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Transport Properties of Magnetic Tunnel Junctions Comprising NiFeSiB/CoFeB Hybrid Free Layers

Ji Ung Cho[1], Do Kyun Kim[1], Reasmey P. Tan[1], Shinji Isogami[2], Masakiyo Tsunoda[2], Migaku Takahashi[2], and Young Keun Kim[1]

[1]Department of Materials Science and Engineering, Korea University, Seoul 136-713, Korea
[2]Department of Electronic Engineering, Tohoku University, Sendai 980-8579, Japan

We report on the magneto-transport measurements of MgO magnetic tunnel junctions (MTJs) composed of NiFeSiB/CoFeB as the free layer for two different structures (top-type and bottom-type pinning). The magneto-transport properties of these MTJs were investigated by varying the thickness of the amorphous NiFeSiB layer for a fixed CoFeB thickness. The tunnel magnetoresistance (TMR), measured in both type of structures, exhibit the same or a higher amplitude (up to 230% measured at room temperature in the case of top-type device), comparing to the case of a single CoFeB free layer. These results suggest that hybrids free layers can be used as good candidates for MTJs with reduced saturation magnetization while keeping a high TMR ratio.

Index Terms—**Amorphous, hybrid free layer, magnetic tunnel junction, NiFeSiB.**

I. INTRODUCTION

MAGNETIC tunnel junctions (MTJs) can promisingly be applied to spintronic devices such as magnetic random access memory (MRAM), thanks to the large tunneling magnetoresistance (TMR) effect [1]. Nevertheless, in order to use these structures in applications, some requirements need to be fulfilled: 1) high TMR ratio at room temperature; 2) low saturation magnetization of the materials; and 3) low power consumption of the device, i.e., low value of the so-called resistance-area (RA) product.

Huge values of TMR at room temperature have been reported when MTJs are composed of a MgO tunnel barrier [2], [3]. These high amplitudes have been attributed to the dependence of the tunneling probability on the symmetry of the Bloch states at the Fermi level and to the decay of the evanescent state in the MgO barrier [4]. Moreover, magneto-transport measurements of CoFeB/MgO/CoFeB MTJs have successfully demonstrated that high TMR ratio could be achieved when the CoFeB layer is crystallized in bcc (001) [5]. However, in or order to reach the challenging gigabit scale of MRAM, the use of spin torque transfer (STT) switching technology seems to be indispensable. In the latter phenomenon, one of the main parameter is the switching current density which can be approximated to a quadratic relationship with the saturation magnetization (M_s) [6]. Obviously, a reduction in the magnetization should involve effectively a decrease of the current density. Therefore, attempts to develop new materials with a low M_s while maintaining a high TMR ratio are of great interest. One of the proper solutions is to introduce a free bilayer structure composed of a soft magnetic material while keeping the same interface between the MgO and CoFeB layer. Indeed, a soft ferromagnetic layer combined with a CoFeB top electrode layer is interesting for applications since this bilayered structure should display a high permeability and a low coercive field. However, by investigating the magneto-transport properties of a bilayered NiFe/CoFeB electrode, Yuasa *et al.* [7] showed that the tunnel magnetoresistance (TMR) magnitude in these structures decreased considerably to less than 50%. The last issue addressed, concerning the power consumption, tends to indicate also that dealing with low values of RA seems detrimental to high TMR ratio.

We previously reported on the study of an amorphous ferromagnetic NiFeSiB layer which could partially substitute the traditionally used amorphous CoFeB free layer [8]. Indeed, NiFeSiB shows a lower saturation magnetization value (890 emu/cm^3) but remains interestingly amorphous even at an annealing temperature required to crystallize the CoFeB on the MgO (001) layer. Therefore, the high TMR value compared to the single CoFeB free layer MTJs was maintained to 200% in the case of the hybrid CoFeB (3 nm)/NiFeSiB (1.33 nm) structure. In this study, we present the influence of the thickness of the inserted NiFeSiB layer on the magneto-transport properties of such hybrid MTJs, for the top type pinning structure and the bottom one. We show that in both cases, the high TMR ratio and RA value are conserved and even increased in the case of TMR, and decreased for RA.

