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Magnetic and resonance properties of exchange spring multilayers $[(CoP)_{soft}/NiP/(CoP)_{hard}]_n$

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Magnetic and resonance properties of exchange spring multilayers $[(\mathrm{CoP})_{soft}/\mathrm{NiP}/(\mathrm{CoP})_{hard}]_n$

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Abstract. The magnetic resonance properties of $[(\mathrm{CoP})_{soft}/\mathrm{NiP}/(\mathrm{CoP})_{hard}/\mathrm{NiP}]_n$ exchange-spring multilayer films with a thickness of a nonmagnetic layer 4 nm have been experimentally studied in comparison to data for 2 nm thickness. A noncollinear three-sublattice magnetic structure assumed to be realized similar to the case of 2 nm NiF-layer thickness. The increase in the number of blocks n in the multilayer structure leads to the appearance of the third absorption peak, however, its intensity tends to zero at n → 20.

1. Introduction

Exchange spring magnets are a new class of nanoscale materials which are suitable for solving a number of spintronics problems [1, 2], they are promising systems for applications in permanent magnets [3] and perpendicular magnetic data recording storage devices [4] as well. Spring magnet films consist of hard and soft layers that are coupled at the interfaces due to strong exchange coupling between relatively soft and hard layers [5, 6]. The soft magnetic layer provides a high magnetic saturation, whereas the magnetically hard material has a high coercive field. To achieve the necessary properties of these systems an intermediate magnetic layer might be added [7]. When the interlayer coupling is controllable, e.g. in case of the insertion of a nonmagnetic spacer, new features in magnetic behavior are expected [8]. E.E. Fullerton et al. [9] and J. Zhang et al. [10] studied the magnetization processes in multilayer magnetic springs to determine the change of interlayer coupling at multilayer structure formation.

We showed [11] that an increase in the number of blocks (*n*) for multilayer structure with alternate magnetically hard and soft layers $[(\mathrm{CoP})_{soft}/(\mathrm{CoP})_{hard}]_n$ enhances the effect of the magnetically soft layer on the magnetization of the film structure. The insertion of a nonmagnetic spacer causes extraordinary magnetization and coercivity oscillations. And this spacer affects the coupling between ferromagnetic layers. We observed the exchange-spring behavior and this effect proved to be more pronounced with increasing of the number of structural blocks.

Then we conducted the magnetic resonance study [12] of multilayer exchange springs $[(\mathrm{CoP})_{soft}/\mathrm{NiP}/(\mathrm{CoP})_{hard}]_n$ with intermediate layer NiP thickness 2 nm. The interlayer coupling was found to depend on the number of layers in the structure but the nature of long-range interactions in a multilayer film is still subject for discussion.

The purpose of this study was to continue research of changing the magnetic state in multilayer film structures consisting of alternate magnetically soft and hard layers separated by a nonmagnetic spacer when the number of blocks *n* increases in this structure. Herewith, the nonmagnetic layer thickness was increased to 4 nm.

2. Materials and methods

$[(CoP)_{soft}/NiP/(CoP)_{hard}]_n$ films were made using a chemical deposition method. This method has certain advantages which include simplicity of its application and a high deposition rate and makes it possible to obtain high-quality interfaces [13] since, in the course of the interfacial reaction, layers form under conditions close to equilibrium.

The phosphorous content in all the layers was 8 at.%. In the magnetically hard layer, CoP was in the hexagonal polycrystalline state. The magnetically soft CoNiP layer had an amorphous state with a nickel content of 30 at.% and a cobalt content of 70 at.%. The intermediate NiP layer was amorphous and nonmagnetic. Its thickness was 4 nm. Such composition of the layers allowed us to avoid sharp structural variations at the interface. We chose the layer thicknesses in order to:

- make the interlayer interaction energy relatively similar to the magnetic energy of the ferromagnetic layer;
- make the interlayer interaction effects more pronounced among other interactions.

We synthesized the $[(CoP)_{soft}/NiP/(CoP)_{hard}]_n$ multilayer structures with the number of blocks $n = 1$, 5, 10, 15 and 20. Both magnetic layers had thickness 5 nm and the nonmagnetic layer thickness was $t_{NiP} = 4$ nm.

The layer thicknesses were controlled by X-ray spectroscopy with a measurement accuracy of ±0.5 nm. The surface roughness was tested on a Veeco MultiMode NanoScope IIIa SPM platform with a resolution of up to 0.2 nm and amounted to ±1 nm in height in the maximum on a basis length of 20 nm.

