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著者	安藤　康夫
journal or publication title	Journal of Applied Physics
volume	105
number	7
page range	07C911-1-07C911-3
year	2009
URL	http://hdl.handle.net/10097/46561

doi: 10.1063/1.3062816

Fabrication of MgO-based magnetic tunnel junctions with CoCrPt perpendicularly magnetized electrodes

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(Presented 11 November 2008; received 24 September 2008; accepted 25 October 2008; published online 6 February 2009)

The applicability of perpendicularly magnetized CoCrPt films to the MgO-based magnetic tunnel junctions (MTJs) was investigated. For this study, CoCrPt films deposited on the Ru buffer exhibited hcp(0002)-oriented growth by sputtering method using the low substrate temperature of 250 °C, low saturation magnetization of around 360 emu/cm^3, and high magnetic anisotropy field of 6 kOe, which is sufficient to retain the thermal stability of the magnetization direction. The MgO-based MTJs with a synthetic ferrimagnetlike structure were fabricated: CoFe was coupled magnetically with CoCrPt through the thin Ru layer. Transport properties with a magnetic field applied perpendicular to the film plane revealed a tunnel magnetoresistance ratio of about 6% at room temperature. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3062816]

Magnetization reversal induced by spin-transfer torque is promising as a scalable writing scheme for high-density magnetoresistive random access memory. Both a small critical switching current density (below 0.5 MA/cm^2) and a high thermal stability ($K_uV/k_BT>60$) should be accomplished to obtain highly reliable devices. Here, K_u is the magnetic anisotropy constant, V is the volume of the free layer ferromagnet, and k_B is the Boltzmann constant. In recent years, magnetic tunnel junctions (MTJs) with perpendicularly magnetized electrodes have become attractive for their large magnetic anisotropy, which is required for high thermal stability.[1] According to the theoretical expression, a switching current is directly related to M_sH_{eff}, where M_s and H_{eff}, respectively, signify the saturation magnetization and effective field applied to a free layer. Without an external field, H_{eff} can be expressed as $H_{k\parallel}+2\pi M_s$ and $H_{k\perp}-4\pi M_s$, respectively, for the in-plane and perpendicular magnetized elements, where H_k is the anisotropy field.[2] From this expression, when $H_{k\perp}<H_{k\parallel}+6\pi M_s$, perpendicular magnetic anisotropy MTJs can reduce a switching current to less than that of conventional in-plane anisotropy. Consequently, free layers having low M_s and perpendicular large anisotropy as high as $6\pi M_s$ constitute one approach for achieving both a low switching current and high thermal stability. For this study, we particularly examined a CoCrPt as a perpendicular anisotropy electrode, which has been studied extensively for high-density recording media. Actually, CoCrPt presents some advantages such as a very low M_s of 300–500 emu/cm^3 and a high H_k of about 6 kOe.[3,4] Additionally, CoCrPt grows easily to the c-axis orientation of the hcp structure on the Ru buffer layer using sputtering method at low substrate temperatures (T_s) of less than 250 °C. In contrast, thin films of perpendicularly magnetized material were deposited using methods that are difficult to apply for an industrial technique such as electron beam evaporation for an perpendicularly magnetized multilayer[2] or sputtering deposition at high T_s of about 600 °C for $L1_0$-ordered alloy.[5] As described in this paper, we deposited CoCrPt thin films at various conditions for optimization and measured magnetoresistance properties in MTJs with perpendicularly magnetized CoCrPt layers.

All films were deposited using ultrahigh-vacuum magnetron sputtering systems. The film stack for the optimization of CoCrPt deposition conditions consisted of Ta(5 nm)/Ru(10 nm)/CoCrPt(d nm)/Ta(5 nm) on a thermally oxidized silicon substrate. Here, d signifies the CoCrPt layer thickness. The CoCrPt layers were deposited from the sputtering target, having compositions of $Co_{60}Cr_{20}Pt_{20}$, while heating the substrate to T_s.

