Automated Measuring Unit for Analysis of Thin Magnetic Film Ferroresonance Spectrum

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Abstract—**This paper considers hardware and software for automated analysis of thin magnetic film ferroresonance spectrum to determine the rate of growth and decrease in ferroresonance spectrum (conversion factor parameter). The measuring element of automated system is the strip line which is short-circuited. The measuring unit is used to study $Ni_{80}Fe_{20}$ permalloy films, with thickness of more than 300 Å. Conversion factor, magnetic permeability μ, uniaxial magnetic anisotropy, ferromagnetic spectrum resonance line width, saturation magnetization are analyzed from 50 MHz to 2 GHz frequency range. The magnetic films are used to design frequency selective filters, phase shifters and weak-field magnetic sensors. The thin magnetic film sensors are high sensitive magnetometers, with wide frequency range, low dimensions and weight [1].**

***Index Terms*—ferroresonance, magnetometers, magnetic sensors, permeability measurement, magnetic films**

I. Introduction

MAGNETIC materials are very important for high frequency electronics. Magnetic materials are applied to design high-sensitive weak-magnetic-field magnetometers. The magnetometers are based on thin magnetic films (TMF) [1]. TMF-magnetometers distinctive feature is a wide bandwidth measuring capability – from 0 Hz to 10^8 Hz with a constant conversion factor.

TMF parameters depend on the application of magnetometer or magnetic sensors. These sensors are used to register magnetic fields of moving and static objects; measure magnetic induction (e.g., for geological investigations). The main parameter for creating high sensitive TMF based on thin magnetic film sensitive sensors is the sensor threshold or the magnetic noise level. The sensitive element conversion factor of thin magnetic film magnetometer is the most important parameter. The conversion factor is proportional to the volume of TMF material [2]. This conversion factor shows the change of magnetic permeability TMF with the change of magnetic field magnitude.

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High TMF conversion factor is necessary to reduce the influence of thermal and electronic component noise on the output signal from the weak magnetic field sensor. This is important when designing the magnetic sensors.

To estimate the conversion factor in TMF, the spectrum of ferromagnetic resonance (FMR) [3] has been investigated. The sensors of weak magnetic field operate using the effect of FMR in ferromagnetic materials. The FMR phenomenon manifests selective absorption of microwave energy at certain frequency of high-frequency magnetic field and the magnitude of constant magnetic field. The structure of measuring system fields is shown in Fig. 1.

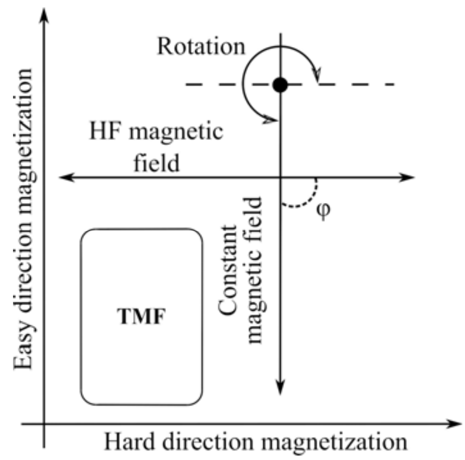

Fig. 1. The magnetic field structure in mesurement system.

The rate of increase and decrease of FMR spectrum is determined by the direction shift of constant magnetic field and the change of magnitude.

The sensitivity of the magnetic sensors is determined by TMF conversion factor. Table 1 shows the characteristics of the magnetic field sensors based on TMF.

We consider two methods for obtaining the FMR spectrum in TMF: the resonance and non-resonance. The resonant method of conversion factor measurement [4] allows to locally determine FMR. It uses HF resonance system made from variable capacitor, inductive line and amplitude detector. Inductive part is designed as microstrip line or enamel insulated coil which are short-circuited.

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The resonant frequency of the system is changed by a variable capacitor.

TABLE I
CHARACTERISTIC OF MAGNETIC SENSORS

Field range	**Frequency range**	**Noise level@ frequency** (T/Hz$^{1/2}$)			
		10^0 Hz	*10^1 Hz*	*10^2 Hz*	*10^3 Hz and more*
from 10^{-13} to 10^{-4} T	*from 10^{-2} to 10^8 Hz*	*$1{\cdot}10^{-11}$*	*$3{\cdot}10^{-12}$*	*$1{\cdot}10^{-12}$*	*10^{-13}*

The non-resonant method uses system [3] where self-resonant frequencies are higher than TMF resonant frequency. This is the main difference between the two methods. The measure system in non-resonant method is shown on Fig. 2.

