360°
Sensitive element rotation angle	360°

III. MEASUREMENT PROCEDURE

The test sample is placed on a subject table. The local area of the sample to be measured must be on the axis of the sensitive element. The sensitive element is brought closer to the test sample. A constant offset field H_{offset} and a modulating magnetic field H_{mod} are created by the orthogonal Fanselau coils. The high-frequency excitation magnetic field H_{HF} should be directed along the direction of the modulating magnetic field H_{mod}. For this, the sensitive element rotates around its axis by knob. The directions of the fields are shown in Fig. 6.

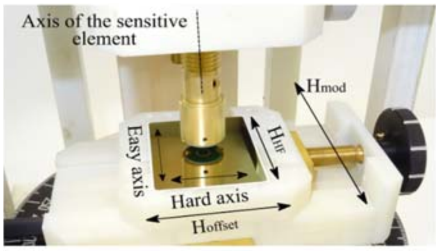

Fig. 6. Directions of magnetic fields: H_{mod} – modulating magnetic field; H_{offset} – constant offset field, H_{HF} – high frequency field

The value of the constant component of the signal at the output of the amplitude detector is maximized when the frequency of the microwave generator is equal to the resonant frequency of the sensitive element microwave resonator. The resonant frequency can be changed by using the tuning capacitor of the sensitive element through a hole in the housing. The magnitude of the variable component of the voltage at the output of the sensitive element with the frequency of the modulating field H_{mod} is measured by using the first synchronous detector. The measurement of the magnitude of the variable component of the voltage at the output of the sensitive element with a double field frequency H_{mod} is carried out by using a second synchronous detector. The amplitude (Fig. 7, a) and angular (Fig. 7, b) dependencies are measured. In order to do this, it is necessary to change the magnitude of the constant offset magnetic field and to rotate the sample. The rotation of the sample is made due to the possibility of rotation of the subject table. The signal value at the output of the first SD is normalized (ordinate axis, Fig. 7).

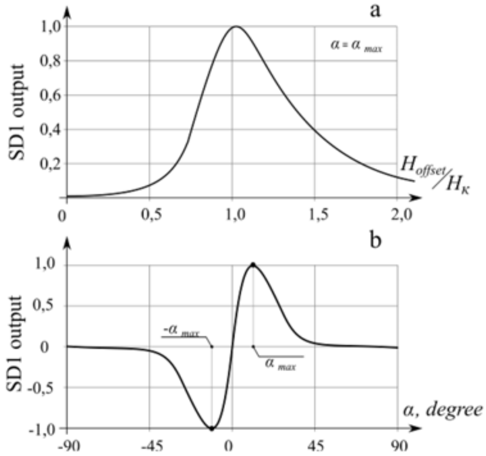

Fig. 7. Results of amplitude and angular dependencies measurements

After obtaining the dependencies (Fig. 7), the approximate value of the anisotropy field H_k of the sample is determined from the maximum of the amplitude dependence (Fig. 7, a), and the direction of the anisotropy field is determined from the angular dependence (Fig. 7, b). Next, the test sample is set so that the constant magnetic offset field is strictly along the axis of the hard magnetization of the film. In order to do it, the object table is rotated with film. After that, the output signal of the second synchronous detector is registered, while changing the magnitude of the constant magnetic field offset H_{offset}. The exact value of the anisotropy field of the sample in the studied region is determined from the maximum of the obtained dependence. To obtain the distribution of magnetic characteristics over the area of the sample, the sample moves in the longitudinal and transverse directions.

IV. EXPERIMENT RESULTS

An experiment was carried out according to the indicated procedure on the studied thin-film sample of the nonstrictive composition of permalloy $Ni_{80}Fe_{20}$, which has uniaxial magnetic anisotropy and has dimensions of 40 × 30 mm. The experimentally obtained distribution of the anisotropy field over the sample area is shown in Fig. 8.

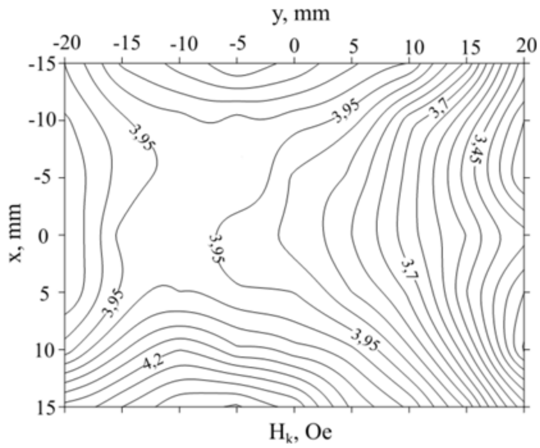

Fig. 8. The results of measuring the distribution of the anisotropy field over the area of a thin-film permalloy sample of composition *Ni80Fe20* with dimensions of 40 × 30 mm

As we can see from Fig. 8, the TMF is heterogeneous along the edges. The change in the anisotropy field of the permalloy film is within 0.5 Oe. One of the heterogeneity reasons is imperfect TMF manufacturing technology.

V. Conclusion

A new unit is proposed for local measurements of the magnetic characteristics of thin ferromagnetic films. It allows to measure samples with a thickness more than 100 Å and dimensions up to 60 × 60 mm. The length of the sensitive element inductive part determines the size of the studied area of the sample. It can vary over the range 1 to 25 mm. This allows to change the degree of locality of measurements. In comparison with well-known FMR spectrometer [7], the new measuring unit has a greater range of measurements locality and it has the ability to measure larger films. The measuring unit can be used for non-destructive testing of the quality and uniformity of thin magnetic films, it gives possibility for quick TMF homogeneity estimation, that is very important for TMF device production.

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