



Room temperature magneto-transport properties of nanocomposite Fe–In₂O₃ thin films



Igor A. Tambasov^{a,*}, Kirill O. Gornakov^b, Victor G. Myagkov^a, Liudmila E. Bykova^a,
Victor S. Zhigalov^{a,b}, Alexey A. Matsynin^{a,c}, Ekaterina V Yozhikova^b

^a Kirensky Institute of Physics, Siberian Branch of the Russian Academy of Sciences, Akademgorodok 50, 660036 Krasnoyarsk, Russia

^b Reshetnev Siberian State Aerospace University, Krasnoyarsk Worker 31, 660014 Krasnoyarsk, Russia

^c Siberian Federal University, Svobodny prospect 79, 660041 Krasnoyarsk, Russia

ARTICLE INFO

Article history:

Received 15 June 2015

Received in revised form

26 August 2015

Accepted 27 August 2015

Available online 10 September 2015

Keywords:

Indium oxide

Fe–In₂O₃ thin films

Weak localization

Disordered semiconductors

ABSTRACT

A ferromagnetic Fe–In₂O₃ nanocomposite thin film has been synthesized by the thermite reaction $\text{Fe}_2\text{O}_3 + \text{In} \rightarrow \text{Fe–In}_2\text{O}_3$. Measurements of the Hall carrier concentration, Hall mobility and magnetoresistance have been conducted at room temperature. The nanocomposite Fe–In₂O₃ thin film had $n = 1.94 \cdot 10^{20} \text{ cm}^{-3}$, $\mu = 6.45 \text{ cm}^2/\text{Vs}$ and negative magnetoresistance. The magnetoresistance for 8.8 kOe was $\sim -0.22\%$. The negative magnetoresistance was well described by the weak localization and model proposed by Khosla and Fischer.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Thin film materials, which have a combination of different physical properties such as optical transparency, electrical conductivity and magnetism at room temperature, are highly promising from the standpoint of scientific research and practical applications [1–3]. These materials can be obtained by two different concepts. The first concept is doping of transparent conductive oxides (TCO) by 3d transition metal (TM) ions [4,5]. The second concept is obtaining composites or hybrid structures, which contains multiple solid phases. For example, bilayer films such as ferrimagnetic layer/TCO layer [6,7] or two-phase (ferrimagnetic-TCO) thin films [8,9] are known. At present, a large number of research efforts are directed to the first concept. However a lot of these studies are controversial. Recently there appears to be an increased interest in the second concept [8,10].

Two important, widely used TCO materials are In₂O₃, and Sn doped In₂O₃ (commonly referred to as ITO) [11–13]. In₂O₃ thin films have been used in gas sensors, transparent thin-film transistors, flat panel displays, electrochromic devices and solar cells [12,14–19]. This is because In₂O₃ simultaneously exhibits high visible wavelength transparency and electrical conductivity. Doping of Fe is very often used to add magnetic properties to In₂O₃ because Fe has a high solubility, up to 20%, in indium oxide [20,21].

Moreover, Fe and Fe₃O₄ are well used for creating composite films based on TCO.

For a sufficiently large doping, there is a probability of obtaining disordered materials with the created composite film [22]. Furthermore, an ultraviolet irradiation can induce disorder in TCO [23]. Quantum phenomena such as weak localization begin to show in these materials [22]. Weak localization can significantly affect the transport properties [24].

Recently, we have used a new thermite reaction between α -Fe₂O₃ and In layers to successfully synthesize ferromagnetic Fe–In₂O₃ nanocomposite thin films that contain Fe nanoclusters imbedded in a In₂O₃ matrix and have soft magnetic properties at room temperature [25]. The nanocomposite Fe–In₂O₃ thin films had a small amount of Fe₃O₄ with no metallic indium and these facts were verified by Mossbauer spectroscopy and X-ray photoelectron spectroscopy. We can expect that the magnetite will affect the magnetotransport properties of the Fe–In₂O₃ thin films. Since ferromagnetic Fe–In₂O₃ nanocomposite thin films were first synthesized, it has been important to know the physical properties of these films. For this reason, we have investigated the magneto-transport properties of Fe–In₂O₃ nanocomposite thin films at room temperature.

