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# Magnetotransport in nanostructured Ni films electrodeposited on Si substrate

***Abstract.*** *The study of electrical resistivity $\rho$ and magnetoresistance MR in nanogranular Ni films was performed over the temperature range 2 - 300 K and at the magnetic field induction $B$ up to 8 T. The Ni layers having a thickness of about 500 nm were prepared by electrodeposition on n-Si wafers. According to an X-ray diffraction study, a strongly textured face-centered cubic structure was formed in the as-deposited films with an average grain sizes of about 10 - 70 nm. Experiments have demonstrated that the magnetic field and temperature dependences of the MR effect in Ni films shown two main peculiarities: (1) dependencies on the mutual orientations of vectors $B$, current and the film plane; (2) two contributions to the MR - negative anisotropic magnetoresistance and positive Lorentz-like MR.*

***Streszczenie.*** *W pracy przedstawiono badania rezystywności $\rho$ i magnetorezystancji MR w cienkich nanoziarnistych warstwach Ni, które wykonano w temperaturach z przedziału 2 - 300 K oraz indukcji pola magnetycznego $B$ większej od 8 T. Warstwy Ni posiadały grubość około 500 nm i zostały wykonane za pomocą galwanizacji na wafle krzemu n-Si. Według dyfrakcji promieniowania rentgenowskiego, w nowo wytworzonych cienkich warstwach uformowała się regularna struktura powierzchniowo centrowana o średniej wielkości ziaren 10 - 70 nm. Doświadczenia wykazały, że w cienkich warstwach Ni w zależności od MR i temperatury występują dwie główne cechy szczególne: (1) zależność od wzajemnej orientacji wektorów: indukcji pola magnetycznego $B$, kierunku prądu i płaszczyzny cienkiej warstwy, (2) dwie składowe MR - ujemna anizotropowa i dodatnia typu Lorenza. (**Magnetoprzewodzenie w nanostrukturalnych cienkich warstwach Ni osadzanych galwanicznie na podłożu Si**).*

**Keywords:** granular materials, nanostructures, magnetoresistance.
**Słowa kluczowe:** ziarniste materiały, nanostruktury, magnetorezystancja.

## Introduction

In spite of the discovery of Giant Magnetoresistive (GMR) effect in nanostructured ferromagnetic/non-magnetic metallic (FM/NM) multilayers [1, 2], the Anisotropic Magnetoresistive (AMR) effect in bulk FM metals and alloys [3-5] is still widely used for various applications. In particular, AMR-based materials are used in different devices such as magnetoresistive sensors, linear and angular position detectors and magnetic field detectors [6-9].

AMR-based materials composed of the FM elements (Fe, Co, Ni) or their alloys are typically used in the form of thin films (layers) prepared by evaporation, sputtering or electrodeposition (ED) techniques [10]. There are several papers on the MR characteristics of FM metals and their homogeneous alloys manufactured by ED methods (see, e.g., Refs. [11-17]). But in spite of numerous papers with the detailed investigations on ED magnetic FM/NM multilayered nanostructures with GMR effect (see, for example, references in [18]), no systematic studies of possible contributions to MR effect in the wide range of temperatures and magnetic fields have been published on electrodeposited Ni films. Among possible contributions we can expect such as Ordinary Magnetiresistive (OMR) effect due to Lorenz mechanism, Tunneling Magnetiresistive (TMR) effect and the above-mentioned AMR effect. Note also that the MR of homogeneous nanogranular FM metallic films is important due to a strong correlation between the GMR magnitude of a FM/NM multilayer and the AMR magnitude of the FM layered materials.

In this work we study influence of temperature and magnetic field on possible contributions into MR transport of the Ni nanogranular films deposited on the n-Si substrate.

## Experimental

In the present work we used underpotential electrodeposition of Ni nanoparticles on the n-Si(100) substrates with 4.5 $\Omega$·cm resistivity. The regimes and electrochemical properties of the samples studied were similar to described in [19]. A thickness of the films was close to 500 nm.

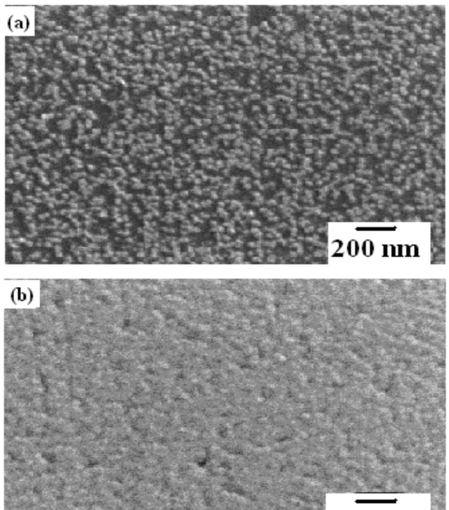


Fig.1. SEM pictures for Ni films after electrochemical deposition during 30 (*a*) and 120 sec (*b*) at the applied potential *E* = -1.000 V

Granular structure of Ni films and their thickness were determined using scanning electron microscope (SEM) LEO-1455VP. SEM pictures for Ni films at the earliest and final stages of ED procedure confirmed their nanogranular structure with the granules dimensions of about 10 – 20 nm at the initial stages of deposition (Fig. 1a). When increasing the deposition times, the films displayed a dense homogeneous layers with 30 – 70 nm grains (Fig. 1b). As was found from X-Ray diffraction (XRD) analysis, the film grains have the face-centered cubic structure with the lattice parameter equal to $a$ = 0.352 nm.