The x-ray diffraction (XRD) profiles for the multilayer including the 15-nm-thick CoCrPt deposited at $T_s=30$ (room temperature), 250, 300, and 350 °C are presented in Fig. 1(a). For the entire range of T_s, only two (0002) peaks derived from Ru and CoCrPt layer were detected, indicating the hcp(0002)-textured growth of the CoCrPt layer. The CoCrPt (0002) peaks shifted to a larger angle as T_s increased, which implies a decrease in the lattice constant along the c-axis close to the Co bulk value of $c=0.4061$ nm (44.6°).[6] Figure 1(b) shows magnetization curves measured using a vibrating sample magnetometer for the same sample prepared at $T_s=30$ and 250 °C with magnetic fields applied perpendicular to the film plane. The easy magnetization axes for all films are perpendicular to the plane. The M_s and coercive force (H_c) for the sample at $T_s=250$ °C and higher temperatures (not shown here) were greater than that of $T_s=30$ °C. In fact, results show that good squareness of the hysteresis loop perpendicular to the plane was obtained at low T_s of 250 °C. Consequently, T_s for the CoCrPt films was

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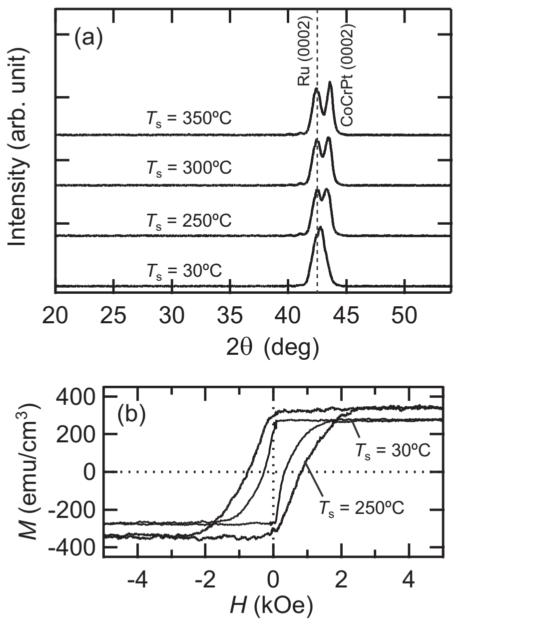

FIG. 1. (a) XRD profiles of Ta/Ru/CoCrPt/Ta structures. The CoCrPt films were deposited at T_s=30, 250, 300, and 350 °C. (b) Magnetization curves with applied field perpendicular to the plane for CoCrPt films deposited at T_s=30 and 250 °C.

fixed at 250 °C. Low M_s of 320–360 emu/cm^3 and high H_k of 5–6 kOe, which satisfied the purposes of this work, were obtained for all samples.

Figure 2(a) shows M_s of the CoCrPt films for thickness d of 2–30 nm. Actually, M_s of the CoCrPt is maintained at d =3 nm, which is sufficient to switch magnetization by spin torque. The M_s of 2-nm-thick CoCrPt film decreased to half that of the others because of the existence of a nonmagnetic region in a few monolayers of initial growth and/or the mixing layer at the interface. Figure 2(b) shows the CoCrPt thickness dependence of the nucleation fields (H_n) for magnetization switching defined in the inset of Fig. 2(a). The H_n has a peak of about 400 Oe at d=4 nm, which indicates that the thermal durability of the magnetization direction for the 4-nm-thick CoCrPt film is greater than that of the others.

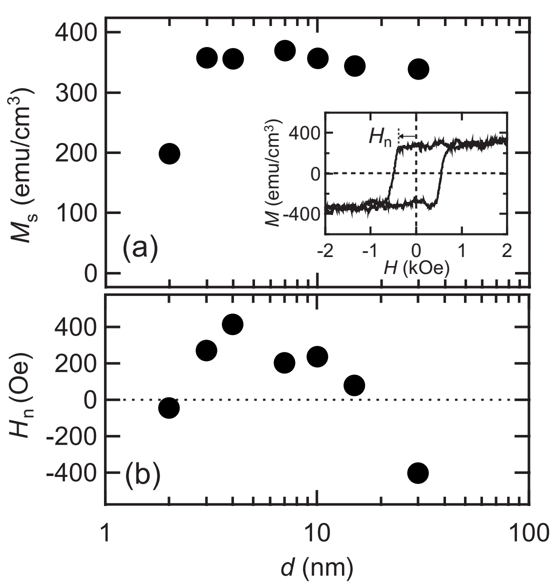

FIG. 2. Dependence of (a) saturation magnetization M_s and (b) nucleation field H_n on the CoCrPt film thickness. The inset shows magnetization curves for the 4-nm-thick CoCrPt film.

