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Extra high frequency study of magnetic order in GMI nanostructures

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The research of the magnetic properties of electron system of low dimensional magnetic nanostructures is presented. Namely we discuss the results of study of multilayered and granular nanomagnets that demonstrate the Giant Magnetic Resistance (GMR) and Giant Magnetic Impedance (GMI) phenomena.

The Electron Spin Resonance/Ferromagnetic Resonance (ESR/FMR) technique of millimeter waveband has been applied to define the magnetic ordering in the nanostructures dependent on the interaction between single magnetic granules/particles. The magnetization of saturation for various types of Co-, Fe- and Ni-nanogranular structures as well as the magnetoresonance response is under discussion.

1 Introduction

The low dimension magnets such as nanometer sized magnetic granules and layers, which are separated by the nonmagnetic or moreover the non-conducting spacer, are of great interest due to the fact that they demonstrate a noticeable value of Giant Magnetic Resistance/Impedance (GMR/GMI) effect [1, 2]. When we deal with granular structures the term Tunnel Magnetic Resistance/Impedance (TMR/TMI) is used as a rule. Contemporary study of such magnets is aimed on their prospective applications in high-frequency and extra-high-frequency spintronics. It was shown [3, 4] that such structures demonstrate a noticeable magnetoimpedance response in the frequency band 30 – 80 GHz. As the magnitude of GMR/GMI/TMR/TMI depends strongly on the magnetic interaction between single particles, so far as the study of the magnetic structure, which depends strongly on the size, shape and distance between the separate particles in given systems is of current interest. Moreover the dynamic methods of study of these prospective materials at frequencies, which are close to the frequencies of their presumable application, are preferable. In the given work some peculiar properties of the ESR-response, dependent on the distance between single particles and their shape are under discussion for several promising structures.

2 Experimental results

We studied the nanostructures of two types: #1-layered structure and #2-nanogranular (or – so-called discontinuous layered structure).

The 1st type structure demonstrates the spin-valve behavior [4]. It consists form the following layers: Si/Ta(50 Å)/Cu(100 Å)/Ta(50 Å)/NiFe(20 Å)/Cu(50 Å)/MnIr(100 Å)/CoFe(25 Å)/Cu(*t*, Å)/NiFe(100 Å) – [4, 7]. The latest layer (NiFe) plays the role of a “free layer”, CoFe is the “pinned layer” and MnIr is the “pinning layer”. Specimens have a various thickness of Cu or Al_2O_3 interlayer (t_{Cu} = 3, 6, 9, 12, 15, 18, 21, 24 Å, $t_{(Al_2O_3)}$ = 3; 6; 9; 12; 15; 18; 21; 24 Å).

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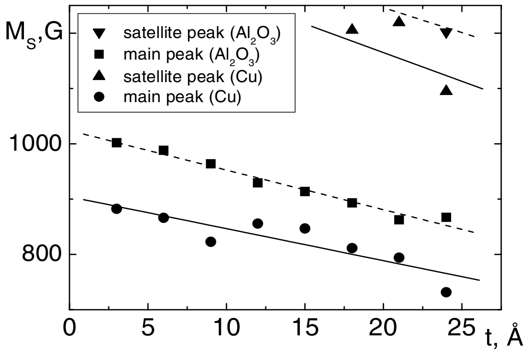


Fig. 1 Magnetization calculated from the resonance frequency – resonance field dependence of FMR response ($f = 30-40$ GHz, $T = 300$ K) for the spin-valve specimen.

Magnetization of the saturation had been estimated from the ESR data (at $f = 30-40$ GHz, $T = 300$ K) by the known Kittel formula as it described in [3]. The Fig. 1 demonstrates the decreasing of the magnetization with the growth of interlayer width. But as one can see from this figure the magnetoresonance response consists of two FMR peaks (the lower one, which corresponds to the NiFe layer and the higher one, which corresponds to the CoFe layer) for the thickness of spacer $t_{SP} > 18$ Å. When $t_{SP} < 18$ Å these peaks run into one peak.

Shapes of the FMR peaks are given in Fig. 2. Let us note that similar results were obtained at our earlier theoretical research [5] concerning the simulation of FMR response for multilayered CoCu nanostructure with buffer layer [6], Fig. 2. The simulation performed by the Monte Carlo technique [5] demonstrate the similar transforming of double peak FMR response into one-peak response while the thick-

