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Studies of morphology and magnetic properties of island magnetic metamaterials

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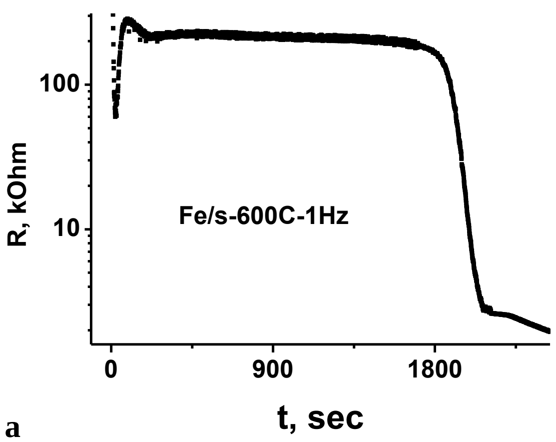
At present, magnetic nanocontacts and tunnel structures with spin-polarized current flowing through them are among the interesting objects of research in spintronics [1]. Spin injection by a current through a nanocontact or a tunnel junction can lead to a significant nonequilibrium spin accumulation in the region immediately near the contact. In particular, the inverse population of the spin subbands of a ferromagnet can occur due to the injection of hot electrons which are non-equilibrium in the spin. In this case, radiative spin-flip transitions of conduction electrons will occur, which can be stimulated indirectly through *s*-*d*-exchange interaction with an electromagnetic wave. The frequency of radiation is determined by the energy of the effective exchange splitting of the spin subbands and lies in the terahertz range. For the manufacture of such contacts, technically sophisticated lithographic methods are mainly used [2]. We have proposed a method for making a multitude of contacts by growing island films.

The combination of in situ electrical measurements and ex situ atomic force research allowed us to develop a technology for growing by pulsed laser deposition on a dielectric substrate (sapphire, MgO) unpercolated island films of ferromagnetic metals (Fe, Ni, Co) to create magnetic metamaterials based on them. In the metmaterials metallic nanocrystals (10-200 nm in size) are separated by a thin layer of a dielectric, a normal metal, or an antiferromagnet.

The influence of growth temperature and growth rate on the morphology and size of islands was studied. It was found that in regimes with low supersaturation: at high temperatures of 400-600 °C and low repetition rates of laser pulses of 1-10 Hz, a stable, reproducible dependence of the morphology of island films on growth conditions is observed, which makes it possible to obtain island films and metamaterials with desired properties.



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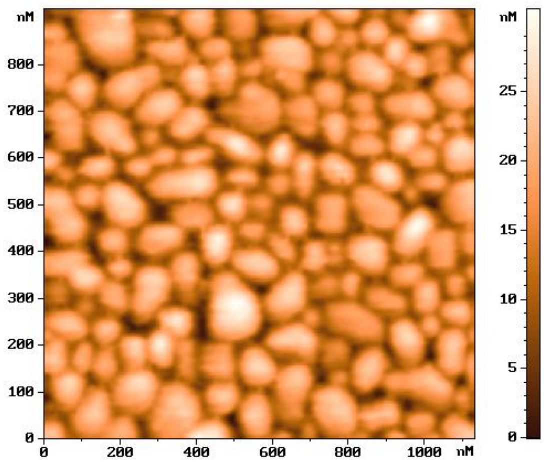

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Figure 1. (a) Typical dependence of island film resistance on thickness during growth and (b) an AFM image of unpercolated islands.

Atomic force and magnetic force microscopy made it possible to investigate the morphology and magnetic structure of ferromagnetic and ferromagnet/antiferromagnet structures, in which the use of annealing in a magnetic field above the Neel temperature forms a unidirectional exchange anisotropy. Magnetic force experiments accompanied by micromagnetic calculations and magnetoresistive measurements made it possible to determine the spatial distribution of magnetization and interpret the magnetic states of metamaterials from ferromagnetic and antiferromagnetic metals. Real AFM images were used for calculating magnetization distribution of islands by means of OOMMF software [3]. The simulated MFM contrast obtained from that micromagnetic calculations was compared with experimental MFM images.

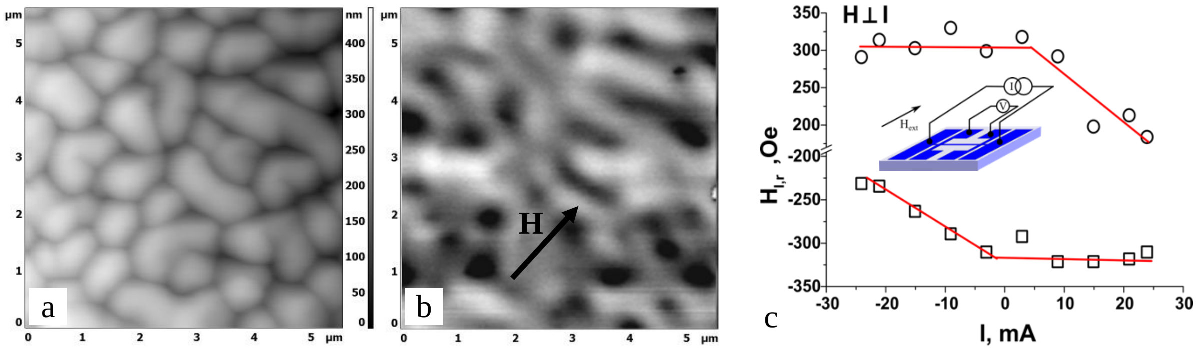

Figure 2. (a) AFM and (b) MFM images of Fe islands covered with FeMn film in presence of external magnetic field H = 672 Oe (shown by an arrow). (c) The dependence of the position change of the left, H_l and right, H_r peaks on the magnetoresistance curve of the Ni/FeMn metamaterial. In the inset in (c) the measurement setup is shown.

In the Figure 2a and 2b the surface morphology and MFM contrast of Fe islands covered with FeMn film in presence of external magnetic field are shown. The lateral dimensions of the islands were about 1 μm, and in height they were about 250 nm. MFM measurements showed that at such sizes the islands behave like separate magnets. At the same time, for small island sizes (100 nm), the characteristic features in the MFM contrast are markedly larger than the island size. MFM measurements in an external magnetic field allow us to state that small islands are magnetically coupled.

In the metamaterial films in the form of Ni islands, covered with a continuous antiferromagnetic FeMn film, strong current effects in anisotropic magnetoresistance were detected. In bridges made of such films and annealed in a magnetic field acting in the sample plane perpendicular to the axis of the bridge, the position of the maxima of the anisotropic magnetoresistance curve depends on the magnitude of the flowing current. This dependence can be explained by the influence of the magnetic field of the transmitted current on the magnetic structure of the ferromagnetic nickel islands of the metamaterial. In the Figure 2c the experimental dependences of the positions of the right H_r and left H_l peaks in the magnetoresistance curve in the Ni/FeMn metamaterial are shown. At low measurement currents, the hysteresis curve for the film and, accordingly, the magnetoresistance curve exhibits an exchange bias [4] in a magnetic field perpendicular to the current. When a sufficiently large current flows in the forward direction, it creates a positive magnetic field that is aligned with the external field at its positive values, and thereby overcome a domain wall pinning and shifts the right peak on the magnetoresistance curve H_r,. When it flows in the opposite direction the magnetic field of the current does not allow it to overcome a domain wall pinning and affect the position of the right peak H_r. The same reasoning is valid for the left peak H_l. However, such reasoning cannot give a full explanation of the observed effect. Further research is required.

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