Spin–Dependent Tunneling in Heusler Alloy–Based Magnetic Tunnel Junctions

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The Magnetoresistive Random Access memory (MRAM) has the potential of surpassing present semiconductor-based RAM devices because it offers high speed, high density, unlimited write/read endurance and in addition, unlike the DRAM and SRAM, is non-volatile, that is, it does not lose information when power is turned off. An MRAM cell consists of a magnetic tunnel junction (MTJ) and a MOS transistor. MTJs in turn consist of a thin insulating barrier between two ferromagnetic electrodes. The most important parameter of an MTJ is its tunneling magneto-resistance ratio (TMR). A high TMR ratio is desired. Half metallic ferromagnets (HMFs) are characterized by complete spin polarization at the Fermi level that corresponds to a high TMR ratio. Heusler alloys are a type of HMF that has been theoretically proven to demonstrate a half metallic nature. We fabricated epitaxial MTJs with a Heusler alloy thin film of $Co_2Cr_{0.6}Fe_{0.4}Al$ (CCFA) as a lower electrode, an MgO barrier and a $Co_{50}Fe_{50}$ upper electrode. A relatively high TMR ratio, up to 109% at room temperature (RT) (317% at 4.2K) has been achieved for these CCFA/MgO/CoFe MTJs, which were *ex situ* post-fabrication annealed at 175^{o}C. The purposes of our present study are to understand the key factors that influence spin dependent tunneling characteristics in these Heusler alloy-based MTJs, and then to further enhance the TMR ratio. Recently, we introduced *in situ* annealing at a temperature T_a, just after deposition of the upper CoFe electrode to investigate how the TMR characteristics vary with T_a. Our results show a significant upward scale in TMR ratios for T_a ranging from RT to 500^{o}C. The TMR ratio increased with increasing T_a from 95% at RT (225% at 4.2K) for T_a of RT to 152% at RT (335% at 4.2K) for T_a of 500^{o}C. To further clarify this dependence of the TMR ratio on T_a, we investigated I vs. V, dI/dV (= G) vs. V and d^2I/dV^2 vs. V characteristics. The bias voltage, V was defined with respect to the lower CCFA electrode. In general, the slopes of the G_{AP} and G_P were distinctly lower for MTJs with T_a of 500^{o}C than those for MTJs with T_a of RT. Precisely, the lower slope G_{AP} was observed for both $V > 0$ and $V < 0$, and the lower G_P for $V > 0$ in the region from $|V| = 0$ to ~0.4 V. These results indicate that the electronic density of states around the Fermi level for minority spins in interfacial regions of both the lower CCFA and the upper CoFe, both facing the MgO barrier, decreased with increasing T_a from RT to 500^{o}C. These led to increased spin polarization of both the CCFA and the CoFe in the interfacial region. These findings are consistent with the increased TMR ratios observed for MTJs with T_a of 500^{o}C.

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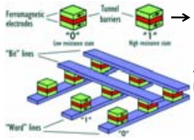
Abstracts

We fabricated epitaxial MTJs with a Heusler alloy thin film of $Co_2Cr_{0.6}Fe_{0.4}Al$ (CCFA) as a lower electrode, an MgO barrier and a $Co_{50}Fe_{50}$ upper electrode. A relatively high TMR ratio, up to 109% at room temperature (RT) (317% at 4.2K) has been achieved for these CCFA/MgO/CoFe MTJs which were *ex situ* post-fabrication annealed at 175°C. The purposes of our present study are to understand the key factors that influence spin dependent tunneling characteristics in these Heusler alloy-based MTJs, and then to further enhance the TMR ratio. Recently, we introduced *in situ* annealing at a temperature T_a, just after deposition of the upper CoFe electrode to investigate how the TMR characteristics vary with T_a. Our results show a significant upward scale in TMR ratios for T_a ranging from RT to 500°C. The TMR ratio increased with increasing T_a from 95% at RT (225% at 4.2K) for T_a of RT to 152% at RT (335% at 4.2K) for T_a of 500°C.

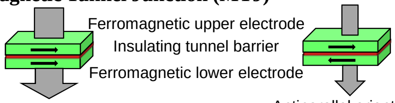
Introduction

Magnetoresitive Random Access Memory (MRAM)

- Non Volatile
- High Speed
- High density
- Unlimited write/read endurance



Magnetic Tunnel Junction (MTJ)



- Parallel orientation
  Current High
  Resistance Low
- Antiparallel orientation
  Current Low
  Resistance High

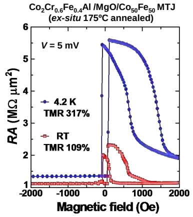
Tunnel MagnetoResistance (TMR) ratio

$$\mathrm{TMR} = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1 - P_1P_2}$$

- TMR ratio – key device parameter of MTJs

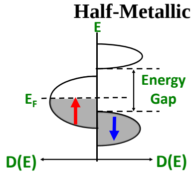
where,
P_i: spin polarization of electrode
R_P: resistance for parallel orientation
R_{AP}: resistance for anti-parallel orientation

- Highly spin-polarized ferromagnetic electrodes are preferable - High TMR ratio.



