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Anisotropic Magnetoresistance of Ni Nanorod Arrays in Porous SiO_2/Si Templates Manufactured by Swift Heavy Ion-Induced Modification

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In this work anisotropic magnetoresistance in nanogranular Ni films and Ni nanorods on Si(100) wafer substrates was studied in wide ranges of temperature and magnetic field. To produce Ni films and nanorods we used electrochemical deposition of Ni clusters either directly on the Si substrate or into pores in SiO_2 layer on the Si substrate. To produce mesopores in SiO_2 layer, SiO_2/Si template was irradiated by a scanned beam of swift heavy 350 MeV $^{197}Au^{26+}$ ions with a fluence of 5×10^8 cm^{-2} and then chemically etched in diluted hydrofluoric acid. Pores, randomly distributed in the template have diameters of 100–250 nm and heights about 400–500 nm. Comparison of temperature dependences of resistance and magnetoresistance in Ni films and n-Si/SiO_2/Ni structures with Ni nanorods showed that they are strongly dependent on orientation of magnetic field and current vectors relative to each other and the plane of Si substrate. Moreover, magnetoresistance values in n-Si/SiO_2/Ni nanostructures can be controlled not only by electric field applied along Si substrate but also by additionally applied transversal bias voltage.

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1. Introduction

Presently, a special interest is arisen in the development of nanostructures exploiting the enhanced magnetoresistive effects [1]. Many of the approaches to the fabrication of such structures are based on porous template-assisted synthesis, in the process of which nanopores in dielectric template (SiO_2, Al_2O_3, and the like) are filled with different nanostructured substances [2]. Very often such fabrication is based on the ion track etch method (ITEM), where selective etching of the latent ion tracks leads to the formation of pores with a large aspect (length-to-diameter) ratio. Moreover, deposition of nanorods onto semiconductor substrates and application of an additional back-side electrode enables the introduction of such nanostructures to MOSFET-like electronic elements called the TEMPOS structures [3, 4]. Of particular interest is the use of the ITEM technology for the fabrication of nanodevices by the electrodeposition procedure leading to the formation of high-quality deposits of the desired material within the pores [5].

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In this paper we compare magnetotransport properties of the Ni nanogranular films deposited on the n-Si substrate and the bundles of Ni nanorods embedded into the n-Si/SiO_2 porous template.

2. Experimental procedures

In the present work we study magnetotransport properties of n-Si/SiO_2/Ni nanostructures as a system of the nanorods-in-pores (NRIPs) randomly distributed within the SiO_2 layer. NRIPs were manufactured by electrodeposition of Ni clusters into the pores in a SiO_2 layer on the n-Si(100) substrate of 4.5 Ωcm resistivity as a template. The procedure and regimes of a mesoporous SiO_2 layer fabrication by the ITEM technology were described in detail earlier [6]. These nanopores having the diameters 100–250 nm and heights about 400–500 nm were filled with Ni to form NRIPs contacting with Si substrate.

To separate the influence of Ni nanorods, Si substrate and Si/SiO_2 interface on the magnetoresistance of n-Si/SiO_2/Ni heterostructure, we have also studied the magneto-transport properties in Ni films electrochemically deposited on n-Si substrates at the same regimes as for the n-Si/SiO_2/Ni nanostructures. The thickness of the films with the granules (approximately 10–70 nm) was close to the height of Ni NRIPs in the n-Si/SiO_2/Ni nanostructures (×500 nm). The procedures of Ni electrodeposition into the pores together with their SEM images and XRD patterns were presented in our previous papers [6–8].

The I–V characteristics and temperature dependences of equilibrium DC resistances $R(U \to 0) = R_0$ of the Ni films and n-Si/SiO$_2$/Ni nanostructures were measured at temperatures 2–310 K and in magnetic fields B up to 8 T. For this goal we used a closed-cycle cryogen-free cryostat system CFMS (Cryogenic Ltd., London). Lakeshore Temperature Controller (Model 331) and PC based control system allowed to change temperature with a rate of 0.1–1 K/min in cooling/heating regimes and to stabilize temperature with the accuracy 0.005 K. The relative error of conductance measurements was less than 0.1%.

