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Reduction of switching fields of submicrometer sized magnetic tunnel junction with NiFe-based synthetic ferrimagnetic free layer

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We fabricated submicrometer sized magnetic tunnel junctions (MTJs) with soft NiFe-based synthetic ferrimagnet (SynF) free layers. An extremely low switching field of 13 Oe was achieved when the stacking structure of the free layer was NiFe(2 nm)/CoFe(0.2 nm)/Ru(0.4 nm)/CoFe(0.2nm)/NiFe(2.1 nm) with 0.4 μm cell. The switching field of the SynF structure was almost independent of the cell width. Small magnetic anisotropy of NiFe and enhanced antiferromagnetic coupling strength from insertion of 0.2-nm-thick CoFe were important attributes for the low switching field in the submicrometer sized MTJs. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2424399]

I. INTRODUCTION

Demagnetizing fields from cell edges increase the switching fields of small ferromagnets, which increase the switching current of a bit in magnetic random access memory (MRAM) when the bit is smaller than several hundred nanometers.[1] Consequently, the power consumption of the whole device to reverse the magnetization of the cell increases markedly. Using the Stoner-Wolfarth single-domain model,[2] the switching field (H_{sw}) of a flat ellipsoid in the easy axis direction can be expressed as follows:[3]

$$H_{sw} = H_{sw1} + H_{sw2}, \quad H_{sw2}(k) = S(k)M_s t/W. \tag{1}$$

In that equation, H_{sw1} is independent of the cell size and corresponds to the anisotropy field ($H_k=2K_u/M$, K_u, uniaxial anisotropy energy; M, magnetization) of a large sample. Depending on the cell size, H_{sw2} is also inversely proportional to cell width W and is directly proportional to magnetic layer thickness t and shape factor $S(k)$. In addition, $S(k)$ is proportional to the aspect ratio $k=L/W$ (L, cell length along an easy axis).[3] Also, S and H_{sw2} become 0 in the ideal case in which k has the lowest value of 1.[3] However, such a low aspect ratio results in a vortex state of domain.[4] Thereby, the total switching field (H_{sw}) to reverse magnetization of the free layer with a low aspect ratio will be larger than that with a high aspect ratio. A synthetic ferrimagnet (SynF) structure for the free magnetic layer was proposed to solve this problem.[5] When the antiferromagnetic coupling strength is sufficiently strong, the SynF free layer can have a single-domain structure, even at a low aspect ratio because the stray fields from edges of the two magnetic layers in the free layer will form a flux closed loop.[6] Hence, the SynF free layer based on the CoFe/Ru/CoFe multilayer has already been examined. Results revealed that H_{sw} is independent of the cell width. However, the CoFe/Ru/CoFe SynF showed a large switching field of about 60 Oe because of the high H_{sw1} value of CoFe. This value is large for a high-density MRAM. Therefore, SynF composed of ferromagnetic material with a low H_{sw1} value is necessary to reduce both terms of Eq. (1). Consequently, NiFe alloy is a candidate because its H_{sw1} value is typically lower than 1 Oe. Through this study, we fabricated submicrometer sized magnetic tunnel junctions (MTJs) with a NiFe-based SynF free layer and examined the size dependence of the switching field.

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II. EXPERIMENTAL PROCEDURE

We prepared MTJs with three different free layers: an ordinary free layer of NiFe(4.9 nm) , a SynF free layer composed of NiFe(2.4 nm)/Ru(0.4 nm)/NiFe(2.6 nm), and a modified SynF free layer of NiFe(2 nm)/CoFe(0.2 nm)/Ru(0.4 nm)/CoFe(0.2 nm)/NiFe(2.1 nm). Free layers' Ru thickness was selected as 0.4 nm because the coupling strength was greatest at that thickness. The stacking structures of MTJs were substrate/Ta(20 nm)/freelayer/Al(1.6 nm)-O/CoFe(2.5 nm)/Ru(0.8 nm)/CoFe(2 nm)/Cr(5 nm)/Au(50 nm). The thickness of each NiFe layer in the free layers was different such that the total saturation magnetization value of all free layers was identical. The NiFe layer had a dead layer of 0.6 nm at the interface adjacent to Ta and of 0.1 nm at the interface adjacent to AlO. The consequent effective thicknesses of the respective free layers were NiFe(4.2 nm), NiFe(1.8 nm)/Ru(0.4 nm)/NiFe(2.5 nm), and NiFe(1.4 nm)/CoFe(0.2 nm)/Ru(0.4 nm)/CoFe(0.2 nm)/NiFe(2 nm). The prepared MTJs had a bottom-free structure to avoid degradation of antiferromagnetic coupling strength caused by large surface roughness of the underlayer in the case of a top-free structure. Our previous study confirmed that antiferromagnetic coupling of SynF free layer of bottom-free MTJs was stronger than that of top-free MTJs.

