Giant tunneling magnetoresistance effect in low-resistance CoFeB/MgO(001)/CoFeB magnetic tunnel junctions for read-head applications

Koji Tsunekawa,[a] David D. Djayaprawira, Motonobu Nagai, Hiroki Maehara, Shinji Yamagata, and Naoki Watanabe
Electron Device Equipment Division, Anelva Corporation, 5-8-1, Yotsuya, Fuchu-shi, Tokyo 183-8508, Japan

Shinji Yuasa,[b] Yoshishige Suzuki,[c] and Koji Ando
Nanoelectronics Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8568, Japan

(Received 9 May 2005; accepted 8 July 2005; published online 8 August 2005)

The giant tunneling magnetoresistance effect has been achieved in low-resistance CoFeB/MgO(001)/CoFeB magnetic tunnel junctions (MTJs) at room temperature. A magnetoresistance (MR) ratio as high as 138%, seven times that of state-of-the-art MTJs for magnetic sensor application, was obtained at room temperature in MTJs with a resistance-area product (*RA*) as low as 2.4 Ω μm^2. Such a high MR ratio at such a low resistance was made possible by introducing an ultrathin Mg metal layer with a thickness of 4 Å between the CoFeB bottom electrode layer and the MgO(001) tunnel barrier layer. The Mg layer was slightly but not fully oxidized, which resulted in a reduction in MR for a thicker MgO barrier (high *RA*) region and in an increase in MR for a thinner barrier (low *RA*) region. The Mg layer improves the crystalline orientation of the MgO(001) layer when the MgO(001) layer is thin. These MTJs will accelerate the realization of highly sensitive read heads for ultrahigh-density hard-disk drives. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2012525]

An ultrahigh-density magnetic recording scheme needs a highly sensitive magnetic read head to compensate for the reduction in the signal-to-noise ratio due to the shrinking of the medium bit size. Several current-perpendicular-to-plane read heads have been proposed for areal densities of 100 Gb/in.^{2} and beyond.[1–4] Among them, the tunneling magnetoresistive (TMR) head with a magnetic tunnel junction (MTJ) is the leading candidate. However, it has a relatively high resistance, which limits the operating frequency and makes the Johnson and shot noises high. The reading data rate and noise considerations dictate that the junction resistance, or resistance-area product (*RA*), of the MTJ in the TMR head be less than 4 Ω μm^2 for the TMR head to compete with the present spin-valve head.[5] To reduce the *RA*, the barrier layer thickness must be reduced. However, it is difficult to reduce the *RA* of an MTJ below 4 Ω μm^2 while maintaining a high magnetoresistance (MR) ratio without a breakthrough in fabrication technology. This is because the tunnel barrier thickness has to be reduced to less than 10 Å to achieve such a low *RA*. Reducing the tunnel barrier thickness that much will drastically reduce the MR ratio. Recently, TMR heads with an MR ratio of about 20% for >100 Gb/in.^{2} areal density have been developed with an *RA* of about 2–5 Ω μm^2.[6,7] However, the demand for even higher areal densities requires an MR ratio significantly higher than 20%.

To date, MTJs with amorphous aluminum-oxide (Al–O) tunnel barrier layers have been the most extensively studied. The MR ratio in such conventional MTJs can be relatively well explained by Julliere's model[8] when experimentally observed spin polarizations are considered. On the other hand, *ab initio* calculations have predicted extremely large MR ratios in Fe(001)/MgO(001)/Fe(001) single-crystalline MTJs, the result of coherent tunneling.[9,10] Experimental studies performed on epitaxial Fe(001)/MgO(001)/Fe(001) MTJs have shown that their MR ratios surpass those obtained with conventional MTJs (Ref. 11) and have reached as high as 188% at room temperature (RT).[12] However, these MTJs have had single-crystal substrates, which limits their practical application. An MR ratio of 220% at RT has been achieved in MTJs with a structure of FeCo(001)/MgO(001)/$Co_{56}Fe_{24}B_{20}$.[13] The CoFe bottom electrode layer is a polycrystalline body-centered cubic with a (001) texture. We recently achieved an even higher MR ratio of 230% at RT in spin-valve-type magnetic tunnel junctions using a highly oriented polycrystalline MgO(001) barrier layer sandwiched by amorphous $Co_{60}Fe_{20}B_{20}$ ferromagnetic electrodes.[14] However, the *RA* of the MTJs was about 420 Ω μm^2, which is too high for TMR head application.

