Thin Solid Films 671 (2019) 18–21

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Influence of metal magnetic state and metal-insulator-semiconductor structure composition on magnetoimpedance effect caused by interface states

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ARTICLE INFO

Keywords:
Magnetoimpedance
Spintronics
Metal/insulator/semiconductor structures
Nanosized semiconductors

ABSTRACT

This article presents the results of a study of the transport properties of metal/insulator/semiconductor (MIS) hybrid structures in alternating current (ac) mode. We prepared a series of samples with different layers of metal, insulator, and semiconductor. We prepared a series of samples with different layers of metal, insulator and semiconductor. Ferromagnetic Fe and non-magnetic Cu and Mn were chosen as metals, the insulators were SiO_2 and Al_2O_3, and n- and p-type Si substrates were used as semiconductors. Temperature dependence of the real part of the impedance showed peculiar peaks below 40K for different combinations of metals, insulators and semiconductors. For all samples the effect of the magnetic field on the transport properties was studied. At low temperatures, the magnetic field shifts peaks toward higher temperatures. Metal magnetic state does not significantly affect this phenomenon. Changing the type of the insulator and its thickness also did not cause any significant effect. However, the effect was observed for samples with different composition. Moreover, the type of conductivity of the substrate, as well as the type of metal, determines the value of magnetoimpedance. The main role in the magnetoimpedance effect is played by recharge of the energy states localized at the insulator/semiconductor interface. This mechanism allows obtaining a MI effect even in “nonmagnetic” MIS structures; magnetoimpedance can be either positive or negative, depending on temperature and frequency. We suggest that the observed ac magnetotransport phenomena could be used for creating magnetic field sensors, working on new principles.

1. Introduction

Magnetoresistance (MR) and magnetoimpedance in various materials and structures attract close attention in the viewpoint of both fundamental research and application in manufacturing new electronic devices. Although the effect was discovered more than half a century ago [1], it still evokes keen interest. A study of the structures with a high field sensitivity of the impedance is a continuously developing area [2,3]. The magnetoresistance is used in magnetic memory slots, different sensors magnetic antennas [4], etc.

Classically, the magnetoimpedance effect is explained on the basis of the skin effect, i.e., the dependence of the skin layer thickness on the effective magnetic permeability in a soft magnetic material [5]. As we reported previously [6], the magnetoimpedance effect can occur in metal/insulator/semiconductor (MIS) hybrid structures due to the presence of the surface states at the insulator/semiconductor interface, which are involved in the recharging processes in an ac voltage applied to the structure. The effect of the magnetic field is mainly related to the shift of energy levels of the surface states at the insulator/semiconductor interface. Thus, the magnetoimpedance effect is grounded on fundamentally new principles.

In the modern world, silicon and silicon-based materials are the main components of the most semiconductor devices, circuits, and microarrays [7]. Therefore, the use of silicon-based structures is promising in terms of the effective introduction of new devices into modern electronics [8].

The aforesaid has stimulated us to explore the transport properties of silicon-based hybrid structures under the action of different external

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https://doi.org/10.1016/j.tsf.2018.12.026
Received 11 September 2018; Received in revised form 13 December 2018; Accepted 13 December 2018
Available online 14 December 2018
0040-6090/

factors.

Previously, we have investigated the MIS structures. We detected the effect of magnetic field on their properties and studied the possibility of controlling a magnetoresistance value via bias voltage [6]. Moreover, we obtained a magnetoresistance value of 10^8% [9]. We made assumptions that the main role in these effects is played by the surface states at the insulator/semiconductor interface. To verify these assumptions and exclude the influence of the magnetic state of a metal, we fabricated a series of samples with different metallic layers.

2. Experimental

To create MIS diodes with Schottky barriers, we prepared a series of samples with different layers of metals, insulators, and semiconductors. As metallic layer materials, we chose ferromagnetic Fe and non-magnetic Mn and Cu. This was done to determine the contribution of the metal magnetic state to the magnetoimpedance. As insulating layer materials, SiO_2 and Al_2O_3 were chosen. This was necessary to clarify the role of an insulator in the magnetoimpedance properties of the structure. The samples were prepared on single-crystal *n*-Si (phosphorus-doped) and *p*-Si (boron-doped) substrates. The substrate surfaces were pre-cleaned by the Shiraki method (chemical etching and long-term annealing at temperatures of 400–650°C.) [10].