Here we present measurements of magnetoresistance up to 8.8 kOe, Hall carrier concentration and Hall mobility.

* Corresponding author.

E-mail address: tambasov_igor@mail.ru (I.A. Tambasov).

2. Material and methods

The nanocomposite Fe–In₂O₃ thin films were obtained by an exothermic reaction in the In/Fe₂O₃ bilayer. This synthesis method is described in detail in our previous work [25].

The film thickness of the nanocomposite Fe–In₂O₃ thin film was determined by AFMDNP 5000 (Nanoink) and was ~100 nm. A chemically pure glass substrate with a thickness of 0.18 mm has been used. The magneto-transport measurements were carried out using a standard four-probe method. Ag contacts on top of the Fe–In₂O₃ thin film were used and sputtered using an Emitech k575x sputter coater. The thickness of the Ag contacts was approximately 50 nm. The measurements of magnetoresistance, Hall carrier concentration and Hall mobility were performed using an original facility based on an electromagnet, a precise Aktakom APS-7151 current/voltage source and an E14-440 L-CARD analog-digital converter. These measurements were measured in DC mode at a fixed value of current.

3. Results and discussion

Fig. 1 shows the dependence of the Hall voltage on the external magnetic field. It can be seen that Hall voltage is nearly linear with respect to the external magnetic field. This linear dependence is normal for semiconductors. It is possible that we did not have an ideal geometry for the Ag top contacts, which could have had an influence on the Hall voltage.

From the Hall voltage, we calculated the Hall carrier concentration (n) and the Hall mobility (μ). The nanocomposite Fe–In₂O₃ thin film had $n=1.94 \cdot 10^{20} \text{ cm}^{-3}$ and $\mu=6.45 \text{ cm}^2/\text{Vs}$ at room temperature.

The resistance of the nanocomposite Fe–In₂O₃ thin film as a function of the magnetic field (B) is shown in Fig. 2.

It should be noted that the magnetoresistance has been defined as $\text{MR}(\%) = \left[\frac{R(H) - R(0)}{R(0)} \right] \times 100\%$, where $R(H)$ is resistance with a magnetic field and $R(0)$ is resistance without a magnetic field. From Fig. 2 it is clear that MR is a negative. The MR for 8.8 kOe was ~–0.22%.

Negative MR is often observed in TCO and TM-doped TCO in the weak localization (WL) regime. However, such cases are usually observed at low temperatures [22,26]. On the other hand, our composite film seems to have a high degree of disorder in the context of a single phase. Thus, it is possible that weak localization can be observed at room temperature. For weak localization, the condition $k_F l = \hbar(3\pi^2)^{2/3} / (e^2 \rho n^{1/3}) > 1$ must be satisfied, where k_F is the Fermi wave vector, l is the mean free path, \hbar is the Planck constant, e is the electron charge, ρ is the resistivity. For our case,

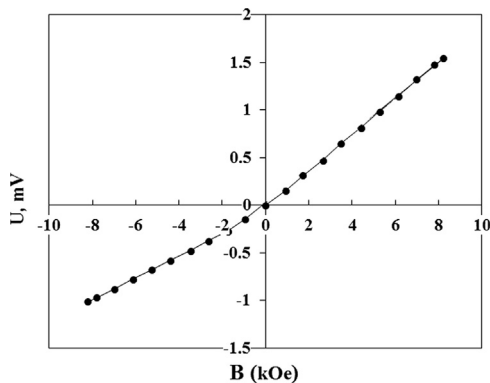


Fig. 1. The Hall voltage versus external magnetic field measured at room temperature.