Large samples consisting of substrate/Ta(5 nm)/

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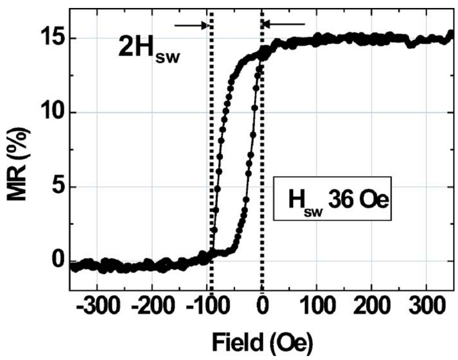

FIG. 1. The magnetoresistance curve of NiFe free layer measured using C-AFM. The distance of the dotted lines indicates $2H_{sw}$.

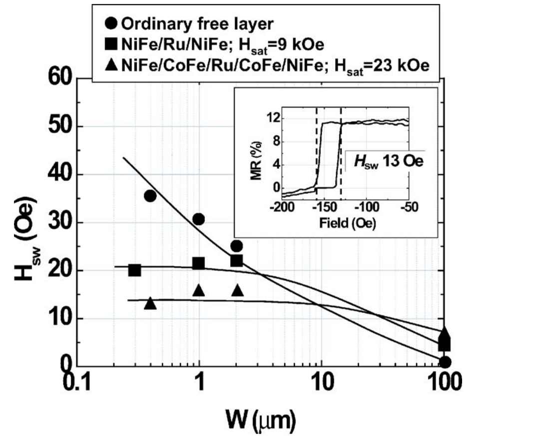

FIG. 2. H_{sw} as a function of cell width W for MTJs with an ordinary free layer (●), SynF free layer of NiFe/Ru/NiFe (■), and NiFe/CoFe/Ru/CoFe/NiFe (▲). Lines are guides for eyes. The inset shows the MR loop of MTJ with NiFe/CoFe/Ru/CoFe/NiFe free layer at W of 0.4 μm. Distance of dotted lines in the inset corresponds to $2H_{sw}$.

NiFe($6.8-0.22t$ nm)/CoFe(t nm)/Ru(0.8 nm)/CoFe (t nm)/NiFe($3.6-0.22t$ nm)/Ru(5 nm) were prepared to investigate the effect of inserting thin CoFe film on the antiferromagnetic coupling property. For these samples, the thickness of the Ru layer was 0.8 nm because it is easier to determine the saturation field (H_{sat}) of SynF in the magnetization curves. For 0.4-nm-thick Ru, severe broadening of H_{sat} caused by high pinhole density occurs. For that reason, H_{sat} was not determined accurately.[11]

All films were deposited on Si/SiO_2(1 μm) substrates using an inductively coupled plasma (ICP)-assisted magnetron-sputtering machine. Subsequently, films with MTJ structure were patterned to submicrometer size (cell width, 0.3–2 μm; aspect ratio, 1–4; rectangular) using electron beam lithography and successive Ar ion milling. We used conductive atomic force microscopy (C-AFM) to measure magnetoresistance (MR) loops of the MTJs.[7] Magnetic fields of up to ±350 Oe were applied to the long axis of the MTJs. This technique enables measurement of MR loops of very small MTJs easily and obviates complicated microfabrication processes for contact holes and top electrodes. The 50-nm-thick Au layer, a capping layer used to mitigate surface oxidation, reduced the contact resistance between the AFM tip and the MTJ top electrode. We defined $2H_{sw}$ as the difference of the fields at which resistance of the sample reached 90% of the full resistance change. Magnetization curves were measured using a vibrating sample magnetometer (VSM) at room temperature.

III. RESULTS AND DISCUSSION

Figure 1 shows a MR curve of the sample with an ordinary free layer. The cell width was 400 nm and the aspect ratio was 1. The loop center shifted to the negative field direction because of stray field coupling between the pinned layer and the free layer. The hysteresis loop showed an inclined switching process even though the field was applied along the easy axis, suggesting a vortex domain structure.

Figure 2 shows H_{sw} as a function of cell width W for MTJs with various free layers. All data plotted here were obtained in the MTJs with aspect ratio of 1. The H_{sw} of the MTJ with an ordinary free layer increased with decreasing W. The value for W of 0.4 μm was 36 Oe. The value of H_{sw} of the cell with an aspect ratio of 1 would be independent of W if the cell were to have an ideal single-domain state. However, the creation of the vortex domain caused by the demagnetizing field makes H_{sw} larger in actual cases. For this reason, the ordinary free layer showed a large H_{sw} value at smaller W, although it has a very low H_{sw1} value of 0.8 Oe. For these analyses, we used an ordinary free layer with only 4.9 nm thickness, the same total thickness as SynF free layer, as a reference because a marked decrease of the MR ratio was apparent at lesser thickness. Practically speaking, it is impossible to compare an ordinary and SynF free layer with the same net thickness, 1.4 nm, because of the magnetic dead layer.

