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Positive magnetoresistive effect in $Si/SiO_2(Cu/Ni)$ nanostructures

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ABSTRACT

A structure consisting of a nanoporous dielectric film (SiO_2) containing alternated layers of metal (Cu/Ni) in the pores on a n-type semiconductor substrate has been formed using the swift heavy ion track technology. Investigations of electrical and galvanomagnetic characteristics of this structure have made it possible to determine conduction mechanisms dominating in different temperature regions. A positive magnetoresistance reaching 30% and 1000%, respectively, was detected in temperature ranges of 175–300 K and lower than 50 K. $Si/SiO_2(Cu/Ni)$ structures could be employed as novel sensitive elements for magnetic field sensors.

1. Introduction

Nanostructured materials are a special state of condensed matter with properties being not characteristic for structures with macro- or microscopic dimensions. Their acquisition using porous dielectric template (SiO_2) on a semiconductor substrate (Si) makes it possible to adapt nanoscaled structures to the standard silicon technology. With that, a formation of pores in amorphous silicon dioxide is possible using the swift heavy ion track technology [1–3].

Deposition of metal in pores forming as a result of swift heavy ion (SHI) irradiation and track etching makes it possible to create metal compositions into pores of SiO_2 [4,5], and in this number multilayered structures. A number of unusual physical phenomena have been observed in these structures, most interesting of which is the magnetoresistive effect [6–9]. This effect reaches maximal values in sequential layers of para-/diamagnetic and ferromagnetic metals [10–12] and it is concerned with the spin-dependent scattering of charge carriers. Three main types of multilayered structures are employed at present:

– Multilayers where neighboring ferromagnetic layers are interconnected by the antiferromagnetic exchange interaction (for instance, Fe/Cr, Ni/Cu);
– Structures consisting of ferromagnetic layers with various values of the coercitive force (for instance $Ni_{80}Fe_{20}/Cu/Co/Cu$), in which the spin orientation changes from the antiparallel one to the parallel one, under the unfluence of magnetic field;
– Spin-valve sandwich structures, where the exchange coupling between ferromagnetic layers strongly diminishes by means of the non-magnetic conducting interleaf of a noble metal (Cu, Ag or Au). With that one of the ferromagnetic layers should touch with the antiferromagnetic material layer, which enables fixing of the magnetization vector in the ferromagnetic layer (for instance, $Ni_{80}Fe_{20}/Cu/Ni_{80}Fe_{20}/FeMn$).

In spite of some distinctions in the mechanisms of magnetoresistive effect exhibition in these systems, these mechanisms have some common features: a negative sign of magnetoresistance; magnetoresistance values up to 100% at helium temperature and 30% at room temperature; saturation magnetic fields up to 2 T.

Preliminary investigations of $Si/SiO_2(Cu/Ni)$ structures have shown a presence of the positive magnetoresistive effect which value can reach hundreds percents at low temperatures. Magnetoresistance parameters (sign, value, type of temperature and magnetic field dependences) unambiguously point out an impossibility of the description of this effect by means of the concept of a spin-dependent scattering of charge carriers.

Therefore, the goal of this investigation was concerned with a revealing of the magnetoresistive effect mechanism being based on the electrical and magnetoresistive properties investigations data of Cu/Ni multilayered structures in SiO_2 pores.

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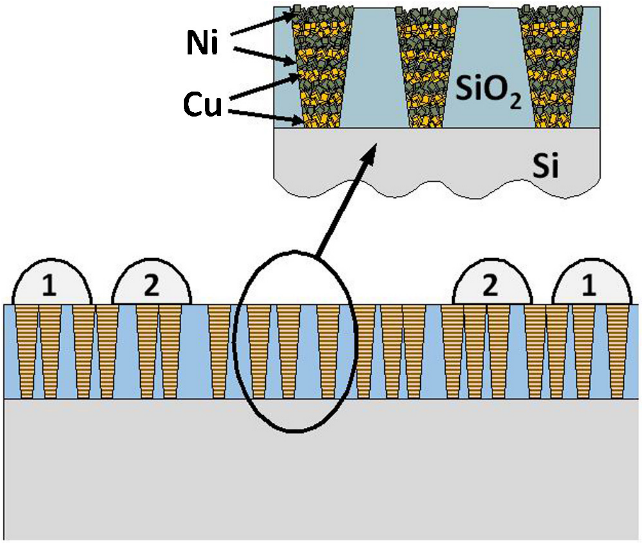

Fig. 1. A schematic representation of the Si/SiO_2(Cu/Ni) structure with the contacts for measuring the electrical properties: 1–indium current electrodes; 2–indium potential electrodes.

Moreover, we consider a possibility for a construction a sensitive element of magnetic field sensor on the base of these structures, with its adaptation to the standard silicon technology.

