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Annealing temperature dependence of critical current and thermal stability factor in MgO-barrier magnetic tunnel junctions with CoFeB based synthetic ferrimagnetic recording layer

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1. Introduction

Recently, spin transfer torque random access memory (SPRAM) utilizing the potential of current–induced magnetization switching (CIMS) for CoFeB/MgO/CoFeB magnetic tunnel junctions (MTJs) has been demonstrated. [1]-[4] To attain even higher capacity nonvolatile SPRAM, the dimension of the MTJs is simply reduced. It results in the degradation of thermal-stability factor (E/k_BT) of the recording layer, hence, it is necessary to keep on enhancing E/k_BT, and reducing a critical current density (J_c) for the MTJs at the same time. In order to satisfy this requirement, we have been investigating the use of a $Co_{20}Fe_{60}B_{20}$ based synthetic ferrimagnetic (SyF) recording layer, and then succeeded in reducing the intrinsic J_c (J_{c0}) down to 2 MA/cm^2, however, the E/k_BT has remained around 40 in this system. [5] One possible way to further grow in E/k_BT, while reducing J_{c0}, is an increase of saturation magnetization (M_s) of CoFeB layer in the recording layer by crystallizing it from amorphous through annealing generally at over 320^{o}C. [6] In this paper, we report the effect of annealing on J_{c0}, E/k_BT and film structure in the MgO-barrier MTJs with a $Co_{20}Fe_{60}B_{20}$/Ru/$Co_{20}Fe_{60}B_{20}$ SyF recording layer and discuss the possible origin of the annealing temperature dependence of them.

2. Experimental procedure

Figure 1 shows a schematic of the MTJs structure, which were deposited by RF magnetron sputtering. The film layers were, starting from the Si/SiO substrate (in nm), Ta(5)/ Ru(10)/ Ta(5)/ NiFe(3)/ MnIr(8)/ $Co_{50}Fe_{50}$(2.5)/ Ru(0.8)/ $Co_{20}Fe_{60}B_{20}$(3)/ MgO(0.9)/ $Co_{20}Fe_{60}B_{20}$(2)/ Ru(0.8)/ $Co_{20}Fe_{60}B_{20}$(1.8)/ capping layer. The junctions with dimension of 100 × 200 nm^2 were fabricated using electron-beam lithography and then annealed at 300, 325 and 350^{o}C under a magnetic field of 4 kOe. The resistance (R) – magnetic field (H) loops of the MTJs were measured using a four-probe method. The J_{c0} and E/k_BT were obtained from the J_c vs. $\ln(\tau_p/\tau_0)$ plot generated from the plot of resistance as a function of pulsed-current with a duration (τ_p) ranging from 30 μs to 1 s.

3. Results and discussion

Figure 2 (a) and (b) plot the J_{c0} and E/k_BT, respectively, as a function of annealing temperature (T_a). J_{c0} as low as 1.5 MA/cm^2 and high E/k_BT of 68 are obtained in the MTJs annealed at 300^{o}C, and then, by elevating T_a to 325^{o}C, we succeed in enhancing the E/k_BT up to 75 while maintaining the J_{c0} as low as 1.6 MA/cm^2. On the other hand, annealing at 350^{o}C finally results in dramatic enhancement of E/k_BT to 109 although J_{c0} increases to 3.2 MA/cm^2.