the calculated value of $k_F l$ at room temperature is 1.351. As a result, the studied film is in the weak localization regime. For the three-dimensional WL regime, the expression for negative MR is given by [27]

$$\left(\frac{\Delta\rho}{\rho(0, T)^2} \right)_{\text{WL}} = - \frac{e^2}{2\pi^2 \hbar} \sqrt{\frac{eB}{\hbar}} f_3(\delta), \quad (1)$$

where $\delta = \hbar / (4eBl_\phi^2) = \hbar / (4eBD\tau_\phi)$ considering the phase-coherence length $l_\phi = \sqrt{D\tau_\phi}$, where τ_ϕ is the electron dephasing time and $D = \mu KT / e$ is the electron diffusion constant. The function $f_3(\delta)$ used in Eq. (1) is given by [27]

$$f_3(\delta) = \sum_{N=0}^{\infty} \left[2(\sqrt{N+1+\delta} - \sqrt{N+\delta}) - \frac{1}{\sqrt{N+1/2+\delta}} \right] \quad (2)$$

On the other hand, the observed negative MR can be explained by the model proposed by Khosla and Fischer (KF), where the third-order expansion of the s - d Hamiltonian exchange was considered. Correspondingly, a semi-empirical expression of the negative MR is given as [28]

$$\text{MR}(\%) = - a^2 \ln\left(1 + b^2 \left(\frac{B}{\mu_0}\right)^2\right) \times 100\%, \quad (3)$$

$$a^2 = A_1 J D(\epsilon_F) [S(S+1) + \langle M^2 \rangle], \quad (4)$$

$$b^2 = \left[1 + 4S^2 \pi^2 \left(\frac{2JD(\epsilon_F)}{g} \right)^4 \right] \left(\frac{g\mu_B}{\alpha k_B T} \right)^2 \quad (5)$$

Here, μ_0 is the magnetic constant, A_1 represents the contribution of spin scattering, J is the exchange interaction integral, $D(\epsilon_F)$ is the density of states at Fermi level, S is the spin of the localized magnetic moment, $\langle M^2 \rangle$ is the average magnetization, g is the effective Lande factor of the localized magnetic moment, μ_B is the Bohr magneton, α is a numerical constant on the order of unity and k_B is the Boltzmann constant.

We used Eq. (1) (WL) and Eq. (3) (KF) to fit the experimental data. Furthermore, we have assumed that these two mechanisms can exist simultaneously and thus we also used Eqs. (1) and (3) for fitting. Fitting results are presented in Fig. 3.

As shown in Fig. 3, the best fit is the summation of Eqs. (1) and (3). For this fit, we have received the following parameters: $a^2 = 1.427 \cdot 10^{-4}$ and $b^2 / \mu_0^2 = 0.5737$. In addition, the phase-coherence length has been defined and was 7.425 nm. Thus, the magnetoresistance of ferromagnetic Fe–In₂O₃ nanocomposite thin films is well described by both weak localization and the model proposed by Khosla and Fischer.

4. Conclusions

In conclusion, we have synthesized ferromagnetic Fe–In₂O₃ nanocomposite thin films and conducted measurements of Hall carrier concentration, Hall mobility and magnetoresistance up to 8.8 kOe. The nanocomposite Fe–In₂O₃ thin film had $n=1.94 \cdot 10^{20} \text{ cm}^{-3}$ and $\mu=6.45 \text{ cm}^2/\text{Vs}$ at room temperature. It has been shown that the magnetoresistance of ferromagnetic Fe–In₂O₃ nanocomposite thin films was a negative. The MR for 8.8 kOe was ~–0.22%. The magnetoresistance of ferromagnetic Fe–In₂O₃ nanocomposite thin films is well described by both weak localization and the model proposed by Khosla and Fischer.