2. Experimental

2.1. Formation and morphology of multilayered structures

Single-crystalline phosphorous doped silicon wafers with (1 0 0) orientation (N_d = 8.87 × 10^{14} cm, R_s = 4.5 Ohm cm^{-1}; "Integral" Minsk, Belarus), were used as substrates for the creation of Si/SiO_2(Cu/Ni) structures. Amorphous silicon oxide layer with 700 nm thickness was formed by the thermal (pyrogenic) oxidation method [13]. Stochastically distributed highly-defect regions (latent SHI tracks) in SiO_2 layer were created by irradiation of ^{197}Au ions with fluence 5 × 10^8 cm^{-2} and energy 350 MeV, which has been sufficient for a "piercing" of the dielectric layer. Ions did not form stable highly-deficient regions in silicon due to the epitaxial recrystallization of damaged areas [14,15]. The introduced number of gold atoms is less than a concentration of the phosphorus addition in n-Si by many orders of magnitude. In this concern resistivity of the silicon substrate was constant. The etching of irradiated samples by the hydrofluoric acid has led to a formation of transverse pores (down to Si surface) with a simultaneous decrease of SiO_2 thickness down to 400 nm due the fact that the etching rate in latent SHI regions was 2–2.5 times higher than the etching rate on non-irradiated regions [2,5].

Further, a multilayer metallic structure containing 20 metallic layers with a thickness of one layer about 20 nm was created in pores of SiO_2 by means of a sequential electrochemical deposition of Cu and Ni from the one electrolyte at different potentials [16]. Metal layers thickness was determined by the quantity of charge which has passed in the process of electrochemical deposition. This parameter was calculated on the base of structural parameters of the SiO_2 porous template (surface area, number of pores per unit area, pore volume). The metal deposition has been carried out in a galvanostatic mode with the use of an electrolyte 0.005 M $CuSO_4$ + 0.5 M $NiSO_4$ + 0.5 M H_3BO_3. A schematic image of the resulting structure is given in Fig. 1.

Structural analysis of the Si/SiO_2(Cu/Ni) structures has been carried out by scanning electron microscopy (SEM) on the LEO-1455VP setup. An electron microscopy investigations of the structures has shown that copper and nickel are deposited in pores selectively; with a homogeneous filling along the entire SiO_2 surface (Fig. 2a). Analysis of the SEM image shows that average pore diameter of ~250 nm are practically similar for the entire surface. The density of filled pores correlates with the irradiation fluence by the order of magnitude.

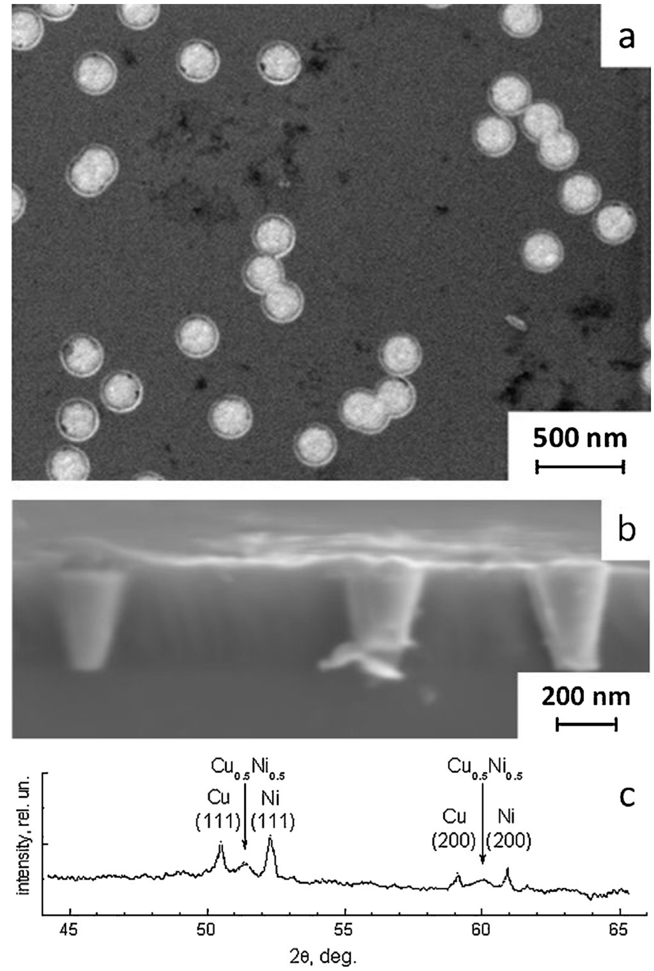

Fig. 2. Scanning electron microscopy images of pores in SiO_2 filled with Cu/Ni layers: top view (a); cross-section (b). XRD pattern of metals deposited into pores (reflexes of the silicon substrate are not indicated) (c).

Cross-sectional view of the Si/SiO_2(Cu/Ni) structure (Fig. 2b) shows that the metal fills pores completely (from the silicon substrate to the SiO_2 surface), exactly conforming the cone shape of a pore. The layer thickness value of every metal in pores has been preset by the charge quantity passed through the structure in the process of electrodeposition. A complete filing of pores by metals evidences that the average layer thickness is about 20 nm.

A determination of the phase composition of the metallic precipitate, determined by the X-ray phase analysis (XRD) method (CuK_α beam), has shown the existence of three phases (copper, nickel and the $Cu_{0.5}Ni_{0.5}$ solid solution). The $Cu_{0.5}Ni_{0.5}$ composition always forms on the Cu/Ni boundary at electrodeposition (Fig. 2c).

2.2. Electrical and galvanomagnetic properties

Measurements of electrical resistance (R) and magnetoresistance (MR) have been carried out by the four-probe method at the direct current mode on the universal measurement system "Liquid Helium Free High Field Measurement System" (Cryogenic Ltd)