THREE DIMENSIONAL STUDY ON THE ANGULAR DISPERSION OF ANISOTROPY IN MnBi FILMS

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Abstract:

A new method for three dimensional study of the angular dispersion of anisotropy in MnBi films have been applied. The direction of the average magnetic moments coincides with the axis of a circular cone making an angle (Θ) with the Z-axis (normal to the film plane).

An external magnetic field (16 KOe) parallel to the film plane was applied with different angles (Ø) w.r.t an arbitrary reference axis lies in the film plane. Using magnetooptical Faraday system with high resolution, the magnetic structure of certain area in the film was observed and recorded on photographic plate.

The projection of the circular base of the cone on the film plane must be of elleptical form. A computer program was constructed to identify this ellipse using the magnetooptical experimental results. The theoretical calculated data based on this method agrees very well with the experimental results.

The appearence of anisotropy phenomena in the film plane which had been reported before can be explained by applying the suggested distribution of moments.

Introduction:

It was established that the magnetization (M) is not uniformaly directed throughout a real uniaxial anisotropic ferromagnetic films, but it sufferes along the easy axis (EA) a local angular deviations from its average direction. The existence of angular dispersion of the anisotropy in ferromagnetic MnBi films has been studied before (1). It was suggested that the spliting angle represents a solid angle around the Z-axis (normal to the film plane).

It is worthy to mention that the magnetization is MnBi films is not strictly directed towards the Z-axis, but it is inclined by a certain angle (θ) on the Z-axis (2-4). This inclination appears as a result of the existance of residual internal stresses in the film after the preperation process (5). Since the magnetostriction coefficient of intermetallic compound MnBi is relatively high ($\simeq 5 \times 10^{-4}$) (6,7), then the magnetoelastic contribution to the energy of the system has a considerable effect on the equilibrium state of (M). The value of the internal stresses in MnBi films depends on the preperation parameters (the temperature of the substrate during the condensation of Bi and Mn, the diffusion annealing temperature,...etc (5). Though, the inclination angle (θ) will differ from one film to another depending on its preperation conditions.

The present work concerns with the study of the distribution of the angular dispersion of anisotropy in such ferromagnetic film in three dimensions taking into consideration the inclination of (M) on the Z-axis.

Experimental Technique:

The MnBi films were prepared by usual vacuum deposition method reported elsewhere (2) on glass substrate in circular from of 15 mm diameter and 800 Å thickness. The coercive force of the used film was 1.96 KOe.

The magnetic structure of the film was investigated by using magnetooptical Faraday system with high resolution and recorded in photographic plate. The ratio of the switched domains in a certain area in the film was evaluated by the weighing method of highly magnified photographic patteren of the magnetic structure with 2% tolerancy.

Results and Discussion:

The usual method to emphasize the presence of angular dispersion in permalloy films, where the magnetization (M) lies in the film plane, is to apply a magnetic field ($H\perp$) of amplitude more than 2 H_k (H_k is the anisotropic field of the film) towards the hard axis of magnetization (HA) to saturate the film in the field direction. As the value of the field ($H\perp$) is reduced the film is disintegrated to domains, where the moments in each neighbour domains are antiparallel and the film is finally demagnetized (8). The major difference between the permalloy film and the MnBi is that, the easy axis of magnetization of the later film is directed out the film plane. This means that this class of film possising a hard plane instead of hard axis of magnetization.

The previous mentioned method was applied to a MnBi film of one domain structure, which wasformed by a magnetic field of amplitude 4 KOe applied parallel to the (EA). Then a magnetic field ($H\perp$) of constant amplitude 16 KOe was applied parallel to the film plane with angle ($\emptyset$) measured relative to an arbitrary reference axis (RA) lies in the film plane. After that, the field ($H\perp$) is reduced to zero and the magnetic structure of a fixed certain area of the film was observed by magneto-optical Faraday system with high resolution. The film is saturated again to one domain structure and the field (H⊥) was applied with other angle (Ø) and the magnetic structure of the same selected area was magnetooptically investigated. The last process was repeated by varying the angle (Ø) 45° each time till 360°. Fig. (1) shows the magnetic structure of the fixed area in MnBi film after applying the field (H⊥) at different values of (Ø).

