TMR Film and Head Technologies

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We have developed Al-O barrier magnetic tunnel junctions (MTJs) and obtained a magneto-resistance (MR) ratio of 27% with a resistance-area product RA of about 3 Ωμm^2. We have also studied Ti-O and Mg-O as new low barrier energy materials for MTJs. Ti-O barrier MTJs showed a very small RA of less than 2 Ωμm^2. We can obtain a high MR ratio of about 100% for Mg-O barrier MTJs with an RA of 2 to 3 Ωμm^2 using a CoFeB magnetic layer for the pinned and free layers. The coercivity of the free layer can be reduced using a $Co_{74}Fe_{26}$/NiFe free layer, which is suitable for head applications. An MR ratio of 40 to 50% was obtained with an RA of 2 to 3 Ωμm^2. Mg-O barrier MTJs are the most promising for future TMR heads for recording densities over 200 Gbit/in^2. We fabricated Al-O barrier TMR heads whose target areal recording density is around 100 Gbit/in^2. These heads have a 25% MR ratio with an RA of 4 Ωμm^2, and the width and height of the TMR head element are 110 nm and 100 nm, respectively. We can obtain an average output signal of about 5000 μVpp at a 150 mV bias voltage (V_b) using a synthetic ferrimagnetic medium. We have also investigated the characteristics of head noise and found that thermal magnetic noise is the dominant noise in our TMR heads. We also investigated the thermal magnetic noise as a function of the exchange coupling field H_{ex} between the pinned and antiferromagnetic layers of TMR heads by using micromagnetic simulations. We clarified the importance of increasing not only the MR ratio but also H_{ex} to realize ultra high density magnetic recording.

1. Introduction

The tunnel magnetoresistive (TMR) head has been considered a promising candidate as a post spin-valve head due to its high magneto-resistance (MR) ratio and current perpendicular to plane (CPP) geometry. The spin-valve head with a current in plane (CIP) geometry is expected to reach its limitation in MR ratio and also have several other issues, for example, its insulator layer should be thin due to the narrow shield-to-shield spacing. The spin-valve head with a CPP geometry (CPP-GMR head) enables the shield-to-shield spacing to be reduced below that possible in the CIP-GMR head, but its MR ratio is only several percent and its impedance is quite low. Therefore, the output voltage of the CPP-GMR head is expected to be low.

We have developed magnetic tunnel junctions (MTJs) from the early stage of research.[1)-5)] MTJs are basically composed of a ferromagnetic free layer, insulator layer, and ferromagnetic pinned layer (**Figure 1**), and their MR ratios are given by $2P_1P_2 / (1-P_1P_2)$ after Juliere,[6)] where P_1 and P_2 are the polarizations of the ferromagnetic layers. P for Ni, Co, and Fe is 0.23, 0.3, and 0.4, respectively. If we could obtain a ferromagnetic material whose P equals 1, we could theoretically obtain an infinite MR ratio. MTJs usually show a high resistance-area product (RA) in spite of their large MR ratio because they have an insulating barrier layer. Even if we obtained an RA of 3 Ωμm^2, the resistance of a 0.1 μm^2 MTJ element would be

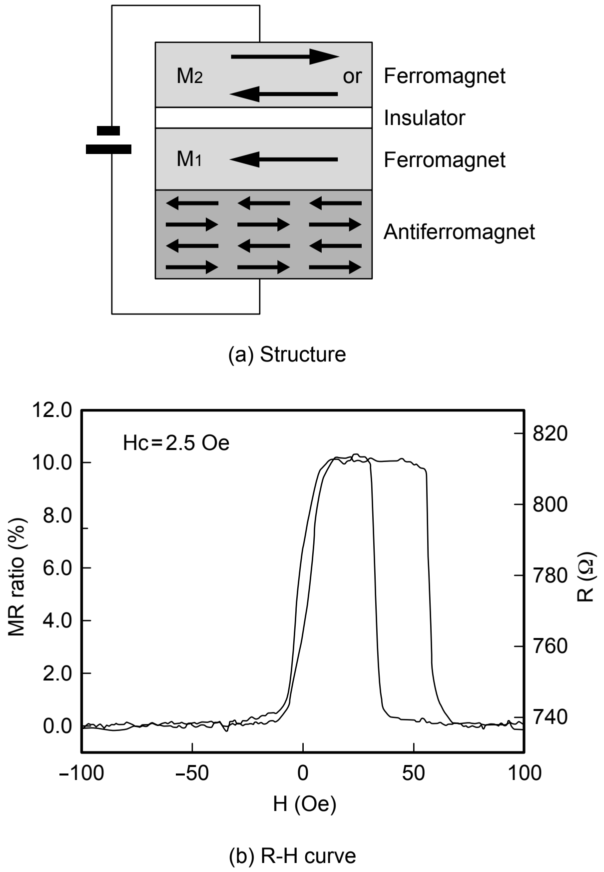

Figure 1
Spin-valve-like property of magnetic tunnel junction (MTJ).

