Magnetoresistance and the Planar Hall Effect in Multilayer Co\(_{0.45}\)Fe\(_{0.45}\)Zr\(_{0.1}\) /(a-Si) Structures

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Abstract—The magnetic and magnetotransport properties of multilayer Co\(_{0.45}\)Fe\(_{0.45}\)Zr\(_{0.1}\) /(a-Si) nanostructures with a 0.7- to 3.5-nm-thick amorphous silicon layer and a 2.5- to 3.5-nm-thick metal layer that are produced via ion-beam sputtering are investigated. It is demonstrated that the resistance of these structures depends on temperature as \(R_{xx} \propto -\log T\), which is typical of metal/dielectric nanocomposites on the metal side of the percolation transition. A negative magnetoresistance (~0.15%) is observed at a thickness of the amorphous silicon layers of no greater than 1 nm. This effect is related to spin-dependent electron transitions between the neighboring layers in the presence of the antiferromagnetic exchange interaction between them. Under the same conditions, a transverse (between the Hall probes) magnetoresistive effect amounts to 6–9%. This phenomenon is related to the anisotropic magnetoresistance and the planar Hall effect, which has not been observed in metal/dielectric nanocomposites in the vicinity of the percolation transition. It is demonstrated that a magnetic memory cell based on such a film structure with the induced magnetic anisotropy can be created.

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1. INTRODUCTION

It is known that, in transition metals and their alloys, an electric field orthogonal to the current is induced when the magnetic moment is oriented in the plane of a sample at certain angle \(\varphi\) relative to flowing current \(I_0\) [1]. In this case, electromotive force (emf) \(V_{PH}\) of the planar Hall effect in a single-domain film is represented as

\[
V_{PH} = \frac{I}{l}(\rho_{\|} - \rho_{\perp}) \sin \varphi \cos \varphi
\]

where \(l\) is the film thickness and \(\rho_{\|}\) and \(\rho_{\perp}\) are the film resistivities in the directions parallel and perpendicular to the magnetization, respectively. It follows from expression (1) that the strongest planar Hall effect (PHE) is realized in thin films, where it is completely determined by the anisotropic magnetoresistance (AMR): The resistance increases when the magnetic moment is oriented along the current and decreases in the transverse configuration \((\rho_{\parallel} > \rho_{\perp})\).

Recently, the PHE has been used widely for the study of the magnetization reversal and the effect of magnetic anisotropy on the magnetotransport properties of various film systems, in particular, systems based on semiconductors with magnetic transition metals. However, the aforementioned studies were performed for homogeneous film systems in the case when the AMR effect represents a significant magnetoresistance (MR) source. Zhao et al. [2] reported on the PHE in granulated (NiFe)\(_x\)(SiO\(_2\))\(_{1-x}\) films with percolation conduction. In these films, the MR behavior can be determined substantially by the spin-dependent effects in the presence of electron tunneling between ferromagnetic granules and/or during electron scattering by intergranular interfaces. However, in this case, the PHE was observed also in samples with metal conduction that are far from the percolation transition and exhibit a significant AMR effect. In samples close to the percolation transition (i.e., at \((x - x_c)/x_c \ll 1\), where \(x\) is the concentration of the ferromagnetic component in a system and \(x_c\) is the critical value of \(x\) which corresponds to the metal–insulator transition), MR is isotropic for the field oriented along the film and the PHE is absent. Note that, in the samples with \((x - x_c)/x_c \ll 1\), the temperature dependence of the resistance is expressed by the formula \(R_{xx} \propto -\log T\) at temperatures equal to or greater than room temperature. This circumstance may be due to both weak localization of carriers and the increasing role of tunneling of spin-polarized electrons between ferromagnetic granules (see [3] and references therein), phenomena that lead to an increase in the isotropic negative MR.

The recent interest in stratified media formed from ferromagnetic transition metal and amorphous silicon has been driven mainly by their possible application as primary materials for spin electronics. Fe/(a-Si) structures have been studied in detail owing to a relatively strong effect of the exchange interaction of ferromagnetic iron layers through the semiconductor silicon layer. This interaction is predominantly antiferromagnetic, and its mechanism is still insufficiently
clear [4–7] because of these systems’ complicated structural features that are related to mutual mixing of the metal and amorphous silicon and formation of iron silicides in the interlayer. Note also that Fe/(a-Si) structures exhibit a relatively weak (0.1–1.0%) negative MR [8, 9] that can be interpreted in the framework of spin-dependent electron scattering similarly to the giant MR effect, which was observed in layered metal Fe/Cr structures [10, 11]. However, the AMR and PHE were not studied in [8, 9].

In this study, we investigate a multilayer Co$_{0.45}$Fe$_{0.45}$Zr$_{0.1}$(a-Si) structure with a ferromagnetic-layer composition that is more complicated than that of the conventional Fe/(a-Si) system. It is demonstrated that the PHE occurs in systems in which the effective thickness of a ferromagnetic metal is no greater than 3.5 nm, so that the temperature dependence is represented as $R_\perp \propto \exp(-T/T_0)$ and the AMR effect is suppressed. We demonstrate the possibility of creating a magnetic memory cell based on such a film structure with the induced magnetic anisotropy.

