Conductive, magnetic and structural properties of multilayer films

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Abstract. Composite-semiconductor and composite-dielectric multilayer films were obtained by the ion beam sputtering method in the argon and hydrogen atmospheres with compositions: \{[(Co\textsubscript{45}-Fe\textsubscript{45}-Zr\textsubscript{10})\textsubscript{x}(Al\textsubscript{2}O\textsubscript{3})\textsubscript{y}]-[\alpha-Si]\}\textsubscript{120}, \{[(Co\textsubscript{45}-Ta\textsubscript{45}-Nb\textsubscript{10})\textsubscript{x}(SiO\textsubscript{2})\textsubscript{y}]-[SiO\textsubscript{2}]\}\textsubscript{56}, \{[(Co\textsubscript{45}-Fe\textsubscript{45}-Zr\textsubscript{10})\textsubscript{x}(Al\textsubscript{2}O\textsubscript{3})\textsubscript{y}]-[\alpha-Si:H]\}\textsubscript{120}. The images of surface relief and distribution of the dc current on composite layer surface were obtained with using of atomic force microscopy (AFM). The dependencies of specific electric resistance, ferromagnetic resonance (FMR) fields and width of line on metal (magnetic) phase concentration \(x\) and nanolayers thickness of multilayer films were obtained. The characteristics of FMR depend on magnetic interaction among magnetic granules in the composite layers and between the layers. These characteristics depend on the thickness of composite and dielectric or semiconductor nanolayers. The dependences of electric microwave losses on the \(x\) and alternating field frequency were investigated.

1. Introduction

A great number of experimental and theoretic works today is devoted to research of UHF magnetic characteristics of multilayer films and structures [1-3]. Created due to the newest nanotechnologies nanosized magnetic materials display unusual characteristics: giant magnetoresistance, intense magnetooptical response etc [2-3]. Multilayer films consisting of nanolayers such as ferromagnetic-dielectric and ferromagnetic-semiconductor, are widely practically used for instance as recording mediums of data with ultrahigh density, sensors of magnetic fields with high sensitivity, magnetoresistive random-access memory [4-7]. This work is devoted to the research of influence of nonstructural characteristics to the conductivity and ferromagnetic resonance characteristics multilayer films of the series D1 - \{[(Me\textsubscript{1})\textsubscript{x}(Al\textsubscript{2}O\textsubscript{3})\textsubscript{y}]-[Si]\}\textsubscript{100}, D2 - \{[(Me\textsubscript{2})\textsubscript{x}(SiO\textsubscript{2})\textsubscript{y}]-[SiO\textsubscript{2}]\}\textsubscript{56}, E - \{[(Me\textsubscript{1})\textsubscript{x}(Al\textsubscript{2}O\textsubscript{3})\textsubscript{y}]-[Si:H]\}\textsubscript{100} where Me\textsubscript{1} = Co\textsubscript{45}-Fe\textsubscript{45}-Zr\textsubscript{10}, Me\textsubscript{2} = Co\textsubscript{45}-Ta\textsubscript{45}-Nb\textsubscript{10}, 0.3<x<0.62, 3<y<12, y \approx 21-30x.

2. Preparation and characteristics of films
The multilayer films were received by the ion beam sputtering method in the argon atmosphere with pressure 0.04 Pa (D1, D2 - series), and with the addition of hydrogen with pressure $10^{-4}$ Pa (E - series). To obtain the D1- and E- series of films the 2 targets were used and deposition of functional layers on a rotating substrate was made. First target was complex and consisted of the Co$_{45}$Fe$_{45}$Zr$_{10}$ alloy plate on the surface of which were fixed Al$_2$O$_3$ 12 weighed plates. Irregular arrangement of plates of aluminum oxide on the surface of target possible to obtain a continuous change in the concentration of metal and dialectic phases of the composite depending on the position of the substrate relative to the target. Second target was semiconductor (Si) target. For sputtering the multilayer composite-dielectric D2-series of films were used also 2 targets. The first target was plate of alloy Co$_{45}$Ta$_{45}$Nb$_{10}$ with fixed weights quartz plates. Irregular arrangement portions of quartz also allow obtain the continuously varying the phase relationship. Second target was quartz plate.

The chemical composition of the films was defined as relation of the atoms of the metal, semiconductor and dielectric by scanning electron microscope JSM-6400 [4-6].

The thickness of the films were 0.4÷1.1 μm and depended on $x$ metal concentration. The thicknesses of composite, dielectric and semiconducting layers were 1÷4 nm and depended on $x$ [6].

The dependence of specific resistance on $x$ for all films series was measured (figure 1). The E-series films are featured by higher resistance comparing to the films of D1-, D2-series in percolation region ($x$=0.35÷0.45) because for the E-series the Si ions form chemical coupling with H this way decreasing the quantity of the electrons in the conductivity band. The decrease of the resistivity on 3-6 order occurs throughout all the series of the films with the increasing of the metal concentration $x$.