300 Ω. Because the resistance and stray capacitance form a low-pass filter, a high-resistance element would not pass a high data-rate (frequency) signal. Therefore, the most important thing for the TMR head is how to reduce its RA. Many efforts have been made to reduce RA. Oxidization of the barrier layer should be optimized by using a thinner Al barrier layer that is deposited on a flat electrical lead surface. Film flatness is a very important factor for obtaining a lower resistance MTJ and avoiding electrical shorting. A low barrier energy material for the insulator layer is also effective for reducing RA. Many barrier materials have also been investigated.

Although Al-O barrier MTJs have been developed from the early stage of the research, new barrier materials such as Ti-O and Mg-O have recently been discovered to be suitable for low-resistance TMR heads. In this paper, we report the electrical characteristics of these MTJs. We then report the read-write performance and noise characteristics of Al-O barrier TMR heads that we fabricated for areal densities around 100 $Gbit/in^2$. Lastly, we report the results of a 3-dimensional micromagnetic simulation for thermal magnetic noise in TMR heads, which has become the main noise source now that the width and height of sensors for densities around 100 $Gbit/in^2$ have decreased to nearly 100 nm.

2. Magnetic tunnel junction

2.1 Brief history

We have been contributing to MTJ research since the discovery that MTJs have a large MR ratio (18%) at room temperature.[1),2)] We first showed that MTJs with an antiferromagnetic pinning layer exhibit spin-valve-like properties (Figure 1).[3)] We also found that an MTJ's MR ratio can be increased to 24% by annealing (**Figures 2** and **3**).[4)] Furthermore, the highest MR ratio we have obtained so far is 42%, which was obtained with a Co74Fe26 composition (**Figure 4**).[5)]

Figure 5 shows the relation between MR ratios and resistance-area product RA that various researchers have reported over the last 10 years for Al-O barrier MTJs. Surprisingly, RA has been reduced by about eight orders of magnitude over this period.

2.2 Fabrication

We fabricated MTJs on surface-oxidized Si wafers or partially NiFe-plated and chemical-mechanical-polished (CMP) $Al_2O_3 \cdot TiC$ substrates by DC magnetron sputtering. **Figure 6** shows the structure of these MTJs. A PtMn antiferromagnetic layer and CoFe/Ru/CoFe synthetic ferrimagnetic layer were used for the pinning and pinned layers, respectively. The barrier layer was deposited in a wedge shape to obtain the barrier thickness dependency using a single wafer. The pin anneal was performed in a vacuum at 260°C for 4 hours with a magnetic field of 1.11×10^6 A/m

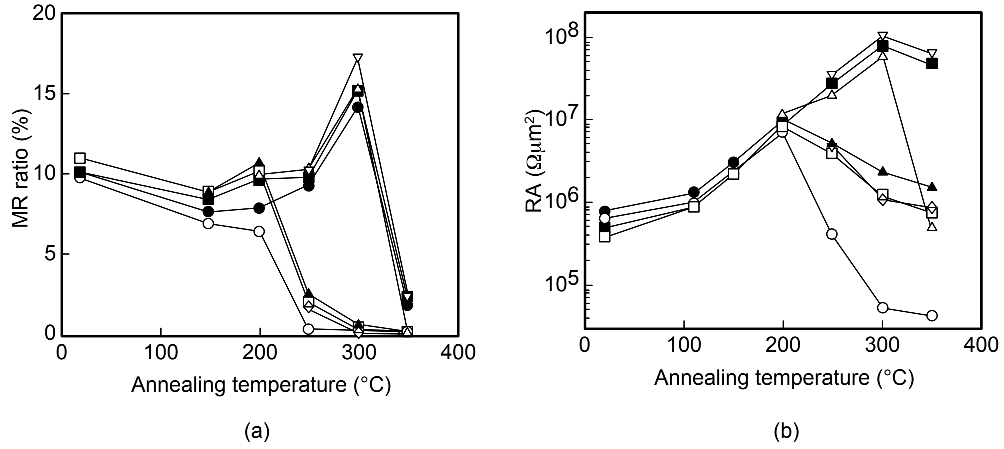

Figure 2
Annealing temperature dependence of tunnel magnetoresistance (TMR) for different samples in the wafer.
(a) Dependence of magneto resistance (MR) ratio on annealing temperature. (b) Dependence of tunnel resistance-area product RA on annealing temperature. Symbols in Figure (a) correspond to symbols in Figure (b).

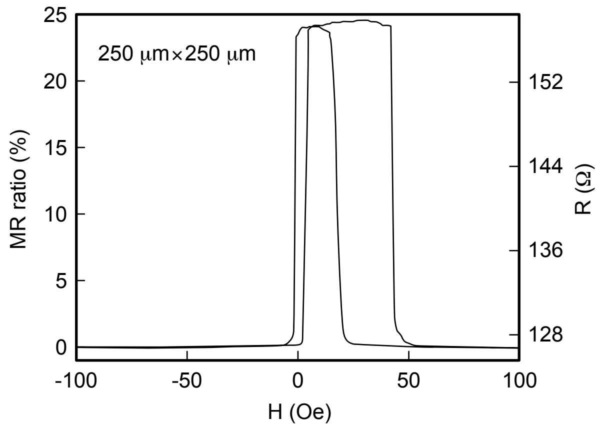

Figure 3
MR curve of MTJ after annealing at 300°C for 1 hour.