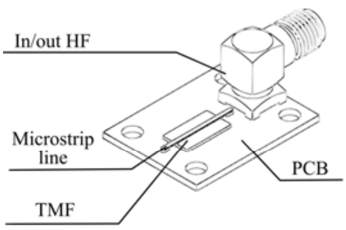

Fig. 2. The non-resonant measuring system.

II. THEORY

The change in the impedance of the measuring system, caused by the introduction of a thin magnetic film is observed when measuring non-resonant system reflection coefficient is displayed by vector network analyzer (VNA).

The introduction of a thin magnetic film adds losses into the measuring system. This leads to the change of the system impedance, which is calculated of reflection coefficient. The VNA was calibrated in the frequency range from 50 MHz to 2 GHz.

The impedance and reflection coefficient of the system are related by (1):

$$\dot{Z}(f) = \frac{1+\dot{S}11(f)}{1-\dot{S}11(f)} Z_S , \tag{1}$$

where Z_S is the characteristic impedance of the line equal to 50 Ω. Impedance of the system includes an active and reactive components [5]:

$$\dot{Z} = R_A + X_L . \tag{2}$$

In (2) R_A is the electrical resistance of the system, and X_L – inductive resistance.

Conversion factor of thin magnetic films represents the rate of change (increase or decrease) in the FMR spectrum. In order to estimate it, we obtain the derivative of $|\dot{S}11|$ with the respect to the angle between direct static magnetic and the high-frequency magnetic fields:

$$K_f = \frac{d|\dot{S}11|}{d\varphi}, \tag{3}$$

where φ is the angle of constant magnetic field (Fig. 1).

An important dynamic characteristic of TMF is a function of the complex magnetic permeability which depends on the frequency. Complex magnetic permeability has no physical meaning. The information is shown only by its components μ' and μ''. Magnetic permeability [5] depends on the properties of a substance and on the magnitude and the direction of the magnetic field.

Complex magnetic permeability is defined by:

$$\mu = \mu' + j\mu'' = \left(\frac{\mathrm{Im}(Z)}{2\pi L}\right)' + j\,\mathrm{Re}(Z)'' , \tag{4}$$

where μ', μ'' are real and imaginary parts of the complex magnetic permeability. The imaginary part μ'' includes total losses in resonance system. Equation (4) computes inhomogeneous magnetic films at the frequencies when influence of the skin effect is minimal. [6]

III. MEASURING UNIT DESIGN

The automated measured unit is used to measure the conversion factor and magnetic losses in thin magnetic films. Fig. 3 shows the measuring unit for obtaining FMR spectrum.

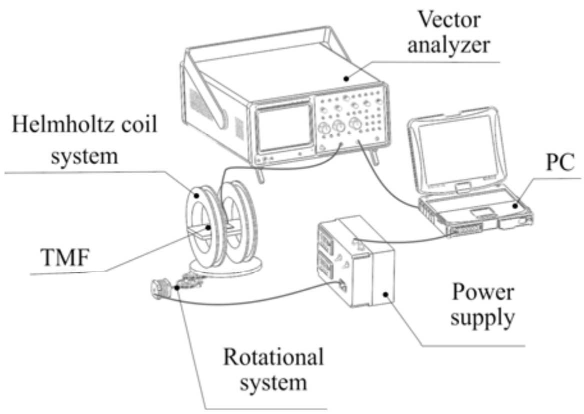

Fig. 3. The measuring system.

The system allows to record and to analyze the FMR spectrum, to calculate conversion factor in TMF. The measured sample is placed in the antinode of a high-frequency magnetic field. The measuring cell is made in the form of a short-circuited segment of the transmission microstrip line. The cell is the load of the vector network analyzer ZVL (R&S, Germany). FMR spectrum is obtained with the direction shift of constant magnetic field. The microwave magnetic field varies in the required frequency range.

A microwave magnetic field and constant magnetic field affects the sample concurrently. The measuring cell is installed in the center of Helmholtz coil.

The coils are used to create a constant magnetic field in the range of 0–20 Oe by applying constant current from DC power supply. The structure of measuring system fields is shown in Fig. 3.

Helmholtz Coils are rotated changing the angle, moving with a minimum step of 0.1 degree. Helmholtz coils can be rotated round the axis, using a stepper motor and reduction gear. This changes direction of constant magnetic field.

The FMR in the sample is observed when the direction of hard magnetization axis of the sample coincides with the direction of the microwave field axis. In this case, the constant magnetic field is directed along the easy magnetization axis.

