

Transfer Curves Characterization of Magnetic Tunnel Junction Based on Hybrid Hysteresis Model

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A characterization method for predicting the transfer curves of magnetic tunnel junction under applied field with different directions is proposed. By combining the Stoner-Wohlfarth model with the energy-based model, the coherent rotation and wall displacement process of domains in free layer are accounted simultaneously. The comparison between measured and calculated resistance shows that the model can accurately predict the magnetic properties of free layer and the transfer curves of magnetic tunnel junction.

Index Terms—Magnetic tunnel junction, tunnel magnetoresistance, magnetic hysteresis, magnetic anisotropy.

I. INTRODUCTION

To improve the linearity, the design of Magnetic Tunnel Junctions (MTJ) typically deploys the cross configuration of easy axes between the free layer and reference layer, and applies an internal bias field to eliminate hysteresis effect [1]-[2]. However, high sensitivity and wide linear range contradict each other, requiring a large number of experiments to support the optimal design of MTJ. Therefore, it is necessary to investigate the characterization method of MTJ transfer curves.

The Stoner-Wohlfarth (S-W) model assumes that each ferromagnetic layer in MTJ can be regarded as a magnetic single-domain and edge effects can be neglected, only considering the coherent rotation of magnetic domain. This model provides a method for predicting the trend of linearity variation [3]-[4]. In contrast, the real MTJ has a multi-domain structure, where domain rotation and domain wall displacement coexist. Therefore, the S-W model is incapable of accurately modeling the transfer curve. To address this issue, this paper combines the S-W model with the energy-based (E-B) model that considers domain wall displacement to establish a hybrid model [5]-[6]. The magnetization direction of free layer is calculated by this hybrid model and accurate prediction of the MTJ transfer curves is then achieved.

of exchange bias field. Under the applied field $\mathbf{H}$, the magnetization of FL, $\mathbf{M}_F$, rotates and the resistance of MTJ varies with the angle between $\mathbf{M}_F$ and $\mathbf{M}_R$. That is, only the variation in magnetization state of FL is considered in this work.

A. Stoner-Wohlfarth (S-W) model

Based on the S-W model, the energy density of FL can be expressed as

$$E = -\mu_0 M_F H \cos(\varphi_F - \theta + \alpha) + \frac{1}{2} \mu_0 M_F H_{an} \sin^2 \varphi_F \quad (1)$$

where μ_0 is the vacuum permeability, φ_F the direction of $\mathbf{M}_F$, α the direction of $\mathbf{H}$ and H_{an} the anisotropy field. Under the applied field, φ_F can be obtained by solving $\partial E / \partial \varphi_F = 0$ and satisfying the condition that the $\partial^2 E / \partial \varphi_F^2 > 0$.

B. Hybrid Hysteresis Model

The applied field $\mathbf{H}$ is decomposed into reversible field $\mathbf{H}_{re}$ and irreversible field $\mathbf{H}_{ir}$ in the E-B model. To account for the effect of internal bias field $\mathbf{H}_{bi}$ in MTJ, the effective field $\mathbf{H}_{eff}$ ($\mathbf{H}_{eff} = \mathbf{H} + \mathbf{H}_{bi}$) is used as the model input, namely

$$\mathbf{H}_{eff} = \mathbf{H}_{re} + \mathbf{H}_{ir} \quad (2)$$

II. METHOD

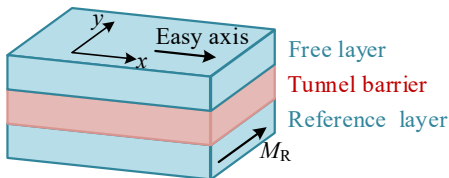


Fig. 1. Structure of MTJ device.

The structure of MTJ device is shown in Fig. 1, which consists of free layer (FL), tunnel barrier and reference layer (RL). The easy axis of FL is set to x-axis. The magnetization of RL, $\mathbf{M}_R$, is fixed in the hard-axis direction under the influence

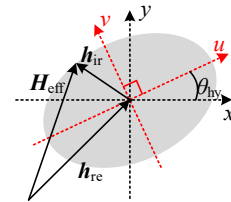


Fig. 2. Illustration of the hysteron used in the hybrid hysteresis model.