II. EXPERIMENTAL PROCEDURE

The stacks of Si/SiO$_2$/Ta(5)/Ru(40)/Ta(5)/hybrid free layer (t)/MgO(1.9)/CoFeB(4)/Ru(0.85)/CoFe(3)/IrMn(7.5)/Ta(5)/Ru(50) (in nm) (top type MTJ) and Si/SiO$_2$/Ta(5)/Ru(40)/IrMn(7.5)/CoFe(3)/Ru(0.85)/CoFeB(4)/MgO(1.9)/hybrid free layer (t)/Ta(5)/Ru(50) (bottom type MTJ) (see Fig. 1) were prepared by dc magnetron sputtering under a base pressure below 5×10^{-9} torr. During the deposition, a magnetic field of 30 Oe was applied in-plane to the substrate to induce anisotropy. We have designed a series of MTJs consisting of x/y electrodes (x and y are $M_s t$ values of Ni$_{10}$Fe$_{65}$Si$_3$B$_{22}$ and (Co$_{50}$Fe$_{50}$)$_{78}$B$_{22}$ layer of free layer, respectively, where x/y being 0.5/3, 1/3, 2/3 and 0/4). Consequently, the hybrid free layers used are, NiFeSiB (0.67)/CoFeB(3), NiFeSiB (1.33)/CoFeB (3), NiFeSiB (2.67)/CoFeB (3), and CoFeB (4) (in nm). The MgO tunnel barrier was formed in a separate chamber by rf sputtering from MgO target. The MTJ samples were annealed in vacuum at 360°C for 1 h under a magnetic

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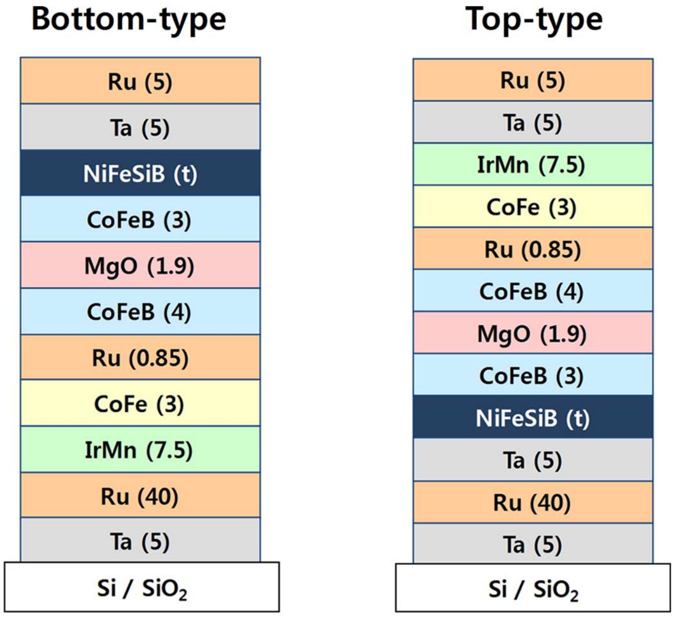

(a) (b)

Fig. 1. Scheme of the MTJs measured with the insertion of NiFeSiB layer to (a) bottom-type (b) top-type structure.

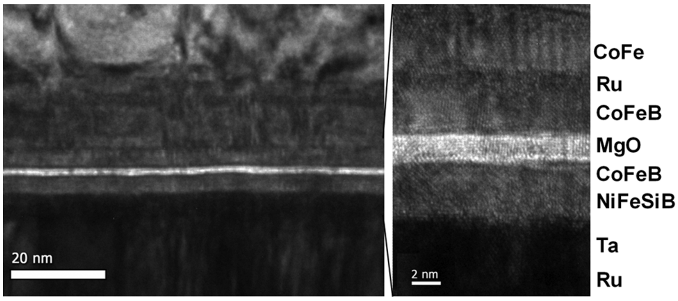

Fig. 2. HRTEM images of the top-type MTJs consisting of a CoFe 2/NiFeSiB 2.67 nm hybrid free layer magnetic tunnel junction before annealing. The layers with light contrast are tunnel barriers.

