Coercivity and Switching Field- Engineered Magnetic Multilayers for 3-D Patterned Media

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We demonstrate the use of an exchange-biased magnetic multilayer structure as a promising basis for developing a three-dimensional-patterned storage medium. The behavior of several multilayered structures is investigated. The structures are of the form Si(001)/Ta/Co/Ta/Co/FeMn/Ta/Co/FeMn/Ta. The memory state is determined by the orientation of the magnetization of each magnetic layer. In order to achieve the independent switching of the magnetic layers necessary to set the state of the three-dimensional (3-D) "memory," the switching field and coercivity are controlled by making use of the increased coercivity and exchange biasing that result from coupling an antiferromagnetic layer to a ferromagnetic layer, and by varying the thickness of each magnetic layer. The change in behavior upon patterning the exchange-biased continuous multilayered films into arrays of 50-μm diameter dots, is investigated. We find that patterning on this scale dramatically changed the switching behavior of the magnetic layers.

***Index Terms*—Exchange bias, FeMn, multilayer, patterned structures.**

I. INTRODUCTION

MULTILAYERED magnetic structures have become key components in magnetic data storage technology, most notably as sensors in read heads for hard drives and as memory elements in magnetic random-access memory arrays (MRAMs) [1]. MRAM consists of a multilayer stack where a free magnetic layer acts as a storage bit. We propose to extend this principle to a stack of magnetic layers each separated by nonmagnetic layers, where each magnetic layer represents a bit (i.e., "0" for magnetization pointing along a reference positive direction), "1" if it points in the opposite direction, to create a three-dimensional (3-D) memory array. By resolving the magnetization of each layer, a stack of such layers can represent a binary code of as many digits as magnetic layers. Several criteria need to be fulfilled in order to use these structures for such applications. First, the layers need to be designed in such a way that they completely switch independently and abruptly at different fields, corresponding to so-called digital switching. This can be achieved most easily by using the exchange biasing effect (i.e., coupling ferromagnetic (FM) layers to antiferromagnetic (AF) layers [2]). Much research has been done on the topic of exchange biasing, and recent reviews of the experimental status [3] and theoretical models [4] are available. Although a comprehensive theoretical model is still currently lacking, the consensus is that exchange biasing is an interfacial effect that occurs when an FM and AF layer interact to behave as one unit. In order for this to happen, the FM and AF layers either need to be grown under a magnetic field, or the sample heated above the Néel temperature of the antiferromagnet and cooled in the presence of a magnetic field. The result is a horizontal shift of the hysteresis loop (the exchange field) and an increase in coercivity. The FM/AF bilayers are separated from other bilayers by thick nonmagnetic spacer layers, such that interlayer coupling between the different bilayers is minimized. The choice of FM and AF material and their thicknesses plays a key role in engineering the coercivity and switching behavior of the total structure. The alignment of the different bilayers in the structure should be preserved at remanence and be stable over time. Finally, all of these properties, when studied on continuous films, should be preserved when patterned into small structures to realize a memory array. In this case, dipole coupling becomes important and it is necessary to preserve the state of alignment in the presence of significant internal dipolar fields.

II. EXPERIMENTS

Si(001)/Ta(5)/Co(5)/Ta(10)/Co(2,3,5)/FeMn(10)/Ta(10)/-Co (5)/FeMn(20)/Ta(5) multilayer structures were grown using dc magnetron sputter deposition techniques in an ultra-high vacuum system with a base pressure of 2×10^{-9} torr. Layers are deposited sequentially by a 6-target sputtering system, controlled by an advanced computer control system. All layers were grown at room temperature with a working pressure of 1.5×10^{-2} mTorr, and a 14 standard cubic centimeter per minute (sccm) Ar gas flow. A magnetic field of 50 Oe was applied *in-situ* during the growth of the magnetic layers in order to induce a uniaxial anisotropy and the exchange bias. Optical lithography techniques were used to pattern the multilayered structures. Thick positive resist AZ9260 was used in spin coating, which was soft baked at 115 °C, UV exposed and developed into circular dot patterns. A complete pattern transfer onto the multilayered structure was accomplished by ion milling with Ar (98%) and O_2 (2%), at a rate of 20 nm/min and a working pressure of 4×10^{-4} mTorr. The sample holder was water cooled and kept at 18 °C. Magnetic characterizations of the unpatterned and patterned multilayered structures were carried out using a QuantumDesign superconducting quantum interference magnetometry (SQUID) magnetometer. The measurements were performed along the sample easy axes at 110 K, starting and ending at the large positive field.

