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Bias-voltage-controlled ac and dc magnetotransport phenomena in hybrid structures

N.V. Volkov [a,b,*], A.S. Tarasov [a,b], D.A. Smolyakov [a], S.N. Varnakov [a,c], S.G. Ovchinnikov [a,b]

[a] Kirensky Institute of Physics, Russian Academy of Sciences, Siberian Branch, Krasnoyarsk 660036, Russia
[b] Siberian Federal University, Krasnoyarsk 660041, Russia
[c] Siberian State Aerospace University, Krasnoyarsk 660014, Russia

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ABSTRACT

We report some ac and dc magnetotransport phenomena in silicon-based hybrid structures. The giant impedance change under an applied magnetic field has been experimentally found in the metal/insulator/semiconductor (MIS) diode with the Schottky barrier based on the $Fe/SiO_2/p$-Si and $Fe/SiO_2/n$-Si structures. The maximum effect is found to observe at temperatures of 10–30 K in the frequency range 10 Hz–1 MHz. Below 1 kHz the magnetoresistance can be controlled in a wide range by applying a bias to the device. A photoinduced dc magnetoresistance of over 10^4% has been found in the $Fe/SiO_2/p$-Si back-to-back Schottky diode. The observed magnetic-field-dependent effects are caused by the interface states localized in the insula-tor/semiconductor interface.

1. Introduction

High expectations in spintronics are related to hybrid nanostructures comprising classical semiconductors and magnetic materials [1]. Whether are these expectations reasonable? On the one hand, the potential of magnetic structures (spin-valve and magnetic tunnel structures) which already find an increasing application in magnetic memory devices is well-known. The obvious advantages of such devices are high operation speed, nonvolatility, and high stability of their characteristics. On the other hand, semiconductor materials due to the properties controllable in wide ranges by temperature variation, doping with impurities, electric field and optical radiation determine the prospects for development of modern semiconductor technologies. It is not clear whether the integration of ferromagnetic (FM) materials and semiconductors will lead to the formation of novel concepts in spin-based electronics or just result in a simple combination of magnetic and semiconductor technology advantages.

Nowadays the main efforts of researches focus on solving the problems of spin injection, detection of the spin state and controlling that in semiconductors. This is the direct way to construct components for the signal processing and transmission in semiconductors using spin degrees of freedom. The possibility to control the orientation of electron spins and measuring spin currents by using special topologies of ferromagnetic elements or circularly polarized optical radiation was demonstrated in Refs. [2–5]. In addition, purely electric methods for controlling spin polarization in hybrid structures were proposed in literature available [6,7]. However, in our opinion, the advantages of semiconductors application in order to control the spin state and mutual transformation of the spin and charge currents in hybrid structures are still far to being exhausted. In the current investigation we have considered some ac and dc magnetotransport phenomena in silicon-based hybrid structures. We investigate ferromagnetic metal/insulator/semiconductor hybrid structures, which contain interface states localized near the insulator/semiconductor interface with the energy structure sensitive to an external magnetic field.

2. The ac magnetotransport phenomena in hybrid structures

First, we consider the $Fe/SiO_2/p$-Si (5 nm/1.5 nm/p-Si wafer) hybrid structure. To investigate the magnetotransport properties, a simple lateral device commonly referred to as a back-to-back Schottky diode (inset in Fig. 1) was fabricated. The bias-sensitive dc magnetoresistance in a high magnetic field was observed in this device [8]. The main contribution to the magnetoresistance of the structure is, most likely made by the processes occurring at the SiO_2/p-Si interface. This result stimulated us to address to

* Corresponding author at: Kirensky Institute of Physics, Russian Academy of Sciences, Siberian Branch, Krasnoyarsk 660036, Russia. Fax: +7 391 243 89 23.
E-mail address: volk@iph.krasn.ru (N.V. Volkov).

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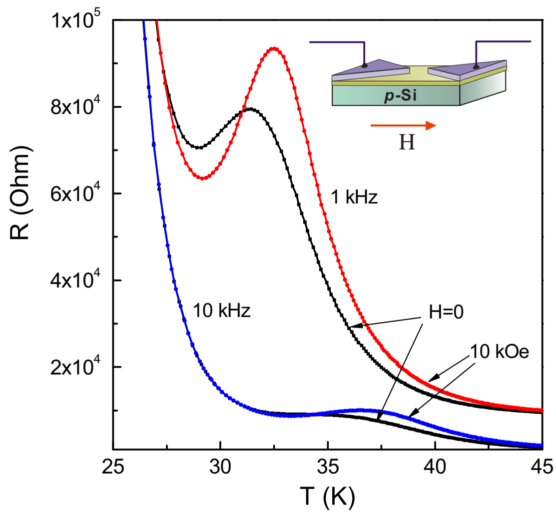

Fig. 1. The temperature dependences of real part of impedance R at various frequencies in zero and 10 kOe magnetic fields.