Ferromagnetic resonance (FMR) is often used to probe the magnetodynamics of ferromagnetic materials in order to understand and improve the performance of spintronics applications [6]. FMR was chosen as a tool for studying multilayers films since this method is sensitive to changes in internal fields of various origin too. The electron magnetic resonance spectra were measured on a “Bruker ELEXSYS E580” EPR-spectrometer operating at frequency 9.4 GHz. The magnetic field was parallel to the film plane. Then the spectra obtained were processed by fitting the experimental integral absorption curve to the sum of Lorentzian lines.

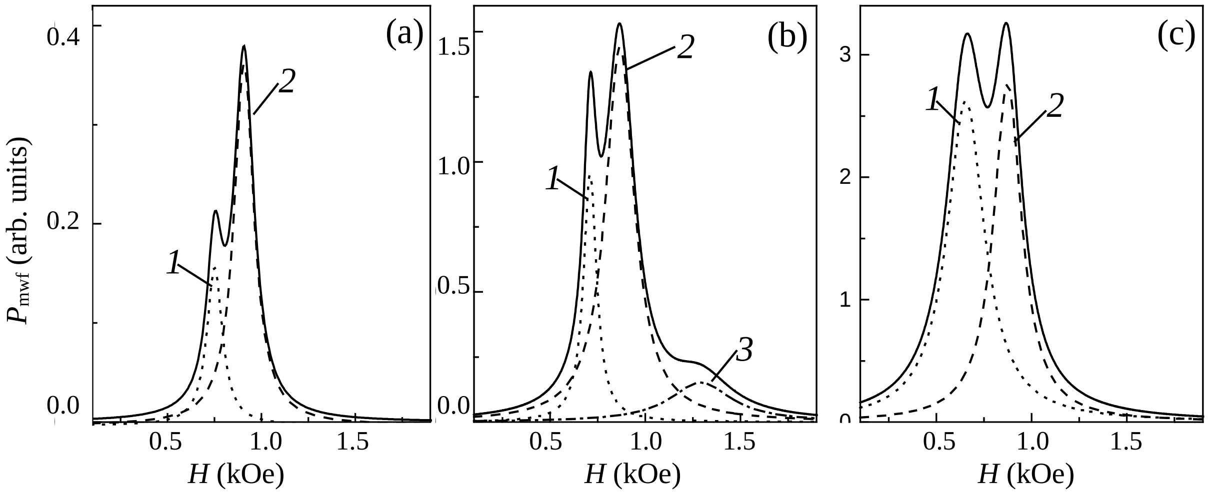

Figure 1. Microwave absorption spectra at temperature 120 K for films with *n* = (a) 1, (b) 5, (c) 20.

3. Results and discussion

According to magnetostatic measurements [11], the saturation field of our films satisfies the condition $H_s \leq 500$ Oe. All the films are in a saturated state at magnetic resonance conditions (see examples of spectra for *n* = 1, 5 and 20 in figure 1). The microwave absorption (P_{MWF}) spectra for a single CoP_{hard}

layer and for a bilayer film $(CoP)_{soft}/NiP$ were measured before [12] and the insertion of a nonmagnetic NiP layer led to the shift of resonance field towards the higher magnetic field.

The FMR-spectrum of a trilayer film with $n = 1$ consists of two microwave absorption lines (see figure 1a) which are found in the region between the resonance fields corresponding to the magnetically hard layer (CoP_{hard}) and the bilayer film (CoP_{soft}/NiP). When the number of blocks (n) is increased, a third peak (curve 3) of microwave absorption arises at higher magnetic fields than first and second lines (curves 1 and 2). With increasing in the number of blocks up to 15, the shape of the FMR-spectrum changes, as well as the resonance field of high-field peak (curve 3) markedly changes (figure 1). Such behavior is quite similar to our previous study where t_{NiF}=2 nm. Although, the 3rd peak disappears at $n = 20$ (see figure 1(c)), whereas, for t_{NiF} = 2 nm, high field peak was still observed at $n = 20$.

The temperature dependences of the resonance field (H_r) were obtained for all films (see figure 2). For films with $n = 5$, 10 and 15, the resonance fields of the low-field peaks (curves 1 and 2) increase with a rise in temperature (T), while the H_r of the high-field peak (curve 3) decreases under the same conditions. (The enumeration of the curves in figure 2 and figure 3 corresponds to the absorption peaks in figure 1.). These dependencies correlate with our data for t_{NiF} = 2 nm. It's worth noting, that the behavior of H_r of low-field lines for the film with the number of blocks $n = 20$ is similar to film with $n = 1$.

