Solid State Phenomena Vol. 213 (2014) pp 56-59
© (2014) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/SSP.213.56

Electrical transport features in $Fe_3O_4/SiO_2/n$-Si hybrid structures

V.A. Vikulov[a,1], A.A. Dimitriev[1], V.V. Balashev[1,2], T.A. Pisarenko[1,2], A.M. Maslov[1,2], V.V. Korobtsov[1,2]

[1] Institute for Automation and Control Processes, 5 Radio St., Vladivostok 690041, Russia

[2] School of Natural Sciences, Far Eastern Federal University, 8 Sukhanova St., Vladivostok 690091, Russia

[a]e-mail: vikulov@iacp.dvo.ru

Keywords: Magnetite, Thin films, Hybrid structure, Conductance channel.

Abstract. The temperature dependencies of the resistivity of planar structures $Fe_3O_4/SiO_2/n$-Si, with Fe_3O_4 films of different thicknesses, were investigated. In the temperature range below 125 K, an anomalous decrease in the resistivity was observed. This effect is explained by switching of the conductance channel from the Fe_3O_4 film to the inversion layer of Si substrate due to the field-assisted tunneling of carriers through the semi-insulating Fe_3O_4/SiO_2 double insulator. Confirmation was obtained by the current-voltage characteristics measured at 80 K. It was found that current-voltage characteristics are *S*-shaped and correspond to the MIS switch diode.

Introduction

Silicon hybrid structures with ferromagnetic layers are of great interest for spintronics. Magnetite (Fe_3O_4) is one of the most promising materials for use in such structures due to the high value of the spin polarization of electrons [1]. In the past, the transport processes in tunnel structures with Fe_3O_4 layers have been investigated in a wide temperature range by both current-perpendicular to-plane geometry (CPP) [2] and current-in-plane geometry (CIP) [3]. In the latter, the conductance channel switching from the Fe_3O_4 film to the inversion layer of Si substrate at temperatures above 250 K was observed. Similar results have been observed in the thin films of Cu [4], Fe_3C [5], Co [6], FeSi [7] deposited on Si substrate with a native SiO_2 layer and in all instances were attributed to the thermo-activated tunneling mechanism. In this paper, we demonstrate that the conductance channel switching in polycrystalline-$Fe_3O_4/SiO_2/n$-Si hybrid structures also takes place at temperatures below 125 K due to the field-assisted tunneling mechanism.

Experiment

Monocrystalline silicon *n*-type (7.5 Ω×cm) with (100) orientation was used as a substrate on which, by thermal oxidation, an SiO_2 layer with a thickness of 5 nm was grown. The Fe_3O_4 film formation was carried out in an ultra-high vacuum chamber by thermal evaporation of Fe in an atmosphere of O_2 at a constant pressure of oxygen ($1.0\cdot10^{-6}$ Torr); the substrate temperature was 300°C. Film thickness (*d*) was varied by the deposition time of Fe. Determined by spectroscopic ellipsometry, film thicknesses were 34, 46 and 66 nm [8]. For comparison, the 68 nm-thick films were grown on a thick (1200 nm) layer of SiO_2 by the same method. According to reflection high-energy electron diffraction, Raman spectroscopy and atomic force microscopy, the formed magnetite films are structurally continuous polycrystalline with [311] texture. The average grain size increases with the thickness from 25 nm to 36 nm [9].

The transport properties of the samples were studied using a KEITHLEY 2400 current/voltage SourceMeter and an original facility based on a nitrogen cryostat. Temperature dependencies of resistivity $\rho(T)$ were measured by a standard four-probe method in CIP geometry at a constant current j=1 μA and current-voltage characteristics (*I-V*) were taken in a current scanning regime. Current electrodes with a diameter of 0.2 mm were formed collinearly with a step of 1 mm on the Fe_3O_4 film surface by thermal vacuum deposition of Al through a metal mask.

Results and discussion

Figure 1 shows the temperature dependencies of the resistivity of the Fe_3O_4/SiO_2/*n*-Si structures with different thicknesses of Fe_3O_4 film. It can be seen that for the structures with a thick SiO_2 layer, the resistivity continuously increases with decreasing temperature, which is characteristic of the polycrystalline thin films Fe_3O_4 [10].

