Magnetic tunnel junctions using Co/Pt multilayered free layers with perpendicular magnetic anisotropy

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Abstract. Co/Pt multilayered films with perpendicular magnetic anisotropy have a large magneto-optical Kerr effect. To use the films with a submicron magneto-optical light modulator driven by spin transfer switching, we fabricated two types of magnetic tunnel junctions (MTJs) with Co/Pt multilayered films for the free layers. One is an fcc-based MTJ, another is a bcc-based MTJ with CoFeB/MgO/CoFeB junction. The fcc-based MTJ with a Ag buffer layer on the bottom electrode showed a large coercive force of the pinned layer, a large Kerr rotation angle of 0.3 degree in the free layer and a tunnel magnetoresistance (TMR) ratio of 3.8%. In the CoFeB/MgO/CoFeB junction, an X-ray diffraction pattern of an MgO layer showed a large MgO(002)-orientation. However, the TMR ratio was less than 3 %. An MTJ with a Ta buffer layer between the CoFeB layer and the Co/Pt multilayered films in the free layer was prepared. The Ta buffer was used to alleviate a lattice mismatch between bcc-CoFeB/MgO/CoFeB and fcc-Co/Pt multilayer. The peak intensity of the MgO(002)-orientation was increased up to 2 times. This result suggests that the crystalline texture of the bcc-CoFeB/MgO/CoFeB junction is strongly influenced by the fcc-Co/Pt multilayered films.

1. Introduction

Submicron spatial light modulators (SLMs) are promising for use in high-density holographic recording and wide-viewing-angle holographic 3D displays that are not requiring special glasses. We have advanced a magneto-optical light modulation device driven by spin transfer switching (STS MO-LM)[1]-[3], as shown in figure 1. The free layer of a current perpendicular to plane giant magnetoresistive (CPP-GMR) pillar or a tunnel magnetoresistive (TMR) pillar works as a light modulation layer. The top electrode of the device is formed with a transparent electrode such as Indium Tin Oxide (ITO) or Indium Zinc Oxide (IZO). Incident polarized light entered through the transparent top electrode is subject to diffraction at the free layer. The polarization plane of the diffracted light is modulated by the magnetization direction of the free layer, reversed by STS. The diffraction angle ($\varphi$) is defined by the following equation; $\varphi = \sin^{-1}(\lambda/2p)$, where $\lambda$ and $p$ are a wavelength of the incident light and a pitch length between pixels[4]. In conventional SLMs, the value of $p$ is larger than 5 $\mu$m, resulting in $\varphi < 6^\circ$. On the other hand, the STS MO-LM is a high-resolution device with high-speed modulation of the polarization plane. The value of $p$ in the STS MO-LM can be set at less than 1$\mu$m, which leads to a sufficient wide-viewing-angle of $\varphi > 30^\circ$. However, a large magneto-optical effect is required for practical use of this device. It is well known that Co/Pt and Co/Pd multilayered films show a large Kerr rotation angle and a strong perpendicular magnetic anisotropy[5]. Magnetoresistance (MR) properties of CPP-GMR and TMR devices with
ferromagnetic/noble metal multilayered films with perpendicular magnetic anisotropy such as CoFe/Pt and CoFe/Pd have been investigated for use in high-density magnetic random access memories[6],[7].

In this paper, we report on two types of magnetic tunnel junctions (MTJs) with Co/Pt multilayered films for free layers. One is an fcc-based MTJ, another is a bcc-based MTJ with CoFeB/MgO/CoFeB junction. The magneto-optical Kerr effects, TMR properties, and X-ray diffraction patterns of MgO films were investigated.

2. A fcc-based MTJ

In this section, magnetic properties, X-ray diffraction (XRD) patterns, and MR characteristics of an fcc-based MTJ with perpendicular magnetic anisotropy are discussed.

2.1. Experimental details

The film configuration of the MTJ stack is as follows; a Cu-based bottom electrode layer of [Ta(3)/Cu(15)]₁₀/Ta(3)/Ru(3), a Ag(10) buffer layer, a pinned layer of [Co(0.2)/Pd(1.2)]₁₁/Co(0.2), an MgO(0.8) barrier, a free layer of [Co(0.3)/Pt(1.0)]₃, a capping layer of Ta(3), and a metal top electrode layer of Cu(350)/Ru(10) for a pillar. The numbers in parentheses are thicknesses in nanometers. The bottom electrode layer was deposited onto a thermally oxidized silicon wafer by dc ion beam sputtering. The buffer layer and the pinned layer were deposited by dc magnetron sputtering. The MgO barrier was formed by an rf ion beam sputtering method. The free layer and the other layers were
deposited using dc ion beam sputtering. The MTJ stack was post-annealed at 350°C for 1 hour in vacuum of $3 \times 10^{-5}$ Pa. Rectangular pillar of the stack was fabricated by electron beam lithography using a two-step liftoff process [8].

