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Synthesis and Magnetic Properties of $(\mathrm{CoNiP}_{\mathrm{soft}}/\mathrm{CoP}_{\mathrm{hard}})_n$ Multilayers

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Abstract—Magnetic interactions in Co–Ni–P multilayers consisting of alternating magnetically soft and magnetically hard layers are investigated experimentally. Variations in the shape of magnetization hysteresis loops upon the conjugation of magnetically soft and hard layers are found, along with saturation field oscillations that depend on the number of layer pairs.

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INTRODUCTION

The interest in systems with the spin-valve effect is due to their potential for application in spintronic devices [1]. Of primary importance here is the problem of generating spin-polarized electrons. Film systems with the exchange bias effect are convenient objects for solving this problem. The interlayer interaction in such systems is responsible for the formation of a magnetic state. The aim of this work was to investigate the magnetization mechanisms in film multilayers with alternating magnetically soft and hard layers.

EXPERIMENTAL

$(\mathrm{CoNiP}_{\mathrm{soft}}/\mathrm{CoP}_{\mathrm{hard}})_n$ films were fabricated by chemical deposition. The phosphorous content in all layers was 8 at %. In the magnetically hard layer, CoP was in the hexagonal polycrystalline state; in the magnetically soft layer, CoNiP was in the amorphous state. In the latter case, the cobalt and nickel contents were 57.5 and 24.5 at %, respectively. The thickness of each layer was $t = 4$ nm. Such a composition ensured there would be no sharp structural change at the interface between the magnetically soft CoNiP and magnetically hard CoP layers. The contribution from the interface between layers can in this case be ignored, and only the interlayer interaction and the magnetic properties of layers in the multilayer structure are taken into account. The measurements were performed on a vibrating magnetometer at temperatures $T =$ 77–400 K in magnetic fields $H < 10$ kOe. We investigated the variations in the magnetic properties as the number of layer pairs ($n \leq 15$) changed in the multilayer structure.

RESULTS AND DISCUSSION

For a single magnetically soft CoNiP layer, the temperature behavior of the magnetization loops was typical of a magnetically soft ferromagnet (Fig. 1, part **1**). As the temperature rose from liquid nitrogen to room temperature, coercivity $H_C(T = 77.4\ \mathrm{K}) \cong 15$ Oe fell by more than one order of magnitude. No anisotropy in the film plane was observed. For a single magnetically hard CoP layer, the temperature behavior of magnetization was also ferromagnetic, but in this case we had $H_C(T = 77.4\ \mathrm{K}) \cong 950$ Oe. As the temperature rose from liquid nitrogen to room temperature, H_C changed by a factor of ~2 (Fig. 1, part **2**). The situation became noticeably different when the above layers formed a sandwich (Fig. 1, part **3**). It can be seen that the magnetization curve is a superposition of two loops. It is not, however, an algebraic sum of the initial curves, since the inner curve is broadened relative to the initial magnetically soft curve, while the outer curve is noticeably narrowed. Tracing the temperature behavior of the magnetization loops (Fig. 2), we can see that the most temperature-sensitive portion is the one originating from the magnetically hard layer. A further increase in the number of layer pairs (n) smoothed the step feature. At $n = 5$ in particular, the hysteresis is narrower than at $n = 1$, but as n rises to 10, the width of the hysteresis grows and then remains virtually invariable, saturating at $n = 15$. The dependence on the number of pairs in the structure changes the behavior of the magnetic parameters, coercivity in particular (Fig. 3).

As was established in [2], the coercivity of the CoP layers depends on the layer thickness in the range $t =$ 4–50 nm. It rises along with the layer thickness because as the latter grows, the grain size expands and the uniaxial anisotropy of the grain increases as a consequence. Let us note one more interesting point related to the behavior of the magnetization saturation field: Saturation field H_S of the films with odd numbers of layer pairs is higher than that of the films with even numbers of layer pairs, and a dependence of the damped oscillation type is observed. Our results show

