Simulated Magnetoresistive Behavior of Geometrically Assymmetric Spin Valves

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Abstract — **A semi-analytical micromagnetic model is used to study how the magnetoresistive (MR) response is affected by uneven geometries in NiFe/Cu/NiFe spin-valve devices. Devices with unequal stripe heights and thicknesses of the magnetic layers are studied. The calculated devices are 4 µm long, pinned by a transverse field of 16 kA/m and have nonmagnetic spacer thicknesses of 4 nm. Stripe heights are varied from 0.5 µm to 2 µm and magnetic-layer thicknesses from 3 nm to 6 nm. Device responses are analyzed and used to indicate how optimal device geometries may be selected.**

INTRODUCTION

The magnetoresistive (MR) response of spin valves [1] is very sensitive to the transport and geometric properties of the films composing them. This paper examines the effect certain differences in the dimensions of the magnetic layers of spin valves have on device biasing and sensitivity. The linearity of a device, which is also very important to its performance, is not considered in this paper.

Figure 1 illustrates two types of assymmetric spin-valve structures that are studied. The magnetization M of the top NiFe layer is pinned transversely by an antiferromagnetic overcoat layer (not shown in the figure), whereas the magnetization of the bottom layer is free to rotate. The sense current flows longitudinally through the device (from left to right in the figure). In Fig. 1(a) the stripe height w_p of the pinned layer is less than the stripe height w of the free layer. In Fig. 1(b) both magnetic layers have equal stripe heights, but the pinned layer is thinner than the free layer. These examples not only illustrate the influence of the device geometry on its response, but also represent possible design alternatives of the sensing element of devices.

The magnetization of a device is modeled by using a semi-analytical model in which the magnetic layers are treated as single-domain films [2]. The model includes interlayer magnetostatic interaction effects. Magnetocrystalline anisotropy and interlayer exchange interactions in the sample are easily included in the model [2].

The single-domain assumption represents an ideal that is never fulfilled in a real device due primarily to the nonuniform internal demagnetization fields, especially nearer the film edges where they are more pronounced. However a good approximation to the ideal may occur in very small devices. For such devices the transition widths of internal Néel domain walls may exceed the dimensions of the device so that it no longer can sustain domain walls [3].

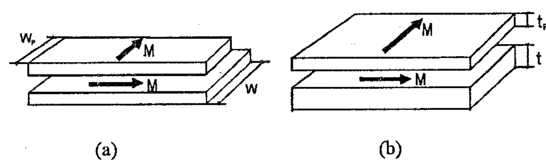

Fig. 1. Schematic diagram of geometrically assymmetric spin-valve structures.

SIMULATION

Giant magnetoresistive (GMR) curves for uniform external transverse fields (acting perpendicular to the sense current in the plane of the device) were calculated for the devices considered in this work. These devices are 4 µm long, pinned by a transverse field of 16 kA/m, and have nonmagnetic spacer thicknesses of 4 nm. The magnetic layers have a magnetization M = 800 kA/m, a value that is typical for NiFe films used in spin valves. The self-field due to the sense current was neglected in the calculations and only magnetostatic energy terms were considered. The shape anisotropy of the layers causes their magnetization vectors to lie completely in the plane of the films. The magnetoresistance of a device (in arbitrary units) is calculated as $\Delta R = 1 - \cos\theta$, where θ is the angle between the magnetization vectors of the layers. This simple formulation represents only the effect of the magnetization of the layers on the magnetoresistance. The dependence of the magnetoresistance on the transport properties of the device, which in turn depend on the geometry of the device, is not considered.

Figure 2(a) shows calculated MR curves for devices having magnetic-layer thicknesses of 5 nm. The solid curve was obtained for a sample having a pinned-layer stripe height of w_p = 0.5 µm and a free-layer

