Temperature-induced variations of magnetization kinetics of FeNi in the FM/SC and FM/AFM heterostructures

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Abstract. Remagnetization kinetics of the bilayer ferromagnetic/superconductor (FeNi/Nb) and ferromagnetic/antiferromagnetic (FeNi/FeMn) ultra-thin films is investigated. Experimental results are obtained by direct observation of domain structure using the magneto-optic visualization technique in a wide temperature range. It is found that proximity of a second layer varies drastically the FeNi magnetic properties, such as domain and domain boundary structures, domain boundary mobility, coercivity. Moreover, the mechanism of magnetization is found to be temperature dependent. The effect of temperature becomes especially pronounced below 50 K.

1. Introduction
The hybrid multilayers, which consist of ultra-thin ferromagnetic layers alternated with either antiferromagnetic or superconducting ones, are considered as promising structures for spintronics. Intensive studies of magnetization reversal process of magnetic hybrid structures with adjacent ultra-thin soft/hard ferromagnetic layers or ferromagnetic/antiferromagnetic layers were performed during last decade. The spin-valve, resistive switching and giant magnetoresistance effects are found in such structures, and some of them have been used as write-reading elements [1]. Nowadays, a great attention is focused on the study of ferromagnetic/superconductor heterostructures (FM/SC), in which the magnetic layer is supposed to be used as an element controlling the superconductor properties [2-7]. Therefore the knowledge of static and dynamic properties of the ferromagnetic film, which is the key element of FM/SC heterostructures, is of importance.

This work is devoted to the direct experimental study of magnetization reversal kinetics of heterostructures consisted of ultra-thin permalloy layer (FeNi) with niobium one and ultra-thin permalloy layer with antiferromagnet FeMn layer. The experiments are performed in a wide temperature range, from 300 K down to 6 K. The in-plane magnetic field effect is investigated since such field saturates magnetization of films easier than the out-of-plane field; that makes this geometry more important for applications. The magnetization reversal processes of the FeNi-layer in the heterostructures are compared with those of single FeNi layer. This comparison helps to explain the variations of FeNi properties, namely, the remarkable increase of coercitivity, the reduction of magnetization speed, and the complication of domain structure, and gives the possibility to separate the influences of interface and superconductor (antiferromagnet) proximity.

2. Experimental
Experiments are performed by the magneto-optic visualization technique (MO), which enables to map
the induction vector component perpendicular to the observed sample surface. The method was successfully used for studies of magnetic flux penetration into bulk and thin layer superconductors as well as for learning the domain structure in thin magnetic films [8]. The magnetic domain boundaries are visualized as light or dark lines depending on the direction of magnetic stray fields at the boundaries. The values and directions of saturated magnetization \( M \) are defined by the brightness of edges of the samples. The coercitivity \( H_c \) is determined as the field at which the magnetization is zero. In the studied films it practically coincides with the field, at which the domain boundaries appear.

The samples were grown by the RF magnetron spattering on a Si substrates in the presence of an in-plane magnetic field. This growth method provides the uniaxial anisotropy in the Si/FeNi, Si/FeNi/Nb, Si/Nb/FeNi films, and the unidirectional anisotropy in Si/FeNi/FeMn films, and good homogeneity of magnetic properties of all films as was proven by the MO observations. The thickness of FeNi-layer was varied from 30 nm to 60 nm. The 30 nm thick Nb-layer had the normal/superconductor state transition at \( T_{Nb}^c \approx 9 \) K. The thickness of FeMn-layer about 10 nm was enough to provide the maximum unidirectional anisotropy of permalloy.

The magnetic field was created by Helmholz coils, which provide good homogeneity of the field in the samples volume.

3. Magnetization reversal of FeNi layer

The samples under study are in the saturated magnetization state at zero external magnetic field, with spontaneous magnetization \( M \) being in the films plane. The domain structure appears only under application of the field \( H > H_c \), where \( H_c < 0.1 \) Oe for Si/FeNi, \( H_c \approx 1.0 \) Oe for Si/Nb/FeNi, \( H_c \approx 2.0 \) Oe for Si/FeNi/Nb, \( H_c \approx 5.0 \) Oe for the field directed along or opposite to the unidirectional anisotropy in Si/FeNi/FeMn, respectively. Magnetization reversals of all these films occur by motion of the 180° domain boundaries (figure 1), which nucleate at the edges and move throughout the samples. The domain boundaries (DBs) look identical as thin “zig-zag” lines in the Si/FeNi and Si/FeNi/FeMn films (figures 1a-1b), despite their mobility differs hundreds times, being lower in hybrids [9]. DBs in Si/FeNi/Nb and Si/Nb/FeNi differ slightly from those in Si/FeNi: hardly seen crosstie walls appear at the sharp angles of growing domains and at defects. The domain boundaries in Si/FeNi/Nb and Si/Nb/FeNi look identical at 300 K; therefore only one image is shown in figure 1.

