REVERSAL MAGNETIZATION AND THE PLANAR HALL EFFECT IN THIN MAGNETIC FILMS WITH SINGLE DOMAIN STRUCTURE

L. Vatskitchev, M. Vatskitcheva, J. Mucha*

Faculty of Physics, University of Sofia, 1164 Sofia, Bulgaria

E-mail: lyuvats@phys.uni-sofia.bg

*Instutute of Physics, Jagellonian University, 30059 Krakow, Poland

Abstract

The magnetization reversal processes in thin magnetic film with uniaxial magnetic anisotropy extend the dominant influence on the planar Hall effect. Numerical analysis based on the uniform rotation of the magnetization in the single domain model gives a possibility to find the critical values of the parameters corresponding to the peculiarities of the Hall curves. The comparison between the theoretical provisions and the experimental Hall curves determines the applicability of the model.

1. INTRODUCTION

1.1. Single domain model and coherent rotation process.

Single domain structure in the film plane supposes the constant magnetization vector **M** ($\mathbf{M}_x$, $\mathbf{M}_y$, 0) with the value $|\mathbf{M}| = M_s$, where M_s is the spontaneous magnetization (saturation) of the magnetic film and $m_x = M_x/M_s$ and $m_y = M_y/M_s$ are the direction cosines. The external magnetic field **H** ($\mathbf{H}_x$, $\mathbf{H}_y$, 0), applied to the angle θ in regard to the easy axis of magnetization (EA) determines the magnetization position $m_x = \cos\varphi$ and $m_y = \sin\varphi$ to the EA. The Stoner–Wohlfarth model [1] of the magnetization processes assigns the asteroid

$$h_x^{2/3} + h_y^{2/3} = 1 \qquad (1)$$

as a critical curve built from the components $h_x = H_x/H_a = h\cos\theta$ and $h_y = H_y/H_a = h\sin\theta$ of the applied magnetic field **H** and the anisotropy field of the film H_a . The critical curve determines the position of the magnetization vector **M** which corresponds to the extreme state of the free energy $E = E_a + E_H$ in the film including the energy of anisotropy E_a and the energy of interaction E_H between **M** and **H**. The static equilibrium condition $\partial E/\partial\varphi = 0$ follows to the equations [2,3]:

$$m_x^2 + m_y^2 = 1 \qquad (2)$$

$$\frac{h_y}{m_y} = \frac{h_x}{m_x} + 1 \qquad (3)$$

$$\sin 2\varphi - 2h \sin(\theta - \varphi) = 0 \qquad (4)$$

The numerical analysis of the equations (2) - (4) in the various typical cases leads to some basic conclusions belong to the shape of hysteresis loop and the critical values of the parameters characterising the coherent rotation of the film magnetization. Depending on the h-values ($0.5 < h < 1$) and the angle θ ($0^o < \theta < 180^o$) on observe (fig. 1a) the continuous rotation of m from the EA ($\varphi = 0$) to the first critical value $\varphi = \varphi_1$, discontinuous jump from $\varphi = \varphi_1$ to $\varphi = \varphi_2$ for $h = h_{cr}$ in the second critical value and continuous rotation from $\varphi = \varphi_2$ to $\varphi = \theta$ (the last value at $h \to \infty$). If $h \leq 0.5$ on observe a continuous rotation of m only with an extreme value $\varphi = \varphi_m$ corresponding to h_m and θ_m (fig. 1b). If $h > 1$ the extreme value is $\sin 2\varphi = 1$ at $\varphi_m = 45^o, 135^o$.

