Hysteresis loop collapse for linear response in magnetic-tunnel-junction sensors

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In our Al_2O_3 magnetic-tunnel junction (MTJ) samples that have a Neel coupling equal to or larger than their easy-axis coercivities, we found that the hysteresis loop totally collapses into a near-linear response upon rotating the easy axis of the sample off the applied field axis. A very high magnetic field sensitivity of 138%/mT (13.8%/Oe), which is among the highest reported so far, with near-linear response, was exhibited by Al_2O_3 MTJs using this loop collapsing technique. This phenomenon can be explained by the switching astroid curve. In order to make this technique applicable in an actual sensor, we devised a two-step procedure whereby both easy-axis and hard-axis fields are used to accomplish the same loop collapsing effect as rotation. These result is one of the best combinations of saturation field and tunneling magnetoresistance ever achieved for MTJs, in addition to the linear nonhysteretic response at zero field that is so important for magnetic sensors. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3076624]

I. INTRODUCTION

Magnetic tunnel junctions (MTJs) are an ideal candidate for low magnetic field sensors because of the high magnetoresistance and low power consumption which are favorable for making portable sensors.[1] In addition to large tunneling magnetoresistance (TMR), low Neel coupling (NC),[2] and small saturation field, another important criterion for an ultrasensitive sensor is a linear response in its hysteresis loop.[3] Coercivity should be eliminated entirely in order to assure low noise in the sensor. Traditionally the coercivity is removed by applying a hard-axis bias field during the sensor operation to eliminate the hysteretic response.[3] In our Al_2O_3 MTJ samples, where the NC is equal to or larger than the easy-axis coercivity, rotating the sample can lead to a collapse of the hysteresis loop and a linear sensor response. By applying an additional static field in the easy axis, we can shift the steepest part of the curve to the 0 mT (Oe) of the sweep field and thus the MTJ sensor can have bipolar low-field response.[4]

II. EXPERIMENT

dc magnetron sputtering was used to deposit the MTJ thin films on thermally oxidized silicon wafers in an ultrahigh vacuum chamber with a base pressure of 2×10^{-8} Pa. The oxide barrier layer was made by first depositing a thin layer of Al metal and then oxidizing it in oxygen plasma of 0.4 Pa argon and 0.3 Pa oxygen. A magnetic field of 7 mT (70 Oe) was applied during magnetic layer deposition to induce the sample's easy axis and pinning direction. The sample structure is substrate/20 Conetic ($Ni_{77}Fe_{14}Cu_5Mo_4$)/1 $Co_{50}Fe_{50}$/1 Al: oxidized/1 $Co_{50}Fe_{50}$/2.5 Conetic ($Ni_{77}Fe_{14}Cu_5Mo_4$)/10 $Ir_{20}Mn_{80}$/7 Ru (all thicknesses in nm). The lower Conetic and CoFe layers are coupled together to form the free layer while the upper Conetic coupled with the CoFe constitutes the pinned layer, exchange biased by the IrMn. The Ru serves as the protective cap layer. Current-in-plane-tunneling technique (CIPT) was used to perform electrical characterization of the blanket films. A *B-H* looper was used to carry out magnetic characterization. The sample was annealed in vacuum at 200 °C for 15 min with an applied magnetic field of 70 mT (700 Oe).

III. RESULTS AND DISCUSSION

Figure 1 shows the hysteresis loop measured by the *B-H* looper for the MTJ sample at room temperature. The blue loop is the data measured along the easy axis. The NC is measured to be 0.43 mT (4.3 Oe) and the coercivity is 0.29 mT (2.9 Oe). The NC of this sample is larger than its coercivity. The sample was then rotated from its easy axis in the *B-H* looper. At a rotation angle of 40°, the hysteresis loop collapsed, yielding a linear response at the inflection point and the coercivity was reduced to almost zero (red loop). This loop collapsing phenomenon is reproducible. The sample was rotated back and forth from 0° to 180° and this loop collapsing phenomenon occurred reproducibly when the rotation reached 40°. At this angle, the steepest part of the hysteresis loop was situated at around 0.5 mT (5 Oe). For the purpose of a magnetic field sensor, a static bias field of 0.5 mT (5 Oe) was applied along the easy axis to shift the operating point to zero mT (Oe) of the sweep field (see the green loop in Fig. 1). CIPT measurements show that the TMR of this sample is 36%. The maximum slope of the green loop extrapolates to saturation at 0.13 mT (1.3 Oe). The field sen-

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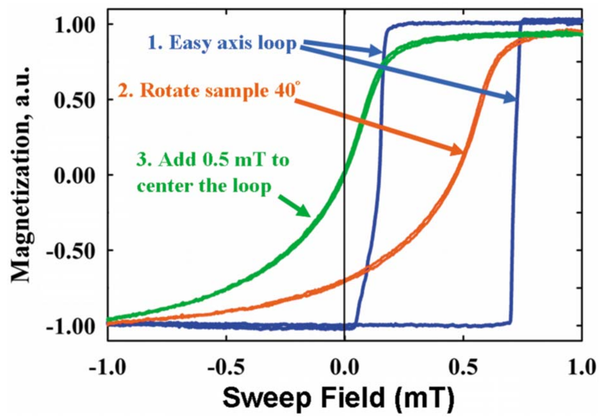

