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Measurement of the critical curve of a synthetic antiferromagnet

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In this paper, we propose a method for a synthetic antiferromagnet structure's critical curve determination. The method is based on reversible susceptibility's singularities detection, as the magnetic field is swept along easy axis, in both positive and negative direction, while a hard axis bias field is also applied. By performing susceptibility measurements with different values of the bias field, the critical curve can be determined. Knowing the critical curve of a synthetic antiferromagnetic structure is essential for devices such as magnetic random access memories. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2953439]

Magnetization reversal is a paramount technological parameter in designing devices using magnetic materials as nonvolatile memories, reading heads, or sensors. Due to packaging constraints, magnetic devices usually have bidimensional geometries as thin films and multilayers, where the magnetization switching occurs in the plane of the device. Thus, controlling the two-dimensional (2D) magnetic switching is technologically valuable in devices using design ideas such as in magnetic random access memories (MRAM). The 2D switching can be described elegantly with the concept of critical curve (CC), which is the locus of in-plane fields at which the irreversible magnetization reversal occurs.[1,2] Slonczewski[1] introduced the idea of CC when he used a geometrical approach to find the equilibrium positions of magnetization for a Stoner–Wohlfarth particle.[3] Soon, it was understood that CC is not only a theoretical concept to describe the magnetization reversal, but also an important technological parameter for magnetic devices.[4–7] Thus, methods for CC determination were proposed and the obtained experimental CC were compared against the astroid corresponding to a magnetic uniaxial system.[7,8]

As the technological applications of magnetic structures became more complex, multifilm structures started to replace single films. One example of such multifilm structures is the synthetic antiferromagnet (SAF), which is a sandwich of two ferromagnetic thin films antiferromagnetically coupled through a nonmagnetic metallic spacer, usually Ru. SAF has many technological applications as hard layer of exchange coupled composite media,[9] soft underlayer for perpendicular recording,[10] pinned and free layers for MRAM cells,[11] hard disk reading heads, or magnetic sensors.[12] The performance of the devices using SAF structures relies heavily on their switching characteristics, which are governed by the individual reversal of the ferromagnetic layers, and the interlayer interaction. Since simple theory of single films does not work easily for coupled films, an equivalent approach had to be developed.[13–15] In the case of SAF, the CC is more complex, as there are two degrees of freedom, the orientations θ_1 and θ_2 of both ferromagnetic layers, assuming that each layer behaves as a single domain. The CC for SAF is obtained as the envelope of the in-plane field trajectories giving a constant angle to the magnetization of one layer, leaving the orientation of the other layer as a variable. Depending of the coupling strength between the two ferromagnetic layers, CC evolves from a simple astroid at zero coupling to a more complicated curve for larger coupling values (see Fig. 5 in Ref. 16). CCs of SAF structures have been extensively studied theoretically due to their importance for toggle MRAM.[16–20] However, in spite of its importance, methods to experimentally determine CC for coupled films are still lacking and a possible reason behind this situation is presented below.

The free energy F landscape for a magnetic system at a given applied magnetic field presents a series of minima and maxima. At equilibrium, the system is in one of its stable states corresponding to one of the energy minima. As the field changes, the configuration of maxima and minima is altered and the stable states of magnetization will shift, and if precessional effects are neglected, the system will remain in its state of free energy minimum. However, for a critical value, the minimum will evolve into a maximum or a saddle point and the stable state will switch to a neighboring minimum. The CC is in essence the locus of these critical field values (but not the locus of free energy's critical points, as the name may suggests). In the case of a single magnetic film, a sufficient condition for a critical state is to have simultaneously $dF/d\theta=0$, $d^2F/d\theta^2=0$, and $d^3F/d\theta^3\neq 0$, where the angle θ describes the magnetization's orientation. For coupled films as SAF, the problem is more complicated because it requires one to find the critical states of a function (free energy) of two variables (θ_1 and θ_2). In this case, the critical states can be found through the solutions of the sufficient condition: $\partial F/\partial\theta_1=\partial F/\partial\theta_2=0$ and $\delta(\theta_1,\theta_2)=(\partial^2F/\partial\theta_1^2)(\partial^2F/\partial\theta_2^2)-(\partial^2F/\partial\theta_1\partial\theta_2)^2=0$. Caution must be paid to the fact that not necessarily all the solutions are critical points. In general, this problem is not trivial and only using numerical methods one can obtain the CC. These theoretical intricacies are reflected also in the ability to experimentally determine the CC of a SAF.