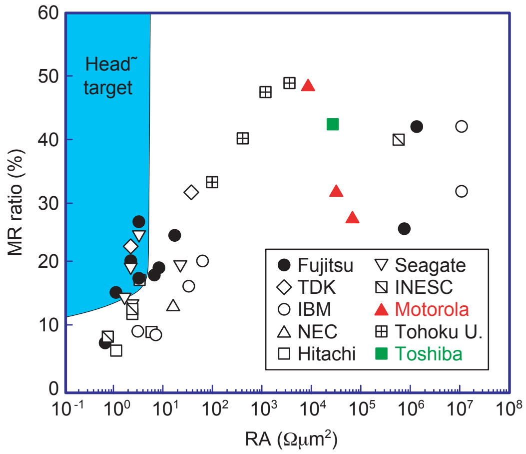

Figure 5
Relationship between MR ratios and resistance-area product RA in MTJs.

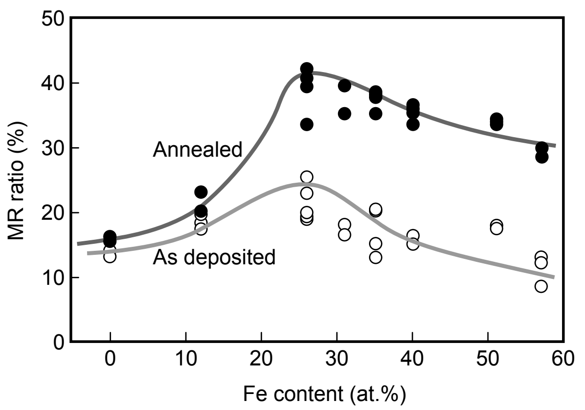

Figure 4
Dependence of MR ratio on CoFe composition in NiFe (24 nm)/$Co_{1-x}Fe_x$(10 nm)/Al-O(1.6 nm)/$Co_{1-x}Fe_x$(10 nm)/IrMn(15 nm) junctions.

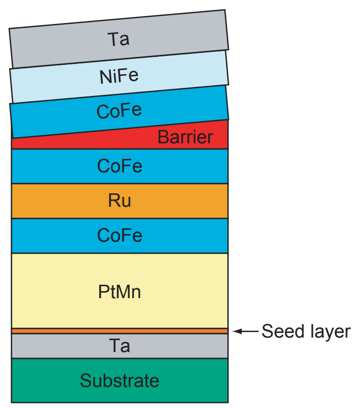

Figure 6
Film structure of MTJ with wedge-shaped barrier layer.

(14 000 Oe). The MTJs were patterned using conventional photolithography, ion-milling, and lift-off. The electrical properties were measured at room temperature under a field of ±7.96 × 10^3 A/m (100 Oe) using the four-probe method.

2.3 MR property

First, we present some typical characteristics of the low-resistance Al-O barrier MTJs we developed. **Figure 7** shows the RA dependence on MR ratio of Al-O barrier MTJs on $Al_2O_3 \cdot TiC$ substrates for three different oxidization times. The Al was oxidized by natural oxidization. The film structure of the MTJs is Ta/PtMn/$Co_{89}Fe_{11}$/Ru/$Co_{74}Fe_{26}$/Al (0.55w. & oxid.) /$Co_{74}Fe_{26}$(1.5)/NiFe(3)/Ta. The numbers in parentheses show the thickness in nm, and "0.55w. & oxid." in this example is the mean thickness of a 0.55 nm Al wedge and successive oxidation after deposition. A good MR ratio of 27% at an RA of about 3 $\Omega\mu m^2$ was obtained. The read/write performance of Al-O barrier TMR heads is described in the next section.

We also studied TiO barrier MTJs. **Figure 8** shows the RA dependence on MR ratio of TiO barrier MTJs on $Al_2O_3 \cdot TiC$ substrates for three different oxidization times. The Ti was oxidized by radical oxidization in this case. The film structure of these MTJs is Ta/PtMn/$Co_{74}Fe_{26}$/Ru/$Co_{74}Fe_{26}$/Ti (0.45w. & oxid.) /$Co_{74}Fe_{26}$(1)/NiFe(3)/Ta. TiO barrier MTJs have a very low RA because of their low barrier height. **Figure 9** shows a typical R-V curve and the bias dependency of the MR ratio of a TiO barrier MTJ. We can obtain a barrier height that is 0.1 eV lower than the 0.5 eV height of Al-O barrier MTJs by fitting the barrier height and width with Simmons' equation of tunneling.[7] $V_{1/2}$ is defined where the TMR decreases to half its zero bias value. $V_{1/2}$ is about 200 mV, which is also smaller than the 450 mV value of Al-O barrier MTJs.

