Metallic (CoFe)/Cu superlattices with record microwave giant magnetoresistive effect

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Abstract. Technology of preparation of (CoFe)/Cu superlattices by magnetron sputtering is discussed. The parameters of growth have been obtained which allows to get superlattices with very high magnetoresistance. Methods of characterization of superlattices are described. Microwave magnetoresistance in millimeter waveband is measured by transmission method. The record value of microwave magnetoresistance exceeding 80% is obtained.

1. Introduction

Magnetic metallic superlattices with exchange-coupled layers found application as sensitive elements for sensors and materials for hard disks [1]. Maximal giant magnetoresistive effect (GMR) is necessary for all applications. Ability to work in a wide frequency range up to tens of gigahertz is essential for computer elements. The superlattices which ferromagnetic layers consist of Co$_1$Fe$_{x}$ alloy and the spacer is made of copper have these merits [2, 3]. Highest magnetoresistance about 110% has been obtained for [Co$_{0.5}$Fe$_{0.5}$/Cu]$_n$ superlattices with many bilayers [4]. Recently for [Co$_{0.6}$Fe$_{0.4}$/Cu]$_n$ superlattices the maximal value of 80% and also high microwave magnetoresistance ($\mu$GMR) at frequencies up to 38 GHz has been obtained [3, 5].

The process of superlattice growth of superlattices is discussed in this paper and necessary parameters is mentioned which allows to get high microwave magnetoresistance. Methods of characterization of superlattices are considered. Data on magnetic field dependence of microwave transmission through superlattices are received.

2. Growth and characterization of superlattices

Synthesis of [Co$_{1-x}$Fe$_x$/Cu]$_n$ superlattices by magnetron sputtering is worked out with high vacuum MPS-4000-C6 equipment produced by ULVAC, Japan. The equipment contains three vacuum chambers: loading chamber, sputtering chamber for insulators and for metals. The sputtering chamber for metals has 6 magnetrons operating on DC. The targets with ø50 mm and thickness of 1.5 – 2.0 mm for ferromagnetic materials and 2 – 5 mm for non-magnetic metals are used. Fastening of the target is realized with melted indium layer. After magnetron targets are fixed, evacuation of the sputtering chamber is carried out using an oil pump with speed of 670 l/min and turbo-molecular pump with speed of 1300 l/s. As soon as residual gas pressure reaches $1\cdot10^{-5}$ Pa, heating of the chamber is turn on operating until temperature 110-120 °C at the outer side of the chamber.

Typical vacuum inside the chamber before sputtering is $6.7\cdot10^{-7}$ Pa. It is found that degree of preliminary pumping influences the magnetoresistive properties of nanostructures. Value of $10^{-5} – 10^{-6}$
Pa is insufficient to get superlattices with high GMR reproducible. The glass plates of Coverglass from Corning with thickness 0.25 ± 0.05 mm and dimensions 25×25 mm² are used as substrates. The method of substrates cleaning includes distilled water flush, acetone storage, wash in acetone using ultrasonic bath, rectified alcohol flush and subsequent hand wiping out with pile-free napkin.

General process-dependent parameters for sputtering are the following: the magnetron power is 100 Wt; argon pressure is 0.1 Pa; argon purity is 99.9998 %; frequency of the substrate rotation is 7 turns/min.; magnetic field at the substrate is 110 Oe; temperature of the substrate during sputtering is (23 ± 2) °C; pressure of residual gases before argon puffing is 3×10⁻⁷ Pa; speed of Co₅₀Fe₁₀ alloy sputtering is 2.7 nm/min.

Disposition of the layers for one grown sample is shown schematically in figure 1. The Ta layer with thickness 5 nm is deposited on the glass substrate and the PyCr (Py means permalloy) layer is deposited over. Eight pairs of layers made of ferromagnetic Co₅₀Fe₁₂ alloy with thickness 1.3 nm, split by spacer Cu with thickness 2.05 nm are grown. Upper PyCr layer is deposited to preserve from corrosion. Designation of this sample is Ta(5)/PyCr(5)/[Co₈₈Fe₁₂(1.3)/Cu(2.05)]₈/PyCr(3) where numbers in round brackets mean thickness of the layer in nm.

![Schematic image of structure of the superlattice.](image)

Optical interferometry and atomic-force microscopy are used to define the surface profile and roughness characterization. Scanning electron microscopy with X-ray energodispersion EDAX system is applied for investigation of local element composition. Vibration magnetometry and magnetoresistive measurements are used for the magnetization curves and GMR characteristics. Period of repetition of bilayers is obtained from low angle diffractometry and also characterization of interfaces.