T. Marukame et al., APL **90**, 012508 (2007)

Half-Metallic Ferromagnet (HMF)



- Existence of energy gap at E_F for one spin direction
- Complete spin polarization at E_F resulting in a high TMR ratio
- Highly favorable for ferromagnetic electrodes used in spintronic devices

$$P_1 = \frac{\rho_1^{\uparrow} - \rho_1^{\downarrow}}{\rho_1^{\uparrow} + \rho_1^{\downarrow}}$$

As $\rho_1^{\downarrow} \& \rho_2^{\downarrow} \to 0$; $P_1 \& P_2 \to 1$; $\mathrm{TMR} \to \infty$

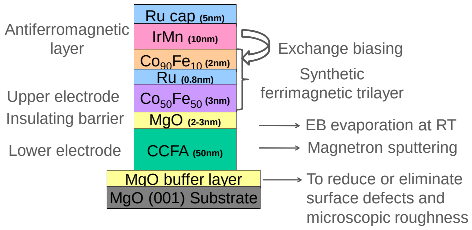
Heusler Alloys

- Half metallic ferromagnetic nature theoretically predicted for many of these alloys
- High Curie temperatures, well above RT
- Examples include : $Co_2Cr_{0.6}Fe_{0.4}Al$(CCFA), Co_2MnGe(CMG), Co_2MnSi(CMS)

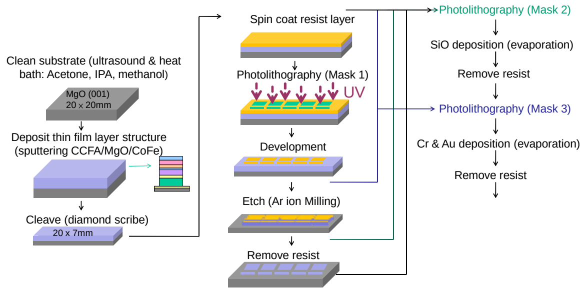
Materials and Methods

Fabricating MTJ layer structure

MTJ Layer structure:
$Co_2Cr_{0.6}Fe_{0.4}Al/MgO/Co_{50}Fe_{50}$ ⟷ (CCFA/MgO/CoFe)
Sputtering Machine - ultrahigh vacuum chamber (with a base pressure of about 6 x 10^{-8} Pa)



Fabrication Procedure



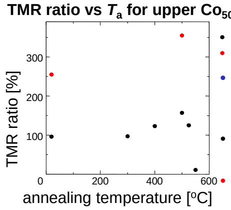
Research Purpose

☺To understand the key factors that influence spin dependent tunneling characteristics in these Heusler alloy-based MTJs, and then to further enhance the TMR ratio.

Enhancing the TMR ratio

Introduced *in situ* annealing of upper electrode at a temperature T_a

TMR ratio vs T_a for upper $Co_{50}Fe_{50}$



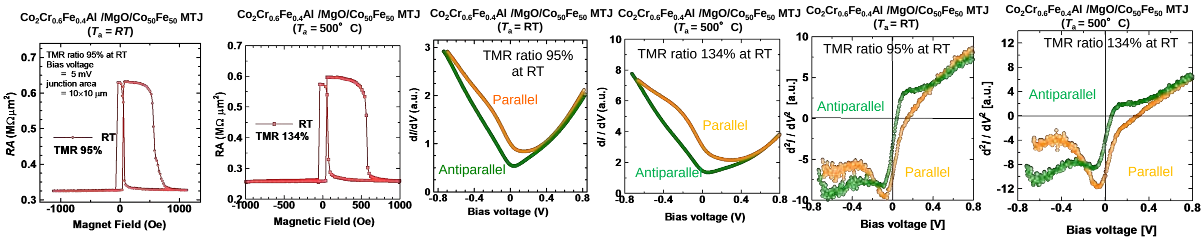
- RT
- 4.2K
- **The TMR ratio increased with increasing T_a**
- T_a of RT - 95% at RT (225% at 4.2K)
- T_a of 500°C -152% at RT (335% at 4.2K)

Results, Discussion and Conclusion

TMR for CCFA/MgO/CoFe

d*I* / d*V* curves

d^2I / dV^2 curves



❖To further clarify this dependence of the TMR ratio on T_a, we investigated *I* vs. *V*, d*I*/d*V* (= *G*) vs. *V* and d^2I/dV^2 vs. *V* characteristics. (The bias voltage, *V* was defined with respect to the lower CCFA electrode).

❖In general, the slopes of the G_{AP} and G_P were distinctly lower for MTJs with T_a of 500°C than those for MTJs with T_a of RT.
❖Precisely, the lower slope G_{AP} was observed for both $V > 0$ and $V < 0$, and the lower G_P for $V > 0$ in the region from $|V|$ = 0 to ~0.4 V.

☺These results indicate that the electronic density of states around the Fermi level for minority spins in the interfacial regions of both the lower CCFA and the upper CoFe, both facing the MgO barrier, decreased with increasing T_a from RT to 500°C.
☺These led to increased spin polarization of both the CCFA and the CoFe in the interfacial region.
☺These findings are consistent with the increased TMR ratios observed for MTJs with T_a of 500°C.

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