The SiO_2 layers with thicknesses of 1–2 nm were formed on the substrate surfaces by a chemical method (the substrates were exposed to an aqueous solution of H_2O_2 and NH_4OH in a ratio of 1:1:1 for 30 min at 60°C). The Al_2O_3 layers were formed by atomic layer deposition (ALD) using a trimethylaluminum precursor (TMA), deionized water, and a nitrogen carrier gas of 99,9999 purity at a growth temperature of 250°C on a PICOSUN R-200 facility. To obtain the thickness of 50–100 nm, 5 to 10 ALD cycles were performed (9,45 nm per cycle). Metallic films with thicknesses of 10–15 nm were deposited by thermal evaporation under ultrahigh vacuum conditions at a sputtering rate of 0,25 nm/min. The base pressure in the Angara chamber [11] was $8{,}6 \times 10^{-6}$ Pa. All the fabricated structures were characterized by cross-sectional transmission electron microscopy (TEM). The magnetic properties were examined by the magneto-optical Kerr effect (MOKE) on a NanoMOKE 2 setup.

Fig. 1 presents cross-sectional TEM images of the Fe/SiO_2/*p*-Si and Cu/Al_2O_3/*n*-Si structure interfaces. One can see that the structure layers are fairly smooth, with well-defined borders, and without interdiffusion. In addition, the metallic films are polycrystalline with grain sizes of about 10–15 nm. The cross-sectional TEM images taken for the entire series of samples were found to be similar to those shown in the figure. Field dependences of the MOKE signal shown in Fig. 1c allow one to conclude that Fe is ferromagnetic and Mn and Cu are nonmagnetic.

The impedance measurements were performed by a two-probe method. Ohmic contacts were formed on the metallic film using silver epoxy and at the bottom of the Si substrate by indium alloying. The contact pad areas were 1 mm^2. I-V characteristics of the prepared MIS structure (Fig. 2) show a rectifying behavior, which is indicative of the formation of a space charge region in silicon and, consequently, of a Schottky barrier at the interface. The impedance measurements were performed in the temperature range of 4,2–350 K in external magnetic field *H* using an Agilent E4980A LCR-meter, a helium cryostat, and an electromagnet [12]. The ac current frequency ranged from 20 Hz to 2 MHz; the applied magnetic field values were up to 0,8 T. The device is schematically illustrated in the inset in Fig. 2.

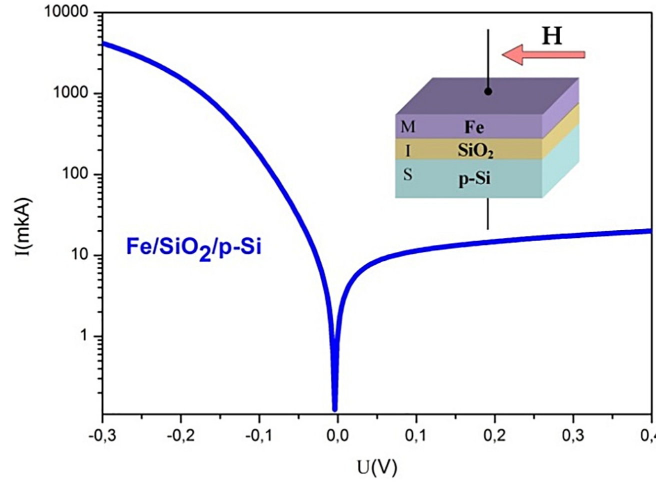

Fig. 2. (a) I − V characteristic of the Fe/SiO_2/p-Si MIS structure.

3. Results and discussion

Firstly, we measured temperature dependences of the real and imaginary parts of the impedance. Below 40 K, an intensive peak in the *R*(*T*) curve was found for all the samples regardless of the layer composition. The obtained data can be interpreted using the admittance spectroscopy measurements [13]. This technique makes it possible to measure the thermal emission rate at a point of the space charge region located in the close vicinity of the crossing point of the Fermi level with energy levels of the surface centers localized at the insulator/semiconductor interface.

In the case of MIS structures, the process of recharging of the localized surface states should be considered as a sequence of events of capture-emission of majority carriers from/to the allowed silicon band and metal electrode. The *R*(*T*) peaks are caused by the delays of recharging processes.