The low angle X-ray diffraction pattern is shown in figure 2 for sample Ta(5)/PyCr(5)/[Co₈₈Fe₁₂(1.5)/Cu(0.95)]₈/Ta(5), where a sequence of minimums is seen. These oscillations are caused by Ta layer which has high scattering potential. Near 2θ = 4° the first Bragg peak is seen due to periodical disposition of the layers in the superlattice. The period of bilayers calculated from these minimums equals to 2.6 nm that is close to a nominal value of 2.45 nm. Small-scale oscillations present at the image between the minimums that point to distinct boundaries between the adjacent layers. X-ray data in high angles confirm that an axial texture present in the samples which <111> axis is perpendicular to the plane of the sample.

In order to get maximal magnetoresistance, magnetic moments in the neighboring CoFe layers has to be antiparallel. Thickness of Cu spacer is chosen to obtain this orientation. Two values of the spacer thickness is used in this work, namely, 0.95 and 2.05 nm, which correspond to the first and second maximums, respectively, of oscillating dependence of interlayer exchange coupling constant on the spacer thickness [6]. The value of maximal magnetoresistance of 80% for sample Ta(5)/PyCr(5)/[Co₈₈Fe₁₂(1.3)/Cu(0.95)]₈/Ta(5) (that is sample No.1) is one of the highest values obtained for metallic superlattices with GMR at a room temperature. The value of ~28% for sample No.2 Ta(5)/PyCr(5)/[Co₈₈Fe₁₂(1.3)/Cu(2.05)]₈/Ta(5) with Cu layer thickness 2.05 nm is also high one, and the magnetic saturation field is low for this sample, that is important for application in sensors.
Figure 2. Low angle X-ray diffraction pattern for the superlattice Ta(5)/PyCr(5)/[Co_{88}Fe_{12}(1.5)/Cu(0.95)]_{24}/Ta(5).

3. Microwave giant magnetoresistive effect

Microwave investigations of superlattices are carried out in frequency range from 26 to 38 GHz by transmission method described in [11]. The sample is placed in a rectangular waveguide cross section, see figure 3. Relative variations of the transmission coefficient module \( d_m = \frac{|D(H)| - |D(H_{\text{max}})|}{|D(H_{\text{max}})|} \) is measured, where \(|D(H)|\) is the transmission coefficient module in magnetic field \( H \) and \( H_{\text{max}} \) is the maximal magnetic field where the sample is in saturated state. Magnetic field is applied in the plane of the superlattice parallel to the narrow side of the waveguide. The vector of DC magnetic field \( H \) is perpendicular to the vector of microwave magnetic field \( \mathbf{H}_m \).

Following to [7], the formula for transmission coefficient \( D \) of electromagnetic wave can be written

\[
D = \frac{2Z_m}{2Z_m \text{ch} k_m d + Z \text{sh} k_m d},
\]

where \( k_m = (1+i)/\delta \) is the wavenumber in metallic media, \( \delta \) is the skin depth, \( d \) is the metal thickness of a nanostructure. The impedance of metallic nanostructure \( Z_m \) is always less than the impedance of free space \( Z \), \(|Z_m| \ll Z\). In a limiting case \( d \ll \delta \), which occurs at centimeter and millimeter wavebands for typical values of nanostructure’s thickness from few nanometers to hundreds of nanometers, one-to-one correspondence between the relative magnetoresistance \( r \) and \( \mu \text{GMR} \) follows from formula (1) i.e.

\[
d_m = r.
\]

This result is valid for metallic exchange-coupled nanostructures with continuous layers far from ferromagnetic resonance condition [7]. Comparison between magnetic field dependence of microwave transmission coefficient at frequency \( f = 26 \) GHz and relative magnetoresistance for sample Ta(5)/PyCr(5)/[Co_{88}Fe_{12}(1.3)/Cu(2.05)]_{24}/Ta(5) is presented in figure 4a. Fairly good correspondence is
seen for these dependences. Formula (2), for example, predicts weak frequency dependence of µGMR. Figure 4b shows accomplishment of this prediction for Ta(5)/PyCr(5)/[Co_{88}Fe_{12}(1.5)/Cu(0.95)]_{24}/Ta(5) superlattice. Let us mention that the microwave magnetoresistance shown in figure 4b is record one [5].

**Figure 4.** Comparison between magnetic field dependence of microwave transmission coefficient at frequency \( f = 26 \) GHz and relative magnetoresistance for sample No.2 (a); magnetic field dependence of microwave transmission coefficient through sample No.1 measured at several frequencies (b).

**4. Conclusions**

The technology of magnetron sputtering is discussed which allows to receive [Co_{90}Fe_{10}/Cu]_{n} superlattices with very high magnetoresistance. Importance of optimal parameters of buffer layer is mentioned to get samples with high GMR. In millimeter waveband the measurements are carried out of magnetic field dependence of transmission coefficient through superlattices. A record value of maximal µGMR higher 80% is obtained for the superlattice which has the spacer thickness corresponding to the first maximum of GMR. The superlattice which has the spacer thickness corresponding to the second maximum of GMR, has low saturation field. Superlattices with high µGMR can be applied in high frequency sensors and microwave devices.

**References**

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