With temperature decrease, the domain pattern remains near the same in the single layer FeNi film, while it varies in the multilayer films (cf. figures 1, 2). Especially drastic modifications of the magnetization reversal process occur in the Si/FeNi/FeMn film: the lower temperature is, the more domain

![Figure 1. The fragments of domain structures in FeNi at magnetization reversal at T = 300 K: (a) Si/FeNi film at H = 2.2 Oe, the whole film size ~5mm*3mm; (b) Si/FeNi/FeMn film at H = 2.4 Oe, the whole film size ~5mm*3mm; (c) Si/FeNi/Nb film at H = 1 Oe, the film size ~0.55mm*5mm.](image)
nucleation centres appear; the microdomains start to nucleate throughout the film below 50 K (cf. figures 1b, 2b). M in the microdomains remains in the film plane, but is oriented perpendicular to the easy axis realized at room temperature (this modification means the turns of unidirected anisotropy into bi-axes one). Simple one-step magnetization process (the nucleation and motion of single domain wall) turns into two-step process: nucleation and expansion of multiple 90-degree domains followed by nucleation and motion of 90-degree domains, which provide the 180°-rotation of M. The domain nucleation field and the bias (shift of the middle point of hysteresis loops) increase tens times, figure 3.

![Figure 2](image2.png)

Figure 2. The same samples, as in figure 1, but at temperature T = 10 K, (a) Si/FeNi at H = 9.5 Oe, (b) Si/FeNi/FeMn at H = 220 Oe, (c) Si/FeNi/Nb at H = 11 Oe.

![Figure 3](image3.png)

Figure 3. Dependence of coercitivity of ferromagnetic permalloy layer upon the temperature in the Si/FeNi/Nb and Si/FeNi/FeMn heterostructures.

The pattern of domain boundaries in Si/FeNi/Nb and Si/Nb/FeNi at temperature decrease varies less than in Si/FeNi/FeMn. The magnetization occurs through the nucleation and motion of the same type of DBs, but with numerous distinct crosstie walls. Such modification of the structure of DBs is especially pronounced seen on FeNi/Nb heterostructures with upper Nb layer (figure 2c). Coercitivity goes up with temperature decrease remaining reasonably small, ~11 Oe in Si/FeNi/Nb and ~10 Oe Si/Nb/FeNi at 10 K (figure 3). Transition of Nb into superconducting state drastically varies the pattern of FeNi magnetization. The appeared in FeNi at magnetization reversal domain boundaries practically turn into waves with multiple “domains” of non-uniform magnetization rotation (cf. figures 2c, 4a) because of colossal broadening of the crosstie walls. These waves spread throughout the FeNi-layer in the direction of the in-plane field rotating the M to the field direction. At the same time, no perpendicular vortices induced at magnetization reversal by domains in FeNi, are observed in the Nb layer (figure 4b); only variations of the stray field near the sample edges evidence the magnetization. Comparing the patterns in figures 4a and 4b and suggesting that the magnetization kinetics of the FeNi-layer is the same both in Si/FeNi/Nb and Si/Nb/FeNi films, we can conclude that the domain wall nucleated at magnetization reversal at the edge of the FeNi-film turns into ripple wave of magnetization expelled into the FeNi interior by screening currents of the Nb layer. Note, that this wave, with the out-of-plane non-uniform rotation of magnetization in the main FeNi volume and with the in-plane rotation of magnetization in the very vicinity to the Nb layer, is excited by the in-plane
magnetic field because of the proximity of Nb to FeNi. One more consequence of the proximity is the asymmetry of magnetization process of FeNi at T < T_{c,Nb}. The FeNi magnetization in the field directed along or opposite to the direction of M at T > T_{c,Nb} begins at different fields (H_c = 6 Oe or 19 Oe, respectively).

Figure 4. Magnetization reversal of FeNi/Nb at T=7.5 K. (a) – Si/Nb/FeNi film, the nucleated domain boundary is turned into a wave of ripple in-plane and out-of-plane magnetization disturbance; (b) – Si/FeNi/Nb film, only the stray fields near the film edges reflect the magnetization variation of the FeNi.

4. Conclusion
The direct visualization of magnetization kinetics of the FeNi-layer in different heterostructures has shown that the proximity of a second layer influences the FeNi magnetic properties. The influence is more pronounced in case when the second layer is evaporated on top of the FeNi layer. This may be a consequence of the magnetostriction effects due to the stresses because of different compression of the layers on cooling.

Large impact of Nb on domain boundary structure in adjacent FeNi is found at magnetization reversal at T < T_{c,Nb}; the screening currents in Nb seems to expel domain boundaries into ferromagnetic interior and cause so large widening of crosstie walls, that remagnetization process goes through non uniform rotation of magnetization.

The drastic variation of magnetization kinetics of FeNi/FeMn heterostructure with temperature decrease is observed. The coercitivity grows by orders of magnitude, and the magnetization reversal process becomes very complicated. The correction of the growth method of FM/AFM films is required before application them in SC/FM/AFM hybrid films for stabilization of FM magnetization direction.

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