Field Angle and Current Density Effects in Submicrometer Spin Valves for Digital Applications

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***Abstract*—We have characterized the magnetoresistive response of giant magnetoresistive spin valve devices, designed for digital applications, as a function of current density and magnetic field angle. The devices are designed to have only two stable states and are characterized by their positive and negative switching fields. The variations in the switching fields of submicrometer devices are compared with a multilayer single-domain model to determine how accurately the switching fields can be predicted. Significant deviation from single domain behavior is observed. Structure in the magnetoresistive response curve, indicating stable micro-domains, is seen in devices with small line widths and small aspect ratios. At large field angles, the micro-domains are stable to high field values and can dramatically effect the switching process. The variation of the switching fields with bias current and field angle depart considerably from the single domain model predictions.**

INTRODUCTION

Digital spin-valve magnetoresistive devices have been proposed for applications in magnetoresistive random access memory (MRAM) [1], digital recording [2], and digital sensors. These devices are similar to the spin valves designed for analog applications in that they contain two magnetic layers, a pinned layer and a free layer, separated by a nonmagnetic spacer layer. In contrast to analog spin valves, the pinning fields and the applied fields in these devices are parallel to the long dimension of the device. The free layer has only two stable states, parallel or antiparallel to the pinned layer. The state may be probed by measuring the device resistance or by sensing a voltage pulse when the state changes.

In the simplest picture, the digital spin valve may be viewed as a single magnetic layer, the free layer, which behaves as a single domain particle and responds to the applied magnetic field, current-induced magnetic fields, anisotropy fields induced during deposition, self magnetostatic fields, and interaction fields from the pinned layer. The device may be characterized by one parameter, the angle of the free-layer magnetic moment relative to the long axis of the device. A schematic of the device structure and the energy potential are shown in Fig. 1. The magnetostatic interaction and the effective exchange interaction between the free and pinned layers cause the potential to be asymmetric. For small devices, where the magnetostatic energy dominates, the antiparallel alignment has the lowest energy. This asymmetry in the potential shows up as an asymmetry in the switching fields with the switching from the antiparallel to the parallel state requiring a larger switching field.

The situation in real devices is in general more complicated than this simple single-domain picture. Micromagnetic effects, such as magnetization curling at the device edges and the formation of microdomains, can significantly change the switching behavior.

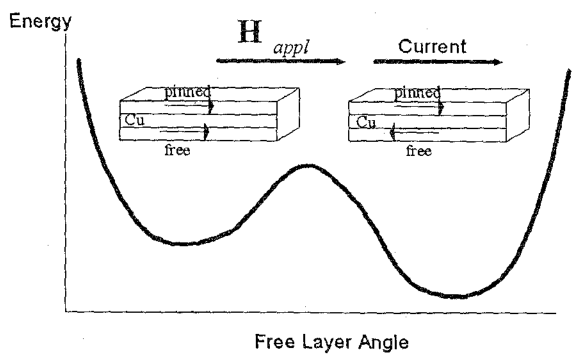

Fig. 1. Schematic of digital spin valve device and energy surface

Applications of digital spin valves in MRAM and read heads will require devices with submicrometer line widths to have predictable and reproducible switching fields. The effect of scaling down the device line widths and varying the device aspect ratio has been studied both experimentally and by modeling [3] [4]. For a fixed, large aspect ratio, as the line width is decreased the switching fields increase roughly as $1/w$, where w is the device width. The switching field is, as expected, proportional to the demagnetizing field perpendicular to the device stripe. It is this field which gives rise to the energy barrier. As the aspect ratio decreases, for a fixed line width, the switching behavior becomes very asymmetric due to the increase of the pinned-layer demagnetizing field in the free layer. This can be seen in Fig. 2, which shows modeled and experimental magnetoresistive response of 1.0 μm wide devices as a function of aspect ratio. As the aspect ratio decreases, the

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experimental data also show that the ideal two state behavior is lost and structure can be seen in the resistive transition, indicating complicated intermediate domain states. The multidomain reversal process is due to the loss of the magnetostatic stabilization effects in long aspect ratio devices and to the increase in the magnetostatic interactions with the pinned layer. The transition to a complicated multi-domain transition process has been predicted and elucidated by magnetic modeling studies [3] [4].

