A comparative study of the effect of ions of different atomic masses on the magnetoresistive properties of Co$_{90}$Fe$_{10}$/Cu superlattices

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Abstract. The effect of inert gas ions with different atomic masses (Ar$^+$, Xe$^+$) on the magnetoresistance of Co$_{90}$Fe$_{10}$/Cu superlattices deposited on a silicon substrate has been investigated by comparison. The Ar$^+$ ion irradiation has been found to decrease the magnetoresistance more significantly than Xe$^+$ ion irradiation, which seems to be due to a larger average projective range for Ar$^+$ ($R_p = 5–6$ nm) than that for Xe$^+$ ($R_p = 3.3–4.3$ nm) and, accordingly, a greater depth of the atom mixing zone ($\approx 2–3 \times R_p$) when ions move from the top layers of the superlattice toward the substrate.

1. Introduction
The work is devoted to a comparative study of the effect of irradiation with inert gas ions of different atomic masses (Ar$^+$ and Xe$^+$) on the magnetoresistance of currently promising Co$_{90}$Fe$_{10}$/Cu superlattices. Multilayer metallic magnetic superlattices are high-demand materials for micro and nanoelectronics due to their giant magnetoresistance effect (GMR effect), which is a significant (by tens of percent) decrease in the electrical resistance when a constant magnetic field is applied. The study of the ion irradiation effect on the magnetoresistive properties of superlattices is an actual task, since there is almost no data on the behavior of modern magnetic superlattices under irradiation.

2. Experimental part
Multilayered Co$_{90}$Fe$_{10}$/Cu magnetic nanostructures were prepared using a ULVAC MPS-4000-C6 high-vacuum deposition machine (Japan). Pure metals were used as targets-cathodes: Cu – 99.99% (oxygen-free), Ta – 99.9%, as well as Co$_{90}$Fe$_{10}$ alloy (deviation from the composition no more than 0.5 at. %) and Ni$_{48}$Fe$_{12}$Cr$_{40}$ alloy (deviation from the composition for chromium no more than 0.5 at. %). The superlattices have the following composition: Si/Ta(10)/(Ni$_{80}$Fe$_{20}$)$_{60}$Cr$_{40}$ (5)/[Co$_{90}$Fe$_{10}$(1.4)/Cu(2.3)]$_{12}$/Ta(3), where Si is the substrate and the layer thickness in nanometers is given in parentheses. Samples 3×8 mm$^2$ in size were prepared from CoFe/Cu superlattice plates to measure their magnetoresistance and irradiate them.

The Co$_{90}$Fe$_{10}$/Cu superlattices were irradiated in an ILM-1 ion implanter equipped with a PULSAR-1M ion source based on a low-pressure glow discharge with a hollow cold cathode [1]. Inert
gas ions with different atomic masses, Ar$^+$ (39.95 a.m.u.) and Xe$^+$ (131.29 a.m.u.), were chosen for irradiation. We used the following ion beam parameters: ion energy $E = 10$ keV, ion current density $j = 100$ μA/cm$^2$, and fluences $F_1 = 1.25 \cdot 10^{15}$ cm$^{-2}$ and $F_2 = 1.0 \cdot 10^{16}$ cm$^{-2}$. A ribbon ion beam with a 2×10 cm$^2$ cross-section was cut from the ion beam of the circular cross-section using a collimator. The samples were moved under the ion beam at a speed of 2 cm/s to avoid their significant heating upon irradiation. The thin chromel–alumel thermocouple was used for estimating the temperature of the targets in the course of irradiation. It was welded to a witness sample made of thin metal foil with a close coefficient of blackness and the same size as the superlattice samples under study. The thermocouple was read by an Advantech Adam 4000 digital multichannel temperature measurement system. The temperature of the witness sample during irradiation in a continuous regime did not exceed 200°C at the maximum fluence of 10$^{16}$ cm$^{-2}$.

The magnetoresistance of the superlattices was measured before and after ion irradiation using an AVM-1 automated machine at the "Center for Technology of New Magnetic Materials," Physical-technological infrastructural complex, Institute of Metal Physics, UB RAS. The resistance of the superlattices in the magnetic field (to 19.5 kOe) was measured using a four-contact method using clamped contacts. The magnetic vector and the current in the plane of the film layers were mutually perpendicular to each other during the measurements. The measurements were carried out at room temperature. The magnetoresistance was found as the relative change in the electrical resistance of the material ($R$), when a magnetic field ($H$) was switched on: $\Delta R/R(H)=[(R(H)−R_s)/R_s] \cdot 100$ %, where $R_s$ is the electrical resistivity of a sample in the case of magnetic saturation, when the magnetic moments of the ferromagnetic layers are parallel; $R(H)$ is the electrical resistivity in magnetic field $H$; and $(\Delta R/R)_{\text{max}}$ is the maximum $\Delta R/R(H)$ value of the field dependence of magnetoresistance.