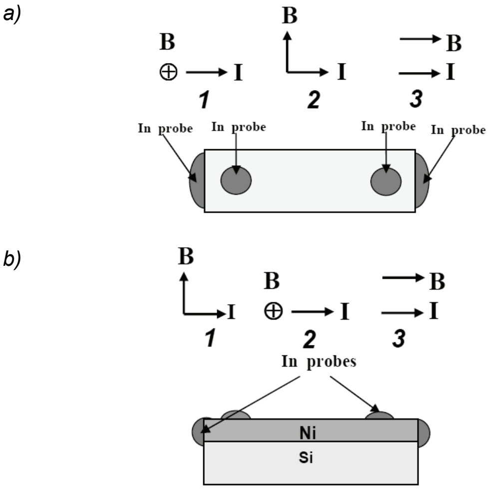


Fig. 2. Schematic images of Indium probes and mutual alignements of magnetic induction B vectors, current I and Si substrate plane at MR measurements in Ni films: top (*a*) and lateral (*b*) views

Temperature dependences of the DC resistivity and MR of the studied Ni/Si structures were measured on the samples of 2 – 3 mm width and 10 mm length with indium ohmic contacts prepared by ultrasonic soldering (Fig. 2). The films thicknesses were measured on the samples chips by means of SEM with accuracy within 3 − 4 %. On the whole the relative error of resistivity measurements was not more than 5 %.

The samples were mounted in a special holder and put in a chamber of the Cryogen-free Close-Cycle Refrigerator System (CCCRS) produced by Cryogenic Ltd. Company (London) that enabled one to make electrical measurements at temperatures ranging 2 – 310 K and at magnetic fields with the induction $B$ up to 8 T. The longitudinal I-V characteristics, equilibrium DC resistivity $\rho(T)$ at bias voltage $V \to 0$) and magneto-resistivity MR($B$) = $\Delta\rho(B)/\rho(0) = [\rho(B) - \rho(0)]/\rho(0)$ (where $\rho(B)$ and $\rho(0)$ are film resistivity with and without a magnetic field, respectively) of Ni/Si structures were measured using electric probe configurations shown in sketches in Fig. 2. As is seen from Fig. 2, we used 3 mutual alignments of magnetic induction *B* and current *I* vectors and the substrate plane in Ni/n-Si structures: $B \perp I$ but so that $B$ is normal (configuration $i = 1$ in Fig. 2) or parallel (configuration $i = 2$) to the plane of Si substrate, or $B \parallel I$ (configuration $i = 3$) so that both vectors $I$ and $B$ are codirectional and lie in the film plane. Such regimes of electric measurements allowed to study AMR effect and also to change the deviation direction of carriers under the influence of the Lorentz force in a magnetic field relative to the substrate plane. With configuration 1 the Lorentz force deviated the carriers to lateral edges of the sample (so that they moved parallel to the film plane), whereas with configuration 2 the carriers were pressed either to the film surface or to the Ni/Si interface, moving normally to the substrate plane under the effect of the Lorentz force. With configuration 3 the carriers moved along magnetic field (along the direction of Ni atoms spins allignement due to influence of magnetic field).

## Results and Discussion

The I-V characteristics of Ni films were linear at low bias voltages (up to 5 V) over the whole temperature range 2 – 310 K (see, insert in Fig. 3) confirming good quality (ohmicity) of electric probes. Temperature dependences of resistivity $\rho(T)$ were measured at constant $I$ = 10 mA in zero magnetic field and 3 different mutual alignements of vector $B$, vector $I$ and Si substrate plane above shown in Fig. 2. The observed $\rho(T)$ curve 1 in Fig. 3, measured at $B = 0$, is characterized by a typical metallic behavior, showing a residual resistivity lower than 20 K and a power-like growth of the resistivity with temperature increase due to scattering of electrons on phonons and Ni atoms spins.

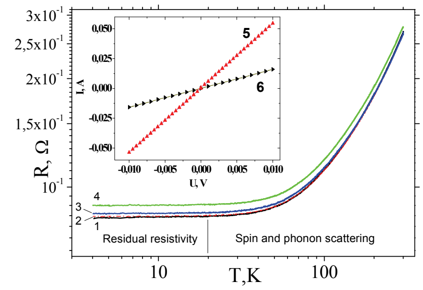


Fig. 3. Temperature dependences of resistivity in zero $B$ (curve 1) and at $B$ = 8 T for different mutual alignements of $B$, $I$ and Si substrate plane shown in Fig. 2: 2 – $i$ = 1, 3 – $i$ = 2 and 4 – $i$ = 3. Insert: I-V characteristics at temperatures 300 K (curve 5) and 2 K (curve 3). All measured was carried out at constant $I$ = 10 mA