In this paper, we show that the method of reversible susceptibility can be used to successfully determine the CC of SAF structures. Recently we have used susceptibility to

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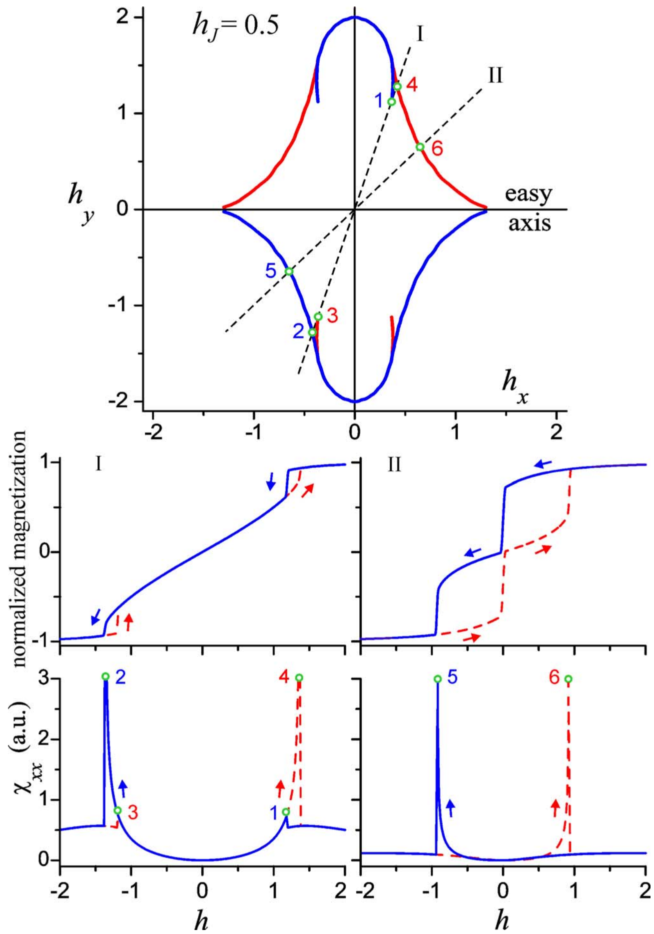

FIG. 1. (Color online) CCs (top) for a symmetric SAF with a coupling h_J=0.5, determined form susceptibility's curves (bottom) peaks locations, as the in-plane dc field is applied at different orientations. Middle: the projection of the normalized magnetization on the applied field's direction.