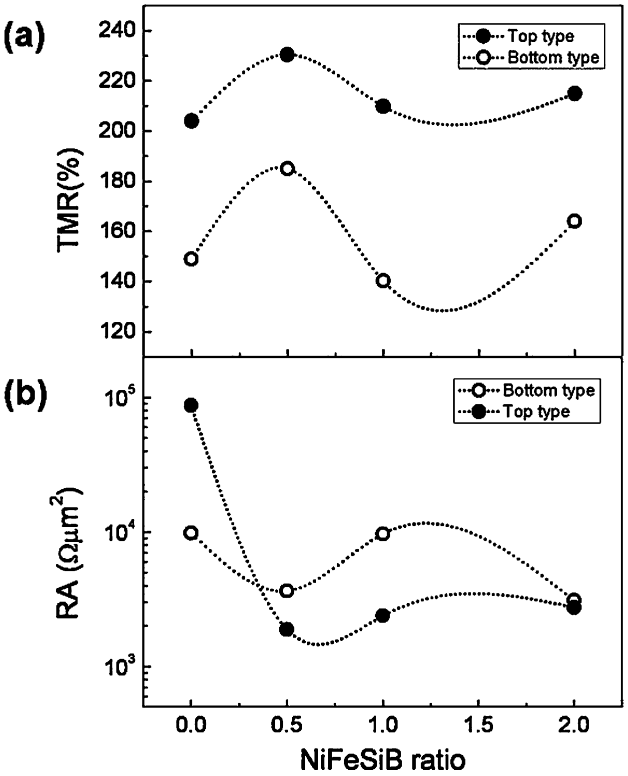

Fig. 3. (a) TMR ratios of the MTJs as a function of the NiFeSiB ratio in the hybrid free layer. The The CoFeB thickness was fixed to 3 nm (NiFeSiB ratio 0.5, 1.0 and 2.0 is 0.67, 1.33, 2.67 nm) and MgO tunnel barrier thickness was fixed to 1.9 nm. (b) Relation between the RA value and NiFeSiB ratio with top and bottom pinning; the dashed lines are guide lines for eyes.

field of 3 kOe (under 1×10^{-6} torr). The interface of the films was investigated by high resolution transmission electron microscopy (HRTEM) and the TMR ratio was measured by the current-in-plane-tunneling (CIPT) technique.

III. Results and Discussion

Fig. 2 shows images of top-type MTJ before annealing. MgO tunnel barrier formed (100) crystallinity. After annealing, the CoFeB layer adjacent to MgO barrier will be crystallized to bcc (001) thanks to the well oriented MgO barrier. Therefore, we could expect high TMR ratio for the hybrid free layer MTJs. It should be noted that the interface between the CoFeB layer and the NiFeSiB one was not clear since both layers displayed an amorphous structure.

Fig. 3 shows TMR and RA value as a function of the NiFeSiB layer thickness in the hybrid free layer for both pinning type structures. For a ratio x/y equal to 0/4 (single CoFeB free layer), the TMR value is 204% and 149% for the top type and the bottom type pinning, respectively. When the amorphous NiFeSiB layer is inserted, the TMR magnitude exhibits similar or higher value for both pinning structure [see Fig. 3(a)]. For a ratio x/y of 0.5/3, 1/3 and 2/3, TMR amplitudes become 230%, 209%, 214% in the case of top-type pinning, and 185%, 140%, 164% in the case of the bottom- type. For all values of x/y ratio, the top-type pinned MTJs show higher TMR values compared to the bottom-type ones [see Fig. 2(a)]. This could be explained in terms of the MTJs structure, especially with the location of the free layer on the top/bottom of the MgO barrier and its probable influence on the quality of the barrier. Actually, the required magnetic couplings between the CoFe and the IrMn layer make impossible the insertion of a Ta layer in the case of the bottom-type MTJs. Consequently, as reported in [9], the top-type structure shows higher TMR ratio because the Ta layer seems to prevent the crystallization of the CoFeB layer before annealing. As a result, MgO (001) orientation is more favorable comparing to the bottom pinning. Therefore, it is well known that high crystallinity of the barrier leads to an increase of the TMR. In other words, in the case of the bottom-type MTJ, the microstructure of the IrMn layer is fcc (111) while the CoFe and Ru layer should be induced into bcc (110) and hcp (001). As a result the CoFeB layer deposited on IrMn/CoFe/Ru structure tends to be bcc (110). Even if a thin IrMn layer and a high B concentration favor an amorphous state, some crystallographic effects probably come from the under-layers below the CoFeB layer during its formation [9].

The variation of the RA product is shown in Fig. 3(b). For both type of pinning structures, the insertion of a NiFeSiB layer coupled to the CoFeB one leads to a decrease of RA values. Even if the reduction is more pronounced for the top-type MTJ, both type of structures display qualitatively the same behavior. The resistance of the devices dominantly comes from the tunnel barrier, the height of which is proportional to the thickness of MgO barrier. However, in our case, even if all MTJs have the same MgO thickness, we observed some significant changes in RA value by inserting the NiFeSiB layer. Another counter-intuitive point is depicted in Fig. 3: the RA and TMR values vary in an opposite way. In fact, as we mentioned before, a high value of TMR should induce a high value of RA. This point is clearly observed when the single CoFeB free layer is measured, but contradicted when the NiFeSiB is inserted. In addition, both TMR and RA values are seems to be oscillating depending on the NiFeSiB thickness. We do not have current explanations for these unexpected observations. However, it is likely that RA value can be affected, not only by the thickness of the MgO layer but by other parameters such as interfacial resistances for instance. The underlying mechanism between the RA value and the TMR ratio remains unclear and deserves much works.

IV. CONCLUSION

We investigated the NiFeSiB thickness dependence on the hybrid free layer of top- and bottom-type pinning MTJs. The TMR ratios and RA values was found to be increased or decreased in a non-monotonic way while the inserted NiFeSiB thickness was increased, demonstrating the potentiality of such devices to be used in applications. The exact mechanism and relationship between the insertion of a NiFeSiB and the TMR/RA variation are under investigation.

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