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Effects of Rapid Thermal Anneal on the Magnetoresistive Properties of Magnetic Tunnel Junction

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The effect of rapid thermal anneal (RTA) has been investigated on the properties of an FeMn exchange-biased magnetic tunnel junction (MTJ) using magnetoresistance and *I-V* measurements and transmission electron microscopy (TEM). The tunneling magnetoresistance (TMR) in an as-grown MTJ is found to be ~27%, while the TMR in MTJs annealed by RTA increases with annealing temperature up to 300 °C, reaching ~46%. A TEM image reveals a structural change in the interface of Al_2O_3 layer for the MTJ annealed by RTA at 300 °C. The oxide barrier parameters are found to vary abruptly with annealing time within a few ten seconds. Our results demonstrate that the present RTA enhances the magnetoresistive properties of MTJs.

Key words : Magnetic tunnel junction, Tunneling magnetoresistance, Rapid thermal anneal

1. Introduction

In recent years, a host of research groups [1-6] have studied the annealing effect on the magnetic and transport properties and thermal stability of magnetic tunnel junctions (MTJ), which are important issues for magnetic random access memory (MRAM) applications. It is well recognized that an annealing process is necessary to improve the properties of MTJs, giving rise to higher tunneling magnetoresistance (TMR) and exchange bias field (H_{ex}) [1-6]. However, to date, studies have centered on MTJs annealed by conventional thermal anneal (CTA), based on a long-time process including slow ramp-up and cool-down.

In this work, we have investigated a novel effect of rapid thermal anneal (RTA) on the properties of MTJs, leading to an enhancement in the tunneling magnetoresistance. Our results demonstrate that an RTA process is more useful and efficient than a CTA process in optimizing the magnetic and transport properties of an MTJ.

The MTJs were deposited on a thermally oxidized Si(100) substrate in a dc magnetron sputtering system with a base pressure of 4×10^{-8} Torr. The generic structure of the MTJs was Si(100)/Ta(50)/$Ni_{81}Fe_{19}$(60)/$Fe_{50}Mn_{50}$(80)/$Co_{84}Fe_{16}$(40)/Al_2O_3/$Co_{84}Fe_{16}$(20)/$Ni_{81}Fe_{19}$(100)/Ta(20) (in Å). A magnetic field of 300 Oe was applied during deposition in order to induce an easy axis in each electrode. The Al_2O_3 barrier was formed by plasma oxidation in an O_2 atmosphere after growing 16 Å thick Al film. A combination of photolithography, ion milling, and lift-off process was utilized to fabricate 50×50 μm^2 junctions. CTA and RTA were performed under vacuum conditions ($< 10^{-6}$ Torr) at various temperatures. A radiating heating furnace (ULVAC, RHL-E) with an infrared lamp was utilized for the RTA process. Table 1 summarizes the process conditions for the CTA and RTA. It should be noted that, in this work, the RTA process (< 7 min) is much faster than the CTA (> 2.5 hr).

Fig. 1(a) shows the TMR curves for samples as-grown and annealed by RTA. The significant enhancement of TMR as well as exchange bias field (H_{ex}) were observed after 10sec RTA process. The TMR versus bias voltage for as-grown and RTA sample is shown in Fig. 1(b). These curves were deduced from $I(V)$ measurements performed in each parallel and antiparallel magnetic configuration. It is

Table 1. Comparison of annealing conditions between CTA and RTA

	CTA	RTA
Ramp-up	15 min	10 sec
Anneal	1 hr	10 sec
Cool-down	~1.5 hr	~6 min
Total process	> 2.5 hr	< 7 min
Temperature	200~300 °C	200~400 °C

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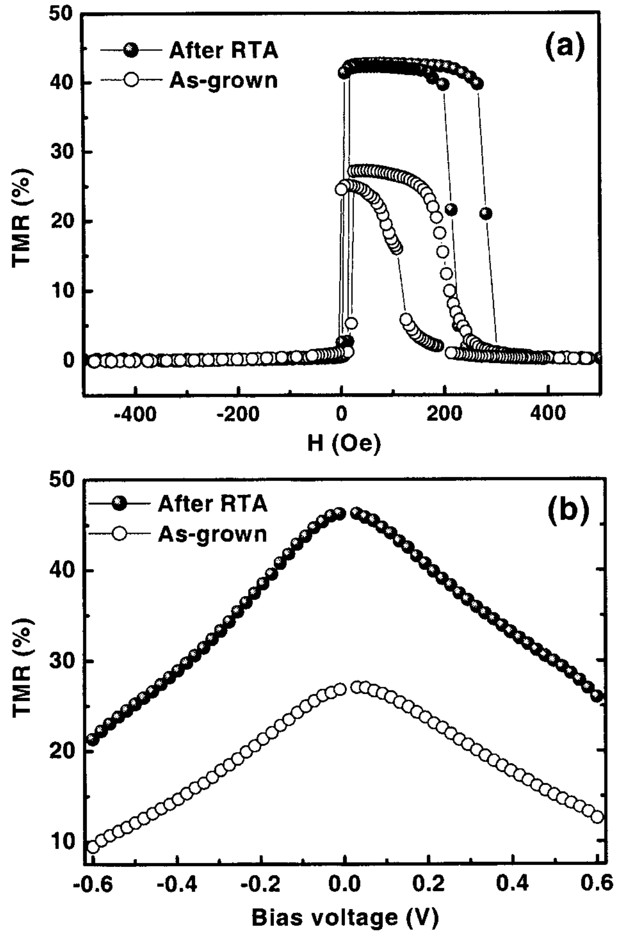