The H_{sw} of the small MTJ was greatly reduced when the free layer was replaced with the SynF multilayer of NiFe/Ru/NiFe. The H_{sw} value at W of 0.3 μm was only 21 Oe. The value of H_{sw1} of the NiFe/Ru/NiFe SynF increased to 4.5 Oe because of reduced torque by the factor of $(t_1-t_1)/(t_1+t_2)$, where t_1 and t_2 are the NiFe free layer thicknesses.[5] Reduced effective thickness of the free layer and closed stray field resulted from the antiparallel configuration of the two magnetic layers are reasons for the H_{sw} reduction. However, the H_{sw} of NiFe/Ru/NiFe multilayer still increased as W decreased because of the degradation of the single-domain structure. Stronger antiferromagnetic coupling and balance of the thickness of the two magnetic layers are important for the SynF single-domain structure.[8] The thickness ratio of two magnetic layers in SynF was 20:14, which was almost balanced, judging from precedent reports.[5,6,9] Therefore, we inferred that weak coupling in NiFe/Ru/NiFe SynF layer was the main reason for this increment. Actually, the antiferromagnetic coupling strength of NiFe/Ru/NiFe system is much weaker than that of CoFe/Ru/CoFe. The exchange constant J_{ex} obtained from the saturation fields (H_{sat}) was 0.58 ergs/cm^2 for the NiFe/Ru/NiFe system and was 2.9 ergs/cm^2 for CoFe/Ru/CoFe.[10] Therefore, inserting only a few monolayers of CoFe between NiFe and Ru is an effective means to strengthen the antiferromagnetic coupling. Figure 3 shows the H_{sat} and H_{sw1} of Ta(5 nm)/NiFe($6.8-0.22t$ nm)/CoFe(t nm)/Ru(0.8 nm)/CoFe(t nm)/NiFe($3.6-0.22t$ nm)/Ru(5 nm)

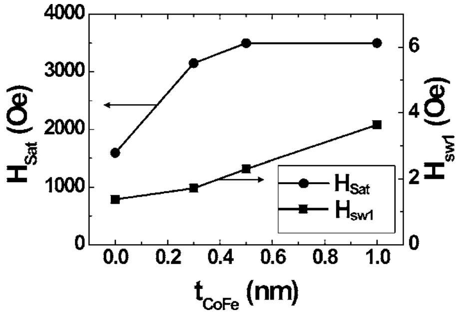

FIG. 3. The saturation field H_{sat} (●) and size-independent part of switching field H_{sw1} (■) of Ta(5 nm)/NiFe(6.8−0.22*t* nm)/CoFe(*t* nm)/Ru(0.8 nm)/CoFe(*t* nm)/NiFe(3.6−0.22*t* nm)/Ru(5 nm) multilayer as a function of CoFe thickness *t*. Multilayers were formed on large size Si wafers: 10×10 mm^2.

multilayer as a function of CoFe thickness *t*. The samples are sufficiently large. Therefore, the demagnetizing field is negligible and H_{sw} should include only the H_{sw1} term in Eq. (1). To maintain equivalence of the total magnetization of the two magnetic layers, thicknesses of the NiFe were reduced with increasing CoFe thickness. The saturation field H_{sat} increased considerably with increasing CoFe thickness and saturated at 0.5 nm. In addition, H_{sw1} increased with CoFe thickness, reflecting the larger magnetic anisotropy of CoFe. Therefore, we chose a CoFe thickness of 0.2 nm for MTJ because the antiferromagnetic coupling was strengthened sufficiently, but the anisotropy field H_{sw1} was influenced little. Based on that result, MTJ with the SynF free layer including 0.2-nm-thick CoFe and 0.4-nm-thick Ru was prepared. This SynF free layer showed H_{sat} of about 23 kOe, whereas the H_{sat} of the NiFe/Ru/NiFe free layer was about 9 kOe. Figure 2 shows that the H_{sw} of the free layer composed of NiFe(2 nm)/CoFe(0.2 nm)/Ru(0.4 nm)/CoFe(0.2 nm)/NiFe(2.1 nm) was lower than that of NiFe/Ru/NiFe. Although H_{sw1} of this multilayer increased to 6.5 Oe, the value of H_{sw} at *W* of 0.4 μm size was only 13 Oe. A MR loop of the MTJ is shown in the inset of Fig. 2. This MR loop shows a MR ratio of only 13%, which is smaller than typical MTJs with AlO tunnel barrier.[12] In the MTJ, the oxidation condition of the Al–O barrier was not optimized thoroughly and no annealing process was performed, which usually enhances the MR ratio greatly.[13] The sharp switching of the loop is evidence of coherent rotation of the free layer with a single-domain structure. It is remarkable that H_{sw} of this SynF free layer was almost independent of cell width. The value of H_{sw} is expected to be low for cells as small as 0.1 μm. Applying the SynF free layer to 0.1 μm MTJ, the power consumption of the writing process in high-density MRAMs can be kept small. Further investigation must be made of thermal fluctuation of the coupled magnetizations in the SynF free layer.

IV. SUMMARY

We investigated the switching field H_{sw} of submicrometer sized MTJs with SynF free layer based on NiFe. The lowest switching field of 13 Oe for 0.4×0.4 μm^2 cells was achieved when the stacking structure of the free layer was NiFe/CoFe/Ru/CoFe/NiFe. Low H_{sw1} value of NiFe and enhanced antiferromagnetic coupling by inserting thin CoFe layers are important to realize the small switching field. Deep submicrometer sized MTJs with low switching field SynF free layers are useful to develop low-power, high-density MRAMs.

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