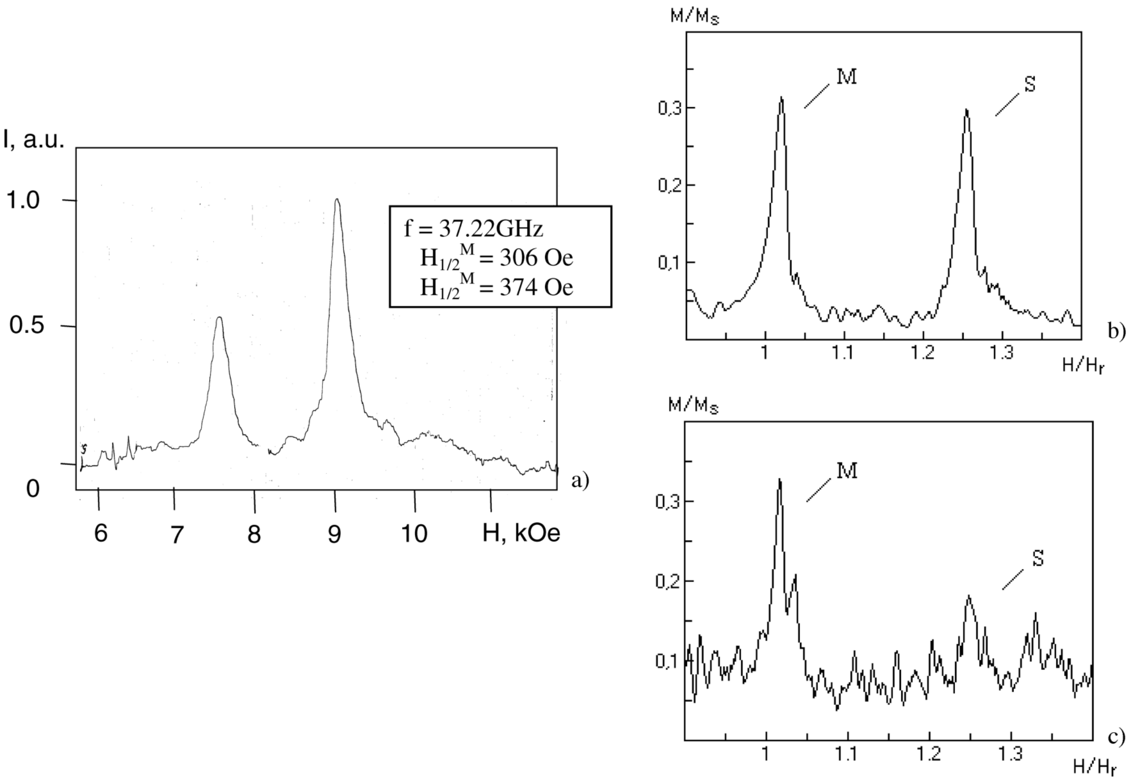


Fig. 2 ESR lineshape: a) Experimental FMR response for spin-valve specimen; b), c) simulation of FMR response from Fe buffered Fe(60 Å)[Co(10 Å)/Cu(t Å)]$_{30}$ nanolayer for $t_{SP} = 20$ Å and $t_{SP} = 10$ Å correspondingly.

ness of interlayer decreases up to magnitudes of the same order (t_{SP} = 12–14 Å) as for the spin-valve samples under measurements.

Thus it is possible to conclude that the strong interaction between the magnetic particles which provide the ferromagnetic order of the nanostructure are noticeable only on the distances less than some critical magnitude t_{cr} = 12–14 Å. This means that the type of magnetism in nanostructure under study is different for large concentrations of magnetic particles $t > t_{cr}$ (most likely it is the FM and AFM order) and for small ones $t < t_{cr}$ (most likely it is the superparamagnetism/SPM or the mixed phase FM/AFM/SPM).

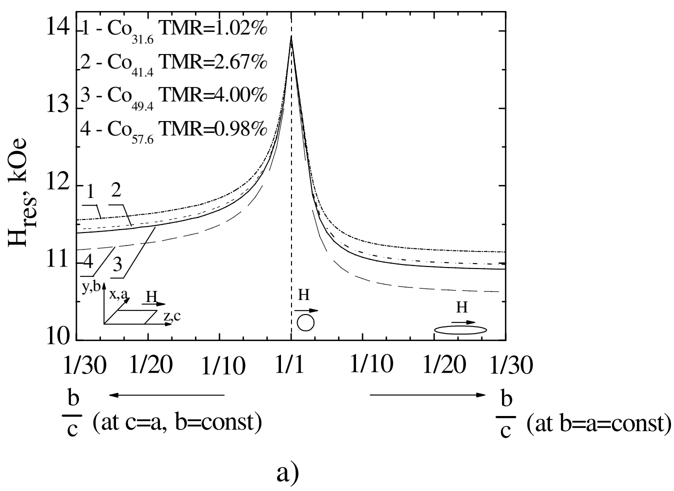
The second system under research is the magnetic nanogranular structure $Co_x(TiO_2)_{1-x}$ with Co volumetric contents of 31.6%, 41.4%, 49.4% and 57.6%. Let us note that due to the known technology of preparation of such structures by the alternate sputtering of Co and Al_2O_3 (or Cu) on the substrate they are called as well "the discontinuous layered systems". This means that the Co-particles are assembled in clusters, having a scale type shape. These specimens exhibit the tunnel magnetic resistance/impedance TMR/TMI phenomena of noticeable magnitudes ($\Delta R/R \approx 4\%$, $\Delta T/T \approx 0.56\%$ for $X = 49.4\%$ at $f = 30-40$ GHz). The analysis of the ESR response allows estimating the shape of the granules that form such system. The usage of the generalized Kittel [3] formula (1),

$$\nu_{res} = \gamma\{[(N^{(x)} - N^{(z)})\, M_s + H_{res}]\,[H_{res} + (N^{(y)} - N^{(z)})\, M_s]\}^{1/2} \qquad (1)$$

which takes into account the shape of ferromagnetic granules together with quasistatic experiment data, gives the results, presented in Fig. 3a. Here M_s – is the magnetization saturation; $N^{(X)}$, $N^{(Y)}$, $N^{(Z)}$ – are demagnetizing factors of ellipsoid, which approximates the specimen, along *OX*-, *OY*-, *OZ*-axes correspondingly.

