Spin-transfer Switching in Magnetic Tunnel Junctions with Synthetic Ferri-magnetic Free Layer

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Abstract. We have fabricated the SyF structure with both high annealing stability and strong interlayer exchange coupling and investigated tunnelling magnetoresistance (TMR) and spin-transfer switching properties of magnetic tunnel junctions (MTJs) with developed SyF free layer. The fabricated SyF with structure of Ta/Ru/CoFe/Ru/CoFeB possessed high annealing stability of 400°C and strong interlayer exchange coupling. Consequently, a large TMR ratio of 122% has been observed after annealing at high temperature of 350°C. In addition, we have successfully observed spin-transfer switching by the net current density of 14 MA/cm² and the large thermal stability factor of 62.

1. Introduction

Spin-transfer switching predicted by Slonczewski [1] and Berger [2] has recently attracted much attention because of its potential application in STT-RAM (spin-transfer torque random access memory). In particular, spin-transfer switching in magnetic tunnel junctions (MTJs) which consist of CoFeB/MgO/CoFeB has been reported a lot owing to their large tunnel magnetoresistance (TMR) ratio and low critical current density ($J_c$) for magnetization switching [3]. However, for making a high-density STT-RAM, it is necessary to further reduce $J_c$ while maintaining a high thermal stability factor ($E/k_BT$, where $E$, $k_B$, and $T$ are the energy potential, the Boltzmann constant, and temperature, respectively) well over 60. While $J_c$ is proportional to the product of the magnetization and the thickness of the free layer, $E/k_BT$ is proportional to the volume of the free layer. Therefore, it is very difficult to meet the above requirements.

Synthetic ferrimagnetic (SyF) structures consisting of two or more ferromagnetic layers which couple antiparallel through non-magnetic spacers such as Ru is expected to provide large volume to withstand thermal fluctuation [4], so spin-transfer switching in MTJs using the SyF free layer have been investigated [5]. However, the effect of SyF free layer is not investigated sufficiently, probably because the interlayer coupling strength of the SyF structure in previous report is not so strong. In addition, the SyF structure has poor annealing stability [6]. This weakness is a serious problem in using the SyFs in the CoFeB/MgO/CoFeB MTJs because high annealing temperature is necessary to obtain a large TMR ratio.

In this work, we have fabricated the SyF structure with both high annealing stability and strong interlayer exchange coupling by optimizing the stacking structure of the multilayer film and investigated TMR and spin-transfer switching properties of MTJs with developed SyF free layer.
2. Experiment
Thin films were deposited on thermally oxidized Si wafers by using magnetron sputtering with a base pressure of $10^{-6}$ Pa. The samples were annealed in the temperature range from 300 to 450°C for 1 h in a $10^{-4}$ Pa vacuum under a magnetic field of 10 kOe. We measured magnetic properties of the SyF structures using vibrating sample magnetometer (VSM). The nano-scaled junctions were fabricated using electron-beam lithography process. The TMR properties were measured at room temperature using a four-probe method with AC bias and magnetic field up to about 2 kOe and the spin-transfer switching properties were evaluated by measuring resistance by 10 µA-step current pulses with the pulse width ranging from 10 µs to 1 s. The current direction was defined as positive when the electrons flow from the bottom (free) to the top (pinned) layer.

3. Results and discussion

3.1. Fabrication of the SyF structure with both high annealing stability and strong interlayer exchange coupling
For optimization of the stacking structure, the dependencies of the saturation field ($H_s$) which represent interlayer exchange coupling strength for the SyF structures with various stacking structures on annealing temperature and Ru middle layer thickness were investigated. Figure 1(a) shows the magnetization curves of the buffer-layer/Co$_{75}$Fe$_{25}$(2)/Ru(1)/Co$_{75}$Fe$_{25}$(2)/Ta(10)-SyFs with various buffer layers of Ta(5), Ru(5), MgO(5) and Ta(5)/Ru(5) (numbers denote thickness in nanometers). Average surface roughnesses ($R_a$) are 0.81, 0.84, 0.88 and 0.80 Å, respectively. Though the reason is not clear, the SyF using Ta buffer didn’t show exchange coupling in any annealing temperature. The as deposited SyFs on Ru and MgO buffers show coupling. However, after annealing at 400°C, the antiparallel alignment of the two ferromagnetic layers wasn’t obtained. On the other hand, the SyF on Ta/Ru buffer shows exchange coupling even after annealing at 400°C, though remanent magnetization increases in part. A possible reason of such high thermal stability may be the highly oriented crystal structure of the SyF could reduce interdiffusion at the Co$_{75}$Fe$_{25}$/Ru interface. Figure 1(b) shows the dependence of $H_s$ on annealing temperature for the SyFs with various buffer layers.

Figure 2 shows the dependence of $H_s$ on annealing temperature for the Ta(5)/Ru(5)/ferromagnetic-layer/Ru(0.8)/Co$_{40}$Fe$_{40}$B$_{20}$(2)/Ta(10)-SyFs with various ferromagnetic-layers of Co$_{40}$Fe$_{40}$B$_{20}$(2),
Ni pulse width (that using Ni of MTJ with SyF free layer in the previous report [5] was observed due to 50°C higher annealing temperature. This result comes from high annealing stability of the developed SyF structure.}

The R-I loop shows spin-transfer switching process, because the value of high and low resistance in the R-I loop and these in the MR curve are almost same. The average current density required to switch the magnetization from parallel (antiparallel) to antiparallel (parallel) shown in figure 4(b) is $J_c^{AP-AP} = 9.1$ MA/cm² ($J_c^{AP-AP} = -9.9$ MA/cm²). Figure 5 shows the dependence of critical current density ($J_c$) on pulse current width. Net critical current density ($J_{c0}$) of 14 MA/cm² and $E/k_B T$ of 62 were estimated. The strong interlayer exchange coupling of the SyF free layer may result in the high thermal stability.
Conclusion
We have fabricated MTJs with SyFs bottom free layer, which had structure of Ta/Ru/CoFe/Ru/CoFeB and possessed both high annealing stability of 400°C and strong interlayer exchange coupling as shown by large $H_c$ of 6 kOe. Consequently, a large TMR ratio of 122% has been observed after annealing at high temperature of 350°C. In addition, we have successfully observed spin-transfer switching by $J_{c0}$ of 14 MA/cm² and large $E/k_B T$ of 62.

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References
[1] Slonczewski J C 1996 J. Magn. Magn. Mater. 159 L1
[2] Berger L 1996 Phys. Rev. B 54 9353
[3] Diao Z, Apalkov D, Pakala M, Ding Y, Panchula A and Huai Y 2005 Appl. Phys. Lett. 87 232502
[4] Saito Y, Sugiyama H, Inokuchi T and Inomata K 2006 J. Magn.Magn. Mater. 303 34
[5] Hayakawa J, Ikeda S, Lee Y M, Sasaki R, Meguro T, Matsuura F, Takahashi H and Ohno H 2006 Jpn. J. Appl.Phys. 45 L1057
[6] Wiese N, Dimopoulos T, Rührig M, Wecker J, Brückl H and Reiss G 2004 Appl. Phys. Lett. 85 2020
[7] Parkin S S P, More N and Roche K P 1990 Phys. Rev. Lett. 64 2304