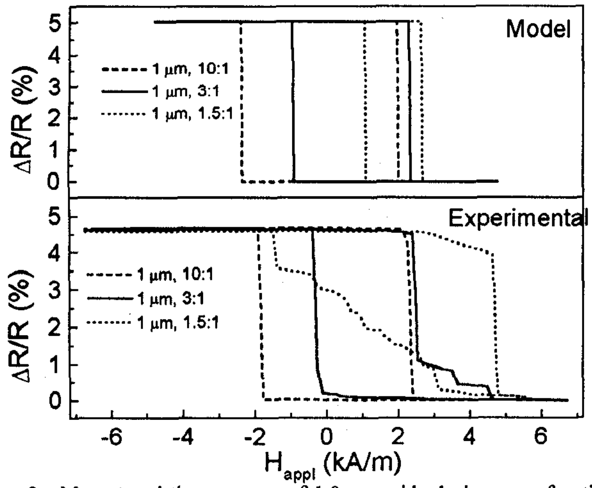

Fig. 2. Magnetoresistive response of 1.0 µm wide devices as a function of aspect ratio, both experimental and simulated with a multilayer single domain model.

In this paper, we will present data describing how the switching fields vary with applied field angle and bias current (which produces off-axis fields). We anticipate, on the basis of single-domain switching models, that the switching fields will be sensitive to the field angle. For applications, it is important to understand the effects of bias current and applied field angle. The bias current is often used to tailor the value of the switching fields or to address a single element connected in a write array. The field angle effects are important in engineering the angle of write lines or the orientation of the sensor relative to the sense fields.

SAMPLE PREPARATION AND MODELING

The samples were fabricated by standard sputter-deposition techniques with the following layer structure: Si substrate $/Al_2O_3/Ta_{5.0}/NiFe_{7.5}/Co_{0.6}/Cu_{3.0}/Co_{0.6}/NiFe_{7.5}/FeMn_{10}/Ta_{5.0}$ where the subscripts denote the layer thickness in nm. The NiFe layers were deposited in field to give an easy axis with $H_k \sim 0.4$ kA/m along the long dimension of the device. The FeMn pinning direction was also set along the long dimensions of the device. The wafers were then patterned with optical lithography and ion beam etching. A Cr-Au contact layer was deposited using a lift-off process. No passivation layers were used. At wafer level, the magnetoresistive response ΔR/R was typically 5% to 7%, and there was an effective ferromagnetic exchange coupling of 0.4 kA/m. This effective exchange coupling was measured on large devices in which the edge magnetostatic effects were minimal.

The magnetoresistive response was modeled using a multilayer single-domain model [5]. This model maps the magnetic layers onto interacting single-domain particles of similar aspect ratio and incorporates magnetostatic interactions, exchange interactions, and magnetic anisotropy effects. Both the free and the pinned layer evolve in response to the applied field and both applied and current induced fields are taken into account. Standard bulk values were used for the layer magnetizations and resistivities. Each Co-NiFe bilayer was treated as a single layer with a weighted average magnetization. The values used for the magnetic anisotropy field, the exchange coupling field, and the pinning field were 0.4 kA/m, 0.4 kA/m, and 11.9 kA/m respectively. Single-domain models will in general overestimate the magnitude of the switching fields since in real devices the magnetization will curl at the device edges to minimize the magnetostatic energy. This softening is accommodated by reducing the effective magnetic thickness which reduces the magnetic charges at the device edges. This softening parameter is adjusted to fit the data. In this paper, the softening parameter (the effective magnetic thickness divided by deposited layer thickness) was set at 0.3.

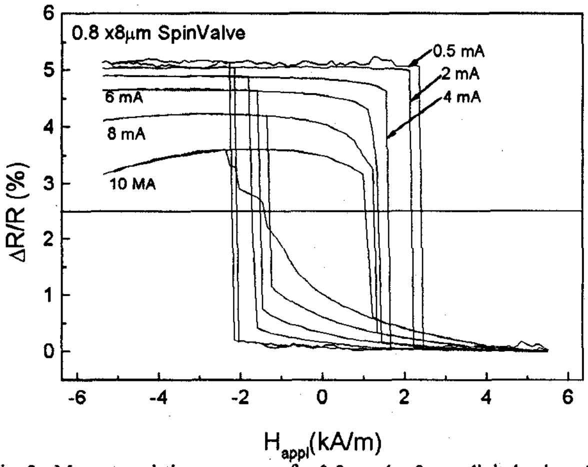

Fig. 3. Magnetoresistive response of a 0.8 µm by 8 µm digital spin valve as a function of bias current.

EXPERIMENTAL RESULTS

Figure 3 shows the magnetoresistive response of a 0.8 µm by 8 µm device as a function of applied bias current. Several effects are observed. The magnetoresistive response decreases due to device heating which both decreases ΔR and increases R. The switching fields decrease and the response becomes more rounded. These effects are due to the magnetic field from the bias current. The field from the bias current in the free layer is perpendicular to the applied field and has an approximate magnitude of $I/2w$. For a 0.8 µm wide device, the current induced field has a magnitude of

0.63 kA/m per mA of device current. This perpendicular field rotates the free layer moment off the device axis and facilitates switching.