MgO barrier MTJs with CoFeB magnetic layers were discovered to show a high MR ratio of over 200%.[8)-10)] **Figure 10** shows the RA dependence on the MR ratio of MgO barrier MTJs on Si substrates. The MgO was deposited by RF spat-

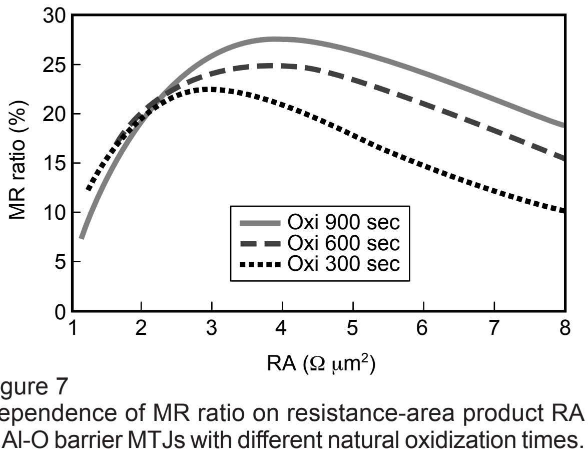

Figure 7
Dependence of MR ratio on resistance-area product RA in Al-O barrier MTJs with different natural oxidization times.

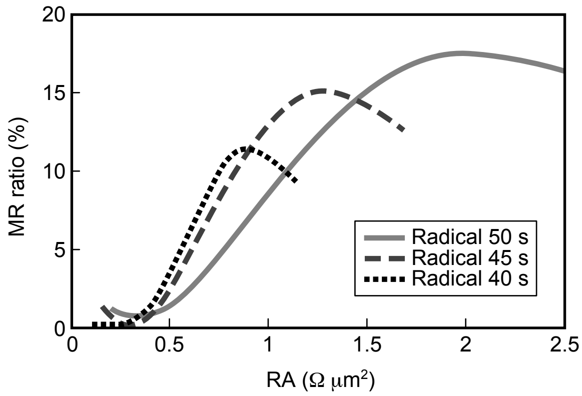

Figure 8
Dependence of MR ratio on resistance-area product RA in Ti-O barrier MTJs with different radical oxidization times.

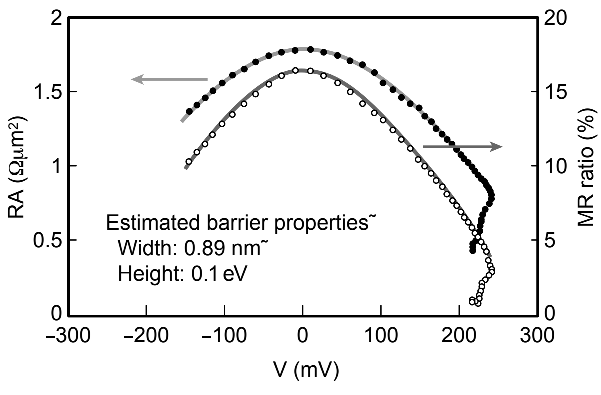

Figure 9
Dependence of RA and MR ratio on bias in Ti-O barrier MTJ.

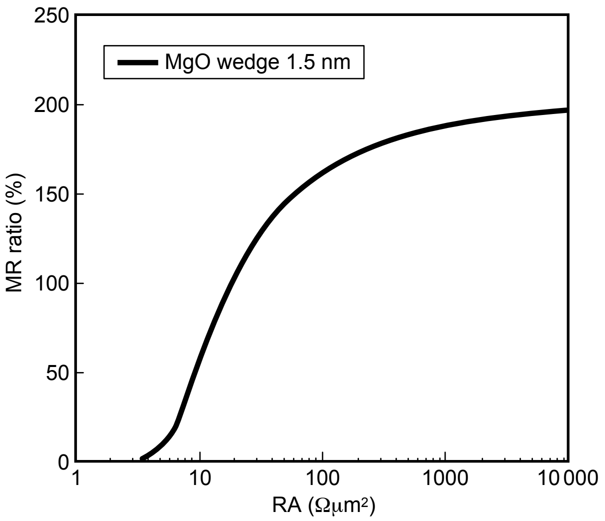

Figure 10
Dependence of MR ratio on resistance-area product RA in MgO barrier MTJs.

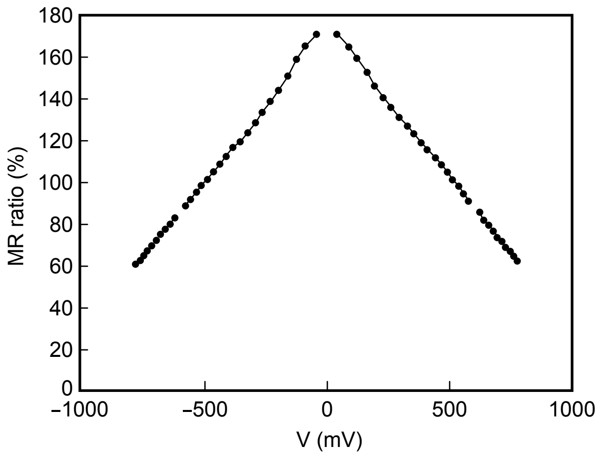

Figure 11
Dependence of MR ratio on bias in MgO barrier MTJ.