Fig. 1. TMR curves (a) and TMR versus bias voltage (b) for the as-grown MTJ and the MTJ after 10 sec-RTA process at 300 °C.

noticeable that for RTA sample, at ±0.5 V, the remaining TMR value is still over half of the low-bias value (>20%). This relatively small bias dependence may imply the good quality of barrier [7-9].

Fig. 2 shows the variation of (a) TMR ratio and (b) exchange bias field against the annealing temperature for the CTA and RTA samples, respectively. The TMR value in the as-grown sample is found to be ~27%. The TMR for the CTA samples increases with annealing temperature up to 230 °C, reaching ~40%. It is attributable to oxygen redistribution and homogenization in the Al oxide barrier during annealing process [3, 5], giving rise to the improvement in the properties of MTJs. After this temperature, the TMR starts to decrease gradually, which can be due to interdiffusion of Mn at the interface of CoFe and FeMn [5] or diffusion of Mn to the oxide barrier [6]. The dependence of the TMR on annealing temperature for the RTA samples is similar to that for the CTA samples. It is observed that junction resistance ranged from a few kΩ to a few hundred Ω with increasing temperature for both the CTA and RTA samples. However, the temperature for the RTA samples showing the maximum value in TMR is higher than that for the CTA samples, e.g. T^{RTA} (TMR ~46% at 250~300 °C) > T^{CTA} (TMR ~40% at 230 °C).

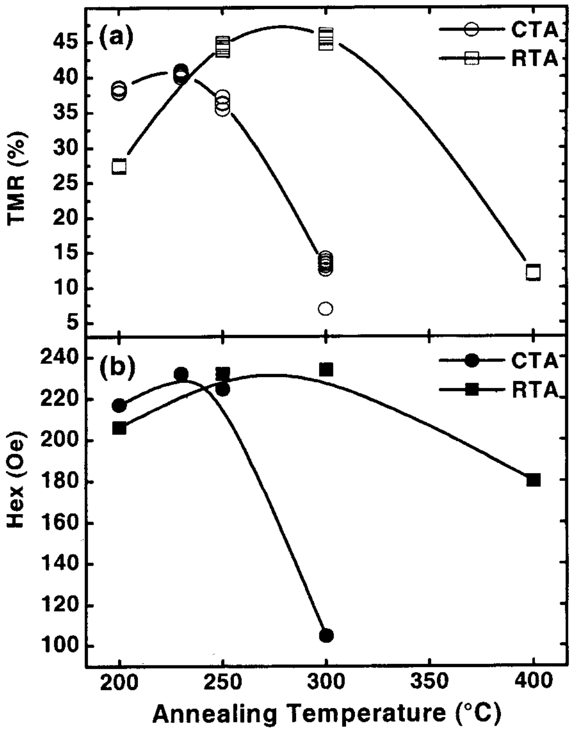

Fig. 2. The variation of (a) TMR ratio and (b) exchange bias field (H_{ex}) against the annealing temperature for the CTA and RTA samples, respectively. The thick gray lines indicate the TMR ratio and H_{ex} of the as-grown MTJ for comparison.

The dependence of exchange bias field (H_{ex}) is illustrated in Fig. 2(b) on annealing temperature for the CTA and RTA samples. In the case of the CTA samples, H_{ex} varies from 180 Oe to 230 Oe with the increasing temperature up to 250 °C. Above this temperature, H_{ex} decreases rapidly with increasing temperature. By contrast, H_{ex} in the RTA samples reached a maximum of 230 Oe at 300 °C and decreases gradually at elevated temperature. These results demonstrate that RTA is more useful and efficient than CTA in optimizing the properties of the MTJs.