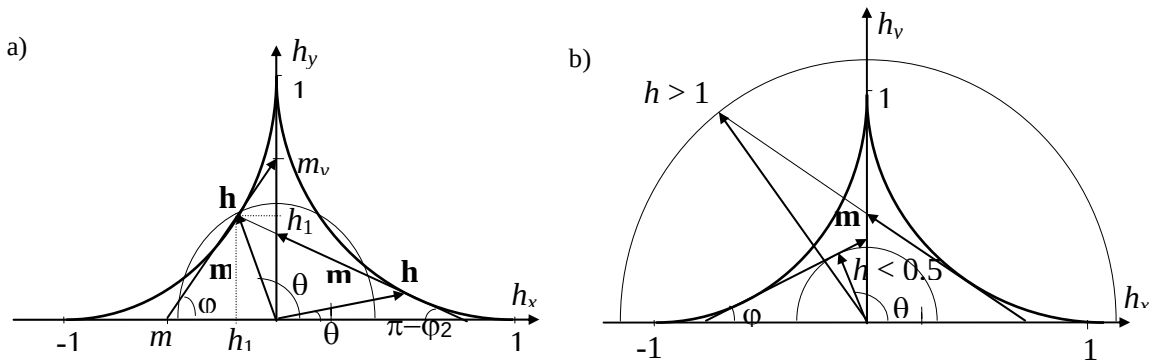


Figure 1. Critical values determined at different h =const: a) $0.5 < h < 1$; b) $h < 0.5$ and $h > 1$.

for the asteroid in I and II quadrant. In III and IV quadrant analogous values can be determined on the basis of the symmetry. The critical values may be calculated from the relations (2) - (4) as

$$\tan\theta_1 = -\tan^3\varphi_1 \text{and} \qquad \tan\theta_2 = -\tan^3\varphi_2 \qquad (5)$$

$$\tan\varphi_2 = \tan\varphi_1[(1 + \tan^2\varphi_1 + \tan^4\varphi_1)^{1/2} - (1 + \tan^2\varphi_1)] \qquad (6)$$

$$\varphi_m = 0.5\text{asin}2h_m \qquad \text{and} \qquad \theta_m = \text{acos}(-\sin\varphi_m) \qquad (7)$$

and taken its into account we will build the relation between θ, φ and h

$$\theta = \varphi + \text{asin}(\frac{1}{2h}\sin 2\varphi). \qquad (8)$$

The model problem is to find the position φ of the magnetization vector **M** for every **h = H**/H_a and θ taking into account for the critical values from (5) to (8). In this case we could be obtain both the function $\varphi = \varphi(h,\theta)$ and the hysteresis loop $M = M(H)$, but the mathematical difficulties prevent the direct solutions of the equations.

1.2. Planar Hall effect (PHE) and magnetization processes in the film.

The electrical field of the planar Hall effect in the thin magnetic film with a rectangular geo-metry (EA is along the *Ox*-axis of the sample and **H** is in the film plane) is

$$E_y = \Delta\rho_s \sin 2\varphi, \qquad (9)$$

where $\Delta\rho_s = (\rho_{s||} - \rho_{s\perp})/2$ and $\rho_{s||}$ and $\rho_{s\perp}$ are the values of the resistance at $\mathbf{M} || \mathbf{j}$ and $\mathbf{M} \perp \mathbf{j}$ respectively (**j** is the current density along *Ox*-axis of the sample).

If the film sample is magnetized to a saturation we can find from (9) the relative Hall voltage normalized in regard to its maximum value [4] at $\varphi = \pi/4$ and the equation (4):

$$u = U_y/U_{y\,\max} = \sin 2\varphi = 2h \sin(\theta - \varphi). \qquad (10)$$

For the magnetic field components we can obtain the equation $u = u(\theta,\varphi)$ but it has not the direct solution. The peculiarities of the reversal magnetization behaviour include the continuous changes of u and discontinuous jumps when the magnetic field vector crosses the asteroid.

2. THEORETICAL BACKGROUND

We can describe the voltage u of the PHE as a field dependence $u = u(h)_{\theta = \text{const}}$ or as angular dependence $u = u(\theta)_{h = \text{const}}$. Initially we might calculate the critical values θ_1, θ_2, φ_1, φ_2, φ_m, θ_m and h_m from the asteroid (fig. 1), because they determine the boundaries of the argument φ. Finally we built the reverse relations $h = h(m)_{\theta = \text{const}}$, $h = h(u)$ and $\theta = \theta(u)$ by numerical calculations taking into account (3), (8) and (10).