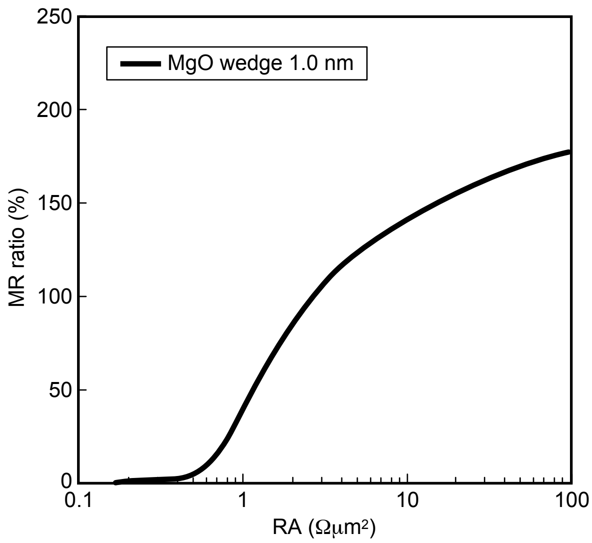

Figure 12
Dependence of MR ratio on resistance-area product RA in MgO barrier MTJs.

tering in this case. The film structure of these MTJs is Ta/PtMn/$Co_{74}Fe_{26}$/Ru/CoFeB(3)/MgO (1.5w.)/CoFeB(3)/Ta. The MTJs were annealed in a vacuum at 350°C after the deposition. An MR ratio of 200% was obtained with an RA exceeding 1 kΩμm^2. **Figure 11** shows the MR ratio dependence on the bias. A high $V_{1/2}$ of 600 mV was obtained.

RA can be decreased by decreasing the thickness of MgO. **Figure 12** shows the RA dependence on the MR ratio of MgO barrier MTJs on Al_2O_3 · TiC substrates, in which the mean thickness of the MgO wedge is 1.0 nm. An MR ratio of 100% was obtained with an RA of 2 Ωμm^2.

Although MTJs with a CoFeB magnetic layer for the pinned and free layers showed a high MR ratio, their coercivity Hc is around 1.99 × 10^3 A/m (25 Oe) which is quite high for head applications. We therefore used a composite film of $Co_{74}Fe_{26}$/NiFe instead of CoFeB film for the free layer. This decreased the MR ratios to about half the value of the CoFeB free-layer MTJs but also decreased Hc to less than 3.98 × 10^2 A/m (5 Oe). **Figure 13** shows the RA dependence on the MR ratio of MgO barrier MTJs on Al_2O_3 · TiC substrates with an MgO thickness of 0.97, 1.00, and 1.03 nm, respectively. The film structure of these MTJs is Ta/PtMn/$Co_{74}Fe_{26}$/Ru/CoFeB/MgO/$Co_{74}Fe_{26}$(1.5)/NiFe(3)/Ta. An MR ratio of around 40% was obtained with an RA of 2 Ωμm^2. These MTJs are very promising for use in future HDD read heads.

3. TMR heads with Al-O barrier

We fabricated first-generation prototype TMR heads whose target areal recording density is around 100 Gbit/in^2. We focused on Al-O barrier TMR heads and fabricated them using conventional photolithography, successive ion milling, and lift-off. The TMR head stack is made of Ta/PdPtMn/CoFe/Ru/CoFe/Al & oxid. /CoFe/NiFe/Ta and stabilized by a permanent-magnet (CoCrPt) abutted junction. The TMR film for the prototype heads has an RA of 4 Ωμm^2 and an MR ratio of 25%. **Figure 14** shows a TEM image of the air-bearing surface of one of these TMRs. The width and height of the TMR element are 110 nm and 100 nm, respectively. The read write measurement was performed at a 150 mV bias voltage (V_b). The average output signal is around 5000 μVpp from a synthetic ferrimagnetic medium having a remanence-thickness product $B_r\delta$ of 3.7 Tnm (37 Gμm). This output signal is four times larger than that of a conventional spin-valve CIP-GMR head. The magnetic read track width Twr is about 120 nm. The output signal voltage is sufficiently high, and Twr is sufficiently narrow to achieve a 100 Gbit/in^2 recording density.

We also investigated the characteristics of head noise. Its voltage spectrum is shown in **Figure 15**. The noise voltage obtained by integrating the noise voltage spectrum is typically around 180 μVrms.