In this letter, we report our attainment of an *RA* of about 2.4 Ω μm^2 and an MR ratio of up to 138% at RT in MTJs using CoFeB/MgO/CoFeB. To realize such a high MR ratio with a very thin MgO layer, we found it effective to insert a 4 Å Mg metal layer between the amorphous CoFeB bottom electrode layer and the MgO barrier layer. Note that Lin and Mauri inserted an Mg metal layer between a polycrystalline CoFe bottom electrode and MgO barrier in CoFe/MgO/NiFe MTJs.[15] In this case, however, the MgO

[a]Electronic mail: tsunekawak@mhc.anelva.jp
[b]Also at: PRESTO, Japan Science and Technology Agency (JST), Kawaguchi, Saitama 332-0012, Japan.
[c]Also at: Graduate School of Engineering Science, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan.

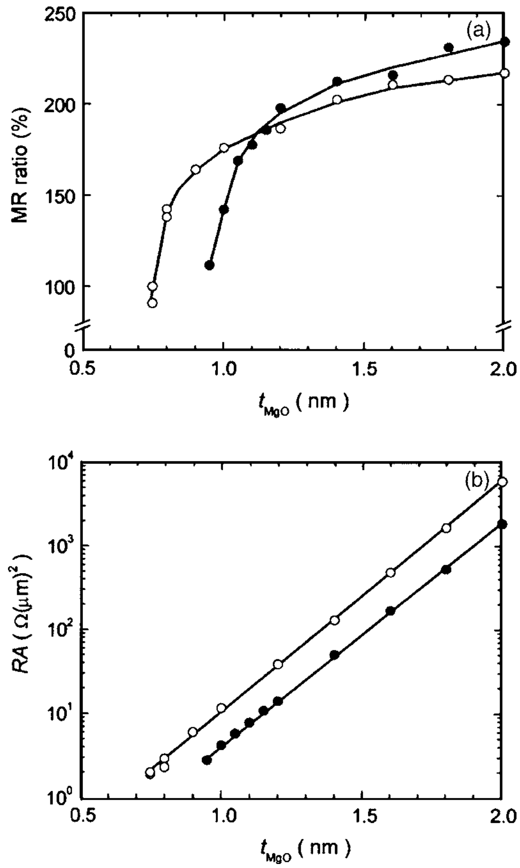

FIG. 1. TMR of CoFeB/Mg(0 or 4 Å)/MgO(7–20 Å)/CoFeB MTJs at RT. (a) MR ratio plotted as a function of MgO layer thickness (t_{MgO}). (b) *RA* plotted as a function of MgO layer thickness. Open and solid circles represent MTJs with and without Mg layer, respectively.

tunnel barrier was prepared by reactive sputtering of Mg in an oxygen atmosphere, and the Mg layer was mainly intended to prevent oxidation of the surface of the CoFe layer during deposition.

We deposited the thin films for the MTJs onto a thermally oxidized Si(001) wafer using a magnetron sputtering system (ANELVA C7100) with a base pressure better than 5×10^{-9} Torr. The Ar gas pressure during sputtering was kept low (about 0.2 mTorr), except for the deposition of the MgO layer, which was deposited at about 0.9 mTorr. The fundamental structure of the MTJ was substrate/seed layer/PtMn(150)/$Co_{70}Fe_{30}$(25)/Ru(8.5)/CoFeB(30)/Mg/MgO/CoFeB(30)/cap layer (in Å). For MTJs with a low *RA*, the seed and cap layers were Ta(50)/CuN(200)/Ta(30) and Ta(80)/Cu(400)/Ta(50)/Ru(70) (in Å), respectively. The MgO barrier layer was deposited by rf sputtering directly from a sintered MgO target, and the thickness was varied from 7 to 20 Å. The other layers were deposited by dc sputtering. The CoFeB film was deposited using a $Co_{60}Fe_{20}B_{20}$ (at.%) alloy target. The MTJs were annealed in a high-vacuum furnace at 360 °C for 2 h in a magnetic field of 8 kOe. The magnetic transport properties were evaluated at RT in unpatterned MTJ films using the current in-plane tunneling technique[16] and also in deep-submicron-sized MTJs (with a junction area of about 100×200 nm) using the dc four-probe method. The deep-submicron MTJs were prepared using micro-fabrication techniques (electron-beam lithography, Ar-ion milling, etc.).