By adopting a series of elliptic hysterons with the same rotation angle θ_{hy} , as shown in Fig. 2, this model can characterize both hysteresis anisotropy and domain wall displacement. For one hysteron, half of the major axis is defined as κ and half of the minor axis is defined as $L\kappa$. Therefore, its

irreversible field $\mathbf{h}_{ir}$ is known, and the unknown reversible field $\mathbf{h}_{re}$ at each calculation step is updated by

$$\mathbf{h}_{re} = \begin{cases} \mathbf{h}_{re}, & |\mathbf{H}_{eff} - \mathbf{h}_{re}| < h_{ir} \\ \mathbf{H}_{eff} - h_{ir} \frac{\mathbf{H}_{eff} - \mathbf{h}_{re}}{|\mathbf{H}_{eff} - \mathbf{h}_{re}|}, & |\mathbf{H}_{eff} - \mathbf{h}_{re}| \geq h_{ir} \end{cases} \quad (3)$$

It is evident $\mathbf{h}_{re}$ and $\mathbf{h}_{ir}$ follow (2), and $\mathbf{H}_{re}$ is obtained by summing the outputs of all hysterons with a probability density function related to κ .

In the original E-B model, the amplitude of $\mathbf{H}_{re}$ is used as the input to the Langevin function to calculate the magnetization, and it was assumed that the magnetization direction is the same as $\mathbf{H}_{re}$. In this case, when an alternating magnetic field is applied, the predicted magnetization direction of the model is parallel to the applied field, which does not conform to the rotational motion process of MTJ's magnetization direction. In this paper, we adopt the S-W model mentioned in Section. A instead of the Langevin function to propose a hybrid model. That is, taking $\mathbf{H}_{re}$ as the input of the S-W model, and the direction and amplitude of the magnetization are calculated by S-W model simultaneously.

C. Modeling of transfer curves

After obtaining $\mathbf{M}_F$ by the hybrid model, the resistance of MTJ is given by [7]

$$R = R_0 + \frac{R'}{1 + P^2 \mathbf{M}_F \cdot \mathbf{M}_R} \quad (4)$$

where R_0 is the resistance not related to tunneling, R' the resistance related to tunneling at $\mathbf{M}_F \cdot \mathbf{M}_R = 0$ and P the spin polarization of tunneling electrons.

III. APPLICATION

A. Identification

There are three types of parameters included in the transfer curves calculation: parameters for the S-W model, parameters for the E-B model, and parameters for the resistance function. These parameters can be identified together by the measurements of the resistance of MTJ under alternating field that applied in different directions. The selection of initial values and the derivation of theoretical ranges of parameters will be detailed introduced in the full paper.

B. Validation

The comparison between the measured results and the calculated results is shown in Fig. 3. ΔR is the percentage change relative to the minimum resistance. It can be seen that both the hysteresis and anisotropy properties exhibit good consistency with the measured results.

IV. CONCLUSION

This paper extends the study of MTJ transfer curves from qualitative analysis to quantitative analysis. The S-W model

which can represent the coherent rotation of single domain is embedded into the E-B model that can characterize the displacement of domain walls between multiple domains. Although the magnetic properties of MTJ free layer, which is difficult to obtain, are not directly tested, the good consistency of the resistance comparison proves the correctness of the proposed method.

It is worth noting that the proposed method takes into account the internal bias field and the angular deviation between the magnetization direction of the reference layer and the easy axis of the free layer. These factors are difficult to quantitatively describe in the manufacture process of MTJ, and the proposed method has certain guiding significance. Subsequent work will use this model to further study the optimal configuration method of bias field for improving sensitivity and linearity

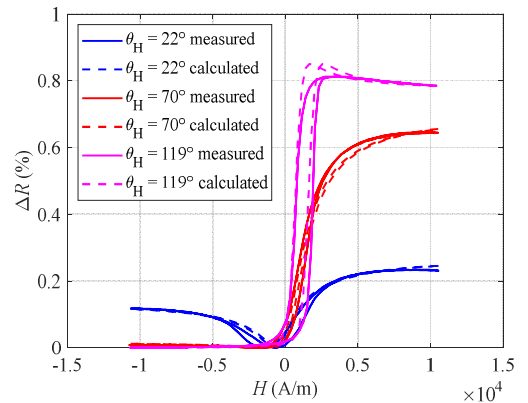


Fig. 3. Comparison between the measured transfer curves and the ones calculated by proposed model.

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