On the other hand, the head noise source of the TMR head is thought to be composed of Johnson noise, shot noise, and thermal magnetic noise. The Johnson plus shot noise can be calculated by the following equation according to Klaassen, Xing, and Peppen:[11)]

$$N_{\mathrm{J+shot}} = \sqrt{2 \cdot e \cdot V_b \cdot R \cdot \Delta f \cdot \coth\left(\frac{e \cdot V_b}{2 \cdot k_B \cdot T}\right)}, \qquad (1)$$

where e is the elementary electric charge, k_B is Boltzmann's constant, T is the absolute temperature, and R is the head resistance at zero electrical bias. Using this equation, the estimated Johnson plus shot noise voltage of this TMR head is 64 μVrms when R = 360 Ω and Δf = 230 MHz. We estimated that the thermal magnetic noise of the TMR head is 170 μVrms ($=\sqrt{N_{\mathrm{head}}^2 - N_{\mathrm{J+shot}}^2}$) under the assumption that the head noise is composed of the three above-mentioned noise sources. The thermal magnetic noise is thought to come from

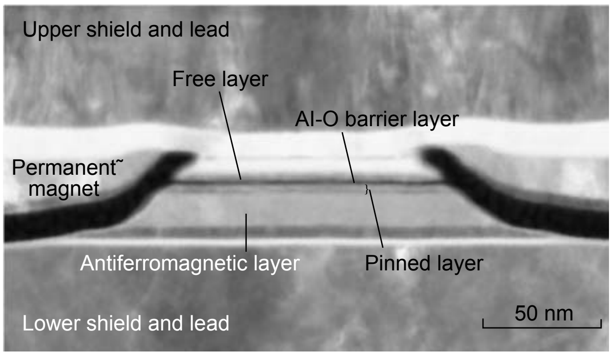

Figure 14
TEM image of first-generation prototype TMR head.

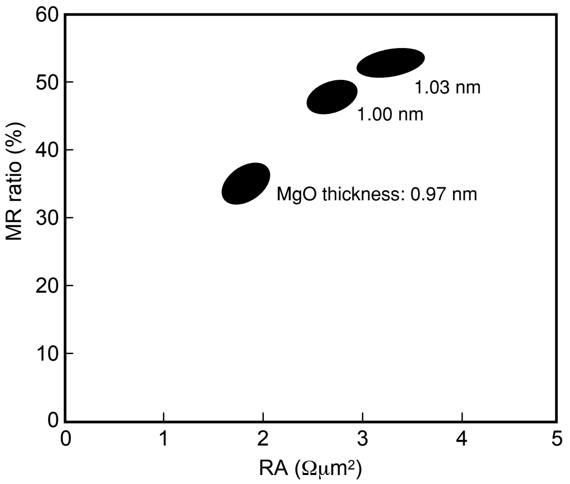

Figure 13
Dependence of MR ratio on resistance-area product RA in MgO barrier MTJs.

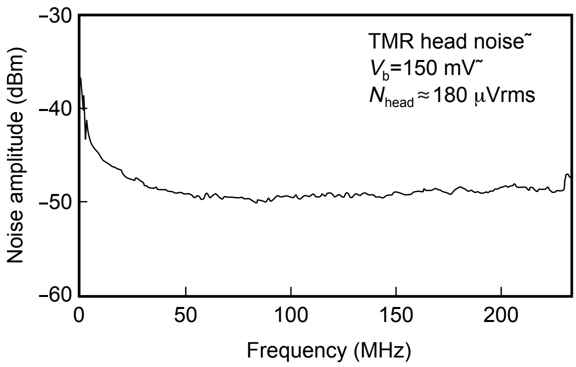

Figure 15
Head noise amplitude spectrum of TMR head.

random magnetic rotations in the TMR element due to the influence of thermal energy. Needless to say, the thermal magnetic noise governs the head noise. We discuss the thermal noise in the next section.

4. Study of thermal magnetic noise by computer simulations

As mentioned above, we are promoting research and development to improve the MR ratio of MTJs from the material-search point of view. Simultaneously, we have already developed first-generation TMR heads that can be used for areal recording densities around 100 Gbit/in^2. The width and height of the sensors of current HDDs for 100 Gbit/in^2 recording have decreased to nearly 100 nm. In order to further increase the areal recording density, it is necessary to downsize the TMR head element. However, as the sensor is downsized, random magnetic rotations due to thermal excitation in the TMR heads increases, and this problem is believed to set the limit of areal recording density.[12)-14)] Therefore, we have also been studying the thermal magnetic noise in TMR heads by using micromagnetic simulations that take the thermal fluctuation energy into consideration. This section describes the dependence of thermal magnetic noise on the exchange coupling field H_{ex} between the pinned and antiferromagnetic layers.

