Proceedings of the European Conference Physics of Magnetism, Poznań 2014

Nonlinear Ferromagnetic Resonance in Micron and Sub-Micron Amorphous Wires

L. Kraus[a,*] and G. Ababei

[a]Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, CZ-18221 Praha 8, Czech Republic
[b]National Institute of Research and Development for Technical Physics,
47 Mangeron Boulevard, RO-700050 Iaşi, Romania

Ferromagnetic resonance in glass-coated amorphous microwires FeSiB and CoFeSiB with the diameters varying from 133 nm to 25 μm and the glass thickness about 10 μm was measured at frequency of 9.5 GHz. Electric polarization of the wire can substantially amplify the microwave magnetic field on the sample surface. This allows us to achieve the threshold fields for nonlinear behavior with microwave power of only few mW. Above some critical value of incident power a distortion of central part of FMR curves is observed for FeSiB wires. For diameters less than 6 μm a series of sharp, nearly equidistant peaks appears with the period δH inversely proportional to the wire diameter. The phenomenon is explained by the parametric excitation of dipole-exchange modes via the first order Suhl spin-wave instability and the spin-wave confinement in very thin wires. In the CoFeSiB wires the nonlinear phenomena cannot be achieved even with the maximum power available (about 25 mW). It is probably because the threshold field is higher due to larger Gilbert damping constant and lower saturation magnetization of this alloy.

DOI: 10.12693/APhysPolA.127.359
PACS: 75.30.Ds, 75.50.Kj, 76.50.+g

1. Introduction

Magnetic microwires and nanowires are potential basic elements for information storage and processing, microwave engineering, spintronics and other applications. High speed of operation is very important for the efficiency of such devices. Nonlinear effects play important role in ultrafast magnetization dynamics and can, therefore, be crucial for such applications. Ferromagnetic resonance is the ordinary experimental technique for investigation of nonlinear effects at microwave frequencies. Until recently, most experimental work on nonlinear FMR has involved only YIG and similar materials because of small damping constants and relatively low RF fields necessary to reach the nonlinear behavior (for a review of early works see e.g., [1]). In metals, where the resonance linewidth is of the order of 10 mT, large microwave powers (up to few kW) were required to achieve the threshold fields for the onset of spin-wave instabilities [2]. Therefore only few high power FMR investigations on permalloy thin films have been published until recently [3].

The electrical conductivity of wires and their shape are particularly suitable for investigation of nonlinear behavior of ferromagnetic metals. It has been shown by Rodbell [4] that the microwave magnetic field on the wire surface can be substantially increased by the electric polarization effect. Alternating polarization of an elongated conducting body by microwave electric field produces electric current along the body and strong circumferential magnetic field h_φ on its surface. The field can be several orders of magnitude higher than the microwave magnetic field in an empty waveguide or cavity. This allows to observe the nonlinear effects with moderate or low power equipments [5]. In our early papers [6, 7] we reported the observation of fine structure of nonlinear FMR spectra in glass-covered amorphous wires with diameters of few μm. In this paper the investigation of fine structure is extended to submicron wires.

2. Experimental

Amorphous glass-coated wires $Fe_{77.5}Si_{7.5}B_{15}$ and $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ were prepared by the Taylor–Ulitovskii method. The diameter metallic core varied from 133 nm to 25 μm. The thickness of glass coating was about 10 μm. The FMR measurements at 9.5 GHz were done by a simple FMR spectrometer with the maximum microwave power of about 25 mW. Sample about 14 mm long was placed in the middle of rectangular TE_{10} waveguide with the microwave electric field and static magnetic field parallel to the wire. The waveguide was short-ended by a tuning plunger, the position of which was set to get the maximum FMR signal. The derivative of reflected microwave power $\mathrm{d}P/\mathrm{d}H$ was obtained by the standard field-modulation technique.

3. Results and discussion

An example of resonance curves measured with different levels of incident power is shown in Fig. 1. At low power the usual resonance curve is observed. With increasing microwave power the amplitude of the curve increases. But at a certain critical value a distortion of the central part of the curve appears with a very sharp peak inside. When the power further increases the distorted part extends in both directions and more and more peaks appear. Among all the peaks a series of well distinguished nearly equidistant peaks can be found.

Some nonlinear resonance curves for wires with different thickness are shown in Fig. 2. The period δH between the subsequent peaks is depicted in the inset of Fig. 2.