Kerr hysteresis loops were measured using micro-magneto-optical Kerr effect microscopy with a polar Kerr mode as shown in figure 2. An incident light emitted by a laser diode (LD) with a wavelength of 408 nm is linearly polarized and enters the sample vertically, focused by an objective lens. The spot size of the incident light with Gaussian distribution is approximately 1 μm. The microscopy utilizes polarization modulation with a photoelastic modulator and has high sensitivity of $1 \times 10^{-4}$ degree for detecting the magneto-optical Kerr effect.

2.2. Results and discussions

The full loop of polar Kerr hysteresis at 408-nm wavelength after annealing at 350°C for 1 hour is shown in figure 3, compared to that without the Ag buffer layer. The coercive force ($H_c$) of the pinned layer with the Ag layer as deposited was 0.72 kOe, while $H_c$ of the pinned layer without the Ag layer as deposited was 0.93 kOe (not shown). After annealing at 350°C, the $H_c$ with the Ag layer increased up to 2.8 kOe, in contrast with the $H_c$ of 1 kOe without the Ag layer as shown in figure 3. The Kerr rotation angles of the free layers with the Ag buffer layer and without the layer were 0.3 degree and 0.24 degree, respectively. Factors in the increase of the Kerr rotation angle may be multiple reflection effect by the high reflectance of the Ag layer or a surface plasmon excitation around the Ag layer. Further detailed investigations are required.

XRD measurements were done for the MTJ stacks. The XRD pattern of the sample with Ag(10)/[Co(0.2)/Pd(1.2)]$_{11}$/Co(0.2)/MgO(90) deposited on the Cu-based bottom electrode is shown in figure 4, compared to that without the Ag layer. The source of the X-rays is CoKα. The Ag layer sample had the oriented textures of fcc-based Pd(111), Ag(111), Cu(111), and MgO(111). No peaks related to Co were detectable. The Ru(3nm) layer as the top of the Cu-based bottom electrode shows a peak of hcp-(0002). An origin of perpendicular anisotropy on ferromagnetic/noble metal multilayered films is considered to be a surface magnetic anisotropy, which is caused by a strain of a lattice misfit. A lattice mismatch for an Ag/Co interface is approximately 2 times larger than that of a Ru/Co interface. The strong perpendicular anisotropy of the Ag buffer layer stack is attributed to the large lattice mismatch of the Ag/Co interface. On the other hand, MgO(002) peaks associated with a high TMR ratio were never seen in either stack.

![Figure 3](image3.png)

**Figure 3.** Polar Kerr hysteresis loops of the stacks without (dotted blue line) and with (solid red line) Ag buffer layers, after 350°C-annealing, at 408-nm wavelength.

![Figure 4](image4.png)

**Figure 4.** X-ray diffraction patterns for the samples of [Co(0.2)/Pd(1.2)]$_{11}$/Co(0.2)/MgO(90) on the Cu-based bottom electrode without (dotted blue line) and with (solid red line)Ag buffer layers, after 350°C-annealing.
The MR curve of the rectangular pillar with the Ag buffer layer after annealing at 350°C is shown in figure 5. The size of the pillar is 100 nm × 100 nm. The applied voltage was 2 mV. The TMR ratio and resistance-area product (RA) were 3.8 % and 10.5 Ωμm², respectively. The relatively low TMR ratio in contrast with MgO(100)-based MTJs was caused by the undesirable MgO(111)-oriented texture.

3. A CoFeB-based MTJ

For a high TMR ratio, we fabricated a CoFeB-based MTJ using Co/Pt multilayer films for free layers with perpendicular magnetic anisotropy.

3.1. Experimental details

The film configuration of the MTJ stack is as follows; a bottom electrode layer of Ta(50)/Ru(3), a pinned layer of Tb₂₈Fe₆₀Co₁₂(30)/Co₄₀Fe₄₀B₂₀(1.2), an MgO(1) barrier, a free layer of Co₄₀Fe₄₀B₂₀(0.6)/[Pt(1.5)/Co(0.3)]₃, a capping layer of Ta(1.8)/Pt(2), and a metal top electrode layer of Cu(350)/Ru(10) for a pillar. The numbers in parentheses are thicknesses in nanometers. The MgO barrier was formed by an rf ion beam sputtering method. The layers except for the MgO barrier were deposited using dc ion beam sputtering. The MTJ stack was post-annealed at 260°C or 300°C for 1 hour in vacuum of 3 × 10⁻⁵ Pa. Rectangular pillar of the stack was fabricated by electron beam lithography using a two-step liftoff process [8].

