PHYSICS AND CHEMISTRY OF SOLID STATE
V. 23, No. 1 (2022) pp. 72-76
Section: Technology
DOI: 10.15330/pcss.23.1.72-76

Vasyl Stefanyk Precarpathian National University

ФІЗИКА І ХІМІЯ ТВЕРДОГО ТІЛА
Т. 23, № 1 (2022) С. 72-76
Технічні науки

PACS: 537.612

ISSN 1729-4428

A.A. Ashcheulov[1], M.Ya. Derevianchuk[2], D.A. Lavreniuk[2]

Effect of Magnetic Field Concentration

[1]*Institute of Thermoelectricity of NAS and MES of Ukraine,* ashcheulovaa@rambler.ru,
[2]*Yuriy Fedkovych Chernivtsi National University,* m.derevianchuk@ukr.net

The peculiarities of magnetic field propagation in an anisotropic magnetic medium are considered and the dependences of the longitudinal and transverse components of the magnetic field on the geometric dimensions are established. For the first time, the possibility of concentrating the magnitude of the magnetic field has been shown and its value has been optimized. A model of an anisotropic magnetic concentrator is developed, and a method for creating artificial anisotropic classical materials is proposed. The application of this method of the magnetic field concentration makes it possible to increase the sensitivity of photo-, thermomagnetic detectors and the efficiency of galvano-thermomagnetic coolers, as well as electromagnetic and magnetoelectric measuring systems.

Keywords: tensor, magnetic permeability, anisotropy, concentration, magnetic field.

Received 15 October 2021; Accepted 27 January 2022.

Introduction

It is known that a magnetic field, like an electric field, is the basis of modern energy, electronics, radio, computing, as well as other fields of science and technology [1].

Currently, the development of new technologies and technological systems requires the construction of cost-effective electrical systems.

Magnetic field concentrators are widely used in devices for increasing the magnetic induction of a magnetic field in a given area - in medical devices, in magnetic traps, in devices for increasing the octane number of petroleum products, in various photographic [2], thermal [3], efficiency of galvanothermomagnetic coolers [4, 5] and other receiving devices operating in a wide spectral range.

The main requirement for them is the creation of an increased value of the magnetic induction in the gap where the sensitive element of a particular device is located. [6] Basically, this problem is solved by changing the geometric shape of the magnet tip.

I. Mathematical model of the effect of magnetic field concentration

Consider a medium characterized by the anisotropy of magnetic permeability coefficient $\hat{\mu}_{ii}$ the main crystallographic axes *Ox, Oy, Oz* of which coincide with the axes *Ox´, Oy´, Oz´* of the selected laboratory coordinate system. The magnetic permeability tensor $\hat{\mu}$ of such a medium is represented as follows [7, 8]:

$$\hat{\mu} = \mu_0 \begin{vmatrix} \mu_{11} & 0 & 0 \\ 0 & \mu_{22} & 0 \\ 0 & 0 & \mu_{33} \end{vmatrix} \quad (1)$$

If the crystallographic axes *Ox, Oy* are rotated around the axis *Oz* of the lateral face of a rectangular plate so that the angle between the axes *Ox* and *Ox´* is equal to α ($0 < \alpha < 90^{\circ}$), then the tensor $\hat{\mu}$ in this case can be represented as follows:

$$\hat{\mu} = \mu_0 \begin{vmatrix} \mu_{11}cos^2\alpha + \mu_{22}sin^2\alpha & (\mu_{11} - \mu_{22})sin\alpha \cdot cos\alpha & 0 \\ (\mu_{11} - \mu_{22})sin\alpha \cdot cos\alpha & \mu_{11}sin^2\alpha + \mu_{22}cos^2\alpha & 0 \\ 0 & 0 & \mu_{33} \end{vmatrix} \quad (2)$$

In the case of creating from such an anisotropic material a rectangular plate of length a, height b (a >> b) and width c (a >> b > c) the selected crystallographic axes Ox and Oy of which are located in the plane of the side face $(a \times b)$, and axis Ox is located at an angle α to the edge a (Fig. 1), it will be characterized by the presence of both longitudinal $\mu_{\|}$, and transverse $\mu_{\perp}$ components:

