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BROAD-BAND FERROMAGNETIC RESONANCE IN THIN MAGNETIC FILMS AND NANOSTRUCTURES

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The present contribution is aimed to give a brief comparison of the broad-band ferromagnetic resonance methods for characterization of thin magnetic films and nanostructures. It is expected that within 2011 a new broad-band ferromagnetic resonance equipment will be installed in the Institute of Molecular Physics, Polish Academy of Sciences (IFM PAN) in the framework of SpinLab Centre financed by the Ministry of Regional Development - Innovative Economy Programme POiG 2.2 (http://www.poig.gov.pl/).

INTRODUCTION

Ferromagnetic resonance (FMR) has been proved to be one of the most useful method for characterizing thin magnetic films and nanostructures (Heinrich, 1994). A standard X- or Q- band ESR spectrometers are extensively used for this purpose in IFM (Dubowik, 2006;.Dubowik, Stobiecki, Gościańska, Kociemba and Bednarski, 2009) in a conventional way, i.e., in so-called field domain. A thin film sample is "swept" through the resonance by means of external magnetic field *H* (Fig.1a). At the resonance, the microwave losses are increased and the reflected power changes a little. Since, in addition, a small modulated magnetic field H_{mod} is applied with frequency of several kHz, absorption signal is detected with lock-in amplifier and the measured FMR signal is proportional to the field derivative of the imaginary part of rf-susceptibility dχ/dH (Fig.1b). This conventional FMR with a fixed microwave excitation frequency ω and the magnetic system swept across resonance is alsocalled the field-swept FMR.

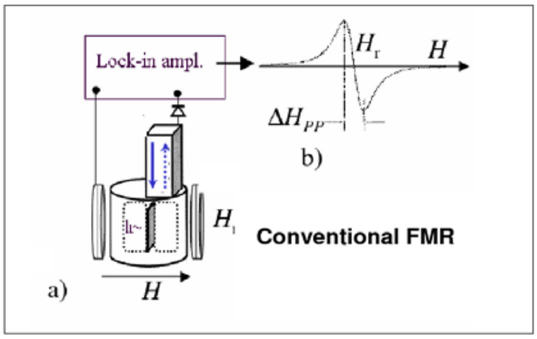

Fig. 1. Sketch of conventional FMR spectrometer (a) with a thin magnetic film placed in the centre of microwave cavity and with field *H* swept across the resonance. Application of a small modulation field H_{mod} and lock-in amplifier results in FMR signal proportional to the first derivative dχ/dH (b).

Nowadays, however, with the increasing demand for high-frequency methods for characterization of magnetic nanostructures (Yamaguchi, Motoi, Hirohata, Miyajima, Miyashita and Sanada, 2008); Sierra, Aliev, Heindl, Russek and Rippard, 2009) novel measuring high-frequency techniques have emerged: vector network analyzer ferromagnetic resonance (VNA-FMR) and pulse inductive microwave magnetometry (PIMM). In contrast to conventional FMR measured in the field domain, VNA-FMR is a frequency domain technique since the microwave excitation frequency is swept at the fixed external field. On the other hand, the PIMM method consists in measurements of time evolution of voltage oscillations resulting from a damped precessional motion of the magnetization. Therefore, PIMM is a time domain technique.

EXPERIMENTAL DETAILS

We will describe briefly some advantages of the two broad-band FMR methods applied to the magnetic thin films and nanostructures in comparison to conventional FMR. The heart of VNA-FMR (Fig. 2) is Vector Network Analyzer (Agilent Technologies, 2000). VNA allows characterization of a transmitted and reflected signals passed to/from a microwave device under investigation over broad frequency range. It consists of a high frequency source, a local oscillator and a mixer arranged in a sophisticated architecture to allow the measurements of all four components of the S-parameters (parameters, which relate incident and reflected electromagnetic waves (Agilent Technologies, 2000)) which are complex.

Hence, in VNA the detection of the transmitted and reflected signals is phase sensitive. What is the most useful for the measurements of the magnetic nanostructures, the measurement of the phase enables the calculation of both the real and the imaginary part of the susceptibility and, hence, to characterize magnetization dynamics in these nanostructures.