3. Details of exposure, measurements, and results

Figure 1 shows the magnetoresistance of the Co$_{30}$Fe$_{70}$/Cu superlattice before and after Ar$^+$ и Xe$^+$ ion irradiation. The Ar$^+$ ion irradiation decreases the magnetoresistance ($\Delta R/R$)$_{\text{max}}$ of the sample from 22.7 to 17.6 % at fluence $F_1 = 1.25 \cdot 10^{15}$ cm$^{-2}$ (figure 1a). At fluence $F_2 = 10^{16}$ cm$^{-2}$, the magnetoresistance of the superlattice is 10.9 %, which is 2.1 times lower than its initial value (figure 1a). The magnetic saturation field also decreases with increasing fluence, and the transition to magnetic saturation becomes more pronounced.

Similarly, the magnetoresistance of Co$_{30}$Fe$_{70}$/Cu superlattices also decreases during irradiation with Xe$^+$ ions (figure 1b). At an ion fluence of $1.25 \cdot 10^{15}$ cm$^{-2}$, the magnetoresistance decreases slightly, from 22.7 to 21.8%. The magnetoresistance continues to decrease up to 17.4 % when the fluence increases to $1 \cdot 10^{16}$ cm$^{-2}$. Consequently, the magnetoresistance at the same fluences decreases to lower values in the case of Ar$^+$ ion irradiation than those in the case of Xe$^+$ ion irradiation.

A decrease in the magnetoresistance of Fe/Cr superlattices under irradiation with 200 and 500 keV gas ions at fluences of $5 \cdot 10^{12} - 5 \cdot 10^{14}$ cm$^{-2}$ in works [2–5] is associated with the ion-beam mixing of Fe and Cr atoms at interlayer boundaries in the superlattice and a change in the interface state. As shown in [6], 10 keV Ar$^+$ ion irradiation of Fe/Cr and Co$_{30}$Fe$_{70}$/Cu superlattices decreases their magnetoresistance at higher fluences of $1.25 \cdot 10^{15} – 1 \cdot 10^{16}$ cm$^{-2}$ due to the same processes. However, this case is a partial mixing in depth from the film surface to the substrate, rather than throughout the entire film thickness because of the smaller projective range of Ar$^+$ ions with energy of 10 keV.

The zone of active mixing during ion irradiation is known to be $2 (2–3) \cdot R_p$, where $R_p$ is the average projective range of ions. We can estimate the depth of the mixing zone of atoms from the film surface to the substrate during irradiation with different ions. The SRIM calculation [7] indicates that the average projective range is 5–6 nm for Ar$^+$ ions and 3.3–4.3 nm for Xe$^+$ ions at an ion energy of 10 keV in the superlattices under study. Then, the depth of the atom mixing zone in the direction from the film surface to the substrate is 10.0–18.0 nm in the case of Ar$^+$ ion irradiation and 6.6–13.0 nm in the case of Xe$^+$ ions. The smaller depth of the zone of atomic mixing during Xe$^+$ irradiation seems to be responsible for the smaller ion effect on the magnetoresistance of the superlattices under study.
4. Conclusions
The study showed that the 10-keV Ar⁺ and Xe⁺ ion irradiation (ion current density is 100 μA/cm²) of the Co₉₀Fe₁₀/Cu superlattice on Si substrate at 1.25·10¹⁵ and 1·10¹⁶ cm⁻² fluences decreased its magnetoresistance with increasing fluence, regardless of the kind of ions. The Ar⁺ ion irradiation decreased the magnetoresistance more significantly, which was apparently due to a larger average projective range \(R_p\) for Ar⁺ than that for Xe⁺ and, accordingly, a greater depth of the atom mixing zone in the direction from the film surface to the substrate.

Acknowledgments
This work was supported by the Russian Scientific Foundation, project no. 19-79-20173. The Russian Foundation for Basic Research (project no. 20-42-660018_r-a) supported partially the preparation of Co₉₀Fe₁₀/Cu superlattices.

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