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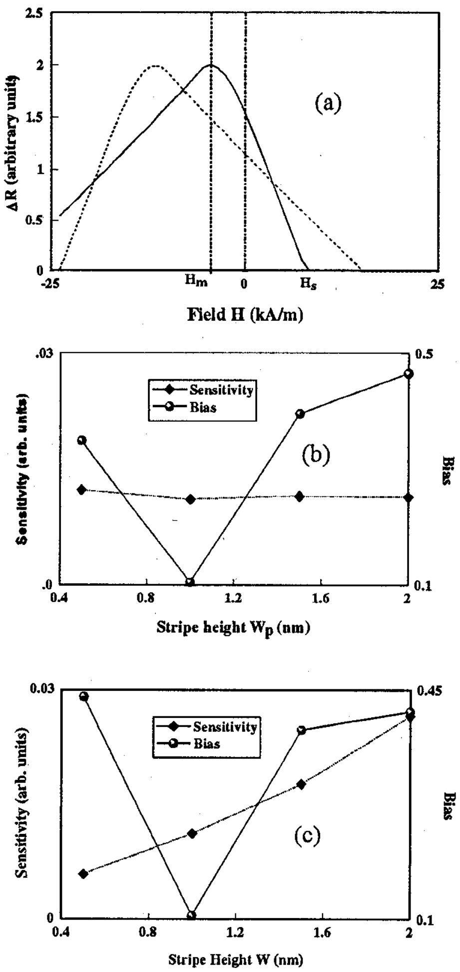

Fig. 2. Magnetoresistive (MR) simulation data for devices with 5 nm-thick magnetic layers and uneven stripe heights: (a) MR curves for device with pinned-layer stripe height $w_p = 0.5$ μm and free-layer stripe height $w = 1$ μm (solid curve) and device with these dimensions interchanged (dashed curve); (b) bias (solid curve) and sensitivity (dashed curve) as functions of w_p for devices with $w = 1$ μm fixed; (c) bias (solid curve) and sensitivity (dashed curve) as functions of w for devices with $w_p = 1$ μm fixed.

stripe height of $w = 1$ μm, and the dashed curve was obtained by interchanging the dimensions of the layers. The self-demagnetization of the magnetic layers and interlayer magnetostatic interactions prevents the devices from being perfectly pinned and from being ideally biased [2]. Also indicated on the solid curve of Fig. 2(a) are points which are used to define the *average sensitivity* and *bias* of a device. H_m is the largest field at which the GMR attains a maximum, and H_s is the saturation field of the device. The average sensitivity of the device is defined as $\Delta R_m/(H_s-H_m)$ and the bias as $-H_m/(H_s-H_m)$. This definition of the bias makes it negative whenever H_m is positive, and greater than 1 if the device is already saturated at zero field. These extreme biasings are undesirable in head applications where the bias should be between 0 and 1. For a device that is ideally biased, $H = 0$ lies midway between H_m and H_s and the bias is equal to 0.5.

The dashed curve in Fig. 2(a) is broader than the solid curve because of the larger self-demagnetization of the free layer with a smaller stripe height, which makes the sample harder to saturate. As the applied field is increased negatively, ΔR starts decreasing from its peak value as the magnetization of the pinned layer begins to reverse towards the applied field. As seen in Fig. 2(a), this occurs sooner for the device with the narrower pinned layer because of the larger self-demagnetization of the layer which opposes the pinning of the magnetization [2].

Calculated sensitivities and biasing for devices having free-layer stripe heights $w = 1$ μm, and pinned-layer stripe height w_p that is varied as 0.5, 1, 1.5 and 2 μm, are plotted in Fig. 2(b). Points for devices obtained with $w_p = 1$ μm fixed and w varied from 0.5 μm to 2 μm are plotted in Fig. 2(c) The recession of one edge of a magnetic layer relative to the other, as in Fig. 1(a), generally reduces the interlayer magnetostatic coupling below the case of equal stripe heights. This is because the charges at the edges of the layers become on the average further separated from each other. This decrease in coupling improves the biasing of the device, because the magnetic vectors of the layers become less oriented antiparallel at $H = 0$.

This effect is illustrated by the variation of biases in Figs. 2(b) and (c), which show that a minimal bias occurs when $w_p = w = 1$ μm. The sensitivity in Fig. 2 depends on the balance between the effects of the self-demagnetization of the layers and the interlayer magnetostatic interactions. The sensitivity in Fig. 2(b) varies in the same manner as the bias. It too depends on the interlayer magnetostatic coupling. The more nearly antiparallel to each other are the magnetization vectors of the layers, the larger the saturation field required to bring them to parallel alignment. The self-demagnetization of the free layer has a more domineering effect on the sensitivity of the devices of Fig. 2(c) than the interlayer magnetostatic coupling.

The sensitivity increases steadily with w as the self-demagnetization of the free layer decreases, making it easier to saturate the device.