2.1. Angular dependencies of PHE

If the applied field h = const rotates its direction $0 < \theta < 180^o$ in the film plane (Fig. 1) quasistatically the Hall voltage u changes its sign and period (fig. 2a). At $h = 0.4$

the period of the angular dependence is 360°. The changes of the Hall voltage take place with period 180° at $h = 0.674$ or $h = 1.2$ and show some peculiarities when the magnetic field crosses the asteroid (at $h = 0.674$ – a value determined numerically for $\theta = 100^o$). In this case on observe the hysteresis that appears at $0.5 < h < 1$. The angle θ_m which corresponds to $u_y = 1$ can be found from (8) as

$$\theta_m = 45^o + \mathrm{asin}(1/2h). \tag{11}$$

In the saturation state of the film (at $h \to \infty$) $\varphi \to \theta_m = 45^o$.

2.2. Field dependencies of PHE

The numerical solution of the equation (8) shows the behaviour of the Hall voltage at $\theta = 30^o$, 60° and 90° respectively if the magnetic field changes from $+h$ to $-h$ (Fig. 2b). The critical values φ_{cr} determine the origin of the jump in u at the same values of h_{cr} because $\theta = 30^o$ and 60° are deposited symmetrically about $\theta = 45^o$. No jump at $\theta = 90^o$ where the magnetization vector changes its position smoothly.

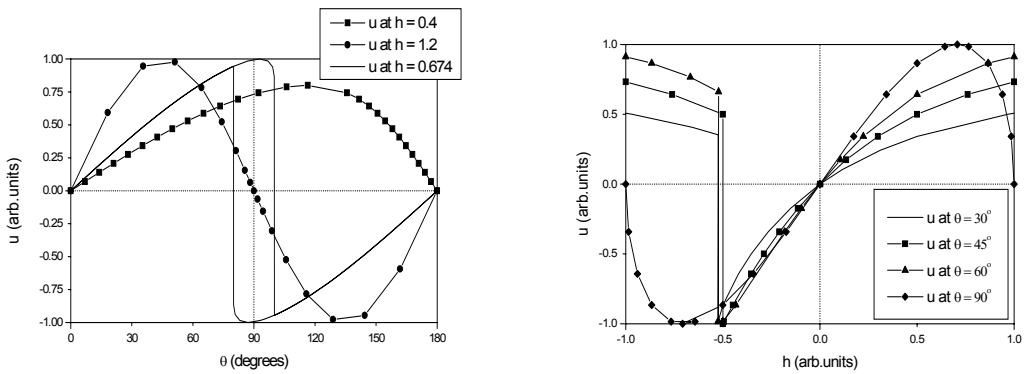
2.3. Hysteresis loops and the Hall voltage

The peculiarities of the hysteresis loops [5] at different θ = const correspond to the changes of the Hall voltage (fig. 3). No hysteresis in the dependencies $m_y(h)$ and $u(h)$ at $\theta = 90^o$ (fig. 3a). The discontinuous magnetization jump from φ_1 to φ_2 at the critical values of h for $\theta = 45^o$ [1] corresponds to the analogous jump in the Hall voltage (fig. 3b). No accordance between the hysteresis jump in $m_x(h)$ at $\theta = 0^o$ because in this case the Hall voltage $u = 0$ theoretically. In the real magnetic films on observe these peculiarities but the processes of the nonuniform rotation of magnetization and the domain wall motion change its character.

3. EXPERIMENTAL RESULTS AND CONCLUSION

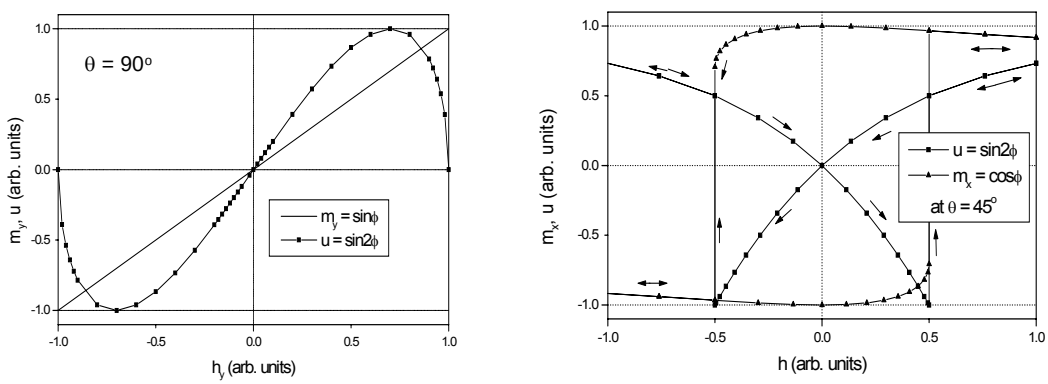
The theoretical curves in Fig. 2 and 3 are based on the uniform rotation of the magnetization in the applied magnetic field. But the real magnetization processes are more complicated. The uniform rotation takes place at relatively strong applied field $h >> 1$ beside the asteroid. If the magnetic field is applied in the EA direction or in the vicinity to this direction magnetization reversal takes place through wall motion whereas