In order to understand the dependence of annealing on J_{c0} and E/k_BT, we examined the T_a dependence of magnetic coupling state between two $Co_{20}Fe_{60}B_{20}$ ferromagnetic layers by evaluating the asteroid curves. Fig. 3 shows the variety of asteroid curves depending on T_a for the same MTJs as shown in Fig. 2. The curves shown in Fig. 3 (a) (T_a = 300^{o}C) and (b) (T_a = 325^{o}C) indicate that the magnetizations of two CoFeB layers in the SyF recoding layer couple antiferromagnetically. [7] On the other hand, the curve shown in Fig. 3 (c) (T_a = 350^{o}C) illustrates that the antiferromagnetic (AF) coupling state disappear, and the recoding layer is likely to behave as a single ferromagnetic layer not a SyF layer, in which the anisotropy field (H_k) is estimated as 120 Oe (see arrows in Fig. 3(c)). Here, Table I presents the dependence of T_a on the M_s of $Co_{20}Fe_{60}B_{20}$ and the AF coupling energy (J_{ex}) in the SyF layer. The M_s of CoFeB is found to increase when the T_a is over 325^{o}C, on the other hand, the J_{ex} does not seem to change so greatly between T_a of 300 and 325^{o}C. The MTJs with SyF recoding layer which has the AF coupling exhibit the low J_{c0}, and then the increased M_s through annealing at 325^{o}C results in high E/k_BT. The disappearance of AF coupling state accompanying with an increase of M_s by the crystallization of $Co_{20}Fe_{60}B_{20}$ is responsible for the rise in J_{c0} and E/k_BT for the MTJs annealed at 350^{o}C.

Figure 4 shows cross section transmission electron microscopy (TEM) images of the part of MgO barrier and the recording layer in the MTJs annealed at 300^{o}C (a), 325^{o}C (b), and 350^{o}C (c). On the same figure, the corresponding line profiles of energy dispersive X-ray (EDX) are shown with regard to Co, Fe, Ru, and Mg elements. The clear distinct of Ru layer from CoFeB layers in the SyF recoding layer can be seen from Fig. 4 (a) and (b) (T_a = 300 and 325^{o}C). This state realizes the antiferromagnetic coupling. When the MTJs is annealed at 325^{o}C, even though the Ru remains between two CoFeB layers, an interface between

CoFeB and Ru does not seem to be clear (Fig. 4 (b)) compared to that of MTJs annealed at 300°C, whereas the Ru diffusion of this level does not separate the antiferromagnetic coupling between two CoFeB. In the case of T_a = 350°C, the Ru layer is not identified in SyF layer (Fig. 4 (c)). It can be also pointed out from EDX line profiles that the Ru diffuses into the adjacent CoFeB layers and proceeds to the entire SyF recording layer. It is appeared that the CoFeB-Ru mixed single recording layer is formed from the CoFeB/Ru/CoFeB by annealing at 350°C, resulting that the antiferromagnetic coupling disappeared.

4. Conclusions

We succeeded in high E/k_BT of 75 together with J_{c0} as low as 1.6 MA/cm^2 by annealing at 325°C for the MgO-barrier MTJs with $Co_{20}Fe_{60}B_{20}$/Ru/$Co_{20}Fe_{60}B_{20}$ SyF recording layer. When the T_a elevates to 350°C, E/k_BT dramatically rises in 109 although J_{c0} also increases to 3 MA/cm^2. The deferent J_{c0} and E/k_BT depending on T_a appeared to be caused by the variety of magnetic properties in the SyF recoding layer through the annealing. When the T_a is 325°C, the antiferromagnetic coupling maintains while increasing the M_s of the CoFeB by the crystallization, whereas the antiferromagnetic coupling state disappear by annealing at 350°C due to the diffusion of Ru into the entire SyF recording layer.

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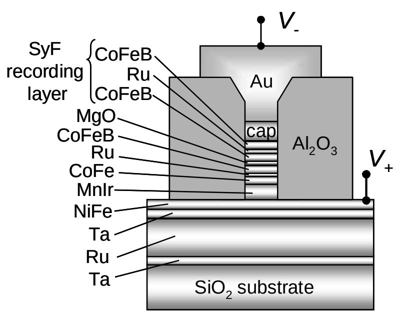

Fig. 1 Schematic diagram of the MTJ structure with dimension of 100 × 200 nm^2. The compositions CoFeB and CoFe are as $Co_{20}Fe_{60}B_{20}$ and $Co_{50}Fe_{50}$, respectively.