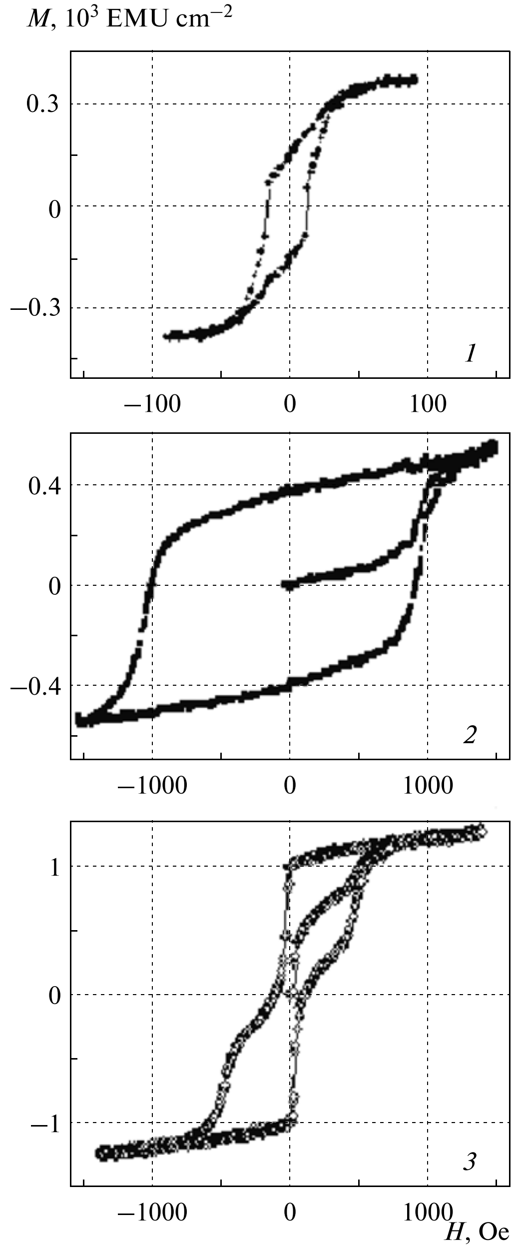

Fig. 1. Field dependences of magnetization for (*1*) CoNiP, (*2*) CoP, and (*3*) $CoNiP_{soft}/CoP_{hard}$ films. $T = 77$ K.

that the interlayer interaction is comparable to the intralayer exchange.

CONCLUSIONS

The dependences in Fig. 2 can be understood if we assume that a magnetically soft layer magnetizes a magnetically hard one due to interlayer exchange interaction, which reduces the saturation field. In the case of multilayer structures, the experimental data can be explained by assuming that in structures with odd numbers of layer pairs, there is a contribution that is not compensated for. Assuming that this contribution is related to the grain anisotropy, it must be compensated for completely, regardless of the number of layers. Another mechanism, related to the presence of either negative exchange interaction between magnetically hard layers via magnetically soft ones or to negative biquadratic exchange between magnetically soft and hard layers, is also possible.

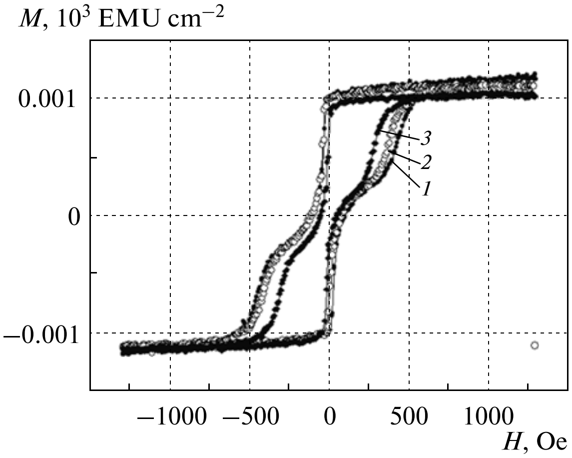

Fig. 2. Hysteresis loops of the CoNiP/Co film at temperatures of (*1*) 110, (*2*) 210, and (*3*) 300 K.

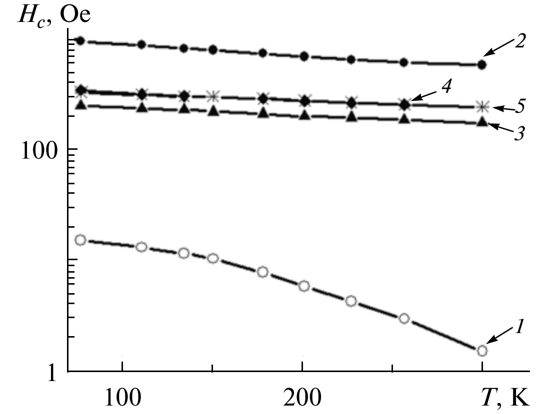

Fig. 3. Temperature dependences of coercivity for (*1*) a single soft layer, (*2*) a single hard layer; (*3*) $n = 5$, (*4*) $n = 10$, and (*5*) $n = 15$.

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