Researches of influence of metal phase concentration $x$ and the multilayer films nanolayers thickness on the dissipation power spectrum (frequency band is 9 kHz – 3 GHz) were carried out (figure 2). Spectrum analyzer INSTEK GSP-7830 to study of dissipation power spectrum of composite-dielectric multilayer films (D2-series) was used. All measurements were obtained at room temperature. The decrease of dissipation power with increasing frequency occurs as a result of decrease of capacitive resistance between metal grains in the dielectric matrix. The increase of dissipation power for frequencies >1.5 GHz occurs as a result of increase of inductive resistance in magnetic metal grains. The dissipation power of films for $x$$>$0.44 begins to increase on the low frequencies because quantity of metal grains increases and inductive resistance of films increases with increase $x$. The dissipation power decreases with increase $x$ for frequencies < 1.5 GHz.

![Figure 1. Dependence of the specific resistance on $x$ for various films series: D1 series — ; D2 series — — ; E series — — —.](image)

The images of surface relief and distribution of the dc current on films surface were obtained with using of atomic force microscopy (AFM) (figure 3). The microscope was ARIS-3500.
Figure 2. Dissipation power spectrum for films of D2-series on the various \(x\): 0.31 - \(\cdots\); 0.44 - \(\cdots\); 0.49 - \(\cdots\) \(x\); 0.56 - \(\cdots\).

Figure 3. Surface relief (a) and distribution of the dc current on composite layer surface (b) for the D2-series films with \(x=0.56\).

The current-voltage characteristics for D2-series of films with various \(x\) were measured. The current direction was through the cross section of the film. The usual current-voltage characteristics as for semiconductor diode on direct current were observed. The similar dependence for the reverse current was observed. The current-voltage nonlinearity strongly dependent on the thickness of the dielectric nanolayers. The current-voltage characteristics allow uses the multilayer films for amplification of the unipolar signals.

The FMR spectra were obtained by an electron paramagnetic spectrometer RE-1306 on the frequency of 9.36 GHz with using a standard modulation index meter [4-6]. The dc magnetic field was directed along the films plane. The alternating magnetic field was perpendicular to the dc field and also was directed along to the plane of the film.

The dependences of the FMR field \(H_{\text{res}}\) and width of line \(\Delta H\) on the concentration \(x\) at temperature 300 K are shown on the figure 4. For the interpretation of the experimental results the standard Kittel formula for resonance field [4-6] was used:

\[
H_{\text{in}}^2 = H_{\text{res}}(H_{\text{res}} + 4\pi<M> + 2K/<M>),
\]

where \(H_{\text{in}} = f/\gamma^* = 3375\) Oe, \(\gamma^* = 2.8\) MHz/Oe, \(<M>\) - average magnetization of the film, \(K\) – anisotropy constant.
The wide maxima on dependences $\Delta H(x)$ are observed (figure 4). These maxima correlate with dependence of width of layers $d(x)$. Maxima can be qualitatively described by demagnetization field dispersion maximum at the large distances between composite layers (in the area of the $d(x)$ maximum), and electron exchange through the semiconductor or dielectric nanolayers have minimum. It leads to the FMR width of line growth and to the maximum of $\Delta H(x)$. The resonance fields magnitudes for all film series decreases at increasing $x$ (figure 4) because $<M>(x)$ is grown.

![Figure 4. Dependence of the FMR field $H_{res}$ and line width $\Delta H$ on the concentration $x$ for films of D1 series - - - -; D2 series - - - ; E series - - - .](image)

4. Conclusion
Research of influence of metal phase concentration $x$ and the width of nanolayers to electric and FMR properties of the multilayer composite-semiconductor and composite-dielectric films of D1-, D2-, E-series has been carried out. The observed maxima of $\Delta H(x)$ correspond of maximum on $d(x)$ of semiconductor or dielectric nanolayer. When the $d(x)$ have maximum the magnetization field dispersion is maximal, and electron exchange through the semiconductor layers is minimal. This results in general FMR width of line broadening and $\Delta H(x)$ maximum is arisen. The resonance fields for all film series decreases at increasing $x$ in agree with grown $<M>(x)$.

The dependences of dc specific resistance $\rho$ for all films series were measured. The great change of $\rho$ is observed for multilayer films E-series. Destroyed chemical bonds in the silicon in semiconductor layers are replaced by hydrogen. This leads to the decrease in electron mobility.

The dissipation power spectrum (frequency band is 9 kHz – 3 GHz) for D2-series of films was investigated

The E-series films can be used for UHF absorbing material and the D2-series films can be used for unipolar signals amplifiers materials.

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