# Permanent-magnet-free stabilization and sensitivity tailoring of magnetoresistive field sensors

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(Received 17 May 2007; accepted 13 June 2007; published online 2 August 2007)

We have exploited the coupling across a ruthenium spacer between a ferromagnetic and an antiferromagnetic layer to stabilize the magnetization in a given direction and tailor the magnetic sensitivity of the sensor for various applications. Ruthenium is used as the nonmagnetic coupling layer and is self-aligned with the ferromagnetic free layer and antiferromagnetic pinning layer, and the thickness is varied to change the slope of the transfer curve in the linear region, i.e., sensitivity. This simple technique is shown to increase the dynamic range of anisotropic magnetoresistive sensors without additional lithography. © *2007 American Institute of Physics*.
[DOI: 10.1063/1.2764243]

## I. INTRODUCTION

Unidirectional stabilization of free layers in anisotropic magnetoresistive (AMR) sensors is important in order to reduce noise, improve reliability, and maintain polarity. Typical solutions utilize permanent magnets or antiferromagnet (AF) tabs on the ends to provide a biasing field across a ferromagnetic (FM) free layer.[1] This method is effective but it does not allow accurate tailoring of the sensitivity. Furthermore, this solution adds lithographic and deposition steps to the overall process.

Another option would be to use an AF layer in direct contact with the free layer; however, this would create a too strong bias.[2–5] Our goal is to mitigate this strong coupling by weakening the exchange interaction with a nonmagnetic spacer layer. Starting from the results of two FM layers sandwiching a nonmagnetic layer, for example, a ruthenium (Ru) layer,[4,6] one can expect reduced coupling between a FM layer and an AF layer. In fact, Ru has been shown to be effective as a nonmagnetic coupling layer in FM/Ru/AF stacks.[7]

In this work, we demonstrate a tailored free layer sensitivity leading to an increased dynamic range in AMR sensors. As expected, we also realize a successful longitudinal, unidirectional stabilization for our rectangular sensor geometry. The addition of a Ru spacer layer accomplishes this with no additional masking or deposition layers, i.e., it is self aligned, and no annealing to reset the AF. We show that this type of bias can replace both exchange tabs and hard magnet bias schemes and can be easily implemented into existing processes.

## II. EXPERIMENT

Trilayer films were deposited on silicon ⟨100⟩ wafers with 150 nm of thermally grown $SiO_2$ on top using dc magnetron sputtering in an ultrahigh vacuum (UHV) system with a base pressure less than $1.0\times10^{-6}$ Pa. No temperature control of the substrate was used. The stack is in a bottom-pinned configuration beginning with 3 nm of Ru used as a texturing layer to provide a smooth surface for the AF layer. The AF layer is 8 nm of $Ir_{20}Mn_{80}$ and was deposited from a binary target at a rate of 0.9 Å/s followed by varying thicknesses of Ru as a spacer layer. In the same deposition step, 25 nm of $Ni_{81}Fe_{19}$ deposited at a rate of 1.8 Å/s was used for the FM layer and the stack was capped with another 5 nm of Ta. It is important to note that the entire stack was deposited in consecutive layers, all without breaking vacuum. A magnetic field of 16 kA/m was applied during the FM deposition to induce a uniaxial, in-plane anisotropy in the magnetic sensing layer. No further annealing to set the pinning of the AF layer was performed. The strength of the exchange bias field was determined from bulk film measurements on a B–H looper, shown in Fig. 1. These data show the shift in exchange bias measured on unpatterned wafers. It is apparent that as the Ru spacer layer thickness is reduced, the hysteresis loop shifts to the right, indicating an increase in the exchange bias. Figure 2 plots the decrease of exchange bias for six different thicknesses of the Ru spacer. The reduction in the exchange bias approximates an exponential decrease, as expected.[5,7] We saw a shift from 3200 A/m for the case where no Ru spacer layer was used to separate the FM and AF layers, down to 10 A/m for the case where 2 nm of Ru

