Observation 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 one of the most promising materials for efficient spin injectors and detectors for Si and Ge because it can be grown epitaxially on Si and Ge substrates by low-temperature molecular-beam epitaxy (LT-MBE), and its conductivity can be widely controlled by B doping [1-4]. For these applications, it is particularly important to prove the presence of spin-polarized carriers in GeFe. In this study, we have successfully observed tunneling magnetoