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Physical nature of anomalous peaks observed in extraordinary Hall effect measurement of exchange biased spin-valves with perpendicular anisotropy

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We experimentally and theoretically demonstrate that the abrupt change in magnetostatic energy during the free and pinned [Co/Pd] layer reversal by an external magnetic field and the magnetic field dependent extraordinary Hall effect (EHE) coefficient are the main physical reasons for the anomalous peaks observed in EHE measurement of exchange biased [Pd/Co]/Cu/Co/[Pd/Co]/FeMn giant magnetoresistance spin-valves with perpendicular anisotropy (EBPA-SVs). The correlation of the anomalous EHE peaks to the extrinsic magnetic properties of EBPA-SVs paves a way to indirectly evaluate these properties. © *2011 American Institute of Physics*.
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I. INTRODUCTION

In recent years, there has been a shift in interest from magnetic thin films and spin valves with in-plane anisotropy toward those with perpendicular anisotropy. This has been driven by the technical promises that they can provide high thermal and magnetic stabilities for nano-sized spintronics device applications.[1,2] For these systems, the extraordinary Hall effect (EHE) has been extensively used to measure the intrinsic magnetic properties, such as switching field and exchange bias field,[3–6] because the Hall resistivity, ρ_H, has been experimentally confirmed to be dominantly proportional to the perpendicular component of the magnetization ($M_\perp$) as described in Eq. (1).

$$\rho_H = \frac{V_H t}{I} = R_0 H + R_S M_\perp, \tag{1}$$

where V_H is the Hall voltage, t is the film thickness, I is the applied electric current, H is the applied magnetic field perpendicular to the film direction, and R_0 and R_S are the ordinary and extraordinary Hall coefficients, respectively.[7]

However, despite concerted efforts on discovering various new physical phenomena in EHE, such as the reversal of EHE polarity, the scattering mechanisms in heterogeneous systems, and the adoption of Berry phase concepts, which contribute toward the understanding of EHE,[4,8–11] the practical expansions and the application scopes of EHE measurement still remain as future challenges because there are several unknown contributing effects to EHE, which can be used for characterizing extrinsic properties of magnetic thin films and spin valves with perpendicular anisotropy for advanced spintronics and magnetoelectronics.[8]

In this letter, we report on the physical nature and the new practical applications of anomalous peaks accidently observed in EHE measurement of exchange biased [Pd/Co]/Cu/Co/[Pd/Co]/FeMn spin-valves with perpendicular anisotropy (EBPA-SVs) when the free and the pinned layers are magnetically reversed by an externally applied field. In order to understand the physical nature of the anomalous peaks, we attempted to interpret this physical phenomenon in view of the physical correlation between ρ_H and magnetostatic energy of EBPA-SVs, $E_{ms}(M_\perp)$, which is closely related to the perpendicular anisotropy, the interlayer coupling energy, and the giant magnetoresistance (GMR), by establishing a physical model describing the physical relationship between interlayer coupling and $E_{ms}(M_\perp)$, perpendicular anisotropy and $E_{ms}(M_\perp)$, and GMR behavior and ρ_H, respectively. The validity of the proposed model was experimentally verified by varying the perpendicular anisotropy and the interlayer coupling energy, which are directly relevant to the $M_\perp$ of the EBPA-SVs, by inserting Co and Pd or Ta respectively, at the [Pd/Co]/Cu interface. In addition, theoretical calculations numerically describing the dependence of ρ_H on the GMR and the $E_{ms}(M_\perp)$ were carried out to compare the proposed model with the experimental observations.

II. OBSERVATION OF ANOMALOUS EHE PEAK AND PROPOSED MODEL

The Ta(20)/[Pd(0.6)/Co(0.4)]$_2$/Cu(2.2)/Co(0.7)/[Pd(0.6)/Co(0.4)]$_2$/FeMn(10.8)/Ta(20 nm) EBPA-SVs were deposited using a DC magnetron sputtering system.[12] The magnetoresistance and EHE were measured using a DC four-point probe system under a magnetic field of ±2 kOe applied perpendicular to the film plane, and the M-H loops were measured using a vibrating sample magnetometer. Figure 1 shows the EHE, M-H, and R-H (GMR) loops obtained from Ta(20)/[Pd(0.6)/Co(0.4)]$_2$/Cu(2.2)/Co(0.7)/[Pd(0.6)/Co(0.4)]$_2$/FeMn(10.8)/Ta(20 nm) EBPA-SVs. As can be seen in Fig. 1, the EHE loop had the same intrinsic magnetic properties of the GMR EBPA-SVs as those observed from M-H and R-H measurements. However, the EHE loop apparently exhibited anomalous peaks at the switching field of free and pinned layers, where the magnetization of the ferromagnetic layer is reversed by an externally applied field. By considering

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