### 2. SAMPLES AND THE MEASUREMENT PROCEDURE

Multilayer Co$_{0.45}$Fe$_{0.45}$Zr$_{0.1}$(a-Si) structures with 100 bilayers are produced on a vacuum setup via ion-beam sputtering of targets made of Co$_{0.45}$Fe$_{0.45}$Zr$_{0.1}$ and Si on glassceramic substrates at room temperature. The complicated composition of the metal is necessary for stabilization of the amorphous structure of the ferromagnetic material, which is stable at room temperature. For this purpose, we add 10% of an amorphizing agent (zirconium) to ferromagnetic (iron and cobalt) atoms. The films are sputtered on a rotating substrate for several hours. The thickness of the layers is determined from the preliminarily measured deposition rate: $d_m = 2.5–3.5$ nm for Co$_{0.45}$Fe$_{0.45}$Zr$_{0.1}$ and $d = 0.7–3.5$ nm for a-Si. Argon with a purity of 99.992% is the inert gas that is used. In the course of sputtering, argon is continuously renewed, so that the chamber is filled through a measuring valve and evacuated with a diffusion pump.

To control the discontinuity of metal layers, we also produce two-layer structures: 1.3- to 3.0-nm-thick Co$_{0.45}$Fe$_{0.45}$Zr$_{0.1}$ films that are deposited on amorphous silicon with a fixed thickness of about 10 nm.

After obtaining the layered structures, we employ photolithography to produce conventional samples shaped as double crosses for measurements of the electric conductance and the Hall effect. The width and length of the conducting channel are $W = 1.2$ mm and $L = 4.2$ mm, respectively. The length and width of the profile peaks (probes) on the side surfaces of sample are 0.8 and 0.4 mm, respectively, and the distance between them is 1.4 mm.

The Hall effect and MR are studied with a computerized setup and an HP3457A precision multimeter. The voltage between the Hall ($V_H$) and potential ($V_y$) probes and the current ($I$) flowing through a sample are measured at a constant drag voltage in the presence of positive and negative magnetic fields $H$. On the basis of the experimental results, we find the resistance of a sample between potential probes, $R_{xx} = V_x/I_x$, as well as the transverse resistance $R_{xy} = V_y/I_y$.

### 3. RESULTS AND DISCUSSION

Figure 1 demonstrates the dependence of the resistance of films on the magnetic field for (Co$_{0.45}$Fe$_{0.45}$Zr$_{0.1}$(a-Si)$_{100}$ structures with the amorphous silicon and metal thicknesses $d_s = 0.7–3.5$ nm and $d_m = 2.5–3.5$ nm, respectively, at room temperature. During the measurements, the field is applied in parallel to the plane of the structure and the flowing current. In this configuration, the resistance must increase with increasing $H$ in the presence of the AMR effect [1]. In the case under study, the explicit AMR effect is absent even in the structures with the maximum metal thickness (3.5 nm). Instead of this effect, we observe a negative MR at $d_s \leq 1.9$ nm and $d_m = 2.5–2.8$ nm, so that its value reaches a maximum at an a-Si thickness of about 1 nm. Note that this a-Si thickness corresponds to the maximum antiferromagnetic interaction in Fe/(a-Si) structures in the case of a high-resistance interlayer (i.e., at a relatively low content of iron silicides in a-Si) [6, 7].

The inset in Fig. 1 shows the resistance of two-layer Co$_{0.45}$Fe$_{0.45}$Zr$_{0.1}$(a-Si) structures at room temperature for the metal thickness ranging from 3.0 to 1.3 nm. The data presented indicate that the percolation transition from the metal to tunneling conduction, which is accompanied by an exponential increase in the resistance with decreasing $d_m$ takes place at $d_m \leq d_m \approx 2.2$ nm. This level is slightly higher than the critical metal thickness $d_m = 2$ nm, which corresponds to a similar transition in multilayer Co/SiO$_2$ or Co$_{0.8}$Fe$_{0.2}$/Al$_2$O$_3$ structures with an insignificant solubility of metal in a dielectric matrix [12, 13]. This phenomenon, in turn, indicates relatively weak effects of mutual diffusion of metal and silicon that result in the formation of silicides in the system under study. A possible reason for this occurrence is the presence of zirconium, which stabilizes the amorphous structure of the ferromagnetic layer. On the other hand, note that the recalculation of resistance $R_1$ of two-layer Co$_{0.45}$Fe$_{0.45}$Zr$_{0.1}$(a-Si) structures into resistance $R_{100}$ for 100 bilayers ($R_{100} = R_1/100$) yields values of $R_{100}$ which are almost two orders of magnitude greater than the results of the direct measurements. This outcome means that the neighboring layers in multilayer structures exhibit discontinuity$^1$ and contact each other via relatively low-resistance (silicon silicide) and/or tunneling (a-Si) contacts, which provide for a decrease in the percolation threshold and a transition to a 3D sys-