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Tunnel magnetoresistance effect in double magnetic tunnel junctions using half-metallic Heusler alloy electrodes

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Double magnetic tunnel junctions (DMTJs) using half-metallic Co_2MnSi Heusler alloy electrodes were fabricated. Their tunnel magnetoresistance (TMR) effects were then investigated. Large TMR ratios were observed as 25% at room temperature and as 320% at 6 K. The bias voltage dependence of tunnel conductance suggests a half-metallic nature of the Co_2MnSi electrode. These results show that high-quality DMTJ with half-metallic Heusler alloy electrodes was fabricated and that the DMTJ exhibited the expected performance. © *2009 American Institute of Physics*.

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I. INTRODUCTION

Half-metallic ferromagnets (HMFs), which have full spin polarization, have attracted great interest because they are expected to improve the performance of spin electronics devices such as magnetic random-access memory and magnetic sensors considerably. Some Co-based full-Heusler alloys ($Co_2MnAlSi$, Co_2FeSi, Co_2MnSn, etc.) are most promising as HMFs because they are expected to have both a half-metallic band structure and high Curie temperature.[1–3] Recently, we fabricated a magnetic tunnel junction (MTJ) with epitaxially grown Co_2MnSi (CMS) Heusler alloy electrodes and an Al-oxide tunnel barrier. This MTJ exhibited a large tunnel magnetoresistance (TMR) ratio of 570% at 2 K.[4] We found that tunneling conductance increased sharply with increasing bias voltage in the tunneling conductance (dI/dV)–bias voltage (V) curves for this MTJ. This result suggests the half-metallic energy gap of CMS.[5]

The double MTJs (DMTJs) are the basic structure of some spin transistors.[6,7] HMFs, used as a spin-injected layer, are key materials to develop spin transistors. We are trying to develop an innovative spin transistor using DMTJ with half-metallic electrodes. For this study, we fabricated high-quality DMTJs with CMS Heusler alloy electrodes and investigated their TMR effects.

II. EXPERIMENTAL METHODS

Single-barrier MTJs with a stacking structure of MgO substrate/Cr(40)/CMS(30)/Al–O(1.3)/CMS(10)/Ta(5) were deposited using magnetron sputtering. Each layer's thickness is shown in nanometers in parentheses. The Al–O barrier layer was formed by inductively coupled plasma oxidation of the metallic Al layer. The prepared MTJs were annealed at 250 °C for 1 h under vacuum with a 350 Oe magnetic field.

The stacked single-barrier MTJs were microfabricated into DMTJs using electron-beam lithography and Ar-ion milling using metallic Ti nanowire as a hard mask stencil. Details of the fabrication process for the DMTJs were reported previously.[8] The junction area of each MTJ is between 50×100 and $500\times 1000\ \text{nm}^2$. Figure 1 presents a schematic illustration of the fabricated DMTJ: electrons flow from the source to the drain through the nanowire. The TMR effects and G-V curves in the fabricated DMTJs were measured using standard ac lock-in techniques with modulation of $1-5\ \text{mV}_{\text{rms}}$ at room temperature (RT) and 6 K.

III. RESULTS AND DISCUSSION

Figure 2 shows a scanning electron microscopy (SEM) image of the fabricated DMTJ with junction area of $100\times 500\ \text{nm}^2$. The 100-nm-wide Ti narrow wire was confirmed to connect the two MTJs. The distance between two MTJs is about 1 μm. A gate electrode was also prepared to allow the device to work as a spin transistor. Figures 3(a) and 3(b) show typical TMR curves of the DMTJ measured at RT and 6 K, respectively. The difference of switching field of the top and bottom electrodes is due to large shape anisotropy of top electrodes. Coercivity of top electrodes in each MTJ was also different because the edge shapes of two MTJs are slightly different. The TMR ratios were 25% at RT and 320% at 6 K. The large increase in TMR ratio with decreasing temperature is so far normal for MTJs with CMS electrodes.[4] But the TMR ratio is slightly smaller than that of the single barrier MTJ reported previously[4] because of damage incurred during microfabrication processes. The resistance-area ($R\times A$) product of the DMTJ was twice as large as the single barrier MTJ at each junction area, which shows that the DMTJ size can be controlled with high accuracy using our microfabri-

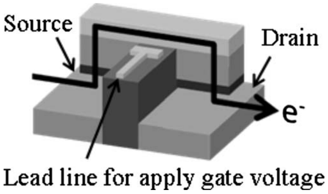

FIG. 1. Schematic illustration of a fabricated DMTJ.

