Modeling of Magnetic Properties of Iron Thin Films Deposited by RF Magnetron Sputtering using Preisach Model

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Abstract: Iron thin films were deposited on glass substrates using RF magnetron sputtering and their optimal deposition conditions were determined. The structure properties were analyzed using x-ray diffraction (XRD) and their magnetic hysteresis loops were obtained by Vibrating Sample Magnetometer (VSM) at room temperature. In this situation, the magnetic field is either parallel or perpendicular to the substrate plane. The main contribution of this work is to characterize the thin layers and present a mathematical model that can get best fit of the characteristics B(H). By using Preisach model, good agreement was obtained between theoretical and experimental results in both cases.

Keywords: Iron (Fe); RF magnetron; thin layer; XRD; VSM; Hysteresis; Preisach model.

1 Introduction

Iron (Fe) is an interesting and attractive material because of its distinguished properties like the spontaneous magnetization in the absence of the magnetic field at room temperature [1–3]. Fe thin films have many application especially electronics and magnetic areas such as digital storage and magnetic sensor technology [4–5].

Several deposition techniques have been used for Fe thin films preparation such as: sputtering [6], pulsed laser deposition [7], electron beam evaporation [8], chemical bath deposition [9], molecular beam epitaxy [10] and ion bombardment [11].

In a recent study about magnetic properties of iron [10], Preisach model was applied to help understand the effect of high concentration of volumetric

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defects due to decreasing grain size in Fe thin films deposited by molecular beam epitaxy. In another study about Galfenol rods (iron-gallium alloy) [12], a model based on the mechanical strain theory and Jiles-Atherton model was developed to quantify the magnetization energy of the Galfenol rods and it was concluded that the hysteresis of the response increases with the rising of the excitation frequency. It appears from the literature survey that rare studies have been devoted to Fe thin layers prepared by RF magnetron sputtering and modeling of these thin layers using Preisach model.

The present study deals with the deposition of Fe thin layers on glass substrates using RF magnetron sputtering, characterization of their structural and magnetic properties and modeling of their magnetic properties using Preisach model. From the main parameters of the experimental hysteresis loops, Preisach formalism is applied to reproduce these hysteresis loops theoretically in both cases where the magnetic field is either parallel or perpendicular to the substrate plane. Finally, a comparison between the experimental and theoretical results gives an idea about the efficiency of the model to predict the magnetic properties of the studied material.

2   Experimental Protocol

Fe thin films are deposited on glass substrates using RF magnetron sputtering technique.

The cleaning procedure consisted of commercial soap and then an ultrasonic bath following these sequences: 20 mn in ethanol, rinse in heated deionised water (90°C), 20 mn in acetone followed by rinse in deionised water and finally dried with nitrogen.

To study the preparation conditions, the parameters such as RF power, the target-substrate distance and the pressure of gas were varied. The preliminary results made it possible to get some decisive information about these parameters which gave: 90W, $1.25 \ 10^{-2}$ mbar and 40 mm for Power, pressure and target-substrate distance respectively, Fig. 1.

Targets of purity 99.99% were pre-sputtered for 5 mn to remove any surface contamination, and the shutter is in place to prevent the substrate from being exposed. The substrate holder was maintained in rotation during pulverization in order to obtain uniform and homogeneous films.