Since the main goal was to investigate the impact of the magnetic field on the transport properties of structures with different compositions, we applied an external magnetic field to the samples. Fig. 3a

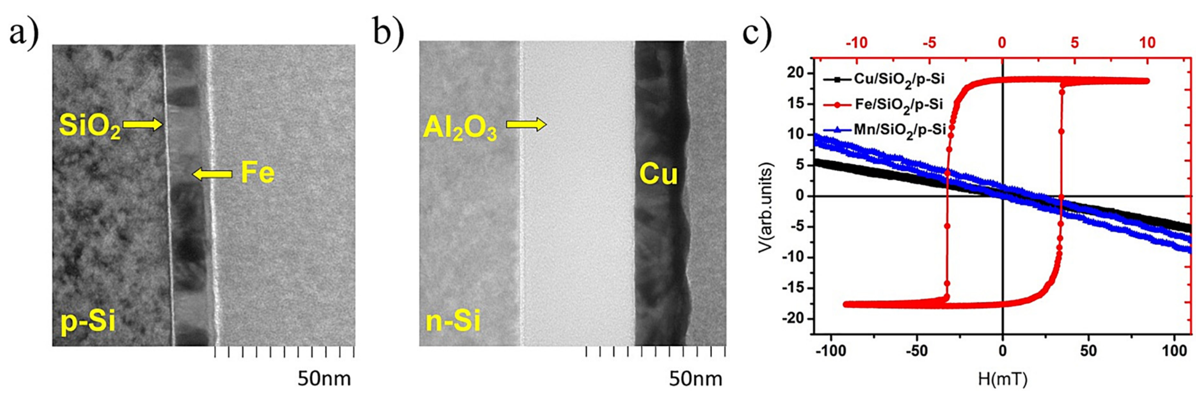

Fig. 1. Cross-sectional TEM images of the structure interfaces: (a) Fe/SiO_2/p-Si and (b) Cu/Al_2O_3/n-Si. (c) Field dependences of the MOKE signal for the MIS samples.

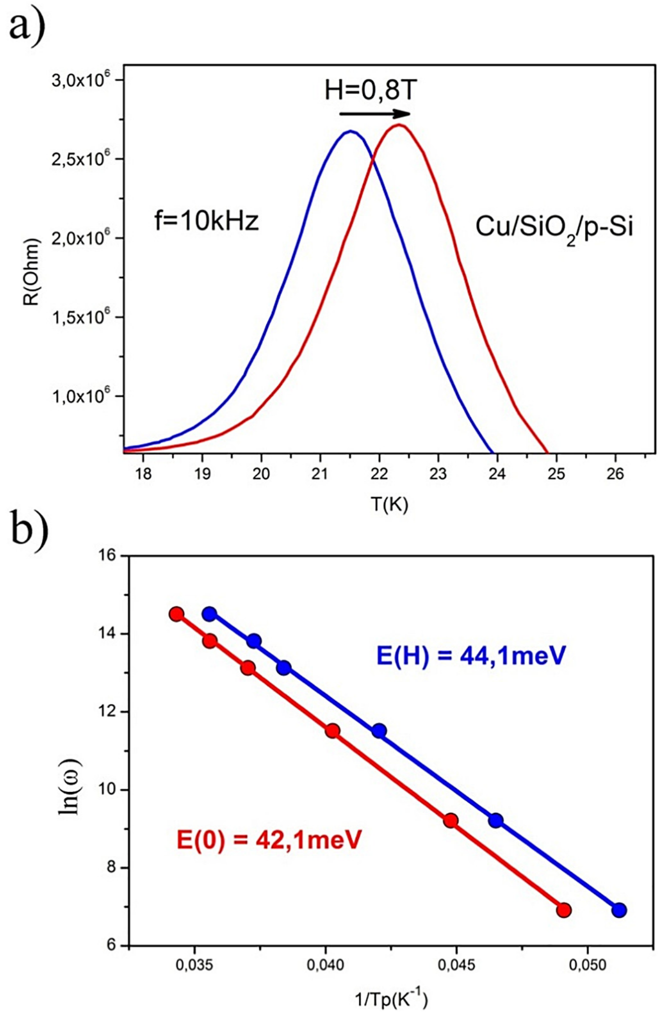

Fig. 3. (a) Temperature dependence of the real part of the impedance at H = 0 and H = 0,8 T for the Cu/SiO_2/p-Si; (b) ln(ω) vs reciprocal temperature peak for determining the energy levels of the interface states for the Cu/SiO_2/p-Si sample.

demonstrates the temperature dependence of the real part of the impedance $R(T)$. When the magnetic field is applied, the pronounced peaks shift toward higher temperatures. The shift of the $R(T)$ features is apparently related to the magnetic field effect on the electronic structure of the surface states. We suggest that the magnetic field causes the shift of the energy levels of the surface states toward higher energies (toward the center of the semiconductor band gap).