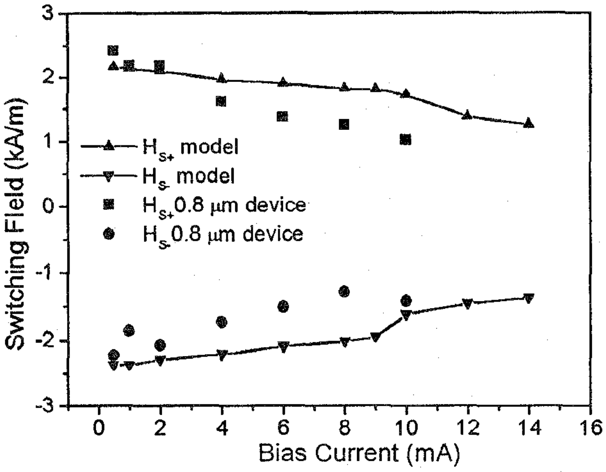

Fig. 4. Experimental and modeled switching fields for a 0.8 μm x 8.0 μm device as a function of bias current.

Figure 4 shows the switching fields as a function of bias current for both experimental and modeled data. The experimental switching fields decrease faster with applied current density than the modeled data. The modeling shows that the decrease of the switching fields at high current densities is sensitive to the strength of the pinning field. This is due to rotation of the pinned layer which assists the switching process.

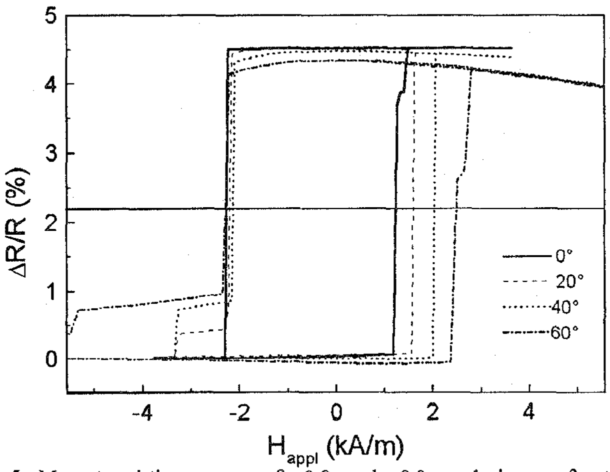

Fig. 5. Magnetoresistive response of a 0.8 μm by 8.0 μm device as a function of applied field angle at 1 mA bias.

The effect of field angle on the magnetoresistive response is shown in Fig. 5. In addition to the shift in switching fields, additional structure in the response curves is observed. The "feet" in the off-axis response curves are due to intermediate domain states that are stabilized by the off-axis field. The experimental and modeled switching fields are summarized in Fig. 6. The modeled switching fields show a smooth decrease as the field is moved off the long axis of the device and achieves a minimum at angles of about 40°. The experimental negative switching fields show a reasonable agreement with the single domain model. The positive switching fields show a monotonic increase in the switching fields and do not show the minimum as predicted by the model. The positive switching fields were very sensitive to the initial device state. If the device was not taken to a high enough negative field and if a microdomain was present in the initial state, the switching fields were dramatically decreased.

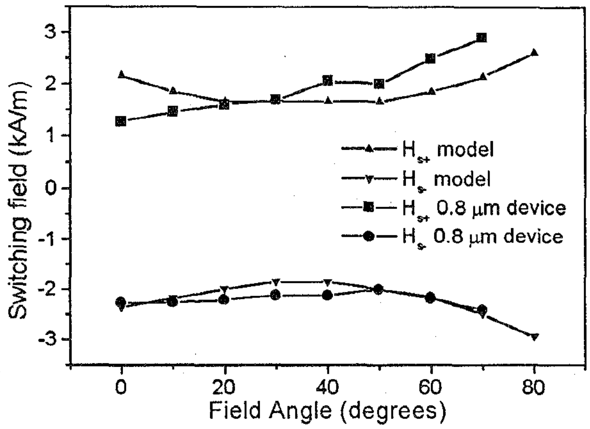

Fig. 6. Experimental and modeled switching fields of a 0.8 μm by 8 μm device as a function of applied field angle.

Conclusions

We have examined the effects of magnetic field angle and bias current on the magnetoresistive behavior of digital spin valves. The switching fields fall off with bias current in a manner qualitatively predicted by a simple single domain model. There is a significant sensitivity of the switching fields to the applied field angle which can not be predicted by single domain models. In all cases it remains difficult to quantitatively predict the switching fields of these devices.

The variation of the switching field as a function of bias current may be useful in MRAM applications as a method to select a given element in a series write array. It may be useful in sensor applications as a method to tune the switching field to the desired level. The sensitivity of the switching field to applied field angle indicates that we may want to vary the applied field geometry from the simple on-axis configuration. However, an improvement in the understanding and predictability of switching in these devices is required before this type of engineering is feasible.

References

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