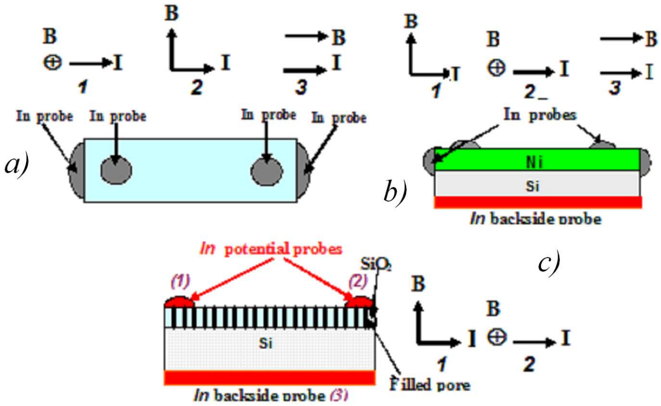

Fig. 1. Schematic pictures of Ni films on Si substrate (top (a) and lateral (b) views) and lateral view of n-Si/SiO$_2$/Ni heterostructure (c) with indium probes and mutual alignments of magnetic induction $\boldsymbol{B}$ vector, current vector $\boldsymbol{I}$ and Si substrate plane at MR measurements.

The arrangement of electric probes, produced by ultrasound welding of indium, and orientations of the vectors of induction $\boldsymbol{B}$ and current $\boldsymbol{I}$ with respect to the substrate plane and Ni NRIPs are shown in Fig. 1. As is seen, the vector $\boldsymbol{B}$ both for Ni films and n-Si/SiO$_2$/Ni structures was directed either normally to (I–B configuration 1) or along (I–B configuration 2) the plane of Si substrate. The magnetoresistance (MR) of the samples studied was calculated by the well-known relation MR $= \Delta R/R(0) = [R(B) - R(0)]/R(0)$, where $R(B)$ and $R(0)$ are the resistances with and without the magnetic field, respectively.

3. Results and discussion

All the measurements of $R_0(T)$ and MR(T) were fulfilled in two regimes when vector $\boldsymbol{I}$ of current was parallel to Si substrate but additional transversal bias voltage between top and backside probes was either zero ($U_{\mathrm{tr}} = 0$) or non-zero (-2 V $< U_{\mathrm{tr}} < +2$ V). As it was shown in our previous paper [7], for the first regime with $U_{\mathrm{tr}} = 0$ the samples of Ni films displayed a typical metallic behavior of $R_0(T)$ with a power-like increase of the resistance with temperature in the temperature range 2–310 K due to the scattering of electrons on phonons (at high temperatures) and Ni spins (for intermediate temperatures).

To compare MR(T) behavior for the Ni films and n-Si/SiO$_2$/Ni nanostructure, we need to take into account the following circumstance. When measuring resistance of the n-Si/SiO$_2$/Ni nanostructure in B–I configuration 1, current flows normally to Si substrate plane through Ni nanorods bundle under top probes. In this case, as was shown in [8, 9], the n-Si/SiO$_2$/Ni nanostructure behaves in an electrical sense as two oppositely connected Schottky barriers. Thus to compare MR effects in the Ni films and n-Si/SiO$_2$/Ni nanostructure, we measured MR in the Ni film in such a manner that vector I was also normal to the Si substrate (in the Schottky barrier regime).

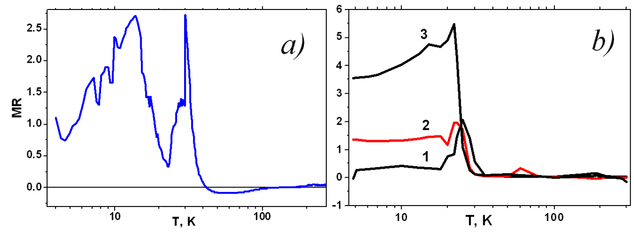

Fig. 2. Temperature dependence of MR(8 T) in the Ni film (a) and n-Si/SiO$_2$/Ni nanostructure (b) at $U_{\mathrm{tr}} = 0$. For Ni film (a) $I = 100$ μA. For n-Si/SiO$_2$/Ni nanostructure (b) $I = 1000$ nA (1), 100 nA (2) and 10 nA (3).