In these photographes a closs look can lead to the following important two facts:

i. The ratio of the switched domains, in which the irreversable magnetization jump was occured (the dark domains in Fig. 1), to the total domains in a certain area (ΔS/S) is a function of the angle (Ø). The following table shows the variation of the ratio (ΔS/S) with the angle (Ø) calculated from the photographes of Fig. (1).

Table (1)

The angle, Ø°	0	45	90	180	225	270
The ratio $\frac{\Delta S}{S}$, %	41.22	36.27	32.48	40.36	49.44	42.73

ii. There are a fixed switched domains in every two magnetic structures corresponding to any successive angles (Ø), meanwhile some domains disappeared from the structure and others appeared (see for example, the zone determined by the arrows in the exposure 1,2).

The obtained results, generally, are in agreement with that reported in (1), except the first fact reported above was egnored in the last study. The reason of egnoring the dependence of the ratio (ΔS/S) on the angle (Ø) in the last work could be due to the representation of (M) along the Z-axis (i.e Θ = 0) which leads to equiratio of (ΔS/S) independing on the angle (Ø). The recent studies on the remagnetization process of MnBi films undoutly confirm the inclination of (M) on Z-axis (2-4). Taking this inclination into consideration, Fig. (2-a) illustrates the schematic representation of the distribution of the moments in three dimensions. It is assumed that the moments of the sample are distributed in form of right circular cone, its axis OO' coincides with the average direction of the moments (M) and inclind by an angle (Θ) on the Z-axis. The apex of the cone represents the origin of the coordinates O. The circular base of the cone has the same inclination angle (Θ) on the X-Y plane, consequently its projection on the X-Y plane is an ellipse, where its centre O' of coordinates (α, β) w.r.t the prenciple axes X and Y (Fig. 2-b). The semi-major axis of the ellipse (A) is inclind by an angle ($Ø_o$) with the (RA) and equals the radius of the circular base of the cone, while the length of the semi-minor axis (B) depends on the angle (Θ).