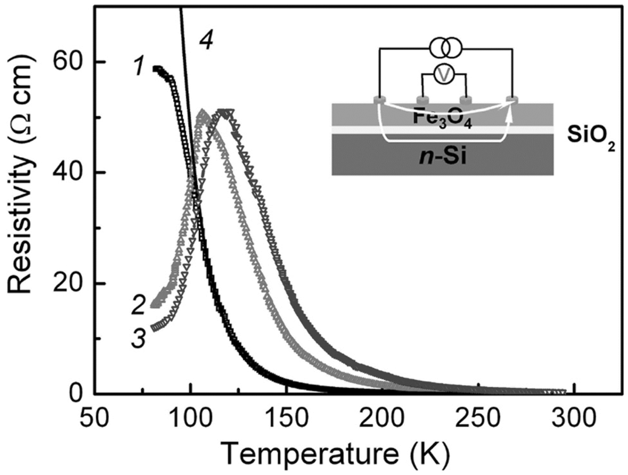

Fig. 1. *Resistivity vs. temperature for the structures with Fe_3O_4 thicknesses (d): 1- 68 nm, 2- 46 nm, 3- 34 nm; 4- 68 nm, formed on a thick (1.2 μm) layer of SiO_2. The inset shows the cross-section diagram of the lateral device geometry of the hybrid structure. Arrows indicate the possible current paths.*

However, for the structures with a thin SiO_2 layer the dependencies of *ρ(T)* are quite different at T<125 K. For the samples with *d*=34 and 46 nm the dependence *ρ(T)* undergoes a maximum followed by a sharp reduction. For samples with *d*=68 nm the deviation from the linear behavior in resistance is noted. Observed behavior of *ρ(T)* may be explained under the assumption of the additional conduction channel formed by an inversion layer located at the SiO_2/Si interface [11]. With temperature decreasing, the resistivity of Fe_3O_4 films increases significantly, which allows the layer of (*semi-insulating*- Fe_3O_4/SiO_2) to be considered as a double insulator in MIS structure. Increase in *ρ*, and hence the potential for current contacts, causes a redistribution of charges in the additional conductive layer. This, in turn, leads to the appearance of a bias voltage on tunnel junctions under the current contacts and, consequently, to an increase in the field-assisted tunneling current through the double insulator. Thus, tunneling resistance is reduced and the current begins to flow through the inversion layer, whose resistance is small compared with the resistance of the magnetite film (Fig. 1, *inset*). In structures with a thick layer of SiO_2, with the same applied current, the value of the electric field is insufficient to implement the conditions and the field-assisted tunneling and current passes only via magnetite film (Fig. 1, *curve 4*).

The formation of the inversion layer near the SiO_2/*n*-Si interface of the Fe_3O_4/SiO_2/*n*-Si structure is caused by the work function difference (χ_{MS}) of the Fe_3O_4 (χ_{Fe3O4}) and *n*-Si (χ_{Si}). Using the values of χ_{Fe3O4}=5.2 eV [12] and χ_{Si}=4.3 eV at a doping level *n*-Si substrate of $1.5\cdot10^{15}$ cm^{-3} [13], one can obtain χ_{MS}=+0.9 eV. This value indicates that the Si surface near the SiO_2/Si interface is strongly inverted, which gives rise to an additional conduction channel (Fig. 2).

In order to get a comprehensive understanding of the electrical transport mechanism in such structures at low temperatures, we have investigated the current-voltage characteristics. Results are shown in Fig. 3.

The *I-V* characteristics of structures with a thick SiO_2 layer exhibit a nonlinear behavior (Fig. 3, *top inset*). According to Ref. 10, the region of low conductance at small voltages can be attributed to the opening of a Coulomb gap in the polycrystalline magnetite film. It is found that the *I-V* characteristics of structures with a thin SiO_2 layer for all thicknesses of magnetite are *S*-shaped.

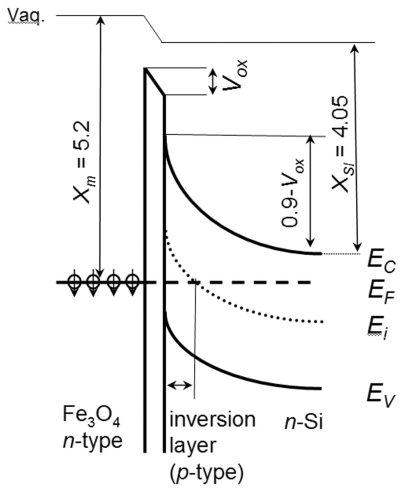

Fig. 2. *Energy band diagram of the* $Fe_3O_4/SiO_2/n$*-Si hybrid structure in thermodynamic equilibrium. Here are:* V_{ox} *– voltage drop on* SiO_2*,* χ_m *– magnetite work function,* χ_{Si} *– Si electron affinity. Values are given in eV.*

Similar characteristics were observed on the silicon MIS switch diode with the *p-n (epitaxial)-I (insulator)-M (metal)* structure [14]. Also, authors in Ref. [14] succeeded in the experiments to obtain negative resistance characteristics using the complementary type *n-p-I-M* diode. We can consider that in the structure of Al/$Fe_3O_4/SiO_2/n$-Si at T=80 K the same diode is realized, where the *n-p* junction is formed by the *n*-Si substrate and *p*-type inversion layer; the Al/(*semi-insulating* Fe_3O_4/SiO_2)/inversion layer acts as an MIS tunnel diode.

The equivalent circuit of Al/$Fe_3O_4/SiO_2/n$-Si structure can be represented by series-parallel connection of resistors of Fe_3O_4 film (*r*), the inversion layer of Si substrate (*ρ*) and MIS tunnel diodes (*q*) (Fig. 3, *inset*).