4.1 Simulation model

To study the thermal magnetic noise of TMR heads, we developed a 3-dimensional micromagnetic simulation model by changing the current direction of the GMR head calculation model.[14)] **Figure 16** shows a micromagnetic simulation model for TMR heads. We calculated the magnetic motion in 2-dimensional arrays of tetragonal cells for each magnetic layer in the TMR element (i.e., the free and synthetic ferrimagnetic coupled pinned layers) using the Landau Lifshitz Gilbert (LLG) equation:

$$\frac{d\mathrm{M_i}}{dt} = \gamma \mathrm{M_i} \times \mathrm{H_{i\text{-}eff}} - \frac{\gamma \cdot \alpha}{M_s} \mathrm{M_i} \times (\mathrm{M_i} \times \mathrm{H_{i\text{-}eff}}), \quad i = 1, 2, \cdots, N. \tag{2}$$

where $\mathrm{M_i}$ and $\mathrm{H_{i\text{-}eff}}$ are, respectively, the magnetization and effective applied field of each cell, and $\mathrm{H_{i\text{-}eff}}$ includes the anisotropy, magnetostatic coupling, exchange coupling, and external field.

To simulate thermal magnetic noise, we introduced a random effective thermal field corresponding to the thermal fluctuation energy into $\mathrm{H_{i\text{-}eff}}$ of the LLG equation. The direction of the effective thermal field is isotropically random, the magnitude distribution is Gaussian with a zero mean, and the dispersion is inversely proportional to the magnetic energy of each cell:[12)-15)]

$$H_{\mathrm{ther}}^2 = \frac{2k_B T\alpha}{V_{\mathrm{cell}} M_S \gamma (1+\alpha^2)\Delta t}. \tag{3}$$

where α (= 0.02) is the damping constant, γ (= 1.76 × 10^7 Hz/Oe) is the gyromagnetic constant, and M_S and V_{cell} are the saturation magnetization and volume of each cell, respectively. The duration of the constant effective thermal fluctuation field Δt was chosen to be 10 ps.

The layer structure was antiferromagnetic/pinned/Ru/reference/Al-O barrier/free. The width

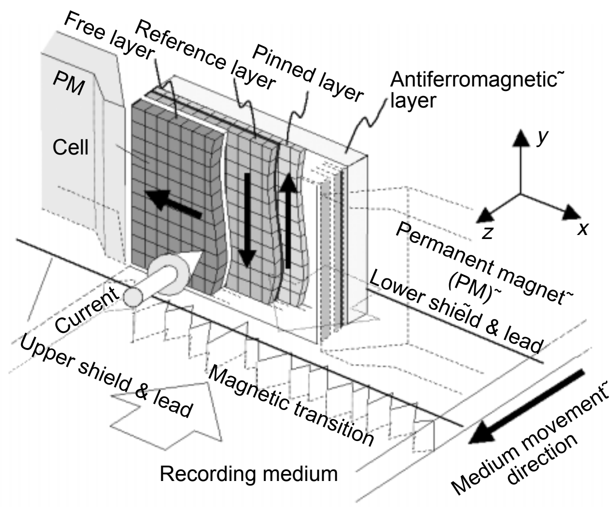

Figure 16
Micromagnetic simulation model for TMR heads.

and height of the free layer were assumed to be 120 and 110 nm, respectively, and the shield-to-shield gap was assumed to be 45 nm.

4.2 Simulation of thermal magnetic noise in TMR heads

Figures 17 (a) and **17 (b)** show the simulated output signals of TMR heads with H_{ex} assumed to be 3.18×10^4 and 1.59×10^4 A/m (400 and 200 Oe). The figures clearly show that reducing H_{ex} to 1.59×10^4 A/m does not affect the output signal. The two heads have a similar peak-to-peak output voltage and symmetrical output waveforms. In contrast, the thermal magnetic noise of the TMR head with the lower H_{ex} has large, irregular, and asymmetrical positive peaks [**Figure 17 (d)**]. **Figure 18** shows the dependence of output signal and thermal magnetic noise on H_{ex}. The output signal is virtually constant, but the thermal magnetic noise more than doubles when H_{ex} is decreased from 3.18×10^4 to 1.59×10^4 A/m (400 and 200 Oe). Reducing H_{ex} increases the thermal magnetic noise but only slightly affects the output signal. The results presented in this paper indicate that it is important to increase not only the MR ratio but also H_{ex} to realize the next generation of TMR heads for ultra high density magnetic recording. Therefore, we have been looking for materials with a large H_{ex}.

Computer simulation is an effective tool for the type of head design and analysis described above. We have used simulation for efficient development of TMR heads and are convinced it has enabled us to develop high-quality TMR heads.