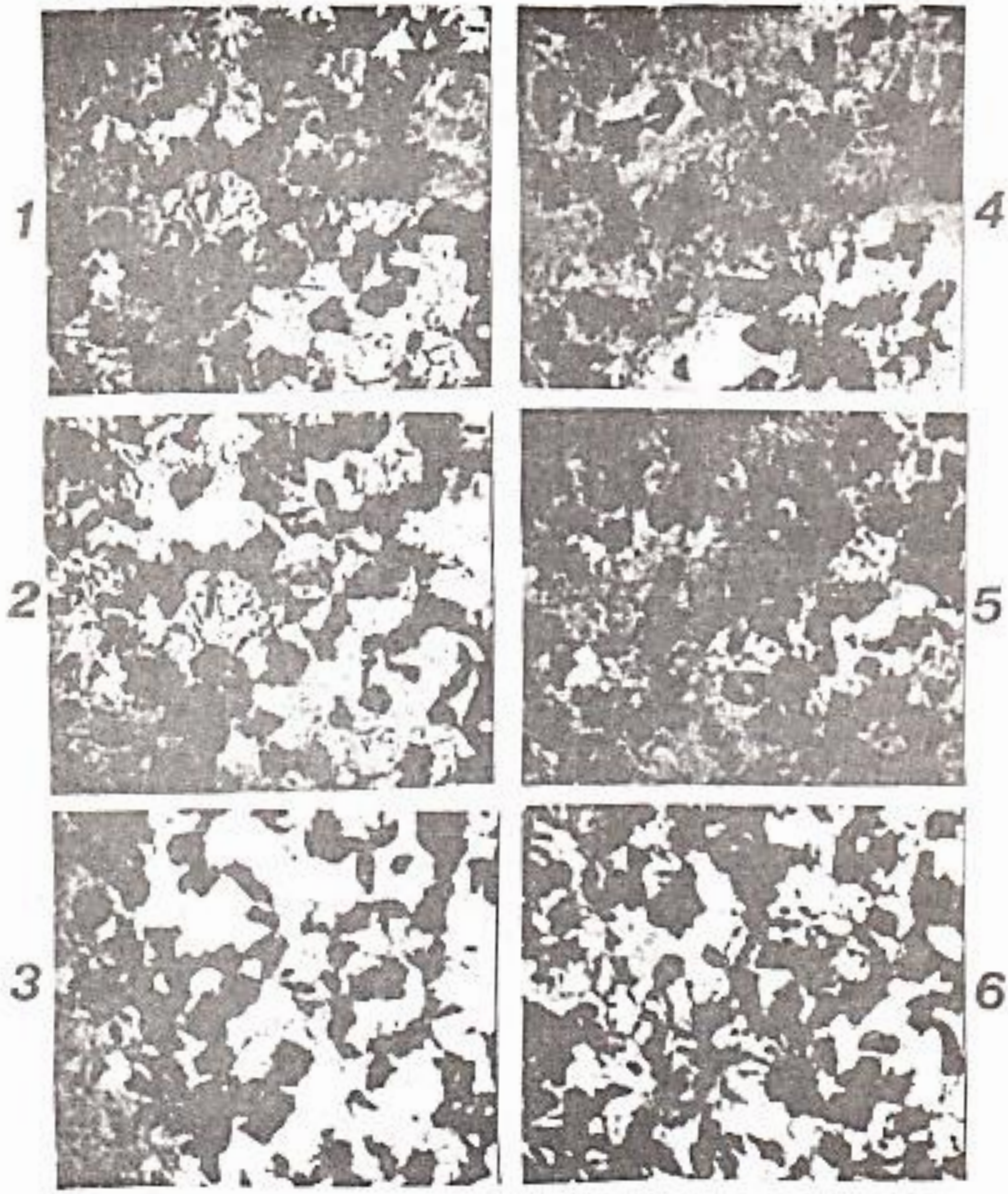

Fig. 1: Magnetooptical Faraday photographs of MnBi film after applying magnetic field (H = 16 KOe) at different angles (Ø) w.r.t the (RA):