III. RESULTS AND DISCUSSION

Two continuous films were investigated first. The first one is a Si(001)/Ta(5)/Co(5)/Ta(10)/Co(5)FeMn(10)-/Ta(10)/Co(5)

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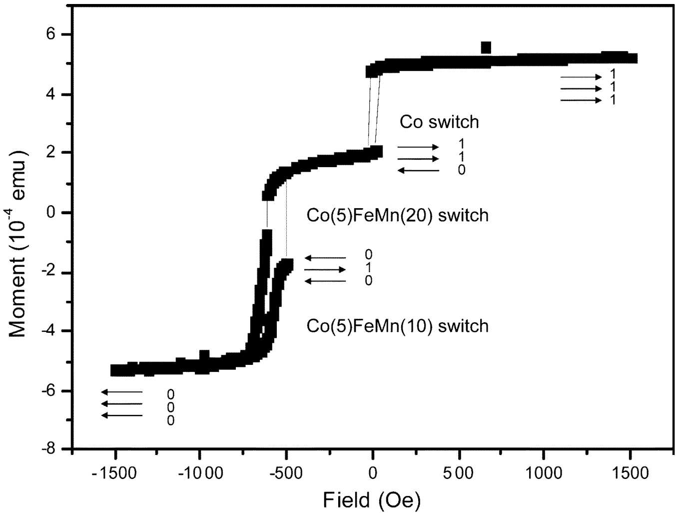

Fig. 1. SQUID measurements of three different magnetic layers separated by Ta layers. The structure, with thicknesses in brackets in nanometers, is Si(001)/Ta(5)/Co(5)/Ta(10)/Co(5)FeMn(10)/Ta(10)/Co(5)FeMn(20)/Ta(5). The arrows in the insets indicate the alignment of each magnetic layer, where the top arrow corresponds to the pinned Co(5)FeMn(20) layer, the middle arrow to the pinned Co(5)FeMn(10) layer, and the bottom arrow to the free Co(5) layer. The numbers indicate the binary code that can be associated with each state of alignment.

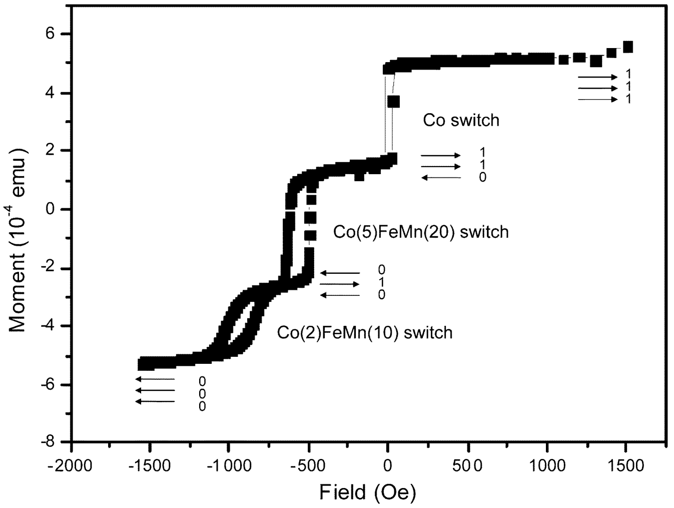

Fig. 2. SQUID measurements of the Si(001)/Ta(5)/Co(5)/Ta(10)/-Co(2) FeMn(10)/Ta(10)/Co(5)FeMn(20)/Ta(5) multilayer structure. The difference with the previous graph is a thinner layer of cobalt for the bottom AF/FM bilayer.