In Fig. 1(a), the MR ratio is plotted as a function of the MgO barrier thickness (t_{MgO}) in CoFeB/Mg(0 or 4 Å)/MgO(7–20 Å)/CoFeB MTJs. An Mg layer thickness of 4 Å was chosen as it resulted in the highest MR ratio in a thin MgO region. The MR ratio gradually dropped as MgO thickness was reduced. When the MgO barrier was thicker than 12 Å, the MTJs without the Mg layer showed higher MR ratios than those with the layer (234% versus 217% for t_{MgO}=20 Å). The relationship was reversed when the MgO layer was thinner than 11 Å. In MTJs without the Mg layer, the MR ratio decreased more steeply when the MgO layer was thinner than 11 Å, while in MTJs with a 4 Å Mg layer, the critical thickness at which the MR ratio significantly decreased was about 8 Å. These results indicate that inserting an Mg layer increases the magnetoresistance in very thin MgO barrier regions, which is favorable for TMR head application.

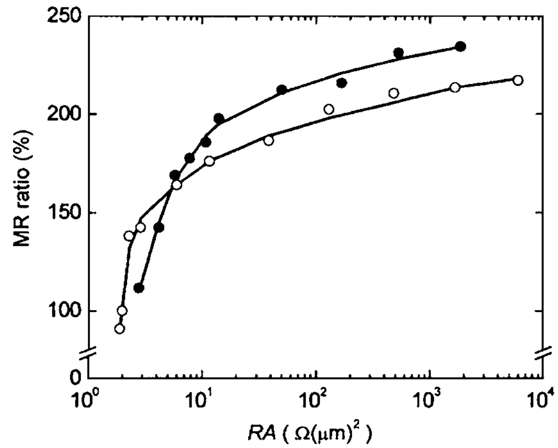

FIG. 2. MR ratio plotted against *RA* in CoFeB/Mg(0 or 4 Å)/MgO(7–20 Å)/CoFeB MTJs. Open and solid circles represent MTJs with and without Mg layer, respectively.

In Fig. 1(b), the *RA* is plotted as a function of the MgO barrier thickness. The *RA* increased exponentially as a function of the MgO thickness, which is typical of ideal tunnel junctions. The potential barrier height energies (ϕ) of both series of MTJs, as determined from the slope of the log *RA* versus t_{MgO} curve, were similar (about 0.39 eV), assuming a free electron mass (9.11×10^{-31} kg) for the effective electron mass (m).[17] It should be noted that the $m\phi$ of our MTJs is the same as that of fully epitaxial Fe(001)/MgO(001)/Fe(001) MTJs prepared using molecular-beam epitaxy.[12] Inserting a 4 Å Mg layer increased the *RA* by a factor of about 3, which corresponds to an increase in the MgO thickness of about 1.6 Å. This means that the inserted 4 Å Mg layer was slightly oxidized. It was not fully oxidized because full oxidation would have increased the tunneling resistance by a factor of more than 10.

The MR ratio of CoFeB/Mg(0 or 4 Å)/MgO(7–20 Å)/CoFeB MTJs is plotted against *RA* in Fig. 2. For MTJs without the Mg layer, the ratio drastically decreased when *RA* was less than 5 $\Omega\ \mu m^2$, while for MTJs with the layer, the ratio remained very high (about 140%) at an *RA* of about 3 $\Omega\ \mu m^2$.