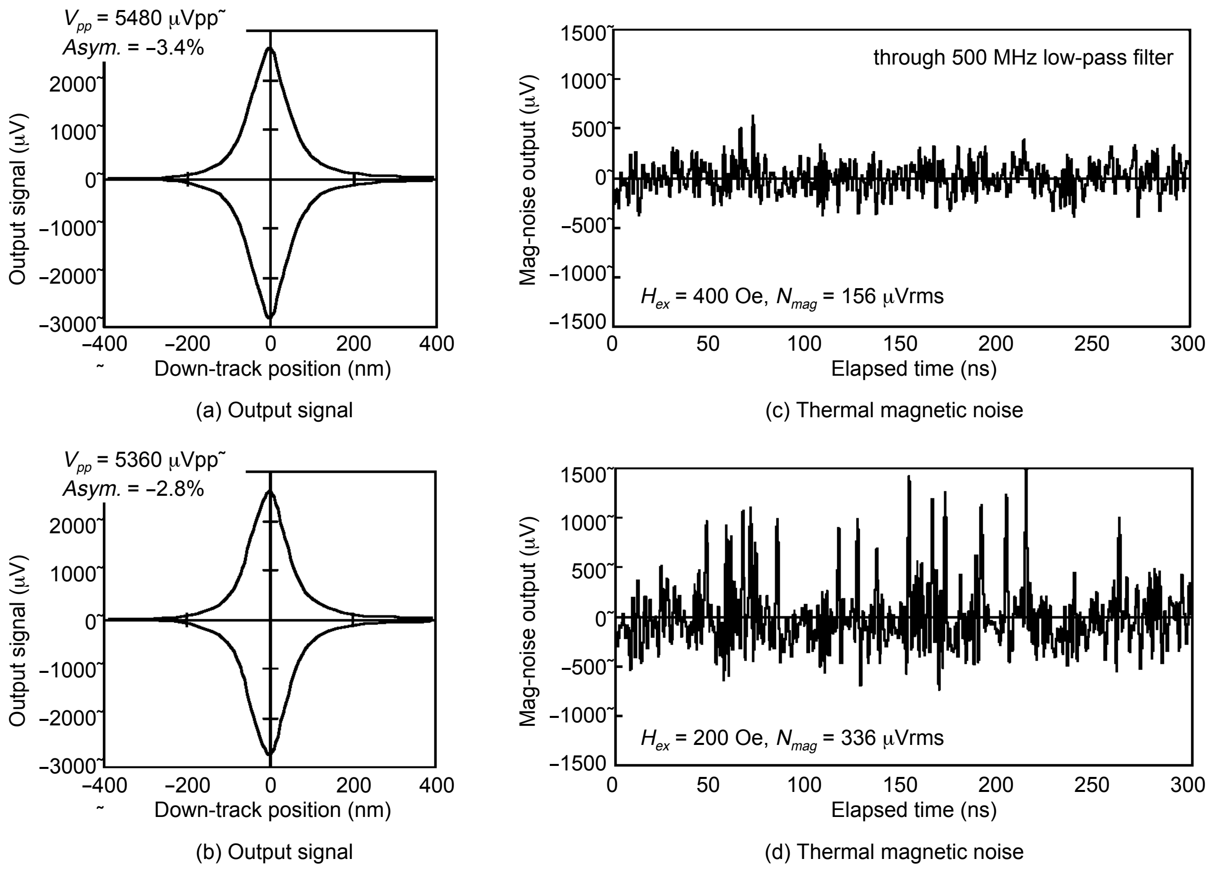

Figure 17
Simulated output signal and thermal magnetic noise waveforms of TMR heads with different H_{ex}.

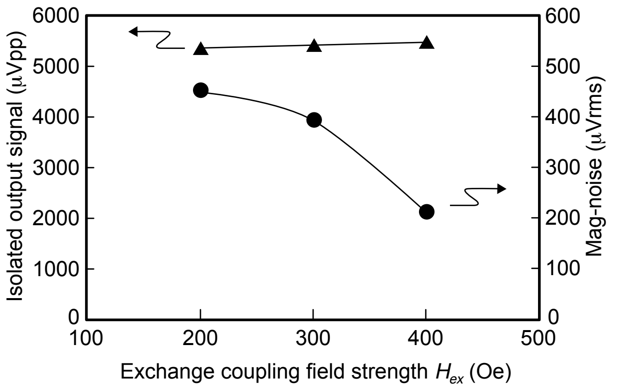

Figure 18
Dependence of output signal and thermal magnetic noise on H_{ex}.

5. Conclusion

We have developed Al-O barrier MTJs and obtained an MR ratio of 27% with an RA of about 3 $\Omega\mu m^2$. We have developed first-generation Al-O barrier TMR heads that can be used for areal recording densities of about 100 Gbit/in^2. These heads showed a large output voltage that was four times larger than that of spin-valve CIP heads. However, we found the thermal magnetic noise is the dominant noise in these heads, and it will be the critical obstacle to further increases of areal magnetic recording density. We also investigated the thermal magnetic noise of TMR heads as a function of H_{ex} by using micromagnetic simulations. We clarified the importance of increasing not only the MR ratio but also H_{ex} to realize ultra high density magnetic recording.

We have also studied Ti-O and Mg-O as new low barrier energy materials for MTJs. Ti-O barrier MTJs show a peculiar characteristic: they have a very small RA of less than 2 $\Omega\mu m^2$. We can obtain a high MR ratio of about 40 to 50% for Mg-O barrier MTJs with an RA of 2 to 3 $\Omega\mu m^2$ by using a CoFeB pinned layer and low-coercivity $Co_{74}Fe_{26}$/NiFe free layer. Not only are Mg-O barrier MTJs the most promising for future TMR heads for over 200 Gbit/in^2 recording densities, they also could be used for the read heads of high-end server HDDs.

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