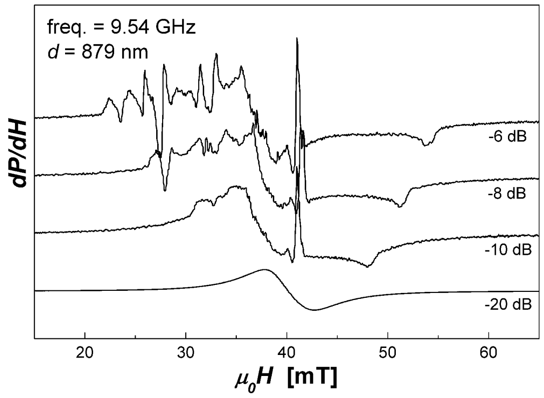

Fig. 1. FMR curves measured with different incident microwave power on the amorphous $Fe_{77.5}Si_{7.5}B_{15}$ wire with the metallic core diameter of 879 nm.

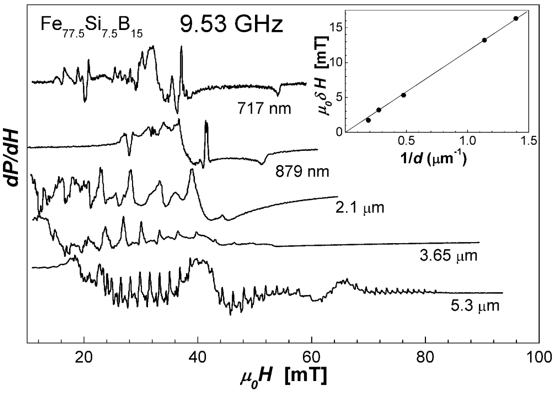

Fig. 2. Nonlinear FMR curves of amorphous $Fe_{77.5}Si_{7.5}B_{15}$ wires with different diameters. Inset: The period of fine structure vs. $1/d$.

As it can be seen, δH is inversely proportional to the wire diameter d. For wires with diameters 9.6 μm and larger the period is so small that the fine structure is smeared out and cannot be already distinguished. On the other hand, for the wires 318 nm and 133 nm the critical microwave field h_c cannot be achieved even with the maximum incident power. In CoFeSiB wires the nonlinear behavior has not been observed at all. It might be due to higher threshold fields h_c, which could not be attained with our equipment.

The origin of the fine structure can be better deduced from the absorption curves $P(H)$, which were obtained by numerical integration of resonance curves. The absorption curves of $Fe_{77.5}Si_{7.5}B_{15}$ wire with diameter of 717 nm for different levels of incident power are shown in Fig. 3. As can be seen, at the field of 36.5 mT, which corresponds to the position of the sharp peak on the resonance curve a narrow dip on the absorption curve occurs for microwave power above the critical value. This clearly indicates that the fine structure of nonlinear FMR curve is caused by the premature saturation of ferromagnetic resonance.

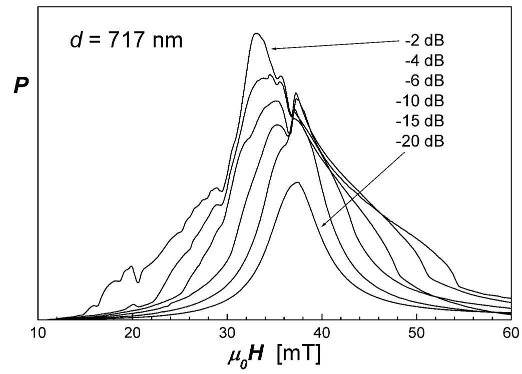

Fig. 3. Absorption curves at different power levels for $Fe_{77.5}Si_{7.5}B_{15}$ wire with the diameter of 717 nm.

The theoretical explanation of the observed phenomenon is based on the Shul theory of spin wave instabilities [8]. According to the theory the nonlinear effects are caused by parametric excitation of spin waves. When the amplitude of uniform precession of magnetization exceeds some critical value it becomes unstable and a spontaneous transfer of its energy into a pair of spin waves with opposite $\boldsymbol{k}$ vectors occurs. Depending on the number of uniform precession magnons taking part in the energy transfer the first order or second order instabilities are recognized. Usually, the first order processes are responsible for the subsidiary absorption and the second order ones for the saturation of main resonance. The threshold field for the first-order instability is usually lower than for the second-order one. If, however, the condition of coincidence of the subsidiary and the main resonance

$$\omega = \omega_{\text{res}} = 2\omega_{\boldsymbol{k}}, \tag{1}$$

is fulfilled, exceptionally small threshold field h_c is observed. Here ω_{res} is the resonance frequency and $\omega_{\boldsymbol{k}}$ the spin wave frequency. Then the first order processes are responsible for the nonlinearity of FMR. To satisfy this condition ω_{res} must be larger than twice the minimum of $\omega_{\boldsymbol{k}}$, i.e. $\omega_{\text{res}} > 2\gamma H$, where γ is the gyromagnetic ratio and H the DC magnetic field (including the effective anisotropy field).