$$\mu_{\|} = \mu_0(\mu_{11}cos^2\alpha + \mu_{22}sin^2\alpha), \quad (3)$$

$$\mu_{\perp} = \mu_0(\mu_{11} - \mu_{22})\, sin\alpha\, cos\alpha \quad (4)$$

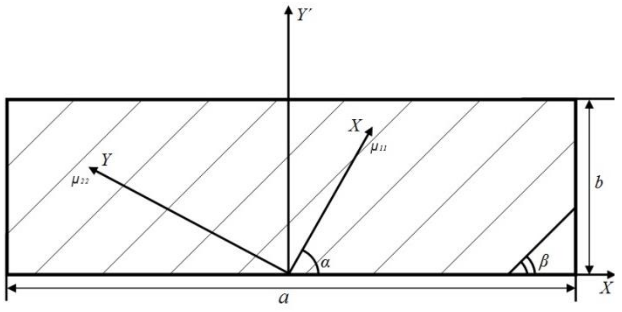

Fig. 1. Artifical anisotropic magnetic plate (crystallographic Z axis coincides with laboratory Z', they are placed perpendicular to the drawing plane).

If such a plate is placed in an external homogeneous magnetic field of intensity $\vec{H}$ so that the vector of intensity $\vec{H}$ is placed perpendicular to the upper and lower faces of this plate $(a{\times}c)$, then in its volume there appear both longitudinal $\vec{B}_{\|}$ and transverse $\vec{B}_{\perp}$ components of the magnetic induction vector $\vec{B}$. Their values can be represented by the formulae:

$$\vec{B}_{\|} = \vec{H} \cdot \mu_0(\mu_{11}cos^2\alpha + \mu_{22}sin^2\alpha), \quad (5)$$

$$\vec{B}_{\perp} = \vec{H} \cdot \mu_0(\mu_{11} - \mu_{22})\, sin\alpha\, cos\alpha. \quad (6)$$

The transverse and longitudinal magnetic fluxes arising in the volume $(a{\times}b{\times}c)$ of the plate are described by the following formulae

$$\vec{\Phi}_{\|} = \vec{H} \cdot \mu_0(\mu_{11}cos^2\alpha + \mu_{22}sin^2\alpha) \cdot b/ac, \quad (7)$$

$$\vec{\Phi}_{\perp} = \vec{H} \cdot \mu_0(\mu_{11} - \mu_{22})\, sin\alpha\, cos\alpha \cdot a/bc. \quad (8$$

The conversion factor m is represented by the formula

$$m = \frac{\mu_{\perp}}{\mu_{\|}} = \frac{(\mu_{11}-\mu_{22})\, sin\alpha\, cos\alpha}{\mu_{11}cos^2\alpha + \mu_{22}sin^2\alpha}. \quad (9)$$

The study of the values of the conversion factor m to the extremum at the angle α $(\partial m/\partial\alpha = 0)$ - showed that the maximum value of m is observed at the angle $\alpha_{opt.} = arctg\sqrt{\mu_{11}/\mu_{22}}$

$$m_{max} = m(\alpha_{opt.}) = \frac{\sqrt{K}(K-1)}{2K}, \quad (10)$$

where $K = \mu_{11}/\mu_{22}$.

Estimates have shown that since a >> b > c the influence of boundary conditions on the volumetric distribution of the magnetic field in the volume of the plate at the ends and side faces can be neglected [9].

Therefore, the formulae for the transverse and longitudinal magnetic fluxes at the optimal angle α take on the form

$$\vec{\Phi}_{\|} = \vec{H} \cdot \mu_0 \frac{2K}{K+1} \cdot \frac{b}{ac}, \quad (11)$$

$$\vec{\Phi}_{\perp} = \vec{H} \cdot \mu_0 \frac{\sqrt{K}(K-1)}{K+1} \cdot \frac{a}{bc}. \quad (12)$$

Thus, the maximum concentration factor l of the investigated device on the one hand is determined by the values of the coefficients μ_{11} and μ_{22} of the plate material, and on the other hand by the coefficient of its shape $(a{\times}b)$.

$$l = \frac{\vec{\Phi}_{\perp}}{\vec{\Phi}_{\|}} = \frac{\sqrt{K}(K-1)}{2K} \cdot (a/b)^2 = m_{max} \cdot (a/b)^2. \quad (13)$$

It should be noted that in this case the equipotential surfaces of the magnetic field inside the volume of the plate are placed at an angle β, the value of which is determined by the expression

$$\beta = arctg\left(\frac{K-1}{K+1}\right). \quad (14)$$

To place the equipotential surfaces of the magnetic field of the transverse component of magnetic induction parallel to the faces $a{\times}c$, it is necessary to orient the crystallographic axes at some angle $\gamma = \alpha_{opt.} - \beta$.