The structure property analysis of Fe films was carried by x–ray diffractometer type Phillips X'Pert Pro which uses Cu Kα radiation (λ=1.5418 Å). The XRD pattern from the sample is shown in Fig. 2. The peak at 44.78 clearly matches the [1 1 0] peak of body centered cubic (bcc) iron with a cell parameter of 2.860 Å [13].
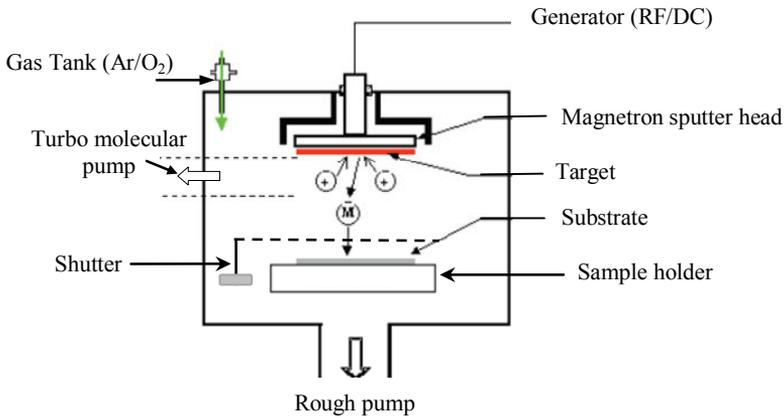
Fig. 1 – *Schematic illustration of magnetron sputtering system.*
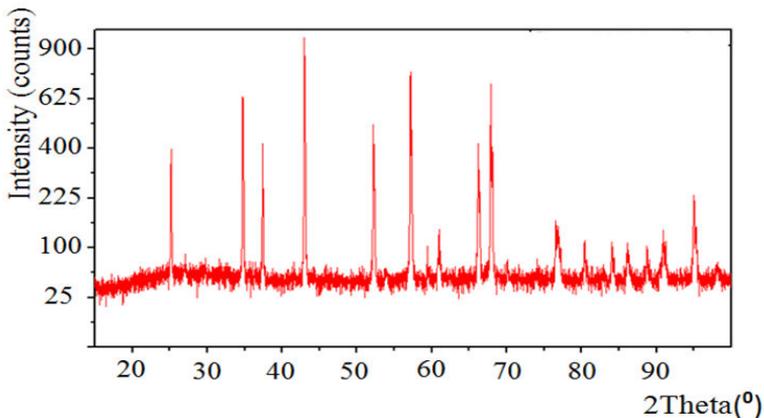
Fig. 2 – *x-rays spectrum of the sample.*

The magnetic measurements were carried out using a VSM type EV9 which can generate a magnetic induction of strength up to 2.6 Tesla parallel and perpendicular to the substrate plane. Fig. 3 shows the hysteresis loops for both parallel and perpendicular cases. These results show that the sample magnetisation is oriented parallel to the plane of the substrate. Indeed, the application of a magnetic field parallel to the substrate plane leads to the magnetic saturation of the sample which corresponds to an induction of 1.38 T. However, a magnetic field of 117 kA/m is not high enough to saturate the same sample in the direction perpendicular to the plane of substrate [14]. These results are in agreement with those reported in literature [15].

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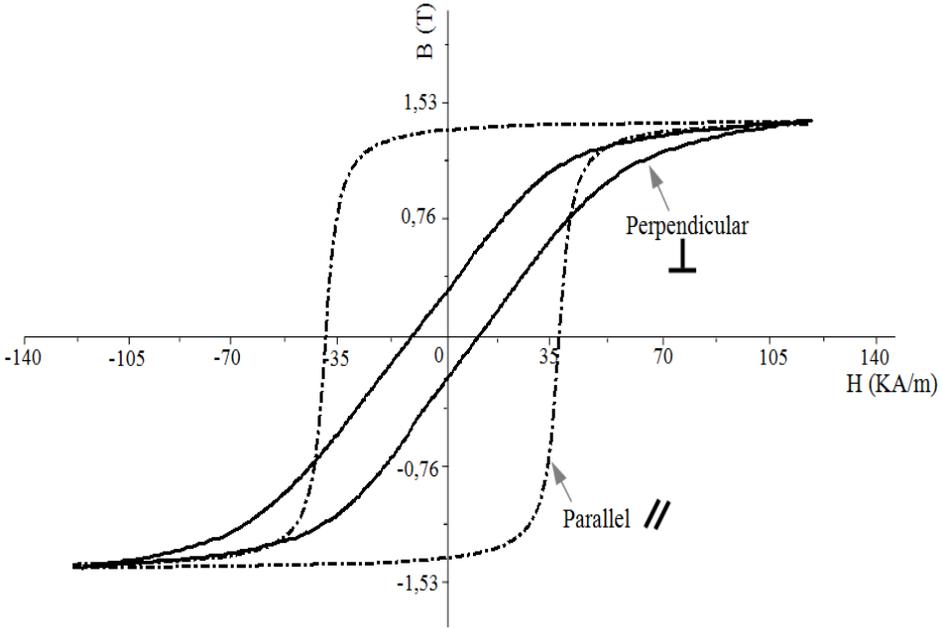
Fig. 3 – *Hysteresis loops of thin layer of Fe (Applied magnetic fields are parallel and Perpendicular to the substrate)*

