ISSN 1062-8738, Bulletin of the Russian Academy of Sciences. Physics, 2014, Vol. 78, No. 1, pp. 26–28. © Allerton Press, Inc., 2014.
Original Russian Text © G.S. Patrin, I.A. Turpanov, K.G. Patrin, E.A. Alekseichik, V.I. Yuchkov, A.V. Kobyakov, 2014, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2014, Vol. 78, No. 1, pp. 46–48.

Magnetic and Electrical Properties of Ge/Co Bilayer Films

G. S. Patrin[a, b], I. A. Turpanov[a], K. G. Patrin[a, b], E. A. Alekseichik[a], V. I. Yuchkov[a, b], and A. V. Kobyakov[a, b]

[a] *Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia*
[b] *Siberian Federal University, Krasnoyarsk, 660041 Russia*
e-mail: patrin@iph.krasn.ru

Abstract—We present the results from experimental studies of the magnetic and electrical properties of double-layered films in a cobalt–germanium system. An intermediate magnetic layer was found to form at the interface and effect the films' magnetic behavior and magnetoresistive effect.

DOI: 10.3103/S1062873814010134

INTRODUCTION

Heterostructures based on semiconducting and magnetic materials attract interest due to the possibility of integrating magnetism and semiconducting properties [1]. Typically, the design of ferromagnetic semiconductor structures is ultimately aimed at controlling their electrical properties by changing their magnetic parameters. In such cases, studying the magnetic and interlayer interactions and mechanisms responsible for their formation is of prime importance.

Earlier [2, 3], we prepared the Co/Ge/Co three-layer films and studied their magnetic properties as they depended on the conditions of preparation and the thickness of the semiconducting interlayers. It was found that, depending on the rate of deposition and substrate temperature, a magnetically two-phase structure forms when hexagonal cobalt granules are distributed over the cubic cobalt matrix. The degree of magnetization suggests thermoactivation, as was successfully described in terms of a modified Stoner–Wolhfarth model [4]. The value of the magnetoresistive effect was ~1%.

EXPERIMENTAL

To understand the mechanism for the formation of the magnetic structure and the role of the interface, we synthesized Ge/Co double-layer films and studied their magnetic and resistive properties. The films were applied to a glass substrate via magnetron deposition using an ultrahigh-vacuum device with four sources (Omnicron) (equipped with a system for determining the thickness of a film during its growth) at a base pressure of $\sim 10^{-10}$ Torr. The substrate's temperature during deposition of the first layer was 150°C, and was adjusted with allowance for the best adhesion. Heating was then switched off to avoid stimulating diffusion processes. The layer thicknesses were determined by X-ray spectroscopy to an accuracy of ±0.5 nm. The surface roughness was checked on a Veeco Multimode Nanoscope IIIa SPM system atomic-force microscope (resolution, up to 0.2 nm); maximum height was ±1 nm at a roughness width cutoff of 20 nm. Film mgnetic and electrical properties were measured on a Magnetic Properties Measurement System SCQID unit (Quantum Design) ($T = 2$–400 K; magnetic field region $H = 0$–4000 kA m^{-1}). The double-layer film structures were studied at a constant thickness of germanium ($t_{Ge} = 8$ nm) and different thicknesses of the cobalt ferromagnetic layers ($t_{Co} = 2$–11 nm). Protective copper layers with $t_{Cu} \sim 50$ nm were deposited on the top and bottom of the investigated Ge/Co structure and also served as the contact pads.

RESULTS AND DISCUSSION

Electron-microscope investigation of the cross sections of our films, performed on a JEM-2100 transmission electron microscope (JEOL), showed that a 4 nm transitional layer formed at the interface between the materials. With thin layers of cobalt, a layer consisting of mixed initial elements formed. Electron microdiffraction also showed that the cobalt layer was a hexagonal phase ($P6_3/mmc$, $a = 0.250$ nm; $c = 0.0460$ nm; distinct lines $d_{101} = 0.191$ nm and $d_{110} = 0.1252$ nm were observed, along with smeared reflex $d_{110} = 0.2023$) and the transitional layer appeared to be Co–Ge alloy, though we cannot exclude the presence of other phases in small amounts. It is known [5] that the structure of Co–Ge alloy remains hexagonal at germanium concentrations of up to ≤17 at %.

The magnetic data for films with $t_{Co} = 2$ nm and $t_{Co} = 7$ nm are given below; they illustrate the changes in magnetization associated with the emergence of intermediate layers. As can be seen from Fig. 1 (magnetization per unit area of film was measured along the Y-axis), the shapes of the loops depend greatly on the thickness of the ferromagnetic metal layers. In

reverse resistances differ by more than an order of magnitude over the investigated range of temperatures, indicating that there is a rectification effect apparently associated with the Schottky barrier junction. At $T > T_C$, resistance was found to depend considerably on the magnetic field (see Fig. 3). For a forward flow of current, the magnetic field's effect only shifts the temperature of the anomaly to the high temperature region. For the reverse flow of current, the step in the magnetic field disappears and we observe a metallic pattern in the temperature dependence of resistance. The electrical resistance also depends on the order in which layers are deposited.

Our experimental data can be explained by allowing for the emerging intermediate layer that belongs to another magnetic phase. In our case, the magnetic characteristics of double-layer films differed from those of purely cobalt films. As the thickness of the cobalt rises from irreducible values, that of the intermediate layer grows to 4 nm. Later, its growth stops and only the pure cobalt layer grows. We must also consider that the magnetization pattern in the intermediate layer is nonhomogeneous. If we accept that the coercive force is defined by magnetic anisotropy [6], it follows from Fig. 1 that the transition layer lowers the magnetic anisotropy; i.e., there is competition between the contributions from the transitional and cobalt layers. The observed behavior of the exchange bias field could be due either to the behavior of the intermediate layer's magnetic anisotropy or to the specifics of interlayer interaction between the transition and cobalt layers.

CONCLUSIONS

Two points in the behavior of electric resistance should be emphasized. The first is the rectification effect, which is not surprising for a semiconductor metal layer. The second point is the great dependence of the resistance on the magnetic field. It appears that such behavior is due to interaction at the interface between layers. The immediate task is determining what the value and sign of the interaction between these layers will be.

It should be noted that the thickness of the transitional layer and the magnetization behavior of the whole structure depend not only on the thickness of the magnetic layer, but also on the order in which the layers are deposited: ferromagnetic or semiconductor. This is, however, a matter requiring special study.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project no. 11-02-00675-a.

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Translated by K. Utegenov