ISSN 1027-5495. Functional Materials, 27, No.1 (2020), p. 75-78.
doi:https://doi.org/10.15407/fm27.01.75

Magnetoresistance features of bismuth films in inhomogeneous magnetic field

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Received July 12, 2019

The magnetoresistance of vacuum-deposited bismuth films is studied in a high-gradient magnetic field. Bismuth films showed a large transverse magnetoresistance effect up $\Delta\rho/\rho_0$ ~ 70 %. Sensors in the shape of narrow rectangular stripes were made from the films. The fields were measured on a system of two Nd–Fe–B magnets which create large fields with a high gradient up to 10^6 Oe/cm. It was found that the magnitude of the magnetoresistance is affected by both the field strength and its gradient. It is shown that the discovered feature limits the possibility of using the bismuth films as sensors of high-strength fields.

Keywords: bismuth films, high-gradient magnetic field, magnetoresistance, sensors of high-strength fields.

Изучено магнетосопротивление конденсированных в вакууме плёнок висмута в высокоградиентном магнитном поле. Плёнки висмута обладали большим поперечным эффектом магнетосопротивления до $\Delta\rho/\rho_0$ ~ 70 %. Из них изготовлены датчики в форме узких прямоугольных полосок. Измерение полей проводили на системе из 2-х магнитов из соединения Nd–Fe–B, которые создают большие поля с высоким значением градиента до 10^6 Ое/см. Установлено, что на величину магнетосопротивления влияет как напряжённость поля, так и её градиент. Показано, что обнаруженная особенность ограничивает возможности использования плёнок висмута в качестве датчиков полей высокой напряжённости.

Особливості магнетоопору плівок вісмуту у неоднорідному магнітному полі. *В.М.Самофалов, О.С.Асєєв.*

Вивчено магнетоопір конденсованих у вакуумі плівок вісмуту у високоградієнтному магнітному полі. Плівки вісмуту володіли великим поперечним ефектом магнетоопору до $\Delta\rho/\rho_0$ ~ 70 %. З них виготовлено датчики у формі вузьких прямокутних смужок. Вимірювання полів проводили на системі з 2-х магнітів з сполуки Nd–Fe–B, які створюють великі поля з дуже високим значенням градієнта до 10^6 Ое/см. Встановлено, що на величину магнетоопору впливає як напруженість поля, так і її градієнт. Показано, що виявлена особливість обмежує можливості використання плівок вісмуту в якості датчиків полів надвисокої напруженості.

1. Introduction

The phenomenon of magnetoresistance consists in a change in the resistance of a conductor when it is placed in a steady-state magnetic field. There are several types of magnetoresistance effects of various natures. The most famous is the Thomson effect (anisotropic magnetoresistance); it occurs when the magnetic field H is turned on perpendicular to the current [1]. The increase in resistance occurs due to the current carrier trajectories' curvature caused by the Lorentz force. Presently, threshold and analog sensors based on this effect are displacing semiconductor sensors. Relatively recently, a giant magnetoresistive effect (GMR) was discovered, which is caused by spin-dependent scattering of current carriers [2, 3]. The GMR effect is strongly manifested in multilayer periodic structures in which the ferromagnetic layers are separated by diamagnetic interlayers with a thickness of several atomic layers. These layers of a certain thickness provide an oscillating exchange interaction between the ferromagnetic layers. A large magnetoresistance is achieved when anti-ferromagnetic ordering occurs in adjacent layers. The use of the GMR effect in magnetic read heads made it possible to increase the recording density on magnetic disks by 1000 times. One should pay attention to the small time interval between the discovery of the effects and their practical use.

This additionally testifies to the relevance of the topic related to the study of the features of transport properties, including those related to the study of the influence of highly gradient fields. These fields have been recently discovered and there have been no special studies of their effect on the galvanic-magnetic properties. It was supposed to study the effect of high-gradient fields not only on magnetoresistance, but also on the Hall effect, tunnel junctions, and contact potential difference. In this brief report, it is planned to study the effect of strongly inhomogeneous magnetic fields on the magnetoresistance of bismuth films. These studies also accomplish a practical goal, namely, the development and manufacture of magnetoresistive sensors for detecting non-uniform high-strength magnetic fields. The disadvantage of existing sensors is the low sensitivity in a wide range of fields. High gradient fields arise in permanent magnets with giant magnetic anisotropy [4–6], as well as in systems of magnets like the Halbach cylinder [7]. In [4–6], when registering such fields, granular Ag–Co films were used, in which the GMR effect reached $\Delta\rho/\rho_0 \sim 30$ % in fields up to 18–20 kOe. In the fields of higher strength, the sensitivity to field changes was low. Bismuth films have a high sensitivity to the field, and it is kept in the fields up to 100 kOe.