Acknowledgment

This study was supported by the Russian Foundation for Basic

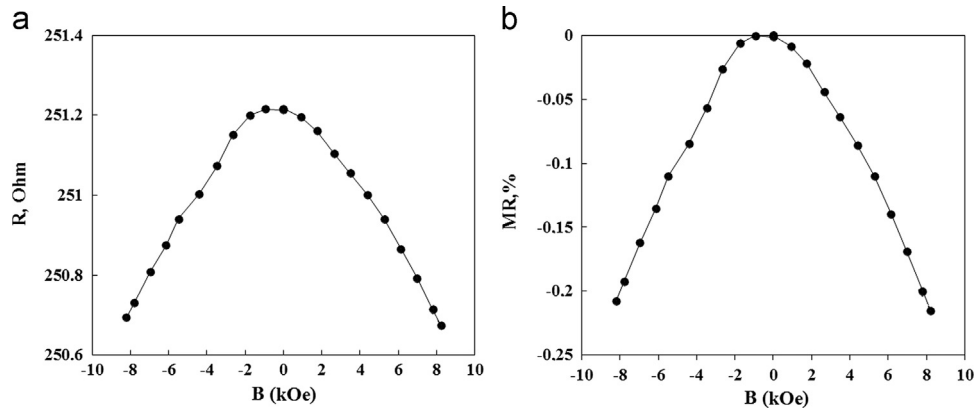


Fig. 2. The resistance (a) and magnetoresistance (b) versus external magnetic field measured at room temperature.

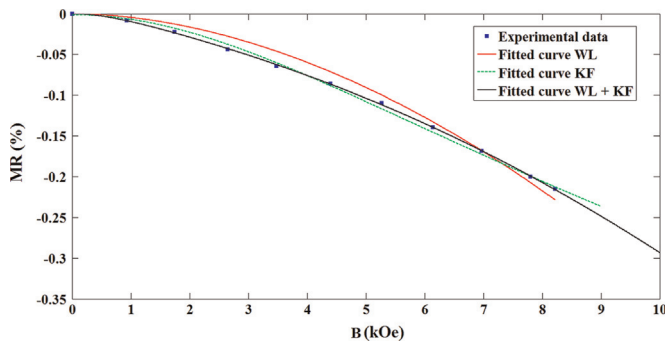


Fig. 3. The magnetoresistance versus external magnetic field. The lines show the fittings of experimental data with Eqs. (1) and (3) and Eqs. (1) and (3), respectively.

Research (Grants # 15-02-00948-A), by the Council for Grants of the President of the Russian Federation (SP-317.2015.1), and by the program of Foundation for Promotion of Small Enterprises in Science and Technology (№ 6662 ГУ2015) (“UMNIK” program).