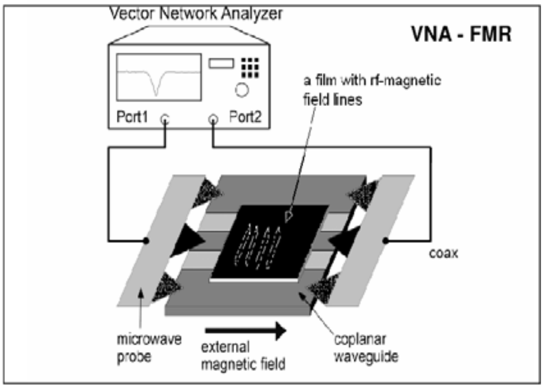

Fig. 2. A sketch of VNA-FMR comprising of VNA, coaxial cables, microwave probes and a coplanar waveguide and a thin magnetic film placed on it. Rf-magnetic field lines are schematically depicted to show that in this arrangement Larmor condition is fulfilled.

The main components of the experimental setup are sketched in Fig. 2. The VNA is connected to a coplanar waveguide (CPW) having a characteristic impedance of 50 using coaxial cables and microwave probes. VNA compares the input and output signals on the coplanar waveguide with respect to their amplitude and phase, allowing measurements of the absorption signal as a function of the frequency. To increase signal to noise ration, the sample is swept in two runs. In the first run the external magnetic field is directed perpendicular to the CPW so that h_{rf} and H are parallel (the Larmor condition is not fulfilled) and the reference spectrum is measured. In the second run the field H is applied along the CPW as it is shown in Fig.2. In such configuration FMR spectrum is expected with less or more complicated FMR absorptions with some noise. After the reference spectrum is subtracted from the noisy FMR spectrum, a pure FMR spectrum without background is obtained at a given external field. Such a procedure enables us to construct a dispersion relation (i.e. the resonance frequency as a function of bias field H) and then, to compare it with the Kittel equations for thin magnetic films with various magnetic anisotropies. Moreover, the magnetic relaxation can be evaluated in the broad range of rf-frequency and/or the magnetic field. Some examples of application of VNA-FMR for investigations of the magnetic properties of thin magnetic films can be found, for example, in Refs. (Sierra et al., 2009; Neudecker, Woltersdorf, Heinrich, Okuno, Gubbiotti and Back, 2006). In VNA-FMR signal-to-noise ratio is higher than in conventional FMR method and this feature enables magnetic nanostructures with a relatively small numbers of spins to be investigated. Moreover, since VNA-FMR can be measured in a small external magnetic field, investigations of the dynamic response of several modes from nanostructures in non-saturated state (i.e., with the domain structure conserved) are possible.

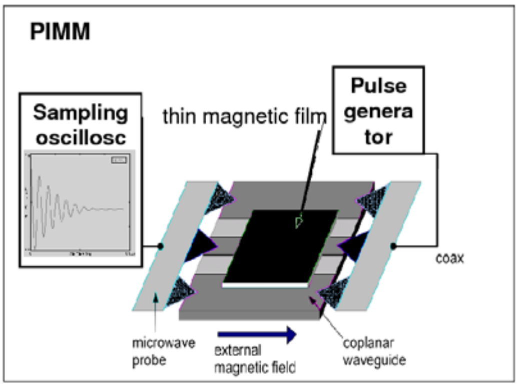

Fig.3. Schematic setup of the pulse inductive microwave magnetometer (PIMM).

In the PIMM measurements a short magnetic field pulse is applied to the coplanar waveguide. The pulse excites in a thin magnetic film placed on the CPW a damped magnetization precessional motion and this dynamic response of magnetization is monitored as a function of time with a fast sampling oscilloscope as it is shown in Fig. 3.

Having measured a set of such responses in various external fields (or its configuration) we can further construct a dispersion relation to evaluate magnetic parameters of an investigated thin film and characterize its magnetization damping, i.e., we can obtain actually the same results as those from VNA-FMR. A systematic discussion of the PIMM method has been given by Silva et al. (Silva, Lee, Crawford and Rogers ,1999).

CONCLUSIONS

In summary, we presented and compared the high frequency methods for ferromagnetic resonance, which are sensitive and suitable for investigating the magnetization dynamics in submicron-scale magnetic structures. One of them is a broadband VNA-FMR spectrometer, which is preferable for the FMR studies under a constant magnetic field. The VNA-FMR, using a vector network analyzer, provides an insight to a modal spectrum with respect to both frequency and effective damping in the various modes. Besides, a pulse-inductive method (PIMM) which can measure the time domain of dynamical properties in an individual ferromagnetic film and a multilayered spin-valve stack. This method is especially useful for the characterization of intrinsic dynamical properties with a state-of-the-art oscilloscope for high-speed sampling.

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