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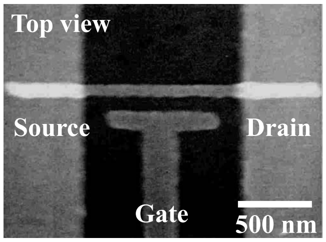

FIG. 2. SEM image of a fabricated DMTJ.

cation process. In addition, almost all TMR curves for the DMTJs exhibited multiple resistance drops, as shown in Fig. 3, because switching fields of the hard magnetic layer differed slightly between the two tunnel junctions.

The source-drain voltage (V_{DS}) dependence of the tunneling conductance (dI/dV) for the fabricated DMTJ is shown in Fig. 4. Bold and thin lines represent curves measured at parallel and antiparallel magnetic configurations, respectively. A positive V_{DS} is defined here as the case in which electron tunneling occurs from the source to the drain. The dI/dV-V_{DS} curve shows that tunneling conductance increased sharply with increasing bias of less than 300 mV, especially for the antiparallel magnetic configuration. The dI/dV-V_{DS} curve shape for the DMTJ resembles that of a single barrier MTJ with the CMS electrode reported previously.[5] This peculiar shape of dI/dV-V_{DS} curve is inferred to reflect the half-metallic band structure of CMS. This result demonstrates that a high-quality DMTJ with a half-metallic CMS electrode was fabricated and that the DMTJ exhibited the expected performance. Finally, we investigate the drain current (I_D)-V_{DS} characteristics in the DMTJ, applying the gate voltage. However, we observed no change in I_D-V_{DS} characteristic against the gate voltage because of the leak current from the gate electrode. Therefore, improvement of the gate electrode structure is necessary to develop a spin transistor using a DMTJ with half-metallic Heusler alloy electrodes.

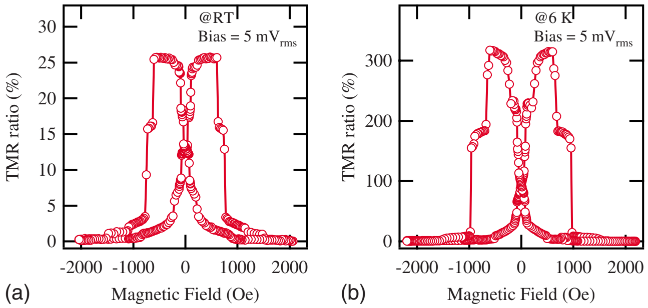

FIG. 3. (Color online) TMR curves for the DMTJ at (a) RT and (b) 6 K.

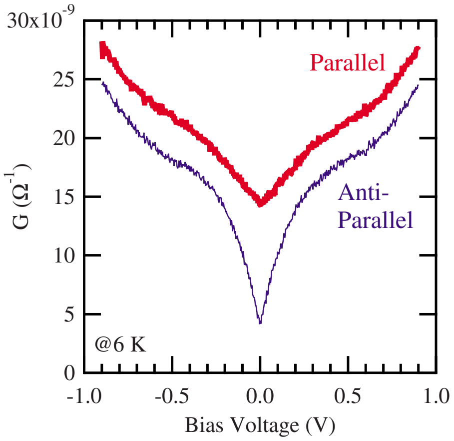

FIG. 4. (Color online) Source-drain voltage dependence of tunnel conductance for the DMTJ. Bold and thin lines are parallel and antiparallel alignments of magnetization, respectively.

IV. SUMMARY

We fabricated DMTJs with a gate electrode using half-metallic Co_2MnSi Heusler alloy electrodes. The DMTJ showed large TMR ratios of 25% at RT and 320% at 6 K. Moreover, the half-metallic electronic band structure of Co_2MnSi was observed in the bias voltage dependence of tunnel conductance. These results demonstrate the fabrication of high-quality DMTJs.

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