References

- [1] E. Chikoidze, M. Boshta, M.H. Sayed, Y. Dumont, *J. Appl. Phys.* 113 (2013) 043713.
- [2] H.Q. Song, L.M. Mei, S.S. Yan, X.L. Ma, J.P. Liu, Y. Wang, Z. Zhang, *J. Appl. Phys.* 99 (2006) 123903.
- [3] Y.K. An, Y. Ren, D.Y. Yang, Z.H. Wu, J.W. Liu, *J. Phys. Chem. C* 119 (2015) 4414–4421.
- [4] Y.F. Tian, Y.F. Li, T. Wu, *Appl. Phys. Lett.* 99 (2011) 222503.
- [5] Y. An, S. Wang, D. Feng, Z. Wu, J. Liu, *Appl. Surf. Sci.* 276 (2013) 535–538.
- [6] P. Li, M.Y. Sun, H.L. Bai, *Thin Solid Films* 520 (2012) 5971–5976.
- [7] R.K. Gupta, K. Ghosh, P.K. Kahol, *Mater. Lett.* 64 (2010) 2022–2024.
- [8] Q. Li, L. Wei, Y. Xie, T. Zhou, G. Hu, S. Yan, J. Jiao, Y. Chen, G. Liu, L. Mei, *Nanoscale* 5 (2013) 2713–2717.
- [9] T. Yu, P. Chen, *IEEE Trans. Magn.* 47 (2011) 3467–3469.
- [10] M.S. Alshammari, M.S. Alqahtani, H.B. Albargi, S.A. Alfihed, Y.A. Alshetwi, A. A. Alghihab, A.M. Alsamrah, N.M. Alshammari, M.A. Aldosari, A. Alyamani, A. M.H.R. Hakimi, S.M. Heald, H.J. Blythe, M.G. Blamire, A.M. Fox, G.A. Gehring, *Phys. Rev. B* 90 (2014) 144433.
- [11] S.Z. Karazhanov, P. Ravindran, P. Vajeeston, A. Ulyashin, T.G. Finstad, H. Fjellvag, *Phys. Rev. B* 76 (2007) 075129.
- [12] C.G. Granqvist, *Sol. Energy Mater. Sol. Cells* 91 (2007) 1529–1598.
- [13] P.D.C. King, T.D. Veal, *J. Phys.-Condens. Matter* 23 (2011) 334214.
- [14] S.Y. Han, G.S. Herman, C.H. Chang, *J. Am. Chem. Soc.* 133 (2011) 5166–5169.
- [15] N. Katsarakis, *J. Phys.-Condens. Matter* 16 (2004) S3757–S3768.
- [16] S. Jeong, J. Moon, *J. Mater. Chem.* 22 (2012) 1243–1250.
- [17] L. Wang, M.H. Yoon, G. Lu, Y. Yang, A. Facchetti, T.J. Marks, *Nat. Mater.* 5 (2006) 893–900.
- [18] E. Fortunato, P. Barquinha, R. Martins, *Adv. Mater.* 24 (2012) 2945–2986.
- [19] T. Wagner, S. Haffer, C. Weinberger, D. Klaus, M. Tiemann, *Chem. Soc. Rev.* 42 (2013) 4036–4053.
- [20] Y.K. Yoo, Q. Xue, H.C. Lee, S.F. Cheng, X.D. Xiang, G.F. Dionne, S.F. Xu, J. He, Y. S. Chu, S.D. Preite, S.E. Lofland, I. Takeuchi, *Appl. Phys. Lett.* 86 (2005) 042506.
- [21] J. He, S.F. Xu, Y.K. Yoo, Q.Z. Xue, H.C. Lee, S.F. Cheng, X.D. Xiang, G.F. Dionne, I. Takeuchi, *Appl. Phys. Lett.* 86 (2005) 052503.
- [22] D. Saha, P. Misra, R.S. Ajimsha, M.P. Joshi, L.M. Kukreja, *Appl. Phys. Lett.* 105 (2014) 212102.
- [23] I.A. Tambasov, V.G. Maygkov, A.S. Tarasov, A.A. Ivanenko, L.E. Bykova, I. V. Nemtsev, E.V. Eremin, E.V. Yozhikova, *Semiconduct. Sci. Technol.* 29 (2014) 082001.
- [24] B. Shinozaki, K. Hidaka, S. Ezaki, K. Makise, T. Asano, S. Tomai, K. Yano, H. Nakamura, *J. Appl. Phys.* 113 (2013) 153707.
- [25] V.G. Myagkov, I.A. Tambasov, O.A. Bayukov, V.S. Zhigalov, L.E. Bykova, Y. L. Mikhlin, M.N. Volochaev, G.N. Bondarenko, *J. Alloy. Compd.* 612 (2014) 189–194.
- [26] D. Saha, A.K. Das, R.S. Ajimsha, P. Misra, L.M. Kukreja, *J. Appl. Phys.* 114 (2013) 043703.
- [27] A. Kawabata, *J. Phys. Soc. Jpn.* 49 (1980) 628–637.
- [28] J.A. Peters, N.D. Parashar, N. Rangaraju, B.W. Wessels, *Phys. Rev. B* 82 (2010) 205207.