In addition, the magnetic field shifts the peak, regardless of the metal contained in the structure. The peak shifts by 0,5–2 K for all the samples. This fact allows us to state that the effect does not depend on whether the metal is ferromagnetic or not. In our case, the effect was approximately the same for ferromagnetic Fe and nonmagnetic Cu and Mn.

For all the samples, we calculated the energy of the surface states in zero and non-zero magnetic field using the relation $ln(\omega) = ln(1/\tau_0) - E_s/(k_B T_p)$ [14]. Here, T_p is the peak position in the $R(T)$ curve at fixed ω. By making a linear fit of the experimental $ln(\omega)$ vs $1/T_p$ dependence, we estimated the energy of the surface states from the slope of the fitting line. The fitting is presented in Fig. 3b for Cu/SiO_2/p-Si at $H = 0,8$ T and $H = 0$. The energies for different samples are given in Table 1 First of all, the energies calculated without magnetic field are very similar to the ionization energies of the dopants. The energies of phosphorus and boron are 46 and 44 meV, respectively [15]. It is reasonable to suggest that the surface state levels in our structures are formed by phosphorus and by boron for the *n*- and *p*-type substrates.

Table 1
Parameters of the Samples.

Sample	Energy (H = 0), meV	Energy (H = 0,8 T), meV	dE, meV
Cu/SiO_2/*p*-Si	42,1	44,1	2
Fe/SiO_2/*p*-Si	43,2	43,6	0,4
Mn/SiO_2/*p*-Si	43,3	43,8	0,5
Cu/SiO_2/*n*-Si	43,1	43,3	0,2
Fe/SiO_2/*n*-Si	42,5	42,5	0
Mn/SiO_2/*n*-Si	41,9	42,1	0,2

Moreover, as can be seen from Table 1, the energy of the surface states in all the samples changes in a magnetic field. Therefore, we concluded that the shift of the $R(T)$ feature in a magnetic field is not related to the ferromagnetic state of a metal. The energy changes in the structures with different metallic layers are of the same order of magnitude. Even in nonmagnetic Cu, the effect is noticeably higher than in the structure with the ferromagnetic Fe layer. However, it can be seen that for the samples with the *n*-type substrates, the energy change is much smaller than in the case of the *p*-type structure. This is probably related to the properties of surface states formed by donors or acceptors i.e., phosphorus or boron, respectively. In addition, the anomalous energy changes were observed for Cu/SiO_2/*p*-Si and Fe/SiO_2/*n*-Si. We attributed this with the quality of the insulator/semiconductor interface. Additional studies on the structural and chemical quality of the interface are needed.

In addition to the aforesaid, the peak shift in a magnetic field was found to be independent of the insulator type. Fig. 4a shows the $R(T)$ curves for the Mn/Al_2O_3/*n*-Si and Mn/Al_2O_3/*p*-Si structures. When Al_2O_3 is used, the $R(T)$ peak shift is observed, as in the case of SiO_2. As in the previous samples, the energy of the surface states was calculated. Moreover, in these structures, we used Al_2O_3 with thicknesses of 50 and 100 nm; the change in the thickness did not significantly affect the $R(T)$ features changing in a magnetic field. Our ongoing studies on the Fe_3Si/*p*-Si epitaxial structure showed that such a change in the impedance in a magnetic field is observed even in the structures without an insulating layer. The above-mentioned results allow us to follow the trend. The thickness and material of the insulating layer do not exert a determining influence on the shift of the energy levels of the surface states and, consequently, on the magnetoimpedance. At the same time, the substrate conductivity type and the type of a metal used determine the value of the MI effect.

In terms of potential application in commercial devices, these structures exhibit the sufficiently high magnetic field sensitivity. The magnetoresistance of the investigated samples was found to be 50–100%. The magnetoresistance is defined as $MR = 100\,\% \times ((R(H) - R(0))/R(0))$.