1) Ø = 0° 2) 45° 3) 90°

4) 180° 5) 225° 6) 270°

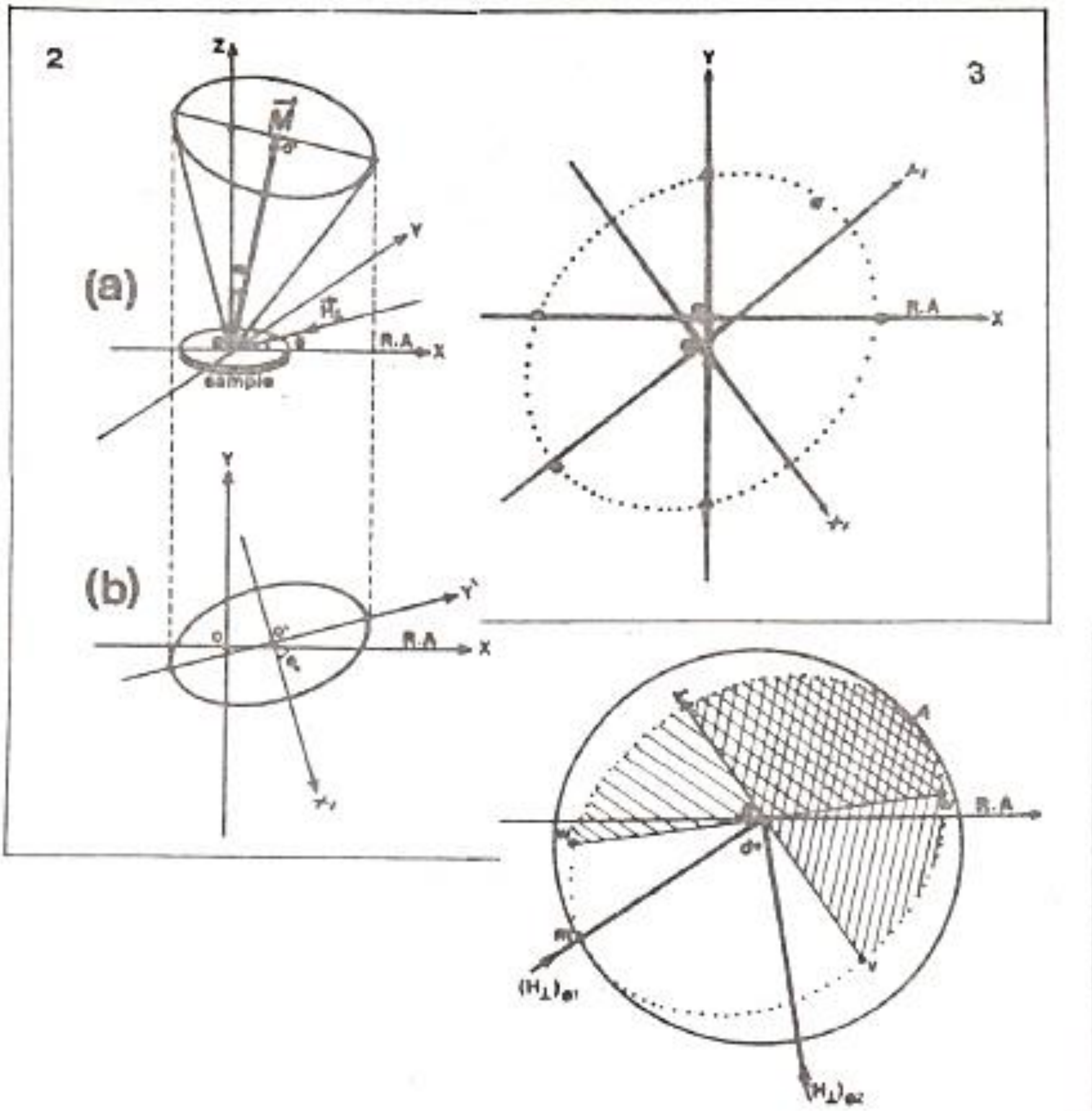

Fig. 2: (a) Schematic representation of the distribution of the moments in conical form.
(b) The projection of the circular base of thecone on X-Y plane.

Fig. 3: The theoretical ellipse obtained from analysing the coefficients of the general equation of conical section. The experimental data of table (1) are also plotted.

Fig. 4: The circular base of the cone obtained from the computer calculation of the elliptical sectors as a function of the angle (Ø) measured w.r.t the (RA).

Regarding to the general rule controlling the interaction between the magnetic field and the magnetic moments, the irreversible magnetization jump occured in domains in which the magnetic moments relative to the applied field are inclined by an angle more then 90° (8). Accordingly, on applying the field (H⊥) by different angles (Ø), then the corresponding values of the ratio (ΔS/S) must be distributed on the circumference of an ellipse which represents the projection of the conical base on the X-Y plane.

Considering the general equation of a conical section in the form:

$$aX_i^2 + 2b.X_iY_i + cY_i^2 + 2d.X_i + 2e.Y_i + f = 0 ,$$

and substituting in X_i, Y_i by the experimental results of (ΔS/S); tabulated in Table (1), where

$$X_i = (\Delta S/S)_i \cos Ø_i \;;$$

$$Y_i = (\Delta S/S)_i \sin Ø_i \;; \quad (i = 1 \text{ to } 6).$$

A computer program was constructed to solve the obtained six equations and the numerical values of the equation coefficients were determined. Fig. (3) represents the obtained ellipse in the form of the last equation with the following coefficients: a = 1, b = - 0.23996, c = 1.14329, d = 0.19330, e = 26858 and f = -1581.1583. The parameters of the obtained ellipse can be evaluated by analysing the equation coefficients. The obtained results are as follows: A = 44.38644, B = 34.98251, $Ø_o$ = - 53.3122° and the coordinates of the centre α = - 1.5890, β = - 5.8164. The inclination angle (Θ) can be calculated from the relation:

$$\Theta = \arccos (B/A) ,$$

which has been found to be equal to 37.98°.