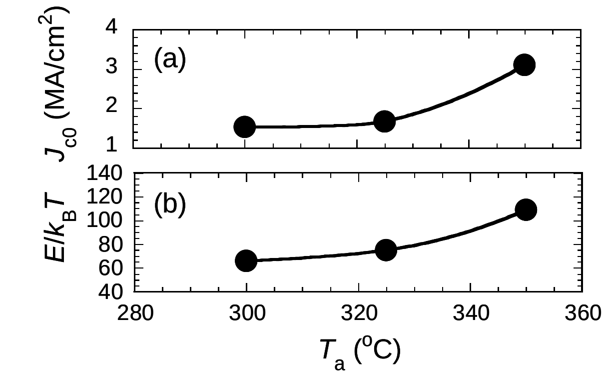

Fig. 2 (a) J_{c0} and (b) E/k_BT as a function of annealing temperature (T_a) in the MTJs with $Co_{20}Fe_{60}B_{20}$(2 nm) /Ru(0.8 nm) /$Co_{20}Fe_{60}B_{20}$ (1.8 nm) SyF recording layer.

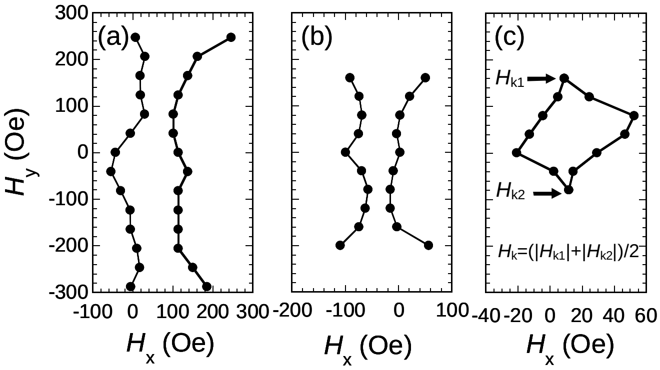

Fig. 3 Variety of asteroid curves in MTJs annealed at 300°C (a), 325°C (b), and 350°C (c).

Table 1 Magnetic parameters as a function of T_a

T_a (°C)	300	325	350
Magnetic coupling	anti-ferromagnetic	anti-ferromagnetic	ferromagnetic or no coupling
$4\pi M_s$ (T) of $Co_{20}Fe_{60}B_{20}$	1.36	1.42	1.43
J_{ex} (mJ/m^2)	-0.17	-0.14	–

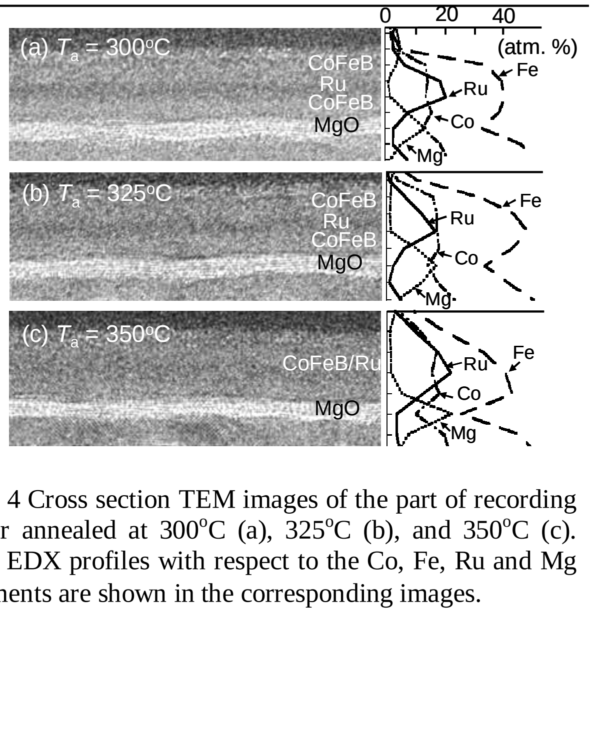

Fig. 4 Cross section TEM images of the part of recording layer annealed at 300°C (a), 325°C (b), and 350°C (c). The EDX profiles with respect to the Co, Fe, Ru and Mg elements are shown in the corresponding images.