Fig. 4b demonstrates the magnetoresistance for different samples at $H = 0,8$ T. The maximum magnetoresistance value of 100% was obtained for the Cu/SiO_2/*p*-Si structure; the minimum value of 50%, for Mn/SiO_2/*p*-Si; and a value of 80%, for Fe/SiO_2/*p*-Si. The samples with the *p*-type substrates were chosen because the change in the energy of the surface states in these samples is higher than in the case of the *n*-type substrates. Thus, the use of such structures is promising for manufacturing magnetic sensors and other devices.

4. Conclusions

Thus, we presented the results of investigations of the ac transport properties of the silicon-based hybrid structures with different compositions in an applied magnetic field. It was found that the magnetic field affects the surface states located at the insulator/semiconductor interface. The shift of the peaks in the temperature dependence of the real part of the impedance was observed. The magnetic state of the metal affected this phenomenon in none of the samples. In addition, the

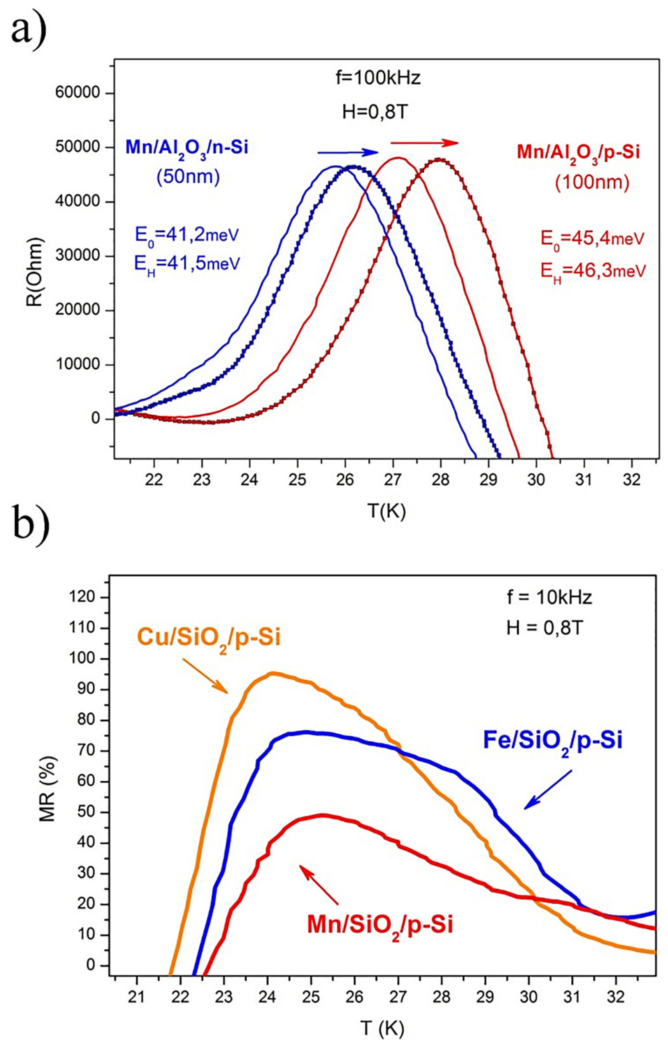

Fig. 4. (a) Temperature dependence of the real part of the impedance at H = 0 (solid line) and H = 0,8 T (closed squares) for Mn/Al_2O_3/p-Si and Mn/Al_2O_3/n-Si. (b)Magnetoresistance of the MIS-structures with p-type substrates.

insulator type and thickness did not make significant changes. Nevertheless, the substrate conductivity type, as well as the metal type, determines the value of the magnetoimpedance effect. This is probably related to the properties of the surface states formed by donors or acceptors. We may expect that using the ion implantation technique will make it possible to synthesize nonmagnetic structures with various dopants, in which the magnetoimpedance effect will be observed at different temperatures.

Acknowledgements

This study was supported by the Russian Foundation for Basic Research, project no. 18-32-00035 and supported in part by the Russian Foundation for Basic Research, Government of the Krasnoyarsk Territory, and the Krasnoyarsk Territorial Foundation for Support of Scientific and R&D Activities, project no. 18-42-243022, and the Ministry of Education and Science of the Russian Federation and the Siberian Branch of the Russian Academy of Sciences, project II.8.70, and the Presidium of the Russian Academy of Sciences, Fundamental Research Program no. 32 «Nanostructures: Physics, Chemistry, Biology, Basics of Technologies».

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