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Theoretical study of the blocking temperature in polycrystalline exchange biased bilayers

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Abstract

The exchange bias between an antiferromagnet (AF) and a ferromagnet (FM) vanishes at a temperature called the "blocking" temperature. The blocking temperature of polycrystalline exchange biased bilayers is theoretically studied on the basis of a thermal fluctuation model. From numerical calculations the dependencies of the blocking temperature on the AF layer thickness, the AF grain size, the hysteresis loop measurement time, the interface exchange coupling, the Curie temperature of the FM layer, the Néel temperature of the AF layer, and the AF uniaxial anisotropy have been obtained. Comparisons of the results with the analytical expressions of the blocking temperature in previous study and with the experimental observations are also provided and discussed.

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Keywords: Exchange bias; Interface coupling; Blocking temperature; Magnetic thin film

1. Introduction

The exchange bias effect, which arises from the interfacial exchange coupling between a ferromagnet (FM) and an antiferromagnet (AF), was discovered more than 40 years ago [1]. It is so named because the phenomenon manifests itself in a shifted hysteresis loop for the bilayer film. There have been numerous studies [2] of the exchange bias effect because of its scientific interest as well its unique application to giant magnetoresistive (GMR) spin-valve read heads and magnetic memory devices.

Since the ambient temperature of a GMR head increases with the bias current during reading operations, the thermal stability of the exchange biasing is of concern for head design and governs the choice of the biasing material. It is well known that exchange biasing is strongly dependent on

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temperature [3]. At a so-called "blocking temperature" T_B, the exchange field, which is equal to the shift of the hysteresis loop, decreases to zero. It is natural to think that T_B should be related to the Néel temperature T_N of the AF. However, T_B has been found to be lower than T_N. For some FM/AF bilayers such as NiFe/NiMn the difference can be more than 400 °C [4]. T_B has also been found to decrease with decreasing AF thickness [5–10] and to decrease with decreasing AF grain size. While there has been intensive experimental study on the blocking temperature in a variety of systems, the theoretical process toward understanding blocking temperature has been slow. In the previous studies [11,12], an explanation is provided for the observed reduction of the blocking temperature with the AF thickness and with the Néel temperature of the antiferromagnet in polycrystalline films based on a thermal fluctuation model. In this article, a comprehensive study of the blocking temperature from numerical calculations based on the thermal fluctuation model is presented. In particular, the dependencies of the blocking temperature on the measurement frequency or time, the AF layer thickness, the AF grain size, the AF uniaxial anisotropy, the interface exchange coupling, and the Néel(Curie) temperature of the AF (FM) are discussed in great detail.

2. Thermal fluctuation model

To determine the effect of thermal fluctuations on exchange bias in a polycrystalline FM/AF bilayer, Fulcomer and Charap employed a "superparamagnetism" model [13] in which the AF layer is approximated by an assembly of grains without inter-grain exchange coupling that extend through the thickness t_{AF}. Stiles and McMichael [14] and Stamps [15] extended the model by considering planar domain wall formation and spin-flop coupling, respectively. The Fulcomer–Charap model is illustrated in Fig. 1. Each AF grain is assumed to have an uncompensated net moment, $\boldsymbol{m}$, at its interface with the FM. This may be the result of an uncompensated interface or the result of surface roughness. Suppose that the AF grains are ferromagnetically exchange coupled to the FM

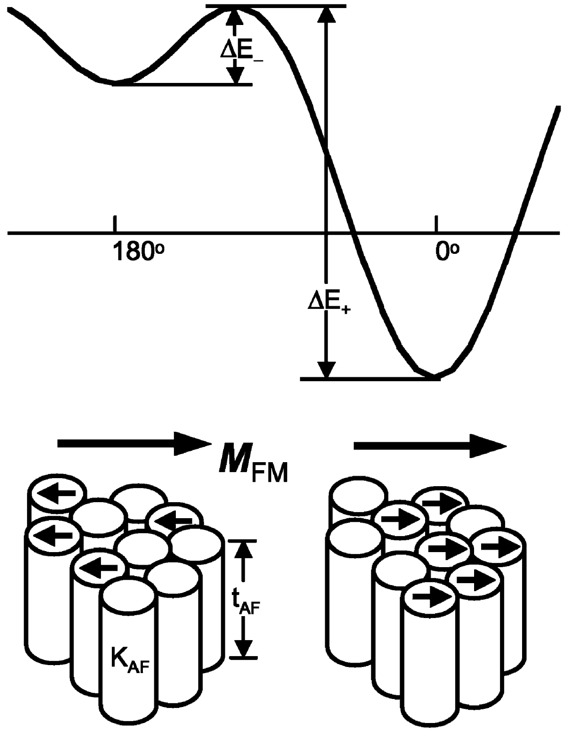

Fig. 1. Schematic representation of the energy states of the AF grains exchange coupled with the FM magnetization M_{FM} at the interface. The columnar AF grains are simply identical with a cross area of S, a length of t_{AF}, and a uniaxial anisotropy constant of K_{AF}. By considering the net moments point right or left at the interface, the AF grains are separated into two groups with a population fraction of n_+ and n_-, respectively. For the case that the magnetization points to right, i.e., with an angle of 0°, two stable states are shown and the barrier energies per unit area for the AF grains are ΔE_+ and ΔE_-, respectively. $\Delta\varepsilon_\pm = \Delta E_\pm S$. As the magnetization reverses, the energy states flip over correspondingly.

magnetization $\boldsymbol{M}_{FM}$ at the interface by a strength J_E. Let the number of grains whose surface moment is parallel (antiparallel) to the FM magnetization be $n_+(n_-)$. The effects we are describing are associated with fluctuations of these AF grains. The time $\tau_\pm$ for an AF grain to overcome an energy barrier $\Delta\varepsilon_\pm$ and switch to another energy state at a temperature T is given by

$$\frac{1}{\tau_\pm} = v_0 \exp\left(-\frac{\Delta\varepsilon_\pm}{k_B T}\right), \tag{1}$$

where v_0 is an "attempt" frequency of magnetic moments of the order of $10^9\,\mathrm{s}^{-1}$ and k_B is the