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Equilibrium Distribution of Magnetization and Processes of Magnetization Reversal in Magnetoelastic Nanostructures

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Abstract—Results are presented from an experimental study of the equilibrium distribution of magnetization and processes of magnetization reversal of magnetoelastic nanostructures in the form of strips with constant or variable width. It is shown that the symmetry of the stable magnetization states in the nanostrip can be broken by a static magnetic field applied perpendicular to the ferromagnet's easy axis. A further change in the states of magnetization allows their manipulation (e.g., moving the domain wall) using the homogeneous mechanical effects induced by applying an electric field to the piezoelectric substrate.

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A number of recent studies have shown the magnetization state of magnetic films and plates can be controlled with very low consumption of energy [1–3]. These results allow us to predict the possibility of creating spintronics nanodevices with record-breaking low energy consumption, i.e., at the level of tens or even units of attojoules per operation to switch the magnetization state [1–4], which are several orders of magnitude less than those in conventional electronic devices. A promising line of creating energy-efficient devices for storing and processing information is reflected in studies of processes in magnetic nanostructures with controlled magnetoelastic properties [1, 5–7]. Elastic stresses induced by a piezoelectric layer are in this case used to switch the state of the elements.

The possibility of domain-wall manipulating in magnetoelastic nanostrips using uniform mechanical stresses was recently demonstrated theoretically [8, 9]. The interest in studying the motion of domains and domain walls is due largely to the development of spintronics devices with nanometer-sized elements. Domain walls are considered key elements of information processing devices, including nonvolatile solid-state memory devices [4, 9–15]. This memory could provide considerably higher recording density than modern hard drives, which along with high read/write speeds allows it to be considered a possible universal memory.

The position or velocity of the domain wall in nanosized strips of a certain shape on piezoelectric substrates can be controlled if the symmetry of the magnetic states in one-dimensional ferromagnets is broken. This approach produces unusual configurations of domain walls and domain-wall velocities on the same order of magnitude [9] as when exposed to magnetic fields or spin-polarized currents, while the energy consumption required to move the domain wall is significantly reduced.

In this work, we performed an experimental study of the equilibrium magnetization distribution and the magnetization reversal processes of magnetoelastic nanostructures in the form of nanostrips with a constant or variable width (Fig. 1). Multilayer magnetostrictive $TbCo_2$/FeCo films with a thickness of ~20 nm were obtained by sputtering on PMN-PT piezoelectric substrates using the Leybold Z550 equipment [16]. The films were synthesized under a magnetic field to form the desired anisotropy and direction of easy magnetization axis in the plane of the multilayer film. Micro- and nanostructures of various shapes were then formed via lithography for our experimental study of the magnetization distribution, the processes of magnetization reversal, and the formation and movement of domain walls in films. Figures 2 and 3 show nanostrips with a parabolic profile.

In the studied nanostrips, the easy magnetization axis was directed along the long side of the strip. Using

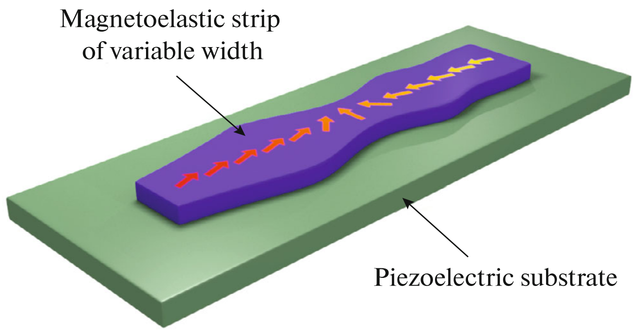

Fig. 1. Model of the domain structure in a magnetoelastic nanostrip with variable width.

mathematical modeling, the domain wall in a nanostrip with a parabolic profile in the equilibrium state was shown to be located at the center of a strip in [9]. When mechanical stress is applied (as a result of applying an electric field to the piezoelectric substrate), the domain wall is shifted to a new equilibrium position, which can be used in logical and storage devices of nanospintronics.

Figure 3 shows data on the magnetic structure of a parabolic-shaped nanostrip obtained by magnetic force microscopy (MFM). The domain structure of nanostrips was studied using a Smart-SPM atomic force microscope (AIST-NT). This microscope had a built-in magnet with software mechanical tuning of the magnetic field in the range of −2000 to +2000 Oe. A technique similar to the one described in [17] was used for registration of the magnetic state: several hundred MFM scans covering the entire cycle of the magnetization reversal of the sample were taken at a small step of changing the magnetic field (1–10 Oe). A video that allowed us to observe the different stages of change in the domain structure of the nanostrip in order was created from the resulting images. Figure 3 presents several MFM scans illustrating the most important changes in the magnetization of a magnetoelastic nanostrip.

PPP-LM-MFMR probes (Nanosensors) with a reduced magnetic moment were used in our MFM measurements. All experiments were performed in air at room temperature. To stabilize the operation of the device while taking a series of images, an operation to correct the amplitude and resonance frequency of the probe oscillations, and to compensate for sample drift, was automatically performed after each scan. The measurements were made using both separate nanostrips to examine their domain structure in detail and arrays of similar nanostrips (Fig. 2b) to observe the variation of magnetization reversal fields.