Then, the equipotential surfaces of the transverse component of the magnetic field are placed parallel to the faces $a{\times}c$, the concentration factor l_1 is determined by the following expression

$$l_1 = \frac{(K-1) \cdot sin\gamma \cdot cos\gamma}{Kcos^2\gamma + sin^2\gamma} \cdot (a/b)^2. \quad (15)$$

In this case, the transverse magnetic flux $\vec{\Phi}_{\perp}$ is located along the length a of the anisotropic plate.

It should be noted that this effect works in both static and dynamic fields.

II. Method of creating materials for an anisotropic magnetic concentrator

The analysis of the literature showed that at the moment there are no real anisotropic magnetic materials that would allow them to be used to create effective magnetic concentrators [10, 11, 12].

The solution to this problem was found by creating artificial anisotropic magnetic materials. The meaning of which is that an artificial anisotropic magnetic material is a system of parallel alternating plates 1 and 2 with thicknesses d_1 i d_2 characterized by different permeability coefficients μ_1 and μ_2, respectively ($\mu_2 \gg \mu_1$) [9].

The calculation of such an artificial anisotropic magnetic material is performed based on the maximum value of the anisotropy factor of magnetic permeability $k = \mu_{\parallel}/\mu_{\perp}$ using the method described in [9]. The source materials of layers 1 and 2 are selected based on the maximum value of the difference in their coefficients ($\mu_2 \gg \mu_1$).

Let us represent such a system in the form of a rectangular parallelepiped (Fig. 2) of length a_1 , height b_1 and width c_1, consisting of parallel layers 1 and 2, which alternate. These layers with thicknesses d_1 and d_2, are made of magnetic materials with permeability coefficients μ_1 and μ_2, respectively ($\mu_2 \gg \mu_1$).

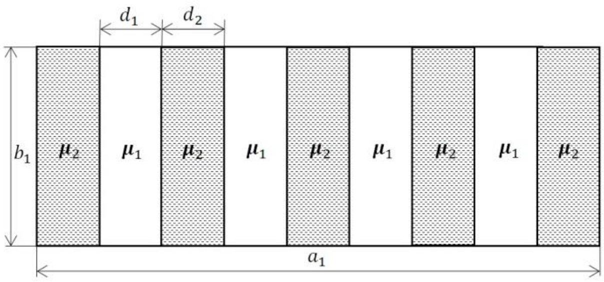

Fig. 2. Structure model of artificial anisotropic magnetic medium. 1– layer of material with magnetic permeability μ_1 and thickness d_1; 2 – layer of material with magnetic permeability μ_2 and thickness d_2.

The values of the longitudinal $\mu_{\parallel}$ and transverse $\mu_{\perp}$, components of the magnetic permeability tensor $\hat{\mu}$ of this alternating system are determined by the following expressions:

$$\mu_{\parallel} = (\mu_1 d_1 + \mu_2 d_2)/(d_1 + d_2), \quad (16)$$

$$\mu_{\perp} = \mu_1 \mu_2 (d_1 + d_2)/(\mu_1 d_2 + \mu_2 d_1). \quad (17)$$

The optimal values of d_1 and d_2 are related by the following relationship:

$$d_2 = d_1 \cdot \sqrt{\mu_2/\mu_1}. \quad (18)$$

This, in turn, allows both independent selection of the source materials and their geometric dimensions, and appropriate optimization, which generally leads to the appearance of anisotropic substances with the required specified magnetic parameters.

The basis of the anisotropic magnetic concentrator is a plate of length a and height b and width c, the alternating layers 1 and 2 of which are located at some optimal angle [13], which is shown in Fig. 3.

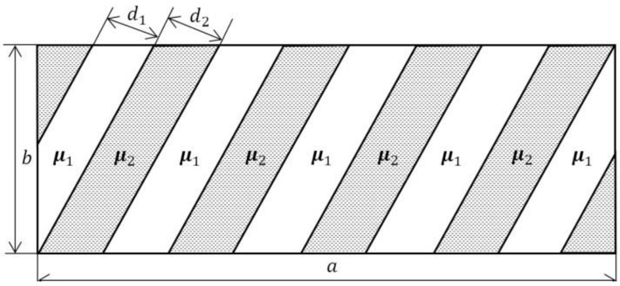

Fig. 3. Anisotropic transforming element made of artificial anisotropic magnetic material.

Table 1, which is given in [11, 12], presents brief characteristics of existing isotropic magnetic materials that can be used to create artificial anisotropic materials.

Table 1.

Coefficients of magnetic permeability of materials.