FeMn(20)/Ta(5) structure, where the bottom Co layer is a free layer and the middle and top Co layers are coupled to FeMn (all thicknesses in nanometers). Fig. 1 shows an M–H loop for this structure, measured by SQUID at 110 K. Each step in the figure is associated with the switching of individual magnetic layers, where it is understood that the coupled AF and FM layer behaves as one entity. The insets in the graph show which layer switches at each step. We see therefore that each plateau in the graph (e.g., between 100 and 400 Oe), is associated with a state where the magnetic layers are in a particular alignment. Calling the alignment of a magnetic layer with the positive magnetic field "1," we can assign a binary code to each type of plateau, which is indicated in the graph. The second structure is Si(001)/Ta(5)/Co(5)/Ta(10)/Co(2)FeMn(10)-Ta(10)/Co(5)FeMn(20)/Ta(5). Here, the cobalt thickness of the middle layer has been decreased to investigate the effect it has on the switching behavior of the structure. In Fig. 2, the M–H loop of this structure is shown. It can be seen that decreasing the thickness of the pinned Co layer has the effect of increasing the exchange bias, which makes the Co(2)/FeMn(10) layer switch at a more negative field value.

FeMn is an antiferromagnet with a bulk Néel temperature of 220 °C [5] and, thus, the Co/FeMn layers are expected to be exchange biased. The free Co layer can be clearly identified in Figs. 1 and 2, because it has not been biased through coupling to an antiferromagnetic layer and, therefore, switches close to the origin (in the particular orientation chosen here). By comparing the two figures, we can deduce that the Co(5)/FeMn(20) layer switches before the Co layer coupled to the 10-nm FeMn film. It is a well-known phenomenon that the exchange bias and coercivity decrease with increasing thickness of the ferromagnetic layer [4], which is consistent with the stronger exchange biasing of the Co(2)/FeMn(10) layer, compared with the Co(5)/FeMn(10) layer of the first sample. On the other hand, the exchange field does not change for AF layer thickness between 10 and 20 nm [4], which explains the near overlap of the two loops in Fig. 1. We see, therefore, that by suitably choosing the FM layer thickness combined with the AF biasing layer, we can control the field at which a certain pinned layer will reverse its magnetization.

Identifying the binary codes corresponding to each digital state shows that we can access some but not all of the possible 3-b codes. In addition, none of these states is preserved at remanence. In order to preserve these states at remanence, it will be necessary to fine tune the FM and AF layer thicknesses and manipulate the exchange bias of the bilayers. A combination of an increased coercivity and a reduced exchange field will be needed in order to achieve this. One other possibility, which we explore next, is to alter the magnetic properties by patterning the multilayer system into small elements.

Fig. 3 shows the M–H loop for a similar sample, but patterned into 50-μm disks, spaced by 50 μm. The structure is Si(001)/Ta(5)/Co(5)/Ta(10)/Co(3)FeMn(10)-/Ta(10)/Co(5) FeMn(20)/Ta(5). The disk separation is such that the magnetic interaction between disks is small, which is the case when the separation is of the order of the element size [6]. After patterning, the hysteresis loop shows an increase in coercivity to almost 1 kOe, with several discrete steps indicating abrupt changes in the magnetization. This is exactly the behavior that is desired for a 3-D memory medium, since each of the magnetic states can be preserved at remanence. The principle of "locking" a structure in a particular magnetic state is demonstrated in Fig. 4 where a minor loop of the same structure is shown. Because the negative field is only ramped to 1000 Oe instead of the 1200 Oe required to saturate the sample, it leaves one of the layers pointing in the opposite direction, resulting in a lower total magnetization value. This shows that for these particular structures, we can control the magnetization alignment at remanence. The number of steps, which we assigned on the continuous films to the magnetization reversal of a magnetic layer, in this sample actually exceeds the amount of layers,

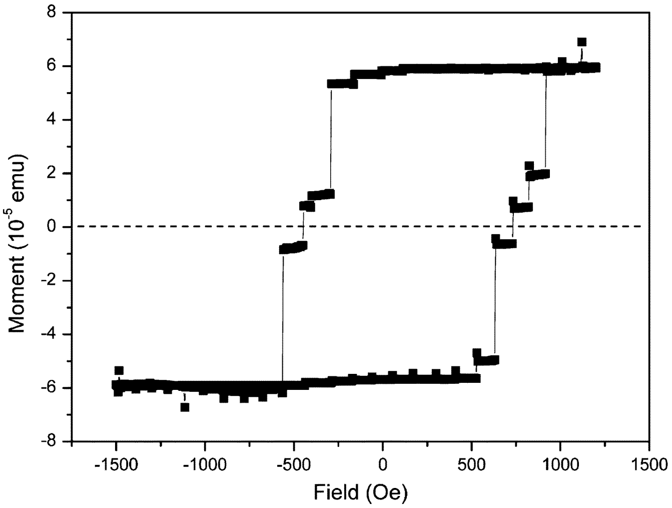

Fig. 3. SQUID measurements of the Si(001)/Ta(5)/Co(5)/Ta(10)/-Co(2) FeMn(10)/Ta(10)/Co(5)FeMn(20)/Ta(5) structure, but patterned in 50-μm dots and spaced by 50 μm. There are several abrupt changes in the magnetization states, not all of which can be accounted for by the magnetization reversal of pinned and free layers. It can be seen that the coercivity has increased significantly compared to the continuous films, and that the saturation magnetization is retained at remanence.

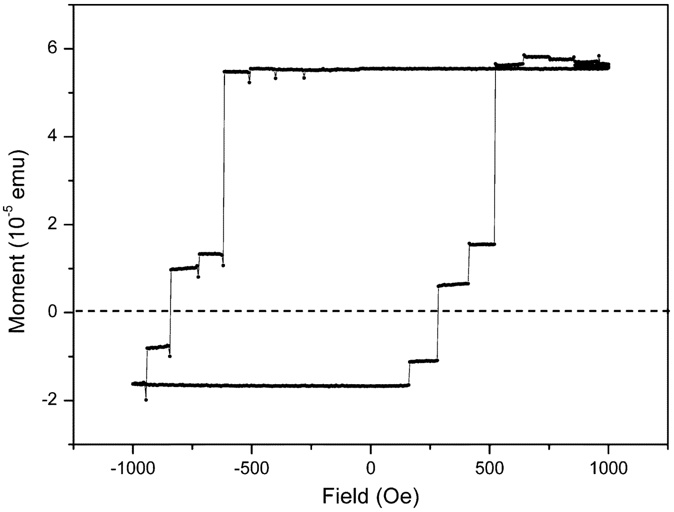

Fig. 4. SQUID measurements of the Si(001)/Ta(5)/Co(5)/Ta(10)/-Co(2) FeMn(10)/Ta(10)/Co(5)FeMn(20)/Ta(5) multilayer, patterned into 50-μm dots and spaced by 30 μm, locked into an intermediate state. The field is insufficient to reverse the magnetization of all layers and the remanent state has a magnetization value which is less than saturation.

probably due to a stabilized domain state in the disks. Although research has been done on the effect of patterning exchange biased structures [7]–[9], the magnitude of this change in coercivity and switching behavior is rather unexpected, especially given the large size of the structures. After measuring the same patterned sample a few times, we found that the loop reverts back to that of the continuous film. This could be due to a training effect, which is known to change the coercivity and exchange bias over a few number of cycles [10].

IV. CONCLUSION

Magnetometry measurements of the continuous FM/AF multilayer structures show that each Co free and pinned layer switches independently. However, the coercivity of each pinned layer is low while the switching field is relatively large, making it impossible to lock the structure into a designated state at zero field (i.e., there is no control over the memory state). Selecting different thicknesses for the FM layer have been shown to influence the switching behavior. Additionally, given that different AF materials have a different effect on the bias field and coercivity [9], it can be expected that varying the material of the AF layer is the means of tuning the switching behavior of these structures. It is expected that carefully choosing the thicknesses and materials for the FM and AF layers will make it possible to create a structure to allow different memory states to be selected. Upon patterning, the behavior of these structures changes dramatically and exhibits a very large coercivity with discrete steps in the M–H loop. This suggests the possibility of locking each layer in a particular direction at zero field.

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