The GMR curves of two devices having magnetic layers of unequal thicknesses are plotted in Fig. 3(a). The solid curve was obtained for a device with a 3 nm thick pinned layer and a 5 nm thick free layer. The dashed curve was obtained by interchanging the dimensions of the pinned

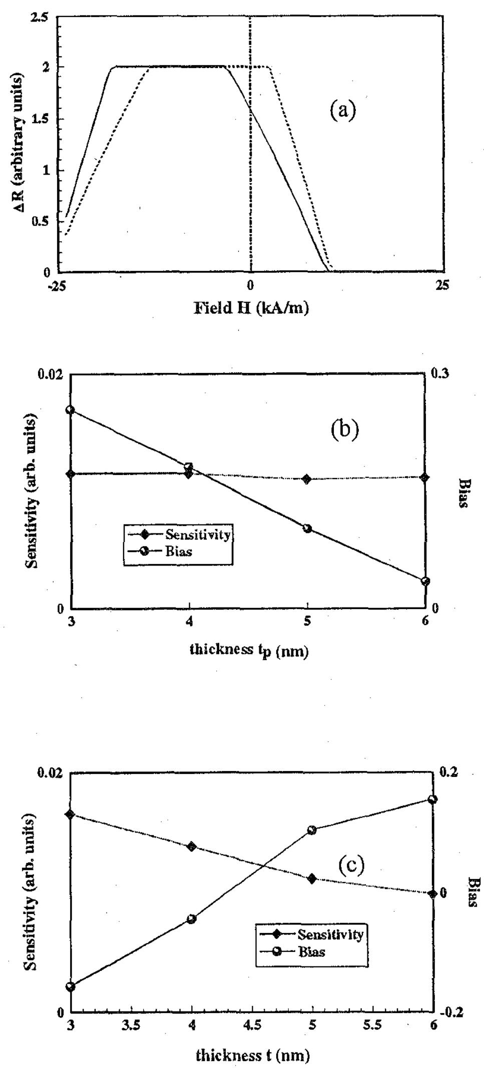

Fig. 3. Magnetoresistive (MR) simulation data for devices with stripe heights of 1 μm and uneven magnetic layer thicknesses: (a) MR curves for device with pinned-layer thickness t_p = 3 nm and free-layer thickness t = 5 nm (solid curve) and device with these dimensions interchanged (dashed curve); (b) bias (solid curve) and sensitivity (dashed curve) as functions of t_p for devices with t = 5 nm fixed; (c) bias (solid curve) and sensitivity (dashed curve) as functions of t for devices with t_p = 5 nm fixed.

and free layer. Two effects are responsible for the better biasing displayed by the solid curve. First, the thinner pinned layer sustains the pinning of the magnetization more. Second, the self-demagnetization of the thicker free layer causes its magnetization to orient longitudinally at zero field. However, this increases the saturation field and hence, reduces the sensitivity of the device. The thicker pinned layer and the lower self-demagnetization of the free layer combine to produce very poor biasing for the dashed curve.

Interlayer magnetostatic interactions increase as the thickness of one magnetic layer is increased while that of the second layer is kept fixed. This is because edge charges are being added to the growing layer. The effect this has on device performance depends on which layer thickness is varied. These effects are summarized in Figs. 3(b) and (c). Sensitivity is virtually constant in Fig. 3(b) for the device dimensions considered. The biasing deteriorates as t_p increases, because both the self-demagnetization of the pinned layer and interlayer magnetostatic coupling increases. The increased self-demagnetization results in the canting, at $H = 0$, of the magnetization of the pinned layer away from its intended direction [2]. Biasing is very poor for the devices of Fig. 3(c) for the reasons given earlier. In addition, the sensitivity decreases steadily with increasing w, as the self-demagnetization of the free layer increases.

Optimal device geometries that are favored by magnetostatic interactions can be obtained by inspection of the plots given in Figs. 2 and 3. In Fig. 2(a) the devices with w_p = 0.5 μm and 2 μm show the best performance characteristics. The device with w = 2 μm is the optimal in Fig. 2(c). The optimal points in Fig. 3 correspond to the intersection of the sensitivity and bias curves. An inspection of all the curves suggests that the optimal point of Fig. 2(c) provides the best overall device geometry. This device has dimensions w_p = 1 μm, w = 2 μm and t_p = t = 5 nm, a sensitivity of 0.027 (arbitrary units) and a bias of 0.42. In practice, the free layer of a device such as this, by virtue of its larger stripe height, will shunt more of the sense current, thereby decreasing the GMR and hence the sensitivity. Self-fields due to this current and any exchange coupling between the layers may significantly alter the response of the device

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