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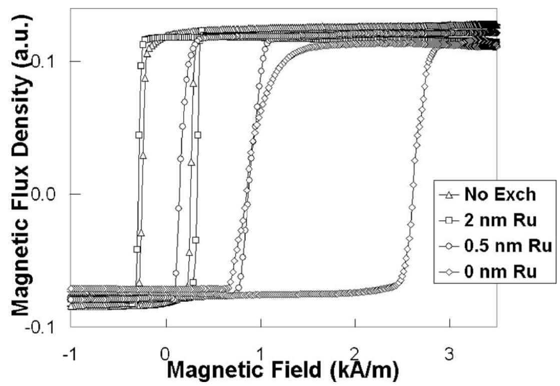


FIG. 1. Exchange bias shift for unpatterned wafer with field applied along axis of induced uniaxial anisotropy (easy axis). Curves are for decreasing Ru spacer layer thickness from left to right with an unbiased NiFe wafer for comparison.

was used. The case of the 2 nm Ru layer is compared here with the case of no IrMn (i.e., no AF exchange) and the two cases are shown to be almost identical.

Patterned elements were then defined using a standard lift-off process in a 10:1 length-to-width aspect ratio. The widths of the elements were 5 $\mu$m in all cases. Aluminum contacts and barber-pole[9] shorting bars were evaporated onto the trilayer elements, also in a lift-off process, and the finished wafer was diced and tested.

To test the exchange bias from the AF layer, two types of samples were prepared: single unbiased elements with a needle geometry and single elements (needles) with barber poles to bias the current at 45° to the magnetization. Testing was performed on the patterned elements with a magnetoresistance looper. Patterned sensors were wire bonded to circuit boards with 25 $\mu$m $Al_{99}Si_1$ wire and mounted on a stage centered between two orthogonal sets of Helmholtz coils. Measurements were taken using a standard four point technique with an instrumentation amplifier readout for accuracy. A magnetic field applied along the hard axis was swept from −10 to 10 kA/m in order to produce the MR transfer curve.

## III. RESULTS AND DISCUSSION

As illustrated by the unpatterned, bulk film loops, the exchange bias between the FM and AF layers depends on the

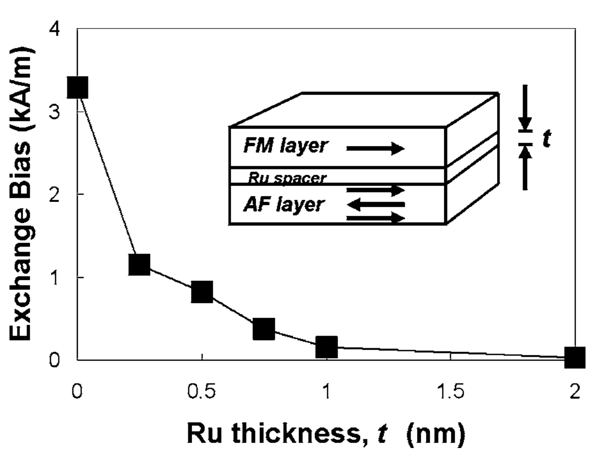


FIG. 2. Varying the exchange bias as a function of Ru thickness. The inset shows the coupled layers. The line is added as a guide to the eyes.

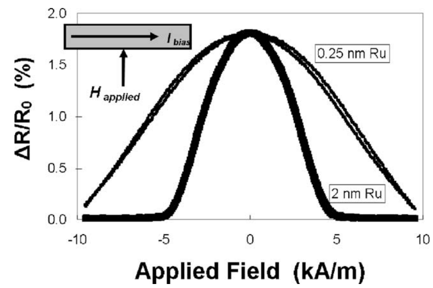


FIG. 3. Magnetoresistance of patterned elements for two thicknesses of the Ru spacer layer. Inset shows the measurement setup.

