Reversible susceptibility studies of magnetization switching in FeCoB synthetic antiferromagnets

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In this paper we present a study of switching characteristics of a series of synthetic antiferromagnet (SAF) structures using reversible susceptibility experiments. Three series of SAF samples were considered in our study with (t1, t2), the thickness of the FeCoB layers of (80 nm, 80 nm), (50 nm, 50 nm), and (80 nm, 20 nm) and with the interlayer of Ru ranging from 0 to 2 nm. A vector vibrating sample magnetometer was used to measure the hysteresis loops along the different directions in the plane of the samples. The reversible susceptibility experiments were performed using a resonant method based on a tunnel diode oscillator. We showed that the switching peaks in the susceptibility versus field plots obtained for different orientations of the applied dc field can be used to construct the switching diagram of the SAF structure. The critical curve constitutes the fingerprint of the switching behavior and provides information about micromagnetic and structural properties of SAF which is an essential component of modern magnetic random access memories.

Introduction

Synthetic antiferromagnet (SAF) structures are very important in designing modern spintronic devices due to their reduced shape anisotropy and reduced switching fields and they have also important application as soft underlayer (SUL) in perpendicular magnetic recording media due to suppressed noise. Magnetic random access memory (MRAM) is an important example of such device where the use of SAF structure is essential. Current problems in increasing the scalability and decreasing the error rate of MRAM devices are closely connected to the switching properties of the SAF structures. These problems can be overcome with a MRAM writing scheme, toggle MRAM, proposed by Savchenko et al. 1 which increases the operating margin of the MRAM elements. In the toggle writing procedure the MRAM free layer has a SAF structure and word and digit fields are applied at 45° with respect to the easy axis of the magnetic anisotropy of the MRAM element. The toggle switching is achieved using a suitable time sequence for word and digit fields which rotate the effective magnetic moment vector of the MRAM cell. Recently, several studies were devoted to the use of the writing scheme in order to optimize the magnetic parameters for toggle MRAM. The theoretical studies of the toggle writing mode in MRAM use the concepts of SAF critical curve which is a generalization of the well-known astroid from the coherent rotation model in the case of uniaxial anisotropy. The critical curve for SAF structure is obtained as the envelope of the field trajectories giving a constant angle to the magnetization of one of the two layers, leaving the other as a variable in the field plane. Depending on the coupling strength between the two ferromagnetic layers in SAF structure the critical curve evolves from a simple astroid at zero coupling to a more complicated critical curve for larger coupling field values. On the SAF critical curve (see Fig. 5 of Ref. 4) one distinguishes two parts: the critical field curve for saturation which is the outermost envelope of the constant angle contours and outside of which the magnetizations in two layers become parallel to each other and the critical curves for switching which are the inner envelopes. The toggle switching mode is achieved only for specific field trajectories in the field plane with respect to
the inner envelopes. Consequently, knowing the configuration of the SAF critical curve is of great importance in order to control its switching characteristics.

Several papers dealing with theoretical aspects of the critical curves for SAF systems7–9 were recently published but there are no published experimental results in which the critical curves are determined for antiferromagnetically coupled magnetic layers. One of the reasons is that switching critical curve is more complex in the case of SAF than in the case of a single magnetic layer. It is well known that in the case of the astroid (or in the general case of the critical curve for a single magnetic layer) the tangent to the astroid passing through the tip of the external applied field vector \( \mathbf{h} \) in the \((h_x, h_y)\) plane gives the orientation of the magnetization at equilibrium for that particular field value and direction.7 Moreover, the parameter value in the tangent point of the parametric critical curve has a value equal to the angle that gives the orientation of the magnetization with respect to the easy axis. For SAF the tangent at the critical curve passing through the point representing the external applied field in the \((h_x, h_y)\) plane gives the orientation of the first layer \( \theta_1 \) while the orientation of the second layer \( \theta_2 \) can be read from the position of the tangent point on the critical curve. The relative low magnetic signal associated with thin magnetic layers in the SAF structure is another reason that makes the experimental measurement of SAF critical curves difficult. We successfully measure the experimental switching critical curve of different magnetic systems with various magnetic anisotropies,8,9 using reversible susceptibility (RS) experiments based on a resonant method. In this paper we will use the same experimental method to study the switching characteristics of a series of SAF structures.

