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A physical model of exchange bias in $[Pd/Co]_5/FeMn$ thin films with perpendicular anisotropy

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A physical model of perpendicular exchange bias (PEB) has been established based on the total energy equation per unit area of an exchange bias system by assuming coherent rotation of the magnetization. The anisotropy energy of antiferromagnetic (AFM) layer, $K_{AFM} \times t_{AFM}$, as well as ferromagnetic (FM) multilayers, $K_{FM,eff} \times t_{FM}$, and the interfacial exchange coupling energy, J_{ex} were considered as primary physical parameters in building up the physical model of PEB phenomenon. It was proposed that the PEB is a result of the energy competition between $K_{AFM} \times t_{AFM}$, $K_{FM,eff} \times t_{FM}$, and J_{ex}; where $K_{AFM} \times t_{AFM} \geq J_{ex}$, is a critical condition to observe exchange bias in the system. In particular, it was revealed that J_{ex} is directly relevant to the net magnetization of FM and AFM spin structure, $J_{ex} \propto \cos \alpha_{AFM} \times \cos \beta_{FM}$, in the perpendicular direction rather than the magnetization angle difference observed in an in-plane system. The physical role of perpendicular anisotropy energy, $K_{FM,eff} \times t_{FM}$ was also found to be significant to enhance the PEB. These physical characteristics are completely different from those are observed from an exchange bias system with in-plane anisotropy. The physical validity of the proposed PEB model was confirmed using different structures of exchange biased $[Pd/Co]_5/FeMn$ thin films with perpendicular anisotropy. The experimentally analyzed results demonstrated that the physical model of PEB proposed in this work is agreed well with the experimentally observed PEB phenomenon. Furthermore, the proposed model was found to be effective to design and to predict a new PEB system for the advanced spintronics applications. © *2010 American Institute of Physics*. [doi:10.1063/1.3471803]

I. INTRODUCTION

Recently, as the demands for higher density, higher speed, and extremely low-dimensional metal based spintronics devices have grown enormously, the interests in the application of perpendicular exchange bias (PEB) to the advanced spintronics devices are being dramatically increased.[1,2] The main reason for this technical trend is that the PEB based giant magnetoresistance or tunneling magnetoresistance spin-valves are expected to provide technically promising properties such as high thermal and magnetic stabilities, and a lower device operating current density that can allow for the development of extremely low dimensional and high reliability devices.[3,4]

The studies on the exchange bias system with perpendicular anisotropy were first started approximately one decade ago. Since then, all of the research efforts relevant to PEB have been mainly focused on the development of new metallic thin film PEB systems[5–8] and the improvement of PEB characteristics more suitable for the advanced spintronics.[9–11] However, despite huge research efforts, the PEB systems still face technical challenges such as an undesirably large coercivity (H_c) and a small exchange bias field (H_{ex}) that limit their application for a variety of spintronics devices. Different from in-plane anisotropy systems, in which the exchange bias mechanism is very well understood,[12–14] current studies of PEB are mainly focused on the empirical methods[5–11] and the lack of well established physical models becomes a major bottleneck in overcoming the scientific challenges. Therefore, developing a physical model for a PEB system, which can clearly elucidate the underlying physics and predict what physical parameters would more effectively influence on the adjustment of the PEB characteristics has been considered to be the most urgent issue to rapidly extend the application of PEB to a wider range of spintronics devices.

In this paper, we present a physical model of PEB established based on the total energy equation per unit area of an exchange bias system by assuming coherent rotation of the magnetization. This model focuses on studying the physical phenomenon of a PEB system in view of the energy competition between the anisotropy energy of antiferromagnetic (AFM) layer, $K_{AFM} \times t_{AFM}$, ferromagnetic (FM) multilayers, $K_{FM,eff} \times t_{FM}$ and the interfacial exchange coupling energy, J_{ex}. Unlike that of an exchange bias system with in-plane anisotropy, this model emphasizes the importance of $K_{FM,eff} \times t_{FM}$ and the physical contribution of J_{ex} to the PEB system. A series of the experimental works using exchange

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