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Fabrication of Magnetic Tunnel Junctions with Synthetic Coupled Free Layer for Highly Sensitive Magnetic Field Sensor Devices

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Abstract

Magnetic tunnel junctions (MTJs) with synthetic coupled CoFeSiB/ [Ta or Ru]/CoFeB free layers were fabricated. The spacer layer (Ta and Ru) thickness and annealing temperature dependences of magnetic property for free layers and TMR effect were systematically investigated. We have observed a linear resistance response against external field and have achieved a high sensitivity over 30%/Oe in MTJs with Ru spacer by optimization of Ru thickness and annealing temperature of MTJs.

1. Introduction

The discovery of the high tunnel magnetoresistance (TMR) effect in magnetic tunnel junctions (MTJs) with (001)-oriented MgO barriers enables us to design highly magnetic field sensors. Low power consumption of MTJs and small device size make them leading candidate for the next generation of magnetic field sensor [1, 2]. A high sensitivity and a linear resistance response to external field are necessary for sensor applications. The sensitivity of sensor devices is defined as TMR ratio/2H_k, where H_k is the magnetic anisotropy field of the free layer [3]. We have to develop MTJs with high sensitivity of more than 100%/Oe in order to detect a small bio-magnetic field such as brain field (ca. 10^{-9} Oe). We fabricated MTJs with CoFeSiB (30)/ [Ta (0.2) or Ru (0.9)]/CoFeB (3) free layers and a high sensitivity of 40%/Oe was achieved in the MTJ with CoFeSiB/Ru/CoFeB free layers in our previous work [4].

Mangetic coupling strength between CoFeSiB and CoFeB is varied by spacer layer materials and its thickness. The spacer layers also affect the crystallization of CoFeB during annealing process of MTJs. Therefore, systematic investigations on spacer layer materials, its thickness and annealing temperature are needed to realize highly sensitive magnetic sensor devices. In this work, we systematically investigated the spacer layer (Ta and Ru) thickness and annealing temperature dependences of magnetic property and TMR effect in MTJs with synthetic coupled CoFeSiB/ [Ta or Ru]/CoFeB free layers to optimize spacer layer material and its thickness.

2. Experiment

The films were deposited onto thermally oxidized Si wafers using ultrahigh vacuum magnetron sputtering system ($P_{base} < 3.0 \times 10^{-6}$ Pa). Ar pressure for preparation of all films was 0.1 Pa. The stacking structure of MTJ films were Si/SiO_2/Ta (5)/Ru (10)/Ta (5)/$Co_{70.5}Fe_{4.5}Si_{15}B_{10}$ (30)/ [Ta (d_{Ta}) or Ru (d_{Ru})]/$Co_{40}Fe_{40}B_{20}$ (3)/MgO (2.5)/ $Co_{40}Fe_{40}B_{20}$ (3)/Ru (0.9)/$Co_{75}Fe_{25}$ (5)/$Ir_{22}Mn_{78}$ (10)/Ta (5)/Ru (8) (in nm). The MTJ devices were fabricated using photolithography and Argon ion milling. Ar ion milling was stopped in the middle of the MgO barrier layer, and the top pinned layers were patterned into 80×40, 40×20, 20 ×10 μm^2 rectangles.

The MTJs were annealed at 325ºC and 350ºC for 1 hour in a vacuum furnace after micro fabrication (first annealing). This first annealing was carried out with a magnetic field of 200 Oe to induce the magnetic anisotropy and obtain a high TMR ratio. The MTJs were annealed again at 200ºC to 280ºC for 15 min in the atmosphere with 90º rotated field of 100 Oe, which is the magnetic hard axis direction of the bottom free layer and easy axis direction of top pinned layer (second annealing). The second annealing induced the rotation of the easy axis of top pinned layer.

The magnetoresistance properties were measured at RT by using the DC four prove method with applied magnetic field swept with a 0.1 Oe step. The direction of the magnetic field was the same as the second annealing.

3. Results and Discussion

Figure 1(a) shows Ta spacer layer thickness dependence of TMR ratio. TMR ratio increased above 0.3 nm for annealing temperature of 350ºC, because the crystallization of CoFeB was promoted by thick Ta spacer layer. A maximum TMR ratio was 251%. Figure 1(b) shows the magnified magnetoresistance curves around zero field. A relatively low coercive field of ca. 10 Oe was observed at 0.2 nm and 0.3 nm. However, for 0.4 nm, complicated behavior against external field was observed because the coupling strength decreased by thick Ta spacer. We concluded that the optimized Ta spacer layer thickness was 0.3 nm to obtain both a high TMR and a low magnetic anisotropy.