The system allows to estimate the magnitude of the magnetometer sensitive element conversion factor. It is controlled by computer software (special package driver). The program includes a system of interaction with user, subsequent data processing and system for the result representation. The system of interaction with user is applied to receive and save data in a text file. The status of measurement process is displayed in "Progress Bar line". In addition, the logs of iteration are shown. E.g., Fig. 4 shows data reception from TMF sample.

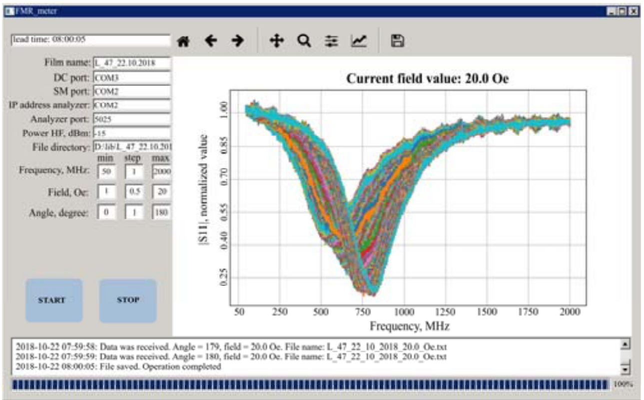

Fig. 4. The interface of program measuring system.

After the data are received, the task scheduler is launched. It reads the data from the user directory and calculates magnetic parameters (conversion factor and magnetic loss) in TMF. The task scheduler algorithm is shown on Fig. 5.

The scheduler determines the frequency, field, and angle at which the maximum value of conversion factor is observed. In addition, it calculates magnetic losses in TMF (2-d and the contour graphs). The data are stored as a chart dependence of conversion factor on the angle, field, and frequency.

The graphs of magnetics losses are saved as 2-d and the contours image.

The task scheduler transfers data for calculation using MATLAB API. The script of MATLAB calculates the frequency, field and angle at which the maximum value of conversion factor is observed. Moreover, it calculates magnetic losses in TMF (2-d and the contour graphs).

The data are stored as a chart dependence on conversion factor from angle, field, and frequency.

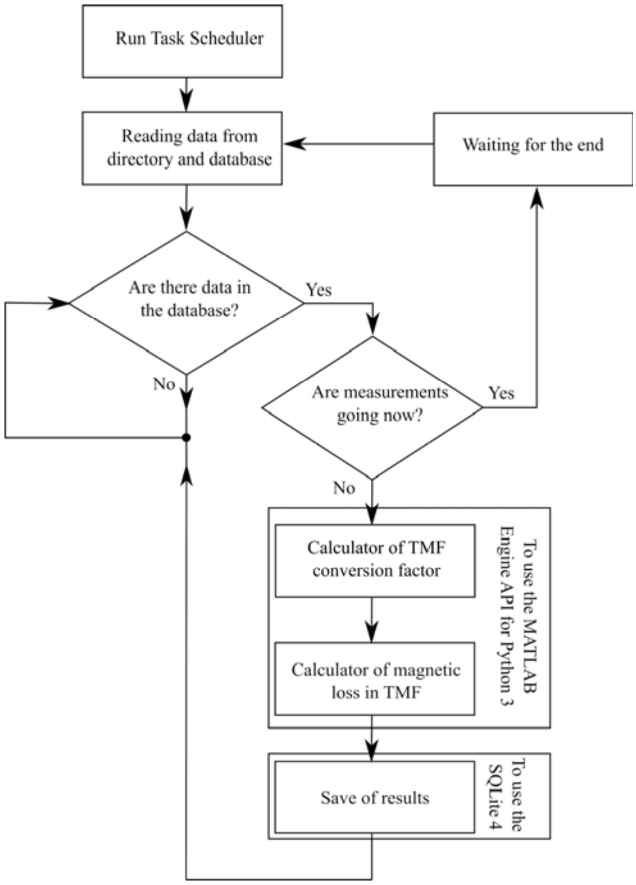

Fig. 5. The algorithm of work automating task manager.

It must be noted, that FMR spectrum is measured from the part of film, which is limited by size of microstrip line in measuring cell. The magnetic parameters of TMF are displayed in the area of sample, which is limited by microstrip line dimensions.

The server part of the program is used in order to present results of conversion factor measuring. Server is based on framework Django 2.0. Browser window represents the measurement data as a table. The table can be sorted. The value of conversion factor is normalized by conversion factor of reference sample. All conversion factors of samples change between 0 to 1. In the catalog of results the system displays data for one film in the form of several charts, using “FancyBox” which is jQuery lightbox script for displaying images, videos and other content.