3.2. Results and discussions

The minor loop of Kerr hysteresis at 408-nm wavelength after annealing at 300°C for 1 hour is shown in figure 6. The loop indicates magnetization reversal of the free layer and shows that the free layer has a binary condition at zero magnetic fields. The $H_c$ of the pinned layer was more than 22 kOe even after annealing, which is the value of the measurement limit for our magneto-optical Kerr effect measuring system. The Kerr rotation angle was 0.23 degree and the $H_c$ of the free layer was no more than 0.1 kOe because of the small $H_c$ of CoFeB in the free layer.

The MR curve of the pillar, 100 nm × 180 nm, is shown in figure 7. The TMR ratio and the RA as deposited were 2.0 % and 17.2 Ωμm². After annealing at 260°C, the TMR ratio increased up to 2.6 %. However that was smaller than the fcc-based MTJ pillar discussed in the previous section.

We measured the XRD patterns of the stacks with CoFeB-based MTJs as shown in figure 8. In these measurements, the source of the X-rays is CuKα. The film configuration of the stack (stack l) is Ta(50)/Ru(3)/Tb₂₈Fe₆₀Co₁₂(30)/Co₄₀Fe₄₀B₂₀(1.2)/MgO(30)/Co₄₀Fe₄₀B₂₀(0.6)/[Pt(1.5)/Co(0.3)]₃/capping. The as-deposited MgO layer showed a large (002) crystalline orientation. By contrast, the MgO(111)-
orientation was never seen. After annealing at 300°C, there was no significant change in the peak intensity of the MgO(002). The Co/Pt multilayered films and the junction of CoFeB/MgO/CoFeB have the fcc and bcc structures, respectively. A current research on MTJs with fcc-based Co/Pd multilayered films and bcc-based CoFeB/MgO/CoFeB junction indicates that a low TMR ratio may be caused by the lattice mismatch between the fcc and bcc phases[9]. The free layer of our stack was modified as follows; Co_{40}Fe_{40}B_{20}(0.6)/Ta(1)/[Pt(0.3)/Co(0.3)]_{2}/[Pt(1.5)/Co(0.3)]_{2}(stack II). The Ta buffer layer was used to alleviate the lattice mismatch. Figure 9 shows the XRD patterns of the stack II as deposited and annealed at 300°C for 1 hour. The peak intensity of the MgO(002)-orientation was increased up to 2 times. After annealing, the intensity increased by 15%, unlike in the case of the stack I. These results suggest that the crystalline texture of the CoFeB/MgO/CoFeB orientation was strongly influenced by the fcc-based Co/Pt multilayered films. According to figure 9, the Ta buffer layer may appear to work properly as a transition layer from the bcc to fcc phases. However, the perpendicular magnetic anisotropy of the stack II for the case of MgO(1 nm) barrier was inadequate, in addition an in-plane magnetization process showed a slight hysteresis around zero magnetic field (not shown). These results may be attributed to an insufficient magnetic connection between the CoFeB layer and
the Co/Pt multilayer in the free layer. The perpendicular magnetic anisotropy of the stack II should be improved by reducing the thickness of the Ta buffer layer and substituting another material such as Ru for the Ta buffer.

4. Conclusions

To use the Co/Pt multilayered films with a submicron magneto-optical light modulator driven by spin transfer switching, we fabricated two types of MTJs. One is an fcc-based MTJ, another is a bcc-based MTJ with CoFeB/MgO/CoFeB junction. The magneto-optical Kerr effects, TMR properties, and X-ray diffraction patterns of MgO layer were investigated. The fcc-based MTJ with an Ag buffer layer on the bottom electrode showed a large coercive force of the pinned layer, a large Kerr rotation angle of 0.3 degree in the free layer and a tunnel magnetoresistance (TMR) ratio of 3.8%. In the CoFeB/MgO/CoFeB junction, the TMR ratio was less than 3%, though an X-ray diffraction pattern of an MgO (30 nm) layer showed a large MgO(002)-orientation. An MTJ with a Ta buffer layer inserted between the CoFeB layer and the Co/Pt multilayered films in the free layer was prepared. The peak intensity of the MgO(002)-orientation was increased up to 2 times. The Ta buffer layer may appear to work properly as a transition layer from the bcc to fcc phases. These results suggest that the crystalline texture of the bcc-CoFeB/MgO/CoFeB junction is strongly influenced by the fcc-Co/Pt multilayered films.

5. References

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Acknowledgments

This research has been supported by the National Institute of Information and Communications Technology in Japan, (program period; 2009–2011).