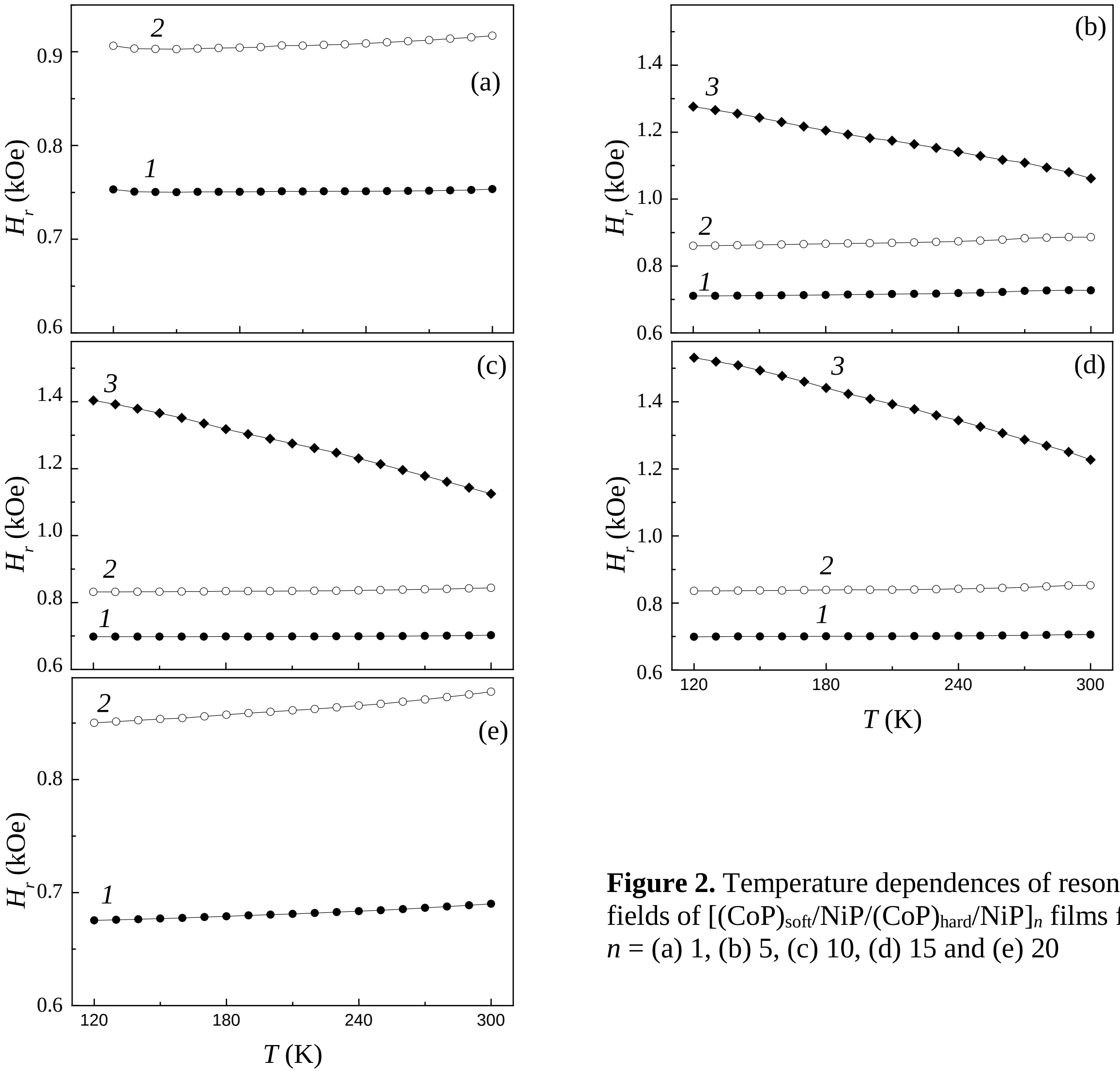

Figure 2. Temperature dependences of resonance fields of $[(CoP)_{soft}/NiP/(CoP)_{hard}/NiP]_n$ films for n = (a) 1, (b) 5, (c) 10, (d) 15 and (e) 20

The temperature dependences of the intensities of absorption lines (*J*) were determined as areas under the corresponding curves in figure 1 and shown for all films in figure3. The line intensities (for curves 1 and 2) are comparable in magnitude for films with $n = 1$ (figure 3a) as it was in [12], however, their temperature dependences are different from previous data for $n = 1$ but with $t_{NiF} = 2$ nm. It could be related to the affection of the thickness of the nonmagnetic layer on the interaction between the nearest neighboring layers. The intensity of curve 3 decreases with increasing of the number of blocks (n) and apparently tends to zero when $n \to 20$.