The RT MR curve of a CoFeB/Mg(4 Å)/MgO(8.5 Å)/CoFeB MTJ prepared under optimized conditions is shown in Fig. 3. An MR ratio of 138% with an *RA* of 2.4 $\Omega\ \mu m^2$ was achieved. This ratio is seven times that of the highest

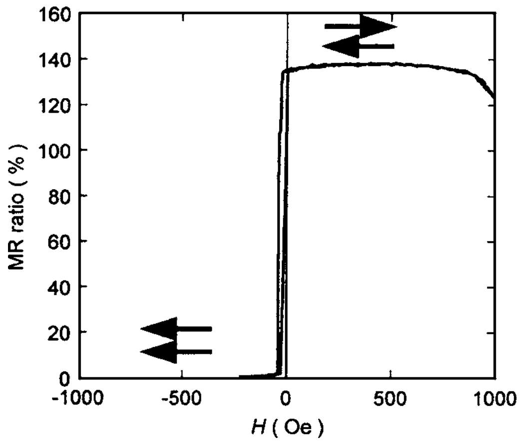

FIG. 3. RT MR curve of CoFeB/Mg(4 Å)/MgO(8.5 Å)/CoFeB MTJ prepared under optimized conditions. Junction was about 100×200 nm. The arrows indicate the magnetization alignments in the top and bottom electrodes.

MR ratio reported to date for low-resistance MTJ devices for TMR head application.

Typical high-resolution cross-section transmission electron microscope (TEM) images of CoFeB/Mg(0 or 4 Å)/MgO(15 Å)/CoFeB tunnel junctions are shown in Figs. 4(a) and 4(b), respectively. There are no clear differences between the images with and without the Mg layer, except that the barrier layer in the MTJ with the Mg layer seems slightly thicker than that without the layer. To clarify the mechanism of the MR enhancement due to the Mg layer, we performed x-ray diffraction analysis. While in-place x-ray diffraction revealed no differences between the MTJs with and without the Mg layer, θ-2θ scan x-ray diffraction revealed a clear difference: The MgO(002) diffraction peak intensity was enhanced by insertion of the Mg layer when the MgO layer was thin, indicating that the crystal orientation of the polycrystalline MgO(001) barrier layer was improved by the Mg layer. The higher crystalline orientation of the MgO(001) barrier layer could have enhanced the coherent tunneling of Δ_1 electrons, resulting in an increased MR ratio.

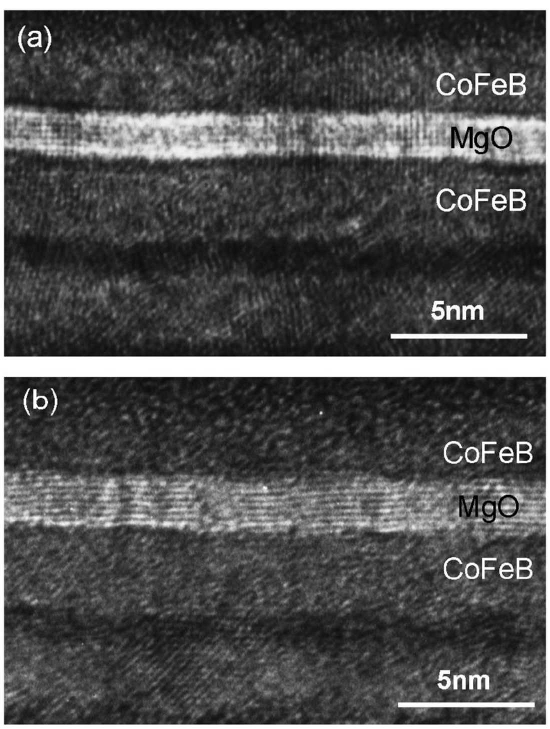

FIG. 4. Typical high-resolution cross-section TEM images of (a) CoFeB/MgO(15 Å)/CoFeB tunnel junction and (b) CoFeB/Mg(4 Å)/MgO(15 Å)/CoFeB tunnel junction.

In conclusion, we have achieved a giant MR ratio of up to 138% at room temperature in low-resistance CoFeB/MgO/CoFeB MTJs with a *RA* of 2.4 $\Omega\ \mu m^2$ by inserting a 4 Å Mg metal layer between the bottom CoFeB electrode and the MgO tunnel barrier. The Mg layer was slightly but not fully oxidized, resulting in a reduction in the MR as the MgO barrier was made thicker (high *RA*) region and in an increase in the MR as it was made thinner (low *RA*) region. Inserting an Mg layer improved the crystalline orientation of the MgO(001) layer when the MgO(001) layer was thin, which could have increased the MR ratio. The achievement of a low *RA* while maintaining a high MR ratio should enable the production of highly sensitive read heads for ultrahigh-density hard-disk drives.

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