3 Preisach model

3.1 Definition of the model

A number of methods to model ferromagnetic hysteresis are available in literature. The well known models are: Preisach model proposed by Ferenc Preisach in 1930's [16] and Jiles-Atherthon model from middle 1980's [17, 18]

Preisach defined the magnetic state of a magnetic material, at time t, by two possible states of magnetisation ($M = +1$ and $M = -1$), that is a rectangular elementary cycle on the input-output diagram. The latter is characterised by the inversion fields of α and β (with $\alpha \geq \beta$) for which there is an irreversible transition from the high state ($M = +1$) to the low state ($M = -1$) and vice versa. Hence, α and β correspond to up and down switching values of the input, respectively.

The calculation of total magnetisation requires knowledge of the statistical distribution of the elementary cycles. This function is called Preisach function [19, 20]. Assuming the input and output variables as function of time, the Preisach function of magnetisation resulting from the application of an $H(t)$ field is given by:

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$$M(t) = \iint \rho\ (\alpha,\beta)\ \Phi_{\alpha,\beta[H(t)]}\,d\alpha\,d\beta \qquad (1)$$

with: (the value is (+1) if $H = \alpha$ and (–1) if $H = \beta$); $\rho\ (\alpha,\beta)$: density function - also referred to as Preisach measure, it depends on the nature of the material; $\Phi_{\alpha,\beta}\left[H(t)\right]$: operator associated to the magnetic entities referred to as elementary Preisach hysteron operator [21, 22].

3.2 Geometrical Interpretation of the model

It has been noticed that there is one-to-one correspondence between operators $\Phi_{\alpha,\beta}\left[H(t)\right]$ and points (α,β) situated on the half plane $\alpha \geq \beta$.

Fig. 4 shows the surface (*S*) which can be divided into two parts *S*+ and *S*– separated by the boundary *L*(*t*), which is time dependent. The surface *S*+(*t*) represents all the entities whose is state of magnetisation is (+1), *S*–(*t*) represents those with state of magnetisation (–1) [23].

Equation (1) can then be written in the following form:

$$M(t) = \iint_{S+} \rho(\alpha,\beta)\,d\alpha\,d\beta\ -\ \iint_{S-} \rho(\alpha,\beta)\,d\alpha\,d\beta. \qquad (2)$$
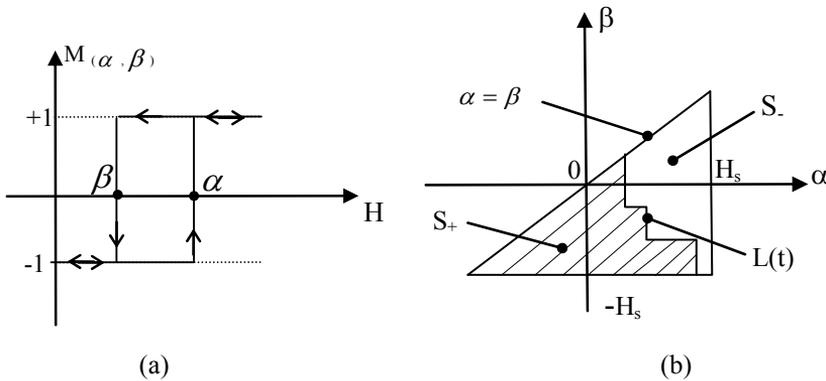
Fig. 4 – *Plane of Preisach* (a) *Elementary cycle;* (b) *unspecified magnetic state.*

3.3 Distribution function

The complete determination of the Preisach model requires the knowledge of the density function $\rho\ (\alpha,\beta)$, which is the basis for the calculation of the total magnetization. Therefore, at time t, two approaches which can explain the magnetization phenomenon in this structure. The first approach relies on extensive experimental hysteresis loops while the second consists of

approximating real loops through some analytical function. The second approach is considered in the present study [20, 24].