Therefore, the task of this work was to study the features of magnetoresistance of bismuth films in high-gradient magnetic fields and thereby to find out the possibility of using them as sensors for recording high-strength magnetic fields. The practical use of bismuth films for measuring fields will

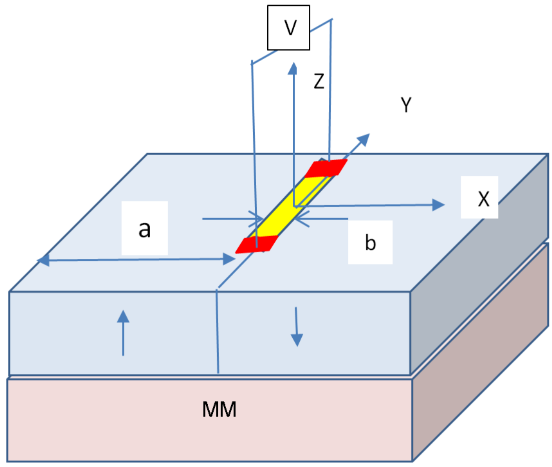

Fig. 1. Measurement scheme of transverse magnetoresistance on a bismuth film.

become possible if an unambiguous relationship between the field and magnetoresistance is experimentally proved, i.e. the field gradient does not affect its values. It should be noted that highly gradient fields arise on systems of magnets with giant magnetic anisotropy [4–6]. They can be considered as a new tool to influence on physical objects. In some works [8], a value equal to the product $(H\nabla H)$ is used as a parameter of influencing on physical and biological systems. So, in superconducting magnets with special tips, this value reaches $(H\nabla H)_{max} = 100$ Tl^2/cm. Similar values $(H\nabla H)$ are also achieved on the simplest magnet systems used in the work.

2. Experimental

Fig. 1 shows the experimental scheme used to measure magnetoresistance in an inhomogeneous field. The intensity of the magnetic field component $Hx(x,z)$ for $z \ll a$ is characterized by the dependence $Hx(x,z) \sim 4\,\mathrm{Ms}\cdot\ln(a/z)$. The gradient of this field is $\nabla Hx(x,z) \sim 4\,\mathrm{Ms}\,(1/z)$ at a distance $z \ll a$. As can be seen, for small z it reaches large values. A homogeneous magnetic field with an intensity of up to 20 kOe was created by an electromagnet. The resistance of the samples was measured using a digital ohmmeter with a relative accuracy of 10^{-4}.

Film bismuth samples in the shape of narrow strips 1–2 μm thick, 0.5–2 mm wide and 12 mm long were fabricated under conditions providing high magnetoresistance values up to $\Delta\rho/\rho_0 = 70$ %. In the measurements, the film sample was placed parallel to the X0Y plane. The distance z from the sample to the X0Y plane was changed using

Table. Magnetoresistance values of bismuth films at various values of homogeneous H_h and inhomogeneous H_{inh} magnetic fields

$\Delta\rho/\rho_0$, $(H)_h$, %	25	17.2	5.9	4.6
$Hx(0,z)_{inh}$, Oe	10100	7300	3270	2870
$Hx(0,z)_{str}$, Oe	14000	10200	4700	4300
$Hx(0,z)$Ag–Co, Oe	12200	9100		
z/a — distance to 0Y	0.01	0.05	0.22	0.28

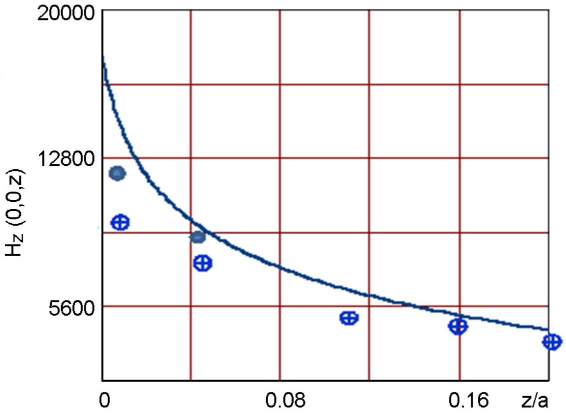

Fig. 2. The calculated dependence of the magnetic field strength averaged over the width of the strip $b = 0.5$ mm (solid line), ⊕ — data of the bismuth film sensor, • — data of the Ag–Co film sensor.

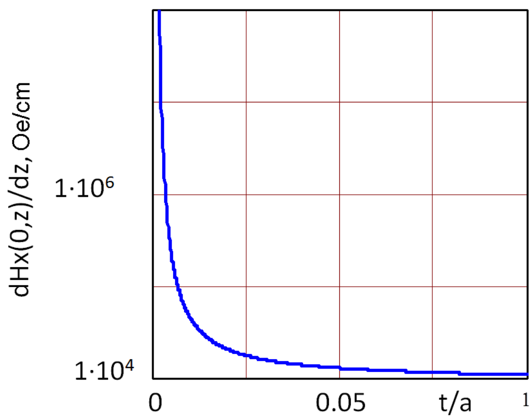

Fig. 3. The calculated dependence of the field gradient component $\partial Hx(0, z)/\partial z$ on the relative distance $z = t/a$.

glass plates of various thicknesses. In magnets based on rare-earth elements, the magnetization is practically frozen in the direction of the easy axis of magnetization because of the large anisotropy; therefore, the calculation by the Kittel method of magnetic charges [9] gives good agreement with experiment [6, 7]. The largest gradients are reached near the OY axis in accordance with the dependence $\nabla Hx \sim 1/r$, where r is the distance from the OY axis. Since the intensity of the stray magnetic field is nonuniform across the width of the plate, we calculated its average value over the width b of the strip, i.e. $Hx_{av} = (1/b)\int Hx(x,z)dx$. The $Hx(0, z)$ dependence in Fig. 2 (solid line) corresponds to the average field values over the plate width $b = 0.5$ mm. Stray fields were also measured using film sensors based on granular Ag–Co films, which had a magnetoresistive effect $\Delta\rho/\rho_0 \approx 15–20$ % in a field of $H \sim 15$ kOe.