When magnetic field H was applied along the easy magnetization axis, the nanostrip was usually magnetized to saturation and in a monodomain state. When magnetic field H greatly exceeding the coercive force of the film (Fig. 3, $H = \pm 680$ Oe) was applied perpendicular to the easy magnetization axis, the vector of magnetization in the nanostructure was oriented along the applied magnetic field. Depending on the history of the magnetization/demagnetization of the nanostrip, two variants are possible for the formation of an equilibrium magnetic structure in lower magnetic fields: with asymmetric (Fig. 3, $H = 140$ Oe) or symmetric (Fig. 3, $H = 40$ Oe) direction of the magnetization vectors at the nanostrip edges. Note that the second variant is close to the model of the domain structure in a magnetoelastic nanostrip with variable width (Fig. 1) proposed in [9].

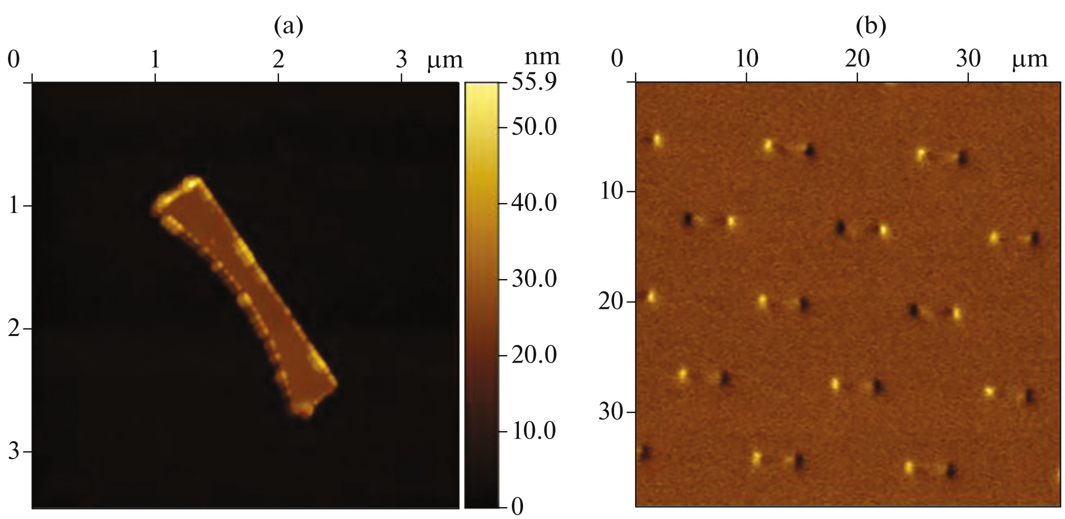

Fig. 2. (a) Topography of a magnetoelastic nanostrip with a parabolic profile (atomic force microscopy) and (b) an array of such nanostrips on a piezosubstrate (magnetic force microscopy).

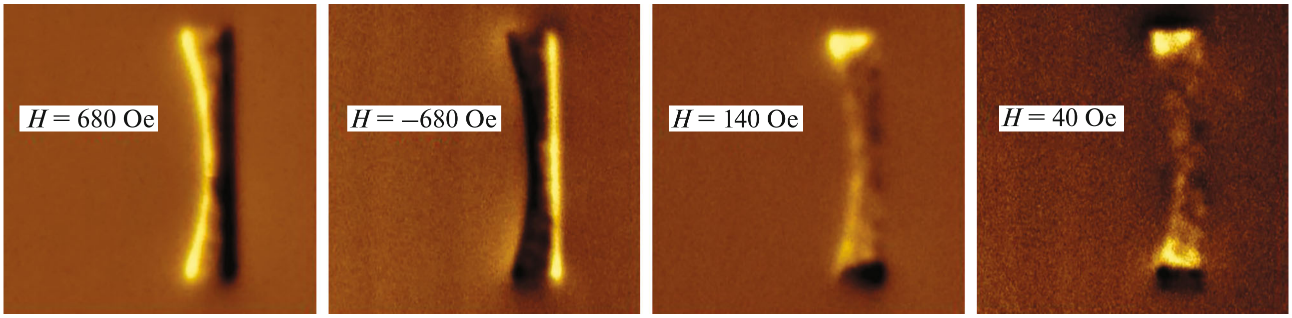

Fig. 3. Magnetic nanostrip with a parabolic profile in the presence of an external magnetic field directed in the film plane perpendicular to the long side of the structure (magnetic force microscopy; the magnetic field strength is indicated on the scans).

CONCLUSIONS

Quasi-static processes of the magnetization reversal of magnetoelastic parabolic nanostrips were studied experimentally. It was shown that the symmetry of stable magnetization states in a nanostrip can be broken using a static magnetic field applied perpendicular to the easy axis of the ferromagnet. It is then possible to split a parabolic nanostrip into two domains. The domain wall in the equilibrium state is in this case located the narrow part of the nanostrip's center. A further change in the magnetization states allows their manipulation (e.g., moving a domain wall) using the homogeneous mechanical effects induced by applying an electric field to a piezoelectric substrate.

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