The experimental data are plotted on the same axes of Fig. (3) after transformation from polar to cartesian coordinates. It is very remarkable noticing the good coincidence of the experimental results with the suggested conical distribution form of the moments.

According to the suggested distribution of moments in the present work, the ratio of the interacting moments with the field $(H\perp)_{Ø1}$ applied by angle (Ø1) w.r.t the (RA), Fig. (4), was determined using the following steps:

i. Representing the applied field by a straight line (mO) directed towards the origin of the coordinates (O) and making an angle (Ø1) with the (RA).

ii. Defining the equation of the line vOv' which is normal to the field direction (mO). This line determine the elliptical sector vAv' which its area is proportional to the number of moments oriented by an angle more than 90° with the applied field.

iii. Solving the equation of the line vOv' with the equation of the obtained ellipse, the coordinates of the intersecting points v and v' are found.

iv. Using these two points, the area of the elliptical sector vOv' (ΔS) was evaluated paying a great attention to the geometry of the considering area.

v. Normalizing the obtained area by deviding on the area of the great circle of the ellipse (S).

On applying the same field by other angle (Ø2), $(H\perp)_{\text{Ø}2}$, the new ratio of switched moments is represented by the area of the elliptical sector wAw'. Other computer program was constructed to calculate the different values of the ratio ($\Delta S/S$) as a function of the angle (Ø) in the range from zero to 360°. The obtained results showed that, the ratio ($\Delta S/S$) is in a circular relationship with the angle (Ø). The radius of the circle equals to the value of the semi-major axis of the ellipse and its centre coincides with the centre of the ellipse (solid circle in Fig. 4). Since the obtained circle is a great circle for the calculated ellipse, which represents the projection of this circle on the X-Y plane by an angle (θ), then this circle must be the circular cone base of the distribution of the moments. This results strongly support the suggested model. Moreover, comparing the two elliptical sectors vAv' and wAw' it can easly be noticed that, there is a fixed zone in which the moments are switching in the two cases (wAv), and for every direction of the applied field one sector disappears (vw) while other appears (v'w') which explain the Faraday observations illustrated in Fig. (1) very well.

According to the suggested distribution of the moments, the radius of the cone base should equal to 50 (in percentage) to confirm the uniform distribution of the moments around the mean direction. The reduced value of the obtained radius (44.38) is due to applying a magnetic field, which is limited in our laboratory to 16 KOe, less than $2H_k$ of the investigated film. Since the anisotropy in MnBi films posseses an amplitude dispersion follows the Gaussian form (4), then the ratio of the effective moments to the total moments should be calculated from the integration of:

$$\frac{1}{\sigma\sqrt{2\pi}} \int_0^{H\perp} \exp - \frac{1}{2} \left(\frac{H-\bar{H}_k}{\sigma}\right)^2 dH,$$

where $H\perp$ = 16 KOe, H_k = 14.07 KOe, σ = 1.985. This ratio equals to 0.88877. This results leads to the reduction of the radius of the circular base from 50 to 44.438, which is very close to the obtained radius in the present calculation (44.38).

The direct conclusion of using the distribution of the moments in a conical form around an inclinded axis leads to the creation of an anisotropic behaviour in the X-Y plane, which explains the observed anisotropic phenomena in the film plane reported in a previous article (3).

From the previous discussion, as a final conclusion, it could be stated that the magnetization of the MnBi ferro-magnetic film posseses angular dispersion and distributed in a right circular cone its axis coincides with the average direction of the moments which inclinde by a certain angle on the Z-axis. This form of distribution can be applied for all ferromagnetic films having a magnetic moment egressing from the film plane.

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