Figure 2(a) shows Ru spacer layer thickness dependence of TMR ratio. TMR ratio was 192% in a MTJ without Ru spacer layer and TMR ratio was improved by insertion of Ru spacer layer. A maximum TMR ratio was 230% at 0.4 nm. The TMR ratio gradually decreased with increasing Ru layer thickness, because the thick Ru spacer layer impedes crystallization of CoFeB. Figure 2(b) shows Ru spacer layer thickness dependence of twice coercive field ($2H_c$) evaluated from MR curves. A low coercive field below 10 Oe was observed in MTJs with 0.4 – 0.7 nm thick Ru layer. Coercive field significantly increased at Ru = 0.9 – 1.2 nm because of very weak magnetic coupling strength between CoFeSiB and CoFeB.

Figure 3 shows the magnified views of magnetoresistance curves in MTJs with 0.3-nm-thick Ta spacer after the second annealing process. A linear resistance response against external field was not observed in MTJs with Ta spacer layer, because the easy axis of both bottom free layer and top pinned layer was rotated by second annealing process.

Figure 4 shows the magnified views of magnetoresistance curves in MTJs with 0.4-nm-thick Ru spacer after the second annealing process. A linear resistance response against external field was successfully observed at second annealing temperature of 260ºC and 270ºC and a high sensitivity of over 30%/Oe was obtained at 270ºC. We found that both a high sensitivity and a linear resistance response are achieved by strong magnetic coupling by strict control of Ru spacer layer thickness and second annealing temperature.

4. Summary

MTJs with synthetic coupled CoFeSiB/ [Ta or Ru]/CoFeB free layers were fabricated. Both Ta and Ru spacer layers improved TMR ratio and reduced magnetic anisotropy of free layers. A linear resistance response was only observed in MTJs with Ru spacer layer. We concluded that CoFeSiB/Ru/CoFeB free layer is useful to realize the highly sensitive magnetic field sensor. Appropriate control of Ru spacer layer thickness and second annealing temperature is required to achieve both a linear resistance response against external fields and a high sensitivity.

Acknowledgement

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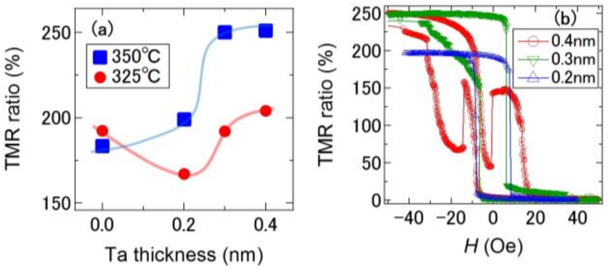

Fig. 1 (a) Ta thickness dependence of TMR raito and (b) magnified views of magnetoresistance curves around zero fields.

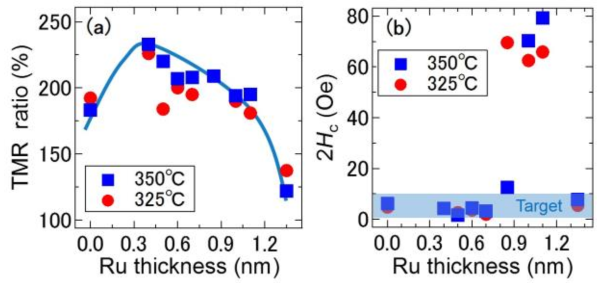

Fig. 2 Ru thickness dependence of (a) TMR ratio and (b) twice coercive field ($2H_c$).

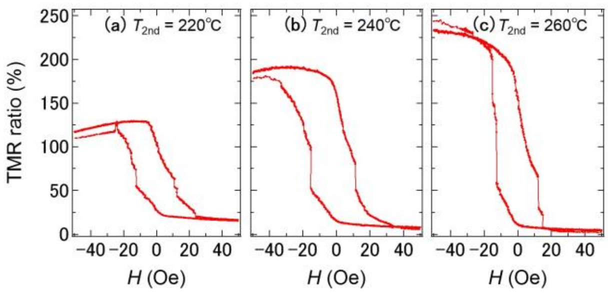

Fig. 3 Magnified views of Magnetoresitance curves in MTJs with Ta spacer. (a) T_{2nd} = 220℃, (b) T_{2nd} = 240℃, (c) T_{2nd} = 260℃

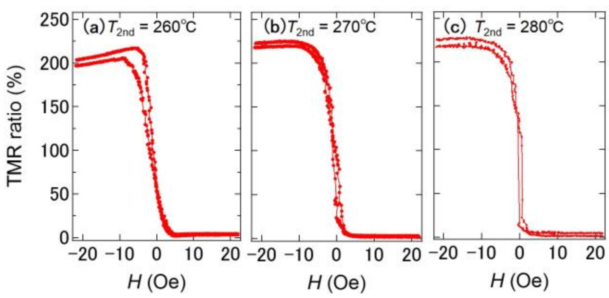

Fig. 4 Magnified views of magnetoresistance curves in MTJs with Ru spacer. (a) T_{2nd} = 260℃, (b) T_{2nd} = 270℃, (c) T_{2nd} = 280℃