The Suhl theory has been developed only for bulk insulators. In tiny ferromagnetic metals the situation is more complicated. First, due to the skin effect the main resonance is not a uniform precession, as in ferromagnetic insulators. Second, because of confinement of spin waves the continuum of spin waves $\omega_{\boldsymbol{k}}$ must be replaced by a discrete spectrum of the dipole-exchange modes $\omega_{m,n,\beta}$, where m and n are the radial and azimuthal mode numbers and β the propagation constant along the cylinder axis. The dispersion relation for $\omega_{m,n,\beta}$ of an axially magnetized long cylinder can be found in Ref. [7]. The dependence of $\omega_{m,n,\beta}$ on the longitudinal propagation constant β is shown in Fig. 4 for two different DC fields (the upper full and dashed curves). The inset of Fig. 4 schematically shows the amplitude of RF magnetization on the wire surface.

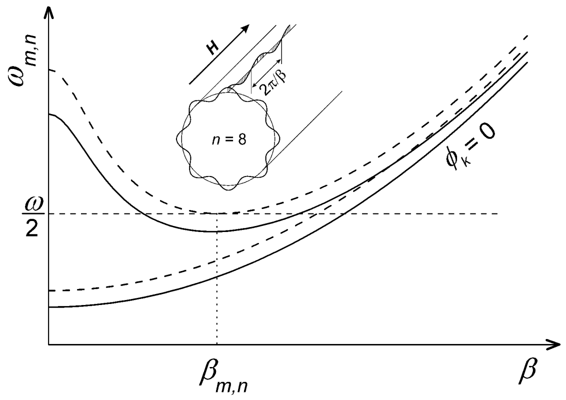

Fig. 4. Dipole-exchange frequency $\omega_{m,n,\beta}$ as a function of longitudinal propagation constant β for two different DC magnetic fields (full curves — $H < H_{m,n}$, dotted curves — $H = H_{m,n}$). The curves $\Phi_k = 0$ represents the bottom of the spin-wave manifold.

It has been shown that the circumferential RF field induced by the electric polarization of the wire excites the circumferential resonance mode with the resonance frequency [9]:

$$\omega_{\mathrm{res}} = \gamma\sqrt{H\,(H + M_{\mathrm{s}})}, \qquad (2)$$

where M_{s} is the saturation magnetization. Then the coincidence condition (1) can be then fulfilled only if

$$\omega/\gamma < 2M_{\mathrm{s}}/3. \qquad (3)$$

When the amplitude of the circumferential mode exceeds the threshold value the pairs of dipole-exchange modes (m, n, β) and $(m, -n, -\beta)$ are parametrically pumped. The critical field of the particular pair depends on its coupling to the main resonance mode. For example, the pairs with odd azimuthal numbers n cannot be excited at all.

The fine structure of the nonlinear resonance can be now explained in the following way: Let the RF magnetic field h_φ be kept constant at some value above the minimum threshold field. When DC magnetic field increases the energy of the dipole-exchange modes also increases and the branches (m, n) gradually emerge from the level $\omega/2$. At the moment when the minimum of $\omega_{m,n}$ just passes $\omega/2$ (shown by the dotted curve in Fig. 4) the number of states available for parametric pumping sharply increases and the dip on the absorption curve appears. The corresponding field $H_{m,n}$ can be obtained by numerical solution.

For the FeSiB and CoFeSiB wires the coincidence condition (3) requires frequency less than 30 and 15 GHz, respectively, which is well satisfied in these experiments. The period δH of fine structure for the FeSiB wires, shown in Fig. 2, well agrees with $H_{m,n}$ calculated for $m = 1$, even numbers n and the exchange constant $A = 8.2 \times 10^{-12}$ J/m, determined from radial standing spin wave spectra [10]. The absence of fine structure for CoFeSiB wires can be explained by insufficient microwave power of our spectrometer. The threshold field h_{c} for the case of coincidence is proportional to the square of the Gilbert damping parameter α and inversely proportional to the saturation magnetization [8]. Because the FMR linewidth of CoFeSiB wires is about twice larger and their M_{s} only about 1/2 of M_{s} for the FeSiB alloy the instability threshold field is about one order higher, which is not available with the maximum input power.

4. Conclusion

We have shown that in the case of coincidence of the main and subsidiary resonance the nonlinear phenomena in thin amorphous wires can be observed even with a low power FMR spectrometer. The fine structure of nonlinear FMR curves can be explained by parametric excitation of dipole-exchange modes of a long cylinder.

Acknowledgments

This work was supported by the project P102/12/2177 of the Grant Agency of the Czech Republic.

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