3. Results and discussion

The main results of the work are presented in Fig. 2 and in Table. Fig. 2 compares the values of inhomogeneous fields with ones of homogeneous fields, at which the same magnetoresistance $\Delta\rho/\rho_0$ was achieved. The measurements were carried out as follows. First, the $\Delta\rho/\rho_0$ values were measured in an inhomogeneous field at a certain distance z; then the sample was placed in a homogeneous field of an electromagnet, where the same values of magnetoresistance were achieved by varying the field. The achieved value of H was measured with a tesla meter. Then we compared the measured homogeneous field with the inhomogeneous one calculated for given z. The measurements showed that the same value of $\Delta\rho/\rho_0$ is achieved at lower values of the homogeneous field as compared to the inhomogeneous one. A particularly large difference occurred when the sample was near the OY axis. In this region, $\nabla Hx > 10^5$ Oe/cm, and the differences in the fields were $\Delta Hx = 1–3$ kOe. As the distance increased to $z/a = 0.25$, ΔHx decreased monotonically to $\Delta Hx = 0.2–0.3$ kOe.

So, magnetoresistance in an inhomogeneous field is lower than in a homogeneous field of the same intensity. For completeness, we compared not only the measured $\Delta\rho/\rho_0$ values with those calculated, but also the $\Delta\rho/\rho_0$ values measured using various types of sensors. These were sensors based on bismuth films and sensors based on granular Ag–Co films. The experimental data shown in Fig. 2 and Table 1 also show different values of the fields at which the same magnetoresistance is achieved. The observed difference in $\Delta\rho/\rho_0$ values in the same field is due to the influence of a large field gradient. The significant difference in the fields measured by various sensors is apparently due to the different mean free paths of the current carriers in the sensitive elements of these sensors. Thus, the mean free path of electrons in bismuth is almost three orders of magnitude higher than in Ag–Co films. We note the behavior of the dependence is similar to the dependence $Hx(x, z_0)$, where z_0 is the thickness of the substrate.

We also studied changes in magnetoresistance in a system of 2 magnets connected towards each other. In this case, the field component $Hz(x, z)$ and the field gradient component $\partial Hz/\partial z$ take on larger values. The experimental dependence $\Delta\rho/\rho_0(z)$ corresponds to the trend described above. Measurements of the $Hx(x, z)$ and $Hz(x, z)$ components of the stray field were also performed using film sensors based on granular Ag–Co films. The technique of measuring and calculating the components of these fields, as well as the features of their gradient, are described in detail in [4–6].

So, the measurements of the magnetoresistance of bismuth films in high-gradient fields showed that its value depends not only on the field strength H, but also on its gradient, i.e. $\Delta\rho/\rho_0(H, \nabla H)$. Moreover, in an inhomogeneous field the magnetoresistance is lower than in a homogeneous field of the same strength. With an increase in the field gradient, this difference increases to $\Delta\rho/\rho \sim 3–5$ %, and the difference in fields of equal ρ values reaches $\Delta H \sim 3$ kOe. It seems, the growth of the gradient should give an opposite effect, since the presence, for example, of various structural inhomogeneities usually leads to an increase in resistance. There is no reasonable explanation for the found effect. The classical theory explains the increase of magnetoresistance in the field H by the curvature of electron trajectories under the action of the Lorentz force. A decrease in the magnetoresistance in a strongly gradient magnetic field in comparison with a homogeneous field can be due to the appearance of a Hall electric field F_H, different from the same field caused by the homogeneous magnetic field. Since the magnetic field is not homogeneous (Fig. 3), the Lorentz force and, consequently, the electric field E_H can be different at different points of the sample above the magnet. Possibly, space electric charges appear in the bismuth film in an inhomogeneous magnetic field. Since there are no space charges in the conductor in a static state, the resulting inhomogeneous electric field is a certain dynamic state, and it leads to a decrease in magnetoresistance.

4. Conclusions

The magnetoresistance of vacuum-deposited bismuth films is studied in a high-gradient magnetic field. It is shown that the magnetoresistance of bismuth films depends on both the magnetic field strength and its gradient. Additional studies are required to elucidate the nature of this phenomenon. The data obtained in this work allow us to concretely believe that it is impossible to use bismuth films to register high-strength magnetic fields due to the ambiguity of magnetoresistance. Compared to homogeneous fields, the difference in field strengths can reach several kOe.

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