**EXPERIMENT**

The samples under study were SAF, FeCoB/Ru/FeCoB with a C overcoat layer and were deposited at room temperature with dc magnetron sputtering with a base vacuum pressure below 3 \( \times 10^{-5} \) Pa. Three series of SAF samples were produced, with the \((t_1, t_2)\) thickness of the FeCoB layers (80 nm, 80 nm), (50 nm, 50 nm), and (80 nm, 20 nm) and with the Ru interlayer thickness ranging from 0 to 20 Å. Hysteresis curves, along the different directions in the plane of the samples, were measured by a vibrating sample magnetometer (VSM). The reversible susceptibility experiments were performed at room temperature using a tunnel diode oscillator circuit. The samples were cut in 5 mm diameter disk coupons and were placed in the sensing coil with both ac and dc fields in the plane of the sample. The dc magnetic field was created by an electromagnet placed on a revolving stage with a protractor for measurement of the field direction. The reversible susceptibility signal was recorded for different orientations of the applied field with respect to the sensing coil axis. For a given orientation of the applied dc field with respect to the sensing coil axis the measured susceptibility signal is a combination of transverse and longitudinal susceptibilities. As it was shown previously in the case of a single thin film this composite susceptibility signal still preserves the same singularities characterizing the switching fields from transverse susceptibility. However, applying the same method for SAF containing two coupled ferromagnetic thin films is not evident. We recently proved10 that for the SAF systems the reversible susceptibility signal varies inversely proportionally with the discriminate \( D=w_{11}w_{22}−w_{12}^2 \) of the free energy for the coupled magnetic thin films, \( \chi_{xx} \propto 1/D(\theta_1, \theta_2) \), where \( w_{11} \), \( w_{22} \), and \( w_{12} \) are the second order derivatives of the total free energy \( w \) of the SAF with respect to \( \theta_1 \) and \( \theta_2 \) which give the magnetization equilibrium orientations in the two magnetic layers. The singular points of \( \chi_{xx} \) are zeros of the free energy discriminant which are points of the critical curve.

**RESULTS AND DISCUSSION**

Shown in Figs. 1(a) and 2(a) are two typical examples of the hysteresis loops of the investigated SAF samples for two different magnetic field orientations. Figure 1(a) presents hysteresis loop of symmetric SAF sample with a ferromagnetic layer thickness of 80 nm separated with a 6 Å Ru in-

![FIG. 1. Experimental hysteresis loop and RS for symmetric SAF.](image)

![FIG. 2. Experimental (a) hysteresis loop and (b) RS for asymmetric SAF.](image)
the magnetization field \( H \) approaches the hard axis, while the open symbols correspond to the peaks observed in the negative-to-positive field scan while the closed symbols correspond to the spin flop field \( H_{sf} \).

The susceptibility curves at two field orientations \((\theta = 0^\circ \text{ and } \theta = 90^\circ)\) for symmetric and asymmetric SAF samples are presented in Figs. 1 (bottom) and 2 (top), respectively. For clarity only the negative to positive saturation field sweep was shown (see arrow). In the case of symmetric SAF sample two peaks per field sweep are observed which correspond to the spin flop field \( H_{sf} \) and return field \( H_r \). The susceptibility curve along the easy axis for the asymmetric SAF sample has three peaks per sweep that besides the \( H_{sf} \) and \( H_r \) peaks also include the direct write field peak mentioned above. A systematic measurement of the susceptibility versus applied field curves along different directions with respect to the easy axis was performed. The critical curve was obtained by plotting all the identified peaks as a function of field direction in a polar chart. The critical curve for the symmetric SAF structure is shown in Fig. 3 (left hand side figure). The right hand side inserts represent the magnetization (top) and susceptibility (bottom) curves at an intermediate field orientation \((\theta = 45^\circ)\). Full symbols correspond to the susceptibility signal peaks observed in the positive-to-negative field scan while the open symbols correspond to the peaks observed in the negative-to-positive field scan. The full and open symbols coincide for almost the entire angular domain, a behavior that is due to very small differences between the return \( H_r \) and spin flop \( H_{sf} \) fields for this particular sample. The obtained critical curve is just the saturation curve of the SAF structure. The saturation critical curve has switching fields of 84 Oe along the easy axis and 275 Oe along the hard axis. As it was previously mentioned, as the coupling between layers increases, the inner critical curves become very small and cannot be easily observed experimentally with field scans along the directions passing through the origin of the \((h_x, h_y)\) plane. In this case more complicated field scans should be designed to reveal other features of the critical switching curve.

CONCLUSION

In this paper we used a different way to characterize magnetization switching in a SAF structure. This is based on measuring the reversible susceptibility signal along different directions in the plane of the sample. We show that the switching peaks in the susceptibility versus field plots obtained for different orientations of the applied dc field can be used to construct the switching diagram.

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