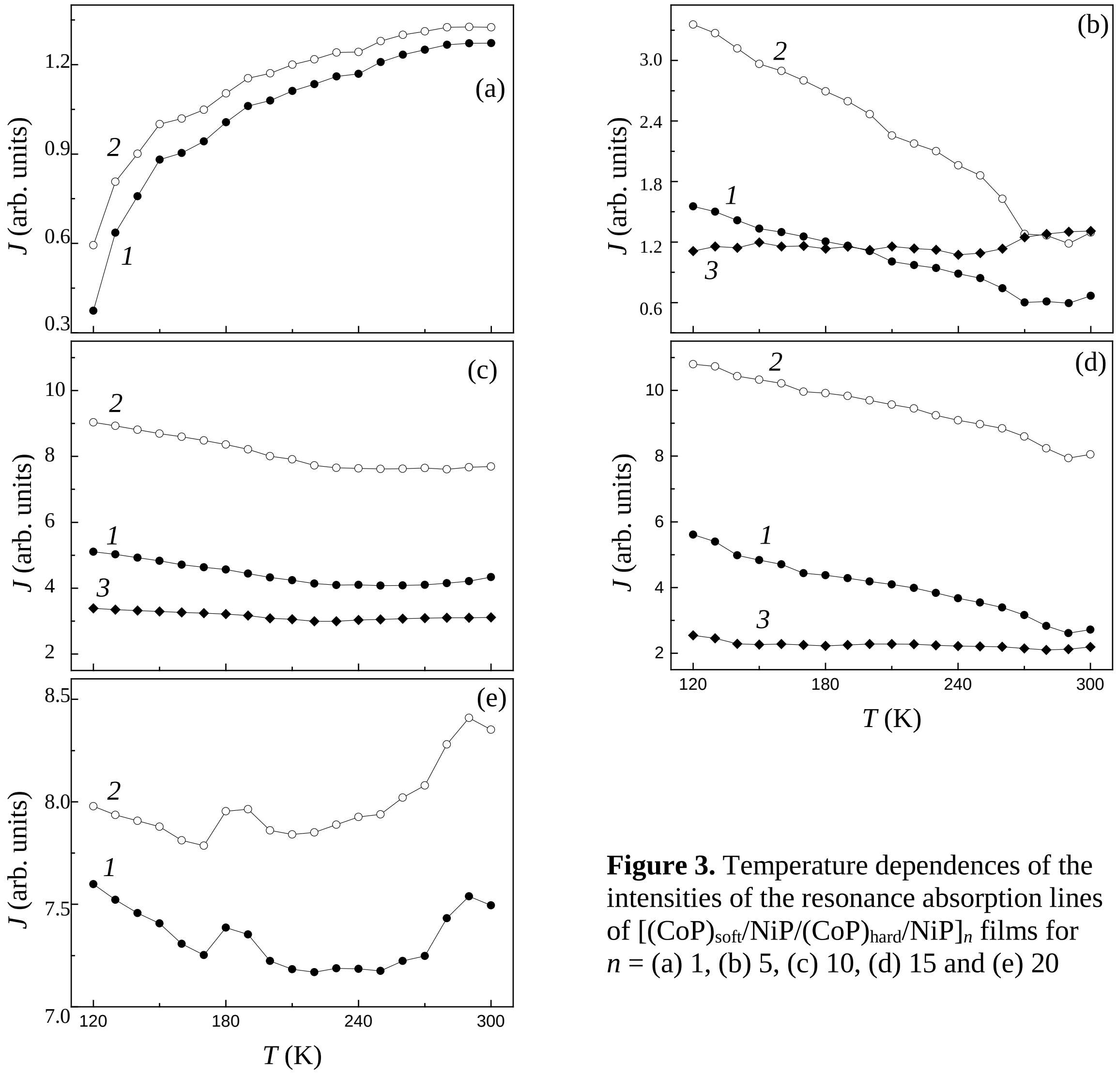

Figure 3. Temperature dependences of the intensities of the resonance absorption lines of $[(CoP)_{soft}/NiP/(CoP)_{hard}/NiP]_n$ films for n = (a) 1, (b) 5, (c) 10, (d) 15 and (e) 20

Since the appearance of the 3rd absorption peak doesn't fit in two-sublattice model, we assumed [12] with considering magnetostatic data [11] that magnetically hard layers subsystem is divided into two skewed sublattices. Accordingly to figure 2 and 3, it is clear that for all multilayer films the microwave absorption peak 2 which has the greatest intensity is located in the region of the magnetic field corresponding to the value of the resonance field for the film (CoP_{soft}/NiP) (see figure 2 in [12]). We may suggest this peak refers to resonance absorption in the subsystem formed by magnetically soft layers. Although, the temperature dependence of H_r for $n = 20$ (figure 2e) is close to that for $n = 1$ (figure 2a) their temperature dependences of the FMR-intensity are not similar (figures 3e and 3a). Also, the origin of an anomaly in the temperature dependence of the FMR-intensity in the region 170 - 200 K for $n = 20$ is not yet clear.

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