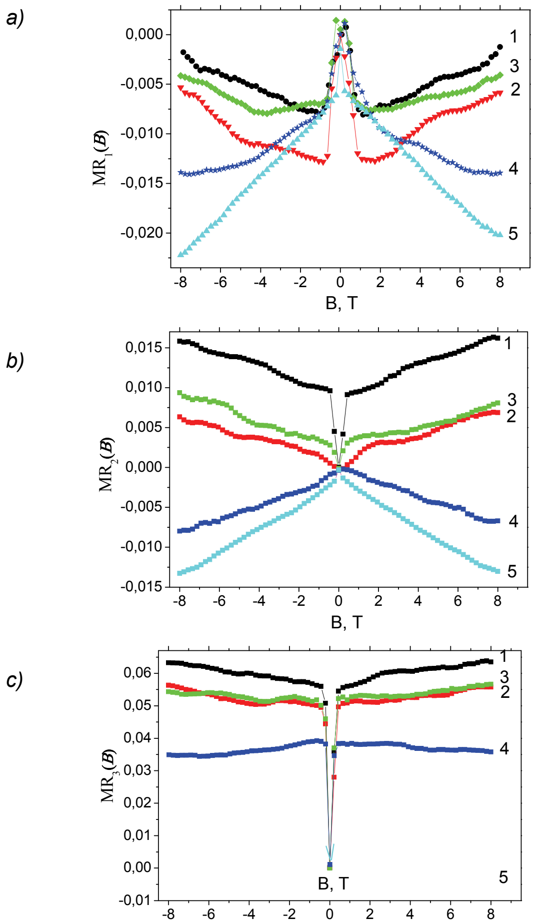


Fig. 4. Magnetic field dependencies of MR at temperatures 2 K (*1*), 10 K (*2*), 50 K (*3*), 100 K (*4*), 300 K (*5*) and different mutual alignements of vector $B$, vector $I$ and the sample plane: $a$ – configuration $i$ = 1, $b$ – configuration $i$ = 2, $c$ – configuration $i$ = 3

Magnetoresistance effect was measured in two regimes. Firstly, we measured the temperature dependencies $\rho(T)$ at $B$ = 8 T in 3 different mutual alignements of vector $B$, vector $I$ and Si substrate plane above shown in Fig. 2. These results are shown in curves 2 – 4 in Fig. 3. Fig. 3 shows that MR of Ni film increases with temperature lowering and strongly influenced by mutual alignements of $B$, $I$ and the sample plane.

To study mechanisms of MR effects in more details, we also made measurements of MR($B$) dependencies at some constant temperatures where could dominate different mechanisms of electron scattering (see, Fig. 3) – scattering on crystal lattice defects in the field of residual resistivity, scattering on Ni atoms spins and on phonons.

As is seen from Fig. 4, at room temperatures magnetoresistance $MR_i$ for configurations $i$ = 1 and $i$ = 2 correspondingly is negative in the whole $B$ region whereas $MR_3(B)$ for the configuration 3 becomes positive in weak magnetic fields being transformed to negative one when $B$ increases. At lowering the temperature below 80 K the $MR_1(B)$ curves begin to display the features of a positive contribution to the magnetoresistive effect (see, curves 1-3 in Fig. 4a) and is transformed to fully positive MR for $i$ = 2,3 (see, curves 1-3 in Fig. 4b,c).

The analysis of transformation of $MR_i(B,T)$ behavior in Ni films depending on mutual alignements of vector $B$, vector $I$ and the sample plane denotes the competition of negative and positive contributions to magnetoresistive effect. Analysis of the $MR_1(B)$ curves at different temperatures demonstrates that at higher temperatures the negative contribution dominates, exhibiting a linear increase of $MR_i(B)$ modulo (see, curves 5 in Fig. 4). A behavior of this negative contribution with a temperature and magnetic field allows for attributing it to AMR contribution due to scattering of the carriers from magnetic spins of Ni atoms. A more sharp decrease of Ni resistivity with a lowering temperature [20], as against nonmagnetic metals, results in dominance of the positive Lorentz-like MR effect with a temperature decrease, giving rise to nearly linear growth of $MR_i(B)$ for $i$ = 1,2 at $B$ > 2 T (see, curves 3-5 in Fig. 4a, b).

**Resume**

Our experiments demonstrated that the magnetic field and temperature dependences of the magnetoresistive (MR) effect in electrochemically deposited nanogranular Ni films observed two main differencies: (1) MR dependencies on the mutual orientations $i$ = 1, 2, 3 of vectors $B$, $I$ and the film (substrate) plane; (2) two competitive contributions to the $MR_i$ – negative anisotropic magnetoresistance (predominant at high temperatures and in high magnetic fields for $i$ = 1, 2, 3) and positive Lorentz-like MR (predominant at low temperatures and $i$ = 1, 2).

*The work was partially supported by VISBY Program of the Swedish Institute, the Joint Institute for Nuclear Research (Dubna, Russia), and the Belarusian State Scientific Program "NANOTECH"*

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