IV. The Evaluation of TMF Conversion Factor

The FMR spectrum is obtained using the automated measuring unit. It uses a non-resonant measurement method. Before starting the measuring process, the following parameters are determined:

– sweep range across the field – in the range between 0 – 20 Oe with the step of 0.5 Oe;

– frequency range of microwave – in the range from 50 MHz to 2 GHz, the number of measurement points is 4500;

– field direction (see Fig. 1); necessary angle between 0 – 180 degrees and step angle 0.1 degree.

The measurement results are recorded in graphs, tables, and texts. Fig. 6 shows the example of the received data from an automated unit.

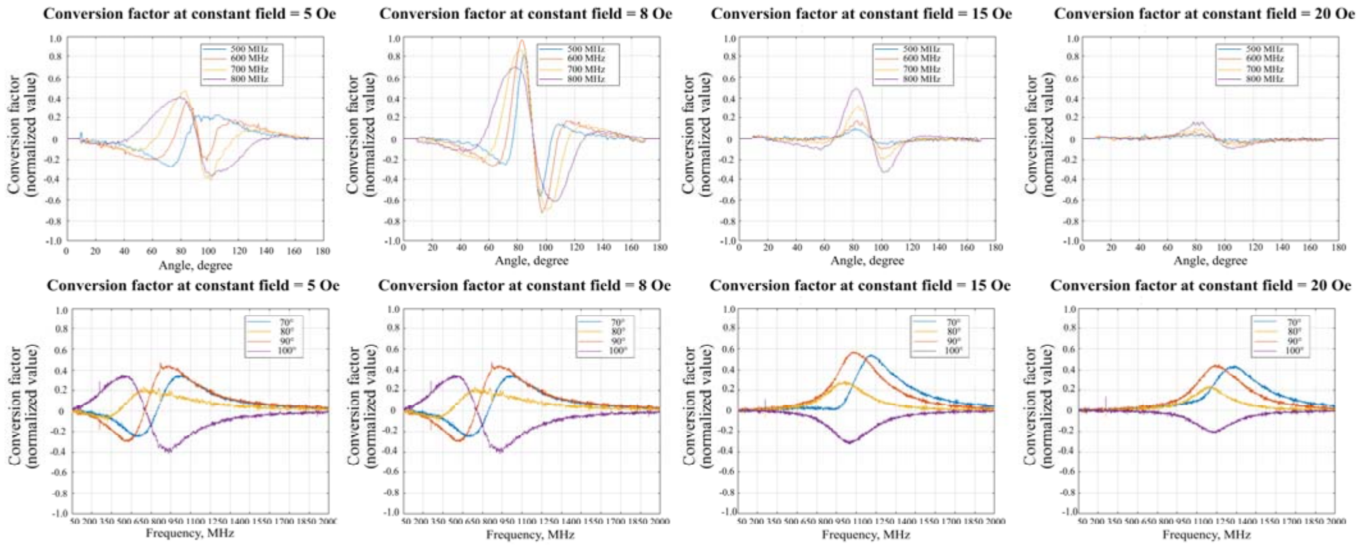

Fig. 6. The example of spectrum ferromagnetic resonance for one sample $Ni_{80}Fe_{20}$ (one layer, thickness is 600 Å).

FMR spectrum shown in Fig. 6 reflects the dependence of maximum FMR conversion factor on frequency and the angle between direction of the hard and easy magnetization axis in TMF. The graphs show the dynamics of the conversion factor changing in the TMF from the magnitude of the constant magnetic field. The graphs of the conversion factor changing in TMF are plotted for each value of the constant magnetic field. It is possible to estimate the dynamics of the conversion factor change depending on the angle, at which constant magnetic field affects TMF.

V. Conclusion

The automated unit allows to measure magnetic characteristics of thin films (the effective saturation magnetization, the field of uniaxial magnetic anisotropy and the width of the FMR spectrum line) which characterize the magnetic losses in the sample. Automated system measuring the characteristics of thin magnetic films for the sensors of weak magnetic fields allows to significantly increase the speed and improve the quality of measurement of experimental TMF samples.

The average measurement time of a sample with a step of the field 0.5 Oe from 0 Oe to 15 Oe, angle from 0 to 180 degrees with a step in 1 degree, frequency from 50 MHz to 2 GHz is approximately 8 hours (about 10^6 points).

The obtained data allow sorting out TMF for sensors of weak magnetic fields. The system is used to estimate the influence of technological conditions (deposition rates, substrate temperatures, sample thickness, number of layers, etc.) on TMF characteristics.

As a result, 150 TMF samples were studied. According to the data obtained samples were selected with the maximum conversion factor. This made it possible to improve the weak magnetic fields sensor parameters, as well as to increase and simplify the selection of samples.

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