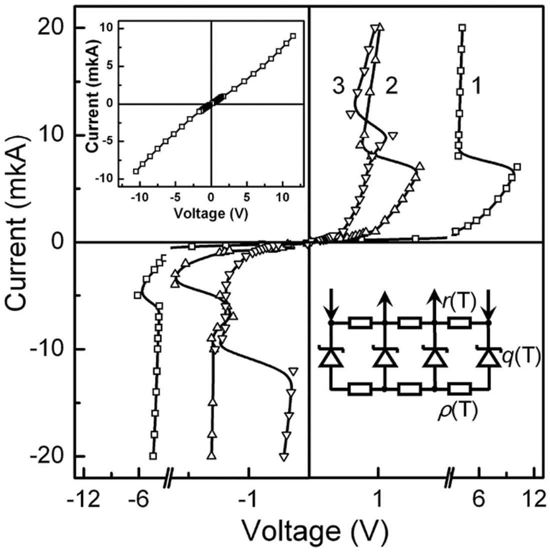

Fig. 3. *The I-V curves at 80 K. Thickness of* Fe_3O_4*: 1- 68 nm, 2- 46 nm, 3- 34 nm. The inset shows: top left – the I-V curves of 68 nm-thick* Fe_3O_4 *film formed on 1.2 μm-thick* SiO_2*; bottom right – an equivalent electrical circuit.*

Conclusions

In summary, the electrical transport properties of Al/polycrystalline $Fe_3O_4/SiO_2/n$-Si structures with different thicknesses of Fe_3O_4 film have been investigated in the temperature range $80<T<300$ K in CIP geometry. We have observed a switching of conductance channel from Fe_3O_4 film to the inversion layer of Si substrate below 125 K. It is shown that switching occurs due to the field-assisted tunneling through the double (*semi-insulating*- Fe_3O_4/SiO_2) insulator. The *S*-shaped *I-V* characteristics indicate that the $Al/Fe_3O_4/SiO_2/n$-Si structures can act as an MIS switch diode at T=80 K.

Acknowledgements

This work was supported in part by the Far East Branch of the Russian Academy of Sciences (project nos. 12-III-A-02-027 and 12-I-OFN-08), the Ministry of Education and Science of the Russian Federation (“Program in Support of Leading Scientific Schools,” project no. NSh_46342010.2), and the Russian Foundation for Basic Research (project no. 11-02-98523_r_vostok_a).

References

[1] Yu. S. Dedkov, U. Rüdiger, and G. Güntherodt. Phys. Rev. B 65 (2002) 064417.

[2] T. L. Qu , Y. G. Zhao, H. F. Tian, C. M. Xiong, S. M. Guo, J. Q. Li. Appl. Phys. Lett. 90 (2007)223514.

[3] Xianjie Wang, Yu Sui, Jinke Tang, Yao Li, Xingquan Zhang, Cong Wang, Zhiguo Liu, and Wenhui Su. J. Appl. Phys. 105 (2009) 07B101.

[4] J. Dai, L. Spinu, K.-Y. Wang, L. Malkinski and J. Tang. J. Phys. D: Appl. Phys. 33 (2000) L65.

[5] Jinke Tang, Jianbiao Dai, Kaiying Wang, Weilie Zhou, Nancy Ruzycki, Ulrike Diebold. J. Appl. Phys. 91 (2002) 8411.

[6] H. B. de Carvalho, M. J. S. P. Brasil, J. C. Denardin, and M. Knobel. Phys. Stat. Sol. (a) 201 (2004) 2361.

[7] S. Witanachchi, H. Abou Mourad, and P. Mukherjee. J. Appl. Phys. 99 (2006) 073710.

[8] V. V. Balashev, V. V. Korobtsov, T. A. Pisarenko and L. A. Chebotkevich. Tech. Phys. 56, (2011) 1501.

[9] V. A. Vikulov, V. V. Balashev, T. A. Pisarenko, A. A. Dimitriev, and V. V. Korobtsov. Tech. Phys. Lett. 38, (2012) 772.

[10] S. Jain, A. O. Adeyeye, and C. B. Boothroyd. J. Appl. Phys. 97 (2005) 093713.

[11] N. V. Volkov A. S. Tarasov, E. V. Eremin, S. N. Varnakov, S. G. Ovchinnikov, S. M. Zharkov. J. Appl. Phys. 109 (2011) 123924.

[12] M. Fonin, R. Pentcheva, Yu. S. Dedkov, M. Sperlich, D. V. Vyalikh, M. Scheffler, U. Rüdiger, and G. Güntherodt. Rev. B 72 (2005) 104436.

[13] S. M. Sze. *Physics of Semiconductor Devices, 3rd Edition*. John Wiley & Sons, Inc., 2007.

[14] Tatsuo Yamamoto and Mitsutaka Morimoto. Appl. Phys. Lett. 20, (1972) 269.