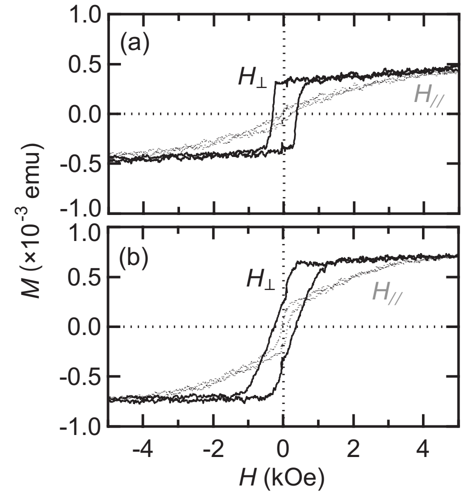

FIG. 3. Magnetization curves for the stacking of (a) CoCrPt/CoFe/Ru/CoFe (bottom electrode) and (b) CoFe/Ru/Co/CoCrPt (top electrode) in the perpendicularly magnetized MTJs. Magnetic fields were applied both perpendicular ($H_\perp$) and parallel ($H_\parallel$) to the film plane.

A c-axis-oriented CoCrPt is well known to have a columnar structure segregating Cr atoms to the grain boundary.[3] The giant tunneling magnetoresistance (TMR) effect caused by coherent tunneling of the MgO barrier deteriorates because of low matching for an electron structure and interfacial ordering between the crystalline MgO and the ferromagnetic electrode if such materials are used as ferromagnetic electrodes in the MTJs. Therefore, the CoCrPt/Ru/CoFe synthetic ferrimagnetlike[7] structure was applied for the MgO-based MTJs, where CoFe will be coupled with the perpendicularly magnetized CoCrPt through a thin Ru layer. The MTJ stack consisted of CoCrPt(4 nm)/CoFe(0.7 nm)/Ru(0.6 nm)/CoFe(1 nm) deposited on Ta/Ru buffer and CoFe(1 nm)/Ru(1 nm)/Co(0.5 nm)/CoCrPt(10 nm) on the 2.5-nm-thick MgO barrier, respectively, for the bottom and top ferromagnetic electrodes. Here, both CoFe and Co inserted between CoCrPt and CoFe function to increase their coupling strength. Figures 3(a) and 3(b), respectively, depict magnetization curves measured individually for the bottom and top ferromagnetic electrode structures with magnetic fields applied perpendicular and parallel to the film plane. The latter structure was deposited on the Ru buffer layer. Although both structures have perpendicular magnetic anisotropy, the top electrode structure has a low remnant magnetization and easy axis component along the in-plane direction. A typical TMR curve in such MTJs fabricated into a size of about 40×80 μm^2 using photolithography and Ar milling method is shown in Fig. 4. A clear resistance change with the magnetic field perpendicular to the plane is observed; its TMR ratio is about 6% at room temperature. This MTJ retains the lowest value of resistance up to 10 kOe, which corresponds to the parallel magnetic configuration of two CoFe electrodes. The broad resistance change is thought to be related causally to the magnetization process of the top ferromagnetic electrode.

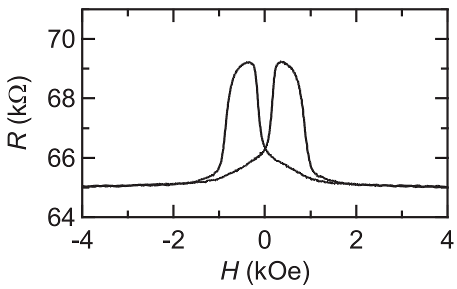

FIG. 4. Typical TMR curve for the MTJ with a synthetic ferrimagnetlike structure using perpendicularly magnetized CoCrPt layers.

The observed small TMR ratios are attributed mainly to the very thin magnetic electrodes near the MgO barrier, which are anticipated for use as discontinuous film, especially the top electrode deposited on the MgO barrier. To increase the magnetic coupling strength, it is effective that a low-M_s material such as CoFeB for an electrode near a barrier and different CoCrPt composition be used. Thereby, the increased ferromagnetic electrode thickness will improve the TMR ratio in such a MTJ.

In conclusion, MgO-based MTJs using a synthetic ferrimagnetlike structure were fabricated, in which CoFe is coupled magnetically with CoCrPt through the thin Ru layer. The CoCrPt films deposited on the Ru layer showed hcp(0002)-oriented growth by sputtering method at a low process temperature. We observed clear TMR curves perpendicular to the film plane, in addition to a TMR ratio of about 6%.

This study was partially supported by NEDO.

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