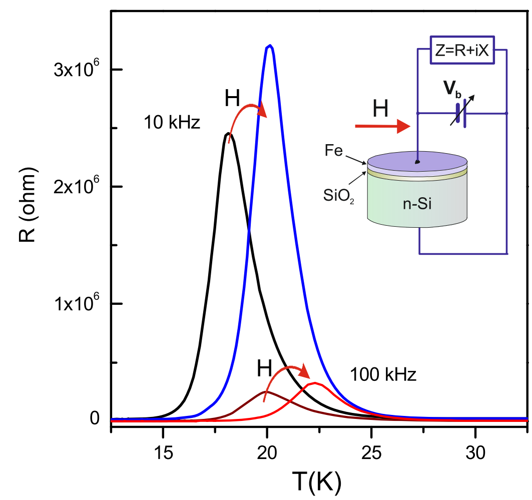

Fig. 2. Temperature dependences of the real part of the impedance at 10 and 100 kHz in zero magnetic field and in 10 kOe. Inset: a schematic of the device and the measurement setup.

impedance spectroscopy [9] used for studying metal/insulator/semiconductor (MIS) structures.

The experimental temperature dependences of the real part of impedance R at different frequencies in zero magnetic field and in a field of 10 kOe are shown in Fig. 1. Hence, the existence of the impedance peak with the frequency-dependent position and amplitude is observed. In addition, the peak parameters appear to be magnetic-field-dependent.

The peaks presence in the temperature dependences of the real part of the impedance is not surprised if one considers that the metal/insulator/semiconductor (MIS) junction with a Schottky barrier at the SiO_2/p-Si interface [8] determines all the transport properties features of the structure. Such features observed in real MIS structures [9] result from recharging of interface states and impurity centers localized at the oxide/semiconductor interface.

Since the features of the ac transport properties are determined by recharging of the interface centers at the SiO_2/p-Si interface, the magnetotransport effects result from magnetic-field-induced rearrangement of the energy structure of these centers. Having used the approximation proposed in a study [9] it was established that the magnetic field shifts energy levels of the interface states upward relative to the top of the valence band by 20 meV, which directly affects the recharging processes [10].

The next structure that was under investigations is the Fe/SiO_2/n-Si hybrid structure where n-Si is used instead of p-Si. In this structure another experimental geometry was utilized. The impedance spectra of the MIS diode were investigated in a two-probe configuration. The schematics of the device and measuring setup are shown in the inset in Fig. 2. One probe connected to the top of the Fe electrode by a two-part silver-filled epoxy adhesive; the other probe connects to the substrate backside by a barrier-free Al–Ga contact.

The impedance of the device was observed to be strongly influenced by magnetic field on in the narrow temperature range 10–30 K. Within this range, as shown in Fig. 2, the intense peak in the temperature dependence of the real part of the impedance exists. As it mentioned above, the occurrence of peaks in the $R(T)$ dependences for this MIS structure is caused exclusively by a recharging delay of the interface states localized near the insulator/semiconductor interface [11].

Fig. 3 shows one can implement positive or negative magnetoresistance or even the alternating magnetoresistive effect at certain H depending on the temperature. The behavior $R(H)$

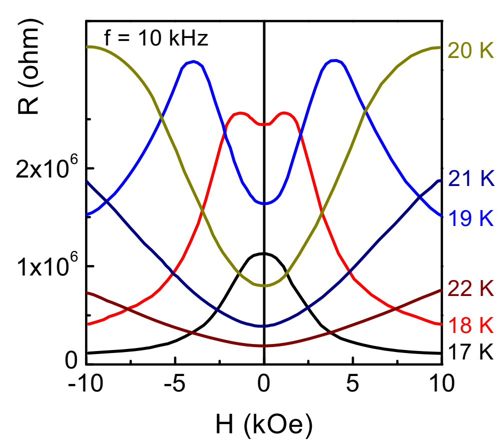

Fig. 3. The real part of the impedance vs magnetic field at different temperatures (f=10 kHz).

depends on what the peak part in $R(T)$ the system is at H=0. This position, in its turn, is entirely determined by the temperature.

As in the previous case, the shift of the $R(T)$ features in a magnetic field and, consequently, the giant magnetoimpedance (GMI) phenomenon in the Fe/SiO_2/n-Si-based MIS diode should be considered from the viewpoint of the magnetic field effect on the energy structure of the interface states localized near the SiO_2/n-Si interface.

In addition, the dc bias voltage V_b influence of the impedance was revealed. This effect can be clearly observed in the frequency dependences of the real part of the impedance (Fig. 4). The applied voltage $V_b<0$ reduces R in the low-frequency region. The negative bias leads to the formation of an area depleted of electrons in the surface layer of the MIS structure. This area operates as an additional dielectric layer, reducing the total capacitance of the structure. At increasing frequency the bias influence of the real part of the impedance decreases. The frequency dependences for $V_b = -5$ V and $V_b=0$ coincide at frequencies close to 1 MHz.

It is noteworthy the magnetoresistance strongly increases (Fig. 5) that in the low-frequency region at an applied bias. In particular, it increases approximately from 50% to 290% at a frequency of 100 Hz At higher frequencies MR do not change noticeably by the V_b bias. We define the magnetoresistance as MR = 100%($R(H)$ – $R(0)/R(0)$).