Coefficients of magnetic permeability of materials. Name of material	Permeability (μ) (H/m)
Metglas	1.25
Nanoperm	10×10^{-2}
Mu metal	2.5×10^{-2}
Permaloy (alloy 80% nickel and 20% iron)	1.0×10^{-2}
Electrical steel	5.0×10^{-3}
Nickel-zinc ferrite	2.0×10^{-5} – 8.0×10^{-4}
Manganese-zinc ferrite	$> 8.0 \times 10^{-4}$
Steel	1.26×10^{-4}
Nickel	1.26×10^{-4} – 7.54×10^{-4}
Platinum	1.2569701×10^{-6}
Aluminum	1.2566650×10^{-6}
Bismuth	1.25643×10^{-6}
Iron (purity 99.8%)	6.3×10^{-3}
Iron (99.95% pure iron scorched in hydrogen)	2.5×10^{-1}
Iron-cobalt alloys	2.3×10^{-2}
Martensitic stainless steel (hardened)	5.0×10^{-5} – 1.2×10^{-4}
Carbon steel	1.26×10^{-4}
Neodymium magnet	1.32×10^{-6}
Fluoroplastic 4, Teflon	1.2567×10^{-6}
Sapphire	1.2566368×10^{-6}
Copper	1.2566290×10^{-6}

The use of selected materials listed in Table 1 allows us to create artificial anisotropic magnetic materials whose anisotropy of magnetic permeability is in a wide range.

Table 2

Characteristics of artificial anisotropic magnetic materials.

Source magnetic materials	*Aluminum* μ_1=1.256665 × 10^{-6} (H/m)	*Copper* μ_1=1.256629 × 10^{-6} (H/m)	*Bismuth* μ_1= 1.25643 × 10^{-6} (H/m)
	Nickel μ_2 = 1.26 × 10^{-4} (H/m)	*Electrical steel* μ_2 = 5.0 × 10^{-3} (H/m)	*Iron-cobalt alloy* μ_2 = 2.3 × 10^{-2} (H/m)
Anisotropy coefficient of artificial layered material $k = \mu_\parallel/\mu_\perp$	8,30491 × 10^1	3,855711 × 10^3	1,803822 × 10^4
Conversion factor *m*, %	97,62	99,95	99,99
Concentration factor *l*, (at *a/b=20*)	390,48	399,79	399,96

Table 2 shows the characteristics of three artificial anisotropic magnetic materials, layers 1 and 2 are made of: aluminum and nickel; copper and electrical steel; bismuth and iron-cobalt alloy.

Analysis of the data in Table 2 indicates that a method has been proposed for creating artificial anisotropic magnetic materials, which are characterized by rather high values of the anisotropy coefficients of the magnetic permeability.

When bismuth and iron-cobalt alloy and a plate with a shape factor *a/b* = 20 are used as source materials, the conversion factor will be *m* = *99,99* %.

The possibility of independent selection of materials for layers *1* and *2* with the required thicknesses d_1, d_2 leads to the appearance of the required anisotropic magnetic structures with given concentration factors.

Conclusion

The considered effect of concentration of a magnetic field with artificially anisotropic magnetic materials expands considerably the capabilities of electrical engineering, instrument making and other related industries.

Ashcheulov A.A. – Professor, Doctor of technical sciences, chief researcher, Institute of thermoelectricity NAS and MES of Ukraine;
Derevianchuk M.Ya. – head's assistant;
Lavreniuk D.A. – engineer.

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А.А. Ащеулов[1], М.Я. Дерев'янчук[2], Д.О. Лавренюк[2]

Ефект концентрації магнітного поля

[1]*Інститут термоелектрики НАН і МОН України, м. Чернівці, Україна,* ashcheulovaa@rambler.ru,
[2]*Чернівецький національний університет імені Юрія Федьковича, м. Чернівці, Україна,* m.derevianchuk@ukr.net

Розглянуто особливості поширення магнітного поля в анізотропному магнітному середовищі і встановлено залежності поздовжньої та поперечної складових магнітного поля від геометричних розмірів. Вперше показано можливість концентрації величини магнітного поля і проведено оптимізацію її величини. Представлено математичну модель анізотропного магнітного концентратора, а також запропоновано метод створення штучних анізотропних класичних матеріалів. Застосування цього методу концентрації магнітного поля розширює можливості та підвищує чутливість фото-, термо- магнітних приймачів та ефективність гальванотермомагнітних охолоджувачів, а також електромагнітних і магнітоелектричних вимірювальних систем.

Ключові слова: тензор, магнітна проникність, анізотропія, концентрація, магнітне поле.