3.4 Analytical approach

Several analytical expressions can be used. One of these approximations is Lorentz function given by [19, 20]:

$$\rho\,(\alpha,\beta) = \frac{K}{\left[1+\left(\dfrac{\alpha}{H_C}-(0.5)\right)^2\right]\left[1+\left(\dfrac{\beta}{H_C}+(0.5)\right)^2\right]}, \tag{3}$$

where K is a fitting parameter of standardisation in order to have $M(Hs(t)) = Ms$ and H_c is the coercitive field.

For a better approximation of the experimental loop, the Lorentzian function is modified by adding parameters. This function takes the form [25]:

$$\rho\,(\alpha,\beta) = \frac{K\,a^2}{\left[a+\left(\dfrac{\alpha}{H_C}-b\right)^2\right]\left[a+\left(\dfrac{\beta}{H_C}+b\right)^2\right]}. \tag{4}$$

The experimental results showed that the two parameters a and b depend on the nature of the material, i.e. remnant induction, the coercitive field and the permeability of the material. A fitting of the parameters a and b is necessary to get a better understanding of $B(H)$ behavior. The parameters a and b are defined as follows [24, 25]:

$$a \in \Re_+^* \text{ and } b \in \left[1\,,\,\frac{Hs}{Hc}\right].$$

The obtained values for parameters *a*, *b* and H_c are 0.00021, 1.00238 and 38 kA/m respectively in the parallel situation and 0.95973, 1.08491 and 10.42 kA/m in the perpendicular case.

3.5 Modified mathematical formulation

The Preisach model and the modified Lorentz function yield the following expression:

$$M(t) = M_{i-1}(t) \pm 2\iint_D \frac{Ka^2}{\left[a+\left(\dfrac{\alpha}{H_C}-b\right)^2\right]\left[a+\left(\dfrac{\beta}{H_C}+b\right)^2\right]}\,d\alpha\,d\beta\,, \tag{5}$$

with*: M_{i-1}* the previous magnetisation moment.

This formulation makes calculation easier.

3.6 Modeling of the descending branch of major loop

This branch is obtained by starting from the positive saturated state, i.e. the plane of Preisach pertaining to those magnetic entities whose state of magnetization is (+1), therefore the plane of Preisach is entirely equal to *S*+.

The magnetization is written as follows [25]:

$$M(t) = M_{i-1}(t) - 2 \int_{H(t_{i-1})}^{H(t)} \left[\frac{Ka\sqrt{a}H_c}{a + \left(\frac{\beta}{H_c} + b\right)^2} \left\{ \arctan\left(\frac{1}{\sqrt{a}}\left(\frac{H_S}{H_c} - b\right)\right) - \right. \right.$$

$$\left. \left. - \arctan\left(\frac{1}{\sqrt{a}}\left(\frac{\beta}{H_c} - b\right)\right) \right\} \right] d\beta. \tag{6}$$

3.7 Modeling of the ascending branch of the major loop

The branch is obtained by starting from the state of the negative saturation. Initially, the total surface of the plane of Preisach corresponds to surface S-. A constant and increasing field is applied to increase S+, until positive saturation magnetization is reached [16, 20].

The major loop of the ascending branch is given by [25, 26]:

$$M(t) = M_{i-1}(t) + 2 \int_{H(t_{i-1})}^{H(t)} \frac{Ka\sqrt{a}H_c}{(a + (\frac{\alpha}{H_c} - b)^2)} \left[\left\{ \arctan\left(\frac{1}{\sqrt{\alpha}}\left(\frac{\alpha}{H_c} + b\right)\right) - \right. \right.$$

$$\left. \left. - \arctan\left(\frac{1}{\sqrt{\alpha}}\left(\frac{-H_s}{H_c} + b\right)\right) \right\} \right] d\alpha. \tag{7}$$