As follows from Fig. 2a, application of the magnetic field B and current I normally to the Ni film plane have a strong effect on resistance dependence on temperature. It exhibits a clearly seen competition between the positive (PMR) and negative (NMR) contributions to magnetoresistance. In accordance with [7], where we studied the MR(B) curves at different temperatures in detail, at $T > 40$ K PMR can be attributed to Lorentz-like MR (LMR) in Si substrate (most clearly it is manifested at $T > 100$ K). The behaviour of the negative-contribution to MR with magnetic field in the temperature range $40 < T < 100$ K, studied in [7] in more detail, allowed to attribute it to the anisotropic magnetoresistive effect (AMR) due to scattering of the carriers on magnetic spins of Ni atoms which are ordered when the temperature decreases [10].

As it is seen from Fig. 2b, the temperature dependence of MR(8 T) for the n-Si/SiO$_2$/Ni nanostructure looks very similar to behaviour of Ni films in Fig. 2a. This similarity is seen both at temperatures $T > 40$ K (see the above described) and also for $T < 30$ K where we observed a huge PMR effect which is controlled by measuring current. As it was shown in [8, 9], the PMR effect in the temperature range 23–25 K can be attributed to the impurity avalanche at a Ni/Si Schottky barrier. The nature of lower temperature PMR effect at $T < 10$ K in the Ni film and n-Si/SiO$_2$/Ni nanostructure (see curve 3 in Fig. 2b) is unknown now.

The experiments have shown that the application of the additional transversal bias voltage U_{tr} between top and backside probes (Fig. 1c) significantly modifies the temperature dependence of the relative magnetoresis-

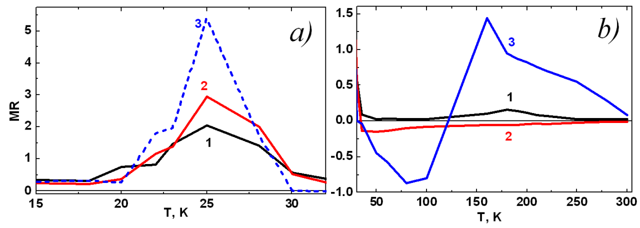

Fig. 3. Temperature dependences for low-temperature (a) and high-temperature (b) MR(8 T) measured in B–I configuration 1 for I = 100 nA and different values of U_{tr}: 0 V (1), +2 V (2), −2 V (3).

tance MR both at low and high temperatures. As can be seen from Fig. 3a, the MR value increases significantly when U_{tr} is applied at temperatures of 20–30 K (in the region of impurity avalanche), so that the maximum of MR(T) becomes more pronounced. The greatest growth of MR at $B = 8$ T and $I = 100$ nA was observed at $U_{\mathrm{tr}} = -2$ V (curve 3 in Fig. 3a).

At temperatures $T > 40-50$ K, where positive LMR and negative AMR mechanisms compete, MR value is also dependent on the magnitude and sign of the bias voltage U_{tr}, although to a lesser extent. In particular, if $U_{\mathrm{tr}} = +2$ V (curve 2 in Fig. 3b) the MR effect becomes negative practically at all temperatures above 35 K. If $U_{\mathrm{tr}} = -2$ V (curve 3 in Fig. 3b), the magnitude of MR changes sign twice with increasing temperature: at T = 35 K — from the positive (due to an impurity avalanche) to negative (due to AMR) and at ×120 K — on the contrary, from AMR to LMR. In the region of the AMR effect in Ni NRIPs maximal values of negative MR reaches −86.3% at 80.0 K, while the maximum "high-temperature" LMR effect reaches 143.6% at 161.4 K.

4. Conclusion

The comparison of temperature dependences of resistance and magnetoresistance (MR) in the Ni films and n-Si/SiO$_2$/Ni structures with Ni nanorods showed that they are strongly dependent on the orientation of magnetic field and current vectors relative to each other and the plane of Si substrate. At temperatures below 30 K PMR due to the impurity avalanche on the Schottky barrier Ni/Si dominates. For $T > 40$ K two effects compete: negative AMR and positive Lorentz-like MR effect. As shown, both of them can be controlled not only by the electric field applied along the Si substrate but also by additionally applied transversal bias voltage.

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