The diagram on Fig. 3a shows the dependence of the resonance magnetic field on the ratio between the ellipsoidal specimen axes. Here a, b, c – are the dimensions of specimen along the *OX*-, *OY*-, *OZ*-axes. First of all let us note, that equal magnitudes of the resonance static magnetic field H_{res} is observed for the case when the specimen is formed by single particles of a planar shape (the left branch in Fig. 3a) and by ellipsoid shaped particles (the right branch in Fig. 3a).

Secondly as it follows from comparison of calculation made with the experimental data, the shape of separate magnetic particles that form the nanogranular structure is close to ellipsoid with axes ratio a/b/c = 6/1/6. These particles are joined together into magnetic clusters with the axes ratio a/b/c = 2/1/6 (Fig. 3b).



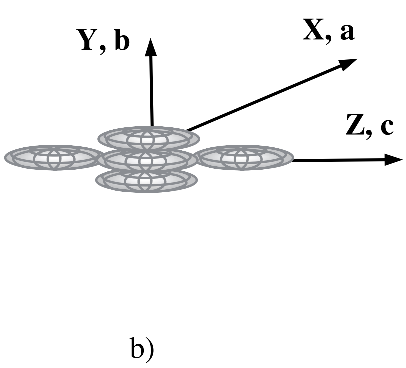


Fig. 3 ESR response for ν = 44 GHz from the $Co_x(TiO_2)_{1-x}$ discontinuous layered nanostructure.

It is important to note as well that the quasistatic magnetization researches (performed vibrating sample magnetometer (VSM) technique in Kharkov Polytechnic University [8]) show that the size of such a cluster is about 40 nm in the case when the system exhibits the superparamagnetic (SPM) behavior. At the same time it was estimated that the average amount of atoms in a single particle is about 90 000. It is important to note that the magnitudes of the space gaps at which the threshold between the ferromagnetic (mainly ordered phase) and the superparamagnetic (mainly disordered phase) takes place are the same for the spin-valve (#1) and discontinuously layered (#2) specimens.

Thus as one can see from the given experimental cycle the magnetic properties of the specimen (and the magnetism type exhibited) depend first of all on the shape and on the distance between single particles (on the magnetic moment of the single particle).

3 Conclusions

Summarizing the ESR/FMR study of two types of specimens we can make the following outcomes.

1. The magnetic features of nanostructures are defined not only by the magnetic order in a single magnetic particle/layer but also by the distance between particles/layers and by the particles shape. As a consequence of this, the anisotropy field that appears in the specimen is the most likely reason to define the type of magnetic order in the specimen.

2. Thus the main information about the magnetic properties of nanostructures is contained not in the integral characteristics of the specimens but in the local ones.

The last sentence means that the technique and corresponding devices, which should be able to detect the FMR/ESR response from the small area of the specimen, (less than 1 micrometer) should be applied. The prototype of such adequate experimental device could be an ESR microspore of scanning field, which physical principles are described firstly in [9].

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References

[1] J. F. Gregg, J. Phys. D, Appl. Phys. **35**, 145 (2002).
[2] A. Slobodskyy, G. Gould, and T. Sloboudskyy, Phys. Rev. Lett. **90**, 246601 (2003).
[3] S. Tarapov, T. Bagmut, A. Granovsky, S. Nedukh et al., J. Infrared Millim. Waves **25**(11), 1581 (2004).
[4] Manh-Huong Phan, Seong-Cho Yu, Cheol Gi Kim, and Manuel Vazquez, Appl. Phys. Lett. **83**(4), 2871 (2003).
[5] A. M. Zabolotskiy, D. P. Belozorov, and S. I. Tarapov, Int. J. Infrared Millim. Waves **25**(10), 1431 (2004).
[6] D. P. Belozorov, V. N. Derkach, S. V. Nedukh, A. G. Ravlik, S. T. Roschenko, I. G. Shipkova, S. I. Tarapov, and F. Yildiz, Int. J. Infrared Millim. Waves **22**(11), 1669 (2001).
[7] S. V. Nedukh and M. K. Khodzitskiy, in: Proc. of 9th Intern. Youth forum, Kharkov, Ukraine, 19–21 April, 2005, p. 116.
[8] S. T. Roshcenko, A. G. Ravlick, I. G. Shipkova, and A. Yu. Zolotarev, Phys. Met. Metallogr. **90**(3), 266 (2000).
[9] S. I. Tarapov, V. N. Samofalov, A. G. Ravlik, and D. P. Belozorov, Int. J. Infrared Millim. Waves **24**(7), 1081 (2003).