4 Experimental Validation of the Preisach model

In order to validate the Preisach model, tests were carried out taking in consideration both cases. By comparison of experimental and theoretical results as shown in Figs. 5 and 6, it can be seen that there is a good fit between the experimental cycles and those generated by the model for a maximum field of 117 kA/m. It is possible to draw a decisive conclusion that Preisach model is a powerful tool to predict magnetic properties of ferromagnetic materials such as iron.
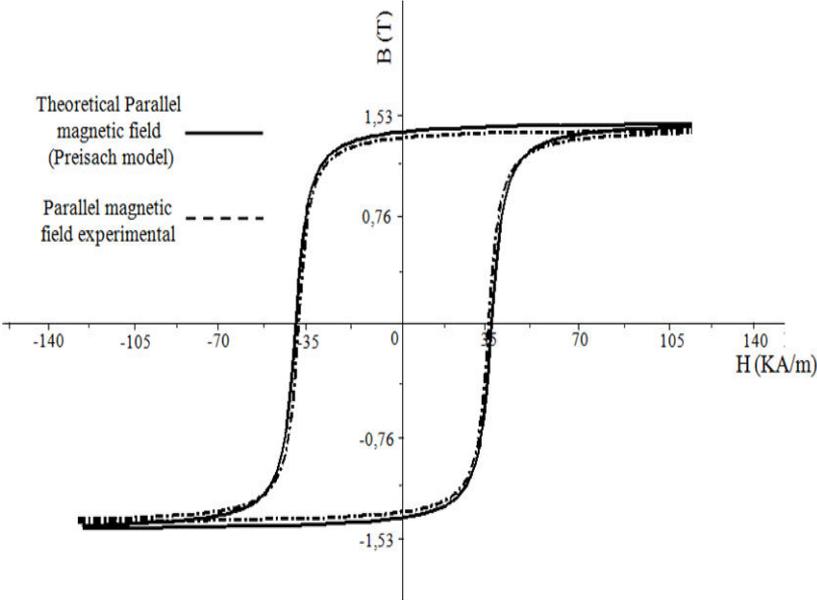
Fig. 5 – *Effect of parallel magnetic field (experimental and theoretical).*
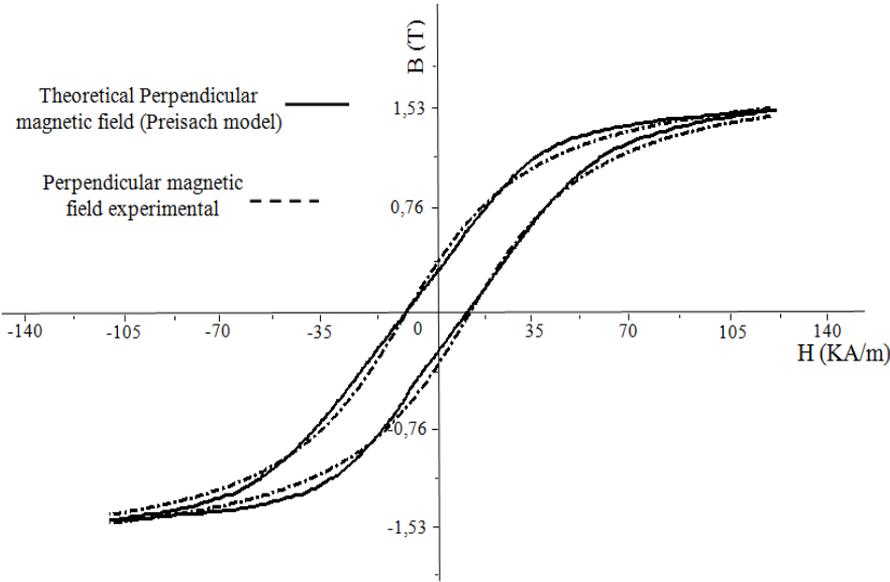
Fig. 6 – *Effect of perpendicular magnetic field (experimental and theoretical).*

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5   Conclusion

In the present study, thin layers of iron were prepared and studied. The approach adopted allows to characterize their magnetic properties at room temperature. In addition, *x*-ray diffraction allowed also to get a better information about their structural properties. The experimental results obtained showed anisotropy properties in these layers prepared under the optimal conditions considered. It was also possible to generate theoretical curves corresponding to hysteresis cycles by applying Preisach model provided the knowledge of few parameters namely: the remanent and saturation inductions, the maximum and coercive fields. The study showed good agreement between the applied Preisach model and experimental results. It is worth mentioning that Preisach model can be used to generate data base which are a reliable alternative for artificial neural networks to predict magnetic properties of materials.

6   References

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