FIG. 1. (Color online) Hysteresis loop measurement by *B-H* looper on the Al_2O_3 MTJ whose NC [0.43 mT (4.3 Oe)] is larger than its coercivity [0.29 mT (2.9 Oe)]. Loop 1 was measured along the easy axis of the sample. Loop 2 was measured with the sample rotated 40°. Loop 3 was measured with the 40° sample rotation and an additional static easy-axis field of 0.5 mT (5 Oe) to shift the steepest part of the red loop to the zero field point.

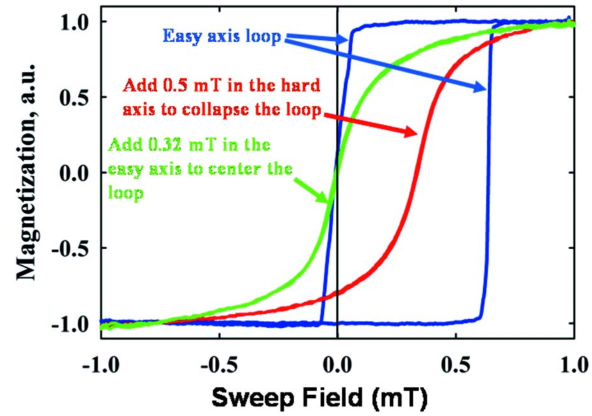

FIG. 3. (Color online) Hysteresis loop measurement by *B-H* looper on another Al_2O_3 MTJ whose NC [0.33 mT (3.3 Oe)] is equal to its coercivity [0.33 mT (3.3 Oe)] and its TMR is 36%. Loop 1 is the hysteresis loop measurement along the easy axis. A static field of 0.5 mT (5 Oe) was then applied in the hard axis to collapse the loop which is shown as Loop 2. The loop was centered at zero field by applying a static field of 0.32 mT (3.2 Oe) in the easy axis and it is displayed as Loop 3.

sitivity of the MTJ sample at the steepest part of the green loop can be calculated from the saturation field and the TMR: 36% divided by 2×0.13 mT=138%/mT (13.8%/Oe). This result is among the largest reported for magnetic field sensors with a linear and nonhysteretic response. Comparing the zero field slopes of the red loop and the green loop, we can see that centering the loop with an easy-axis static field steepens the slope and thus enhances the device sensitivity.

Further studies indicate that the rotation degree needed to collapse the loop is dependent on how much the NC is in excess of the coercivity. We carried out experiments on the loop collapsing phenomenon with more than a hundred samples with similar structures. Figure 2 is the plot of the rotation angle (θ) required to induce the loop collapse, as a function of the difference between the NC and the coercivity (i.e., NC-H_c). In general, θ is inversely proportional to

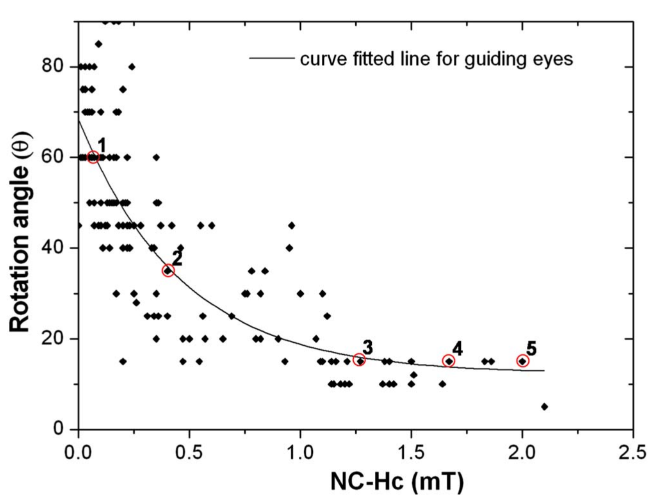

FIG. 2. (Color online) Sample rotation angle θ needed to collapse the hysteresis loop vs NC-H_c (NC minus coercivity). Measurements taken from more than a hundred samples with similar MTJ structures. The data points are fitted with an exponential decay curve for guiding eyes. The circled data points are used to plot Fig. 5. The numbers of these circles data points in this figure correspond to the numbers of the astroids in Fig. 5.