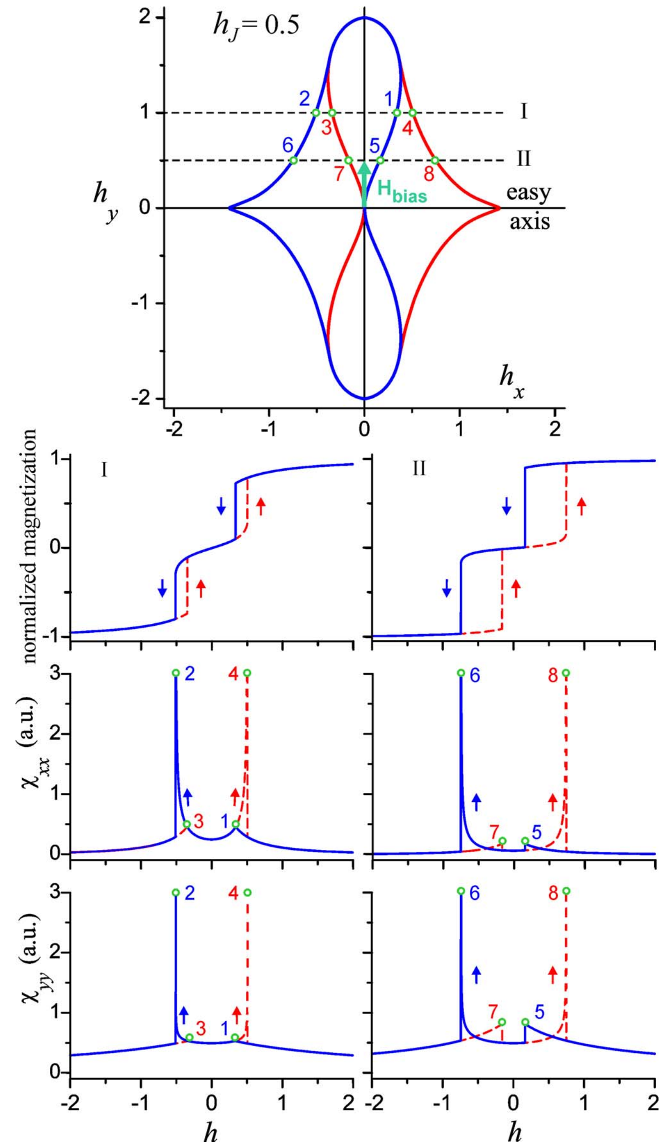

FIG. 2. (Color online) CCs (top) for a symmetric SAF with h_J=0.5, as the magnetic field is swept along easy axis, and a hard axis bias field is also applied. Middle: magnetization's projection on sweeping field's direction.

experimentally find the CC for different magnetic film structures[21,22] and we have shown that this method is more sensitive than the magnetic and resistance hysteresis methods. In a previous paper,[23] we have shown that for a SAF system the in-plane diagonal elements of the reversible susceptibility tensor χ varies inversely proportional with the free energy discriminant (the determinant of free energy's Hessian) computed at the equilibrium position (θ_1^0,θ_2^0), i.e., $\chi \propto \delta(\theta_1^0,\theta_2^0)$. The tensor $\chi_{ij}=\partial M_i/\partial H_j$ is obtained as the derivatives of components of magnetization M with respect to components of applied field H, and i and j refer to the directions (e.g., x, y, and z in Cartesian coordinates).[23] In this way, the problem of finding CC of coupled magnetic films is reduced to the determination of the singular points of susceptibility. Consequently, the problem of experimentally finding CC of coupled magnetic films is naturally solved by probing the reversible susceptibility for different in-plane applied fields and identifying the susceptibility's peaks located at the switching fields. In order to prove the suitability of this method, we have simulated the reversible susceptibility's field variation with the in-plane dc field applied at different orientations θ_H, and we have built the CC (see Fig. 1). The susceptibility and hysteresis curves for two different orientations, for a symmetric SAF with an exchange coupling h_J=0.5, are presented in the middle and the bottom panels of Fig. 1, respectively, the magnetic field sweeping from positive saturation to negative saturation (continuous line) and then back to positive saturation (dotted line). Depending on applied field orientation, the magnetizations' switching can be more or less visible in the hysteresis loops. For a field applied along the second direction (denoted with II in Fig. 1), the switching is very well defined, while for the first orientation (denoted with I), the switching events are not very visible. However, one observes that the susceptibility versus field curves present well defined peaks. For the first orientation, the susceptibility curve has two peaks (denoted with 1 and 2 in Fig. 1) when the dc field sweeps from positive saturation, when the field crosses the interior CC (corresponding to saturation) and the exterior CC (corresponding to switching), and only one peak for the second orientation, because in this case the field trajectory crosses only the exterior CC. When the field trajectory crosses the CC for saturation, both reversible susceptibility's denominator and numerator are zero and the reversible susceptibility has only a removable singularity and will not determine always a "very sharp peak" in susceptibility. When the field trajectory crosses the CC for switching, only the denominator is zero and the reversible susceptibility has a pole or an essential