for the magnetic field enclosed normally to the EA magnetic domains with alternative magetization arise in the film. If $h < 0.5$ on observe domain wall motion. That is way the one domain model describes the behaviour of the magnetization and the PHE qualitatively. Par example no observe the sharp jumps in the angular dependence of the PHE (fig. 4a) or the field dependence of the PHE (Fig. 4b) in thin $Ni_{80}Fe_{20}$ film. The complicated magnetic behaviour of the sample leads to an asymmetry in the Hall curves.



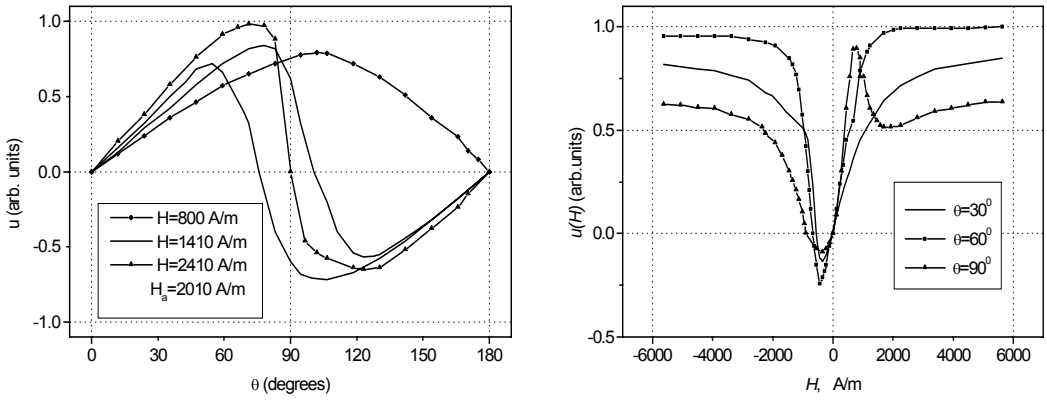
a) b)

Figure 2. a)Angular and b)field dependencies of the Hall voltage obtained by the numerical calculations



a) b)

Figure 3. Magnetization and the Hall voltage versus h at a) $\theta = 90^o$ and b) $\theta = 45^o$.



a) b)

Figure 4. Experimental curves of the a) angular and b)field dependencies of the Hall voltage in $Ni_{80}Fe_{20}$ thin magnetic film.

ACKNOWLEDGEMENTS

We acknowledge the financial support from the National Fund for Scientific Research in Bulgaria.

REFERENCES

[1] E.C. Stoner and E.P. Wohlfarth, “A mechanism of magnetic hysteresis in heterogeneous alloys”, *Philosophical Transactions of the Royal Society,* A248 (1948) 599.

[2] H.J. Oguey, ”Theoretical hysteresis loop of the magnetic films”, *Proceedings of IRE* 48 (1960) 1165.

[3] K. Schüller, “Drehmomenten Kurven und Rotationhysterese bei einahsinger ferromagnetischer Anisotropie”, *Zeitschrift für Metallkunde,* 52 (1961) 492.

[4] Z. Sczaniecki, R. Gontarz, W. Kwiatkowski and H. Ratajczak, “Voltage characte-ristics of planar galvanomagnetic effect in thin ferromagnetic films” *Physica Status Solidi* (a) 7 (1971) 597.

[5] I.D. Mayergoyz, *Mathematical Model of Hysteresis,* Springer-Verlag, N.Y.(1991)

.