(NC-H_c). Therefore we can manipulate the rotation angle θ by controlling the NC and the coercivity. By applying a single field at the rotation angle θ, we can collapse the hysteretic response into a linear one. This one-step loop collapsing procedure is potentially a very useful technique for MTJ magnetic field sensors because it is inherently simpler than the traditional hard-axis biasing method which involves applying an external static field. However, it is not easy to optimize this technique because the rotation angle and the field variables are coupled together. In order to improve this technique and make it applicable to an actual sensor, we devised a two-step procedure in which, first of all, the easy-axis hysteresis loop was collapsed by applying a static field in the hard axis.[3] The vector sum of this hard-axis static field and the easy-axis sweeping field is effectively the same as the sweeping field at the rotated angle θ, thereby collapsing the hysteresis loop the same way. Then a static field in the easy axis was applied to shift the operating point to zero mT (Oe) of the sweep field, as illustrated in Fig. 3. With this two-step procedure, we only need to adjust the field variables to optimize the loop collapsing technique. The TMR of this sample is 36% and the steepest slope at zero field extrapolates to saturation at 0.15 mT (1.5 Oe). Therefore this MTJ has a sensitivity of $36\%/(2\times 0.15\ \text{mT})=120\%/\text{mT}$ (12%/Oe). The switching astroids presented in Fig. 4 helps to clarify the one-step and the two-step loop collapsing behaviors. For the one-step procedure, a sweeping field is applied at a rotation angle (θ) to collapse the loop as illustrated in Fig. 4(a) and the static bias field is used to shift the operating point to zero mT (Oe) of the sweep field. For the two-step procedure, a hard-axis bias field is applied and then a sweeping field is applied along the easy axis to collapse the loop. The static bias field in the easy axis again is used to shift the operating point to zero mT (Oe) of the sweep field. The best results occur operating just outside the switching astroid where the bias field is just large enough to collapse the loop. Figure 5 shows a few switching astroids for increasing values of NC, which corresponds to the circled data points of

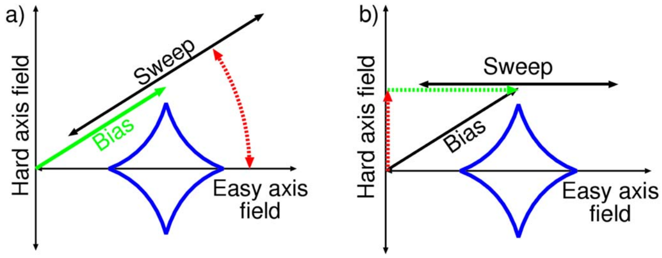

FIG. 4. (Color online) Switching astroids illustrating the mechanisms of (a) the one-step and (b) the two-step loop collapsing procedures. In Fig. 4(a), the dashed arrow corresponds to the sample rotation so that the loop collapses and the bias arrow is the static bias field used to shift the operating point to zero mT (Oe) of the sweep field. In Fig. 4(b), the vertical dashed arrow is the hard-axis static bias field used to collapse the loop and the horizontal dashed arrow is the easy axis static bias field to shift the operating point to zero mT (Oe) of the sweep field. The effective bias in this case is the resultant bias of the vertical dashed arrow (hard axis static bias) and the horizontal dashed arrow (easy axis static bias) which is equivalent to the bias (bias arrow) in Fig. 4(a).

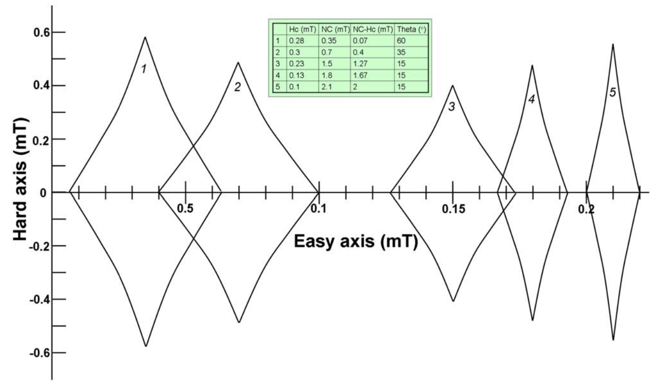

FIG. 5. (Color online) A family of switching astroids for increasing values of NC from the circled data points of Fig. 2. It shows the variation of the astroid sizes with the NC. The inset table lists the coercivity (H_c), NC, NC-H_c, and the rotation angle (θ) needed to collapse the hysteresis loops for these three samples. The numbers of the astroids correspond to the numbers of the circled data points in Fig. 2.

Fig. 2. From this figure we can see how the astroid changes size as a function of the NC. There is a trend toward lower coercivity with increasing NC, and the field needed to collapse the loop does not change much.

IV. CONCLUSION

In our Al_2O_3 MTJ samples where the NC was equal to or larger than the easy-axis coercivity, we found very good results by using a single field applied at an angle between the hard and easy axes to collapse the hysteresis loop into a linear response. By this technique, we achieved a sensitivity of 138%/mT (13.8%/Oe) for a MTJ with a TMR of 33% and a saturation field of only 0.13 mT (1.3 Oe), which is the highest MTJ sensor sensitivity ever published. We also devised a two-step procedure which enables us to optimize this loop collapsing technique by adjusting only the field variables. This loop collapsing phenomenon can be explained by the switching astroid. This loop collapsing technique has important application in making MTJ magnetic field sensors and it has the potential to improve the sensor sensitivity to the picotesla scale.[5]

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