Increase of tunneling magnetoresistance in trilayer structures composed of group-IV ferromagnetic semiconductor Ge$_{1-x}$Fe$_x$, MgO, and Fe

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Group-IV ferromagnetic semiconductor (FMS) Ge$_{1-x}$Fe$_x$ (GeFe) is a promising material for spin injectors and spin detectors for Si and Ge [1-3]. GeFe can be epitaxially grown on Si and Ge substrates by low temperature molecular beam epitaxy (LT-MBE) and its conductivity can be controlled from metallic to insulating by boron (B) doping [4]. Recently, tunneling magnetoresistance (TMR) has been observed in Fe/MgO/Ge$_{0.935}$Fe$_{0.065}$ magnetic tunnel junctions (MTJs) for the first time in MTJs with group-IV FMS, confirming the presence of spin-polarized carriers at the Fermi level in GeFe [5]. However, the TMR ratio reported in Ref. [5] was only 0.27%. Thus, it is necessary to improve TMR in Fe/MgO/GeFe. Here, we show that the TMR ratio is increased up to 1.5% by decreasing the size of the mesa diodes and by increasing the Fe concentration $x$ of Ge$_{1-x}$Fe$_x$.

We have grown Fe / MgO (3 nm)/ Ge$_{1-x}$Fe$_x$ ($x = 6.5\%$, 10.5\%, 14\%, 17.5\%) / Ge:B (B: $4 \times 10^{19}$ cm$^{-3}$) on p$^+$ Ge (001) substrates by MBE. When $x \geq 10.5\%$, although the reflection high energy electron diffraction (RHEED) pattern of the MgO layer became broader with increasing $x$, the RHEED patterns of other layers were streaky. The observed RHEED patterns indicated that the MgO and Fe layers were epitaxially grown on Ge$_{1-x}$Fe$_x$ with the epitaxial relationship of Fe[100][001] // MgO[110][001] // Ge$_{1-x}$Fe$_x$(100)[001] [2].

After the growth, an Al layer was deposited on the samples as a top electrode. We patterned mesa diodes with a diameter of 15, 60, and 150 $\mu$m using photolithography and Ar-ion etching. SiO$_2$ was deposited for passivation. Figure 1 shows the TMR curves observed in the tunnel junction with $x = 10.5\%$. The jumps of the resistance at $\mu_0H = \pm 0.024$ T correspond to the inversion of the magnetization direction of the Fe layer. Figure 2 shows the $x$ dependence of the TMR ratio. Compared with Ref. [5], the TMR ratio was increased by changing the shape and size of the mesa diodes from a square with the size of 700×700 $\mu$m$^2$ to the circle with $\varphi = 60$ $\mu$m when $x = 6.5\%$. The TMR ratio became maximum at $x = 10.5\%$, which is probably due to the enhancement of the ferromagnetic ordering in GeFe. The decrease in the TMR ratio at higher $x$ can be attributed to the degradation of the crystallinity of the MgO layer by the increase in $x$.

This work was partly supported by Giants-in-Aid for Scientific Research including Specially Promoted Research, Project for Developing Innovation Systems of MEXT, and Spintronics Research Network of Japan (Spin-RNJ).

References

Fig. 1 TMR curves observed in the tunnel junction with $x = 10.5\%$ when the bias voltage was 50 mV. The blue and green curves express the major loops. The red curve is the minor loop.

Fig. 2 Fe content ($x$ in Ge$_{1-x}$Fe$_x$) dependence of the TMR ratio. The red point corresponds to the TMR ratio reported in Ref. [5].