The structure of MTJs has been investigated using transmission electron microscopy (TEM) before and after the RTA process in order to clarify the annealing effect on the interface of Al_2O_3 layer with the two electrodes. Fig. 3 presents cross-sectional TEM micrographs (a) for the as-grown MTJ and (b) for the MTJ annealed at 300 °C. The insulating layer for the as-grown MTJ differs remarkably from that for the annealed MTJ. It is clearly seen that the interface of the Al_2O_3 layer in the as grown MTJ looks blurred and wavy. On the other hand, the interface of the Al_2O_3 layer in the annealed MTJ was found to change into relatively clear morphology, which is believed to have a correlation with oxygen redistribution and homogenization in Al oxide barrier during annealing process [3, 5], resulting in the enhancement of the magnetic and transport properties.

In Fig. 4, shown is the variation of (a) the effective barrier thickness (t_{eff}) and (b) height (Φ_{eff}) with annealing time for

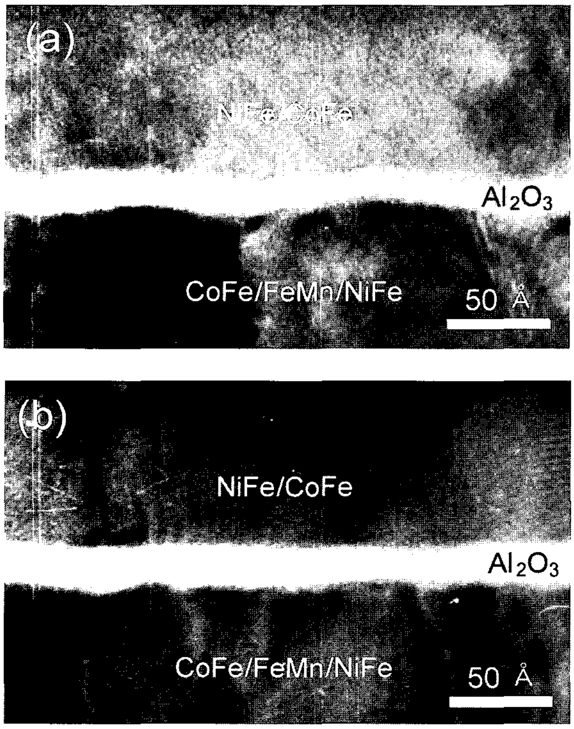

Fig. 3. Cross-sectional TEM micrographs (a) for the as-grown MTJ and (b) for the MTJ annealed at 300 °C.

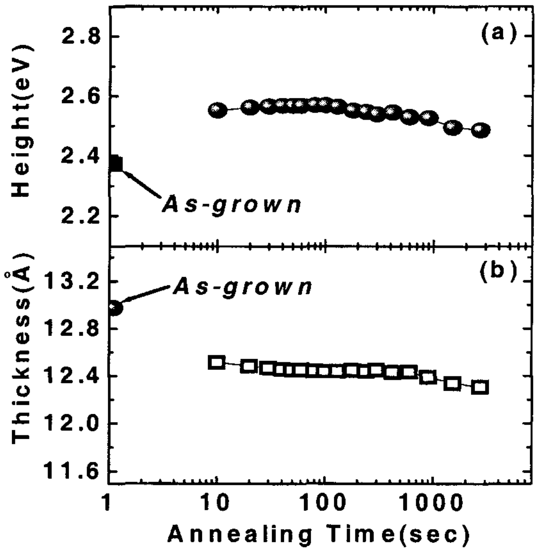

Fig. 4. The variation of (a) the effective barrier thickness (t_{eff}) and (b) height (Φ_{eff}) versus annealing time for an MTJ annealed at 300 °C by RTA.

an MTJ annealed at 300 °C by RTA, as obtained from the I-V curve analysis by fitting to Simons' model. Interestingly, significant changes in the effective barrier thickness (t_{eff} : from 13.0 to 12.5 Å) and height (Φ_{eff} : from 2.35 to 2.55 eV) occur within 10 seconds in the RTA process, indicating that the structural transformation in the oxide barrier such as oxygen redistribution and homogenization [3, 5], takes place abruptly at the initial step of the anneal. After 10 seconds, the barrier parameters vary gradually with annealing time.

In summary, effects of RTA on the magnetoresistive properties of exchange-biased MTJs were investigated and compared with that of CTA. TMR ratio and *Hex* increased up to ~46% and ~230 Oe, respectively, after the very short time RTA process (~10 sec). The effectiveness of RTA process, related to the annealing time required and to the magnetoresistive properties of MTJs, was shown from our results. Thus, this has demonstrated the RTA process could prove useful as alternate thermal treatment for optimizing the properties of MTJs.

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