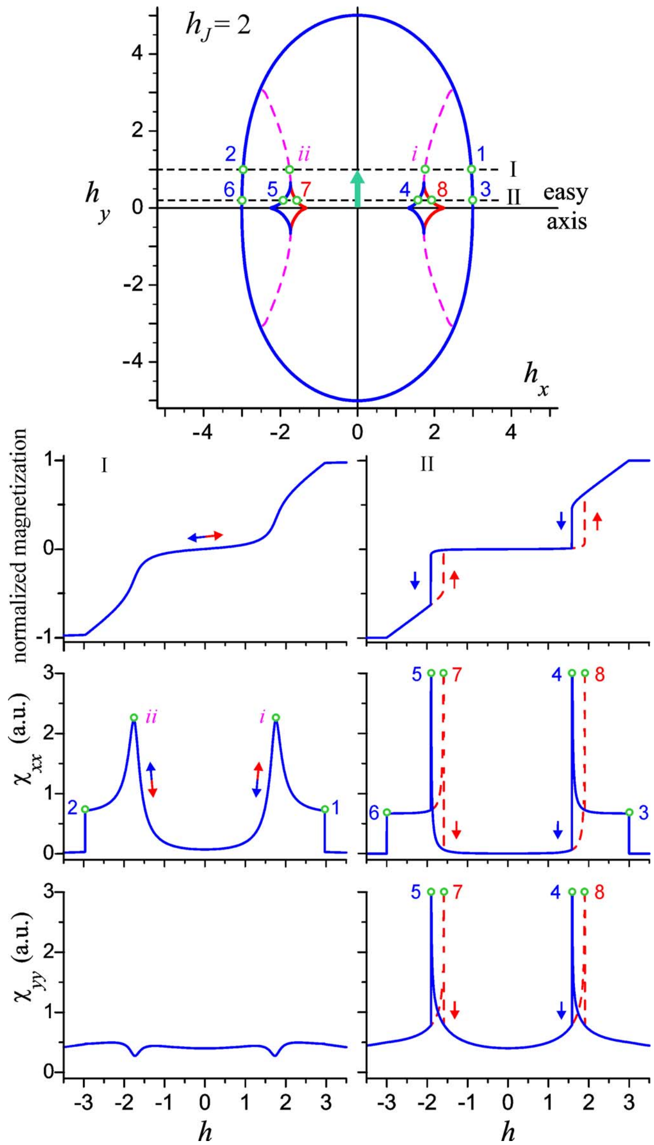

FIG. 3. (Color online) Same as Fig. 2, but with h_J=2.

singularity, which is very visible in susceptibility.

However, the method presented in Fig. 1 does not reveal the entire interior CC because there are portions where the field trajectory is "almost" tangent to it, and a very small increment of θ_H is required in order to build the entire CC. Nevertheless, in an experiment, the θ_H's increment cannot be arbitrarily small, and a strategy to make these portions "visible" is to use field scans that do not pass through origin, applying a bias field perpendicular to easy axis and a sweeping field parallel to easy axis (see Fig. 2). In order to better identify the susceptibility peaks and to build up the saturation CC, both χ_{xx} and χ_{yy}, measured along and perpendicular to easy axis, respectively, can be used. For example in Fig. 2, the χ_{xx} peaks 1 and 3 are more visible in the case I, compared with χ_{yy} peaks 1 and 3, while in the case II the χ_{yy} peaks 5 and 7 are more pronounced.

For applications such as MRAM, the exchange coupling between the two layers should be strong enough to make toggle writing method possible, and in Fig. 3 the simulated curves for h_J=2 are presented. With the increase of h_J, the CC for saturation expands and becomes the outermost curve, the inner curves being the CC for switching. When the field crosses only the outermost CC, both the projection of the total magnetic moment on the sweeping field and susceptibility curves are reversible when the field decreases and then increases. In this case, the intersection with the saturation CC determines only a shoulder (still more visible than in the hysteresis loops) and not a very well defined peak in the susceptibility curves. Moreover the susceptibility curve has two peaks (denoted with *i* and *ii* in Fig. 3) which are not determined by intersections with CC. These "false" peaks can be eliminated by looking only for the peaks of the curves which are not reversible, like in case II in Fig. 3.

In summary, a sensitive method for SAF CCs determination, based on reversible susceptibility singularities detection, is proposed. It was shown that this method can reveal the entire CC for both low and high values of the exchange coupling. Also, the method is general and can be applied for coupled films with nonidentical (asymmetrical) layers. Comparing the hysteresis and susceptibility curves, it was shown that susceptibility measurements are more appropriate for switching investigations of the SAF systems.

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