Ru spacer thickness in our trilayer elements. This has been explained in previous work to be due in large part to the long range exchange coupling that can exist between FM and AF thin films.[2,7] Our Ru thickness range of 2 nm and less could lead to pinholes that would allow direct exchange coupling between the FM and AF layers, but studies by Wang *et al.* indicate that indirect coupling dominates in this bottom-pinned configuration. We saw a shift in the hysteresis curves for Ru buffer layer thicknesses up to 2 nm; however, the shift is already less than 400 A/m at 1 nm.

In order to probe the exchange bias, we use the AMR effect, where the magnetoresistance is defined here as $\Delta R/R_0$.[8] The transfer curves for patterned needles shows a narrowing of the parabolic response as the Ru thickness increases. This is illustrated in Fig. 3 for two different thicknesses. Narrowing indicates that it is easier to turn the magnetization of the film with lower fields. This will result in a magnetic field sensor of higher sensitivity. On the other hand, with thinner layers of Ru, higher dynamic range can be realized with reduced sensitivity. In addition, there is a unidirectional stabilizing exchange bias that allows the sensing elements to be exposed to saturating fields and not be reset. In order to demonstrate this, we used a barber-pole biasing scheme that is sensitive to the direction of the magnetization relative to the current.

The sensitivity of the devices was evaluated as the slope of the MR transfer curve. We show the slopes of selected sensors in the inset of Fig. 4. The exponential decay of the exchange field leads to an increase in sensitivity, as can be seen in the plot of Fig. 4. It is also important to note that the stabilizing field for small exchange bias still allows for the

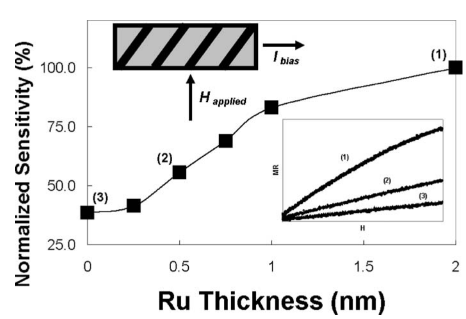


FIG. 4. Normalized sensitivity (to 2 Ru thickness) of patterned elements vs Ru thickness. The line is added as a guide to the eyes. Bottom inset shows measurement setup for a patterned element with barber-pole biasing. Top inset shows transfer curves from three biased elements for small applied fields (1)=2 nm Ru, (2)=0.5 nm Ru, and (3)=0 nm Ru.

resetting of magnetization after a large switching field is applied along the axis of induced uniaxial anisotropy (easy axis). Notably, the unidirectional stabilization was effective even for the 2 nm thick Ru spacer, while the slope indicates little effective coupling. This combination of tunable sensitivity and unidirectional stabilization would allow an AMR sensor to be designed to respond to a wider dynamic range or to be customized for a specific applied field.

It has also been shown in literature that Ru used as a buffer layer between FM layers can help to form a (001)-oriented bcc pinned layer after annealing.[9] While we did not anneal our samples, an increased MR would be expected due to improved texturing by the Ru buffer layer after annealing. In addition, we expect that the exchange bias could affect the noise properties of these sensors. Further experiments are ongoing in these directions.

## IV. SUMMARY

We have demonstrated a technique by which AMR sensors can be stabilized in a given direction of the uniaxial anisotropy with a self-aligned AF layer. The exchange bias can be reduced in a controlled manner with a Ru spacer layer separating the FM and AF layers. This unidirectional stabilization resets the magnetization in the event that it is saturated in the opposite direction. Furthermore, the sensitivity of the MR layer can be tailored to a wider dynamic range. This biasing scheme involves no additional lithographic steps and can be implemented in existing processes for the free layer in any type of AMR sensor.

## ACKNOWLEDGMENTS

We acknowledge help in various stages of this project from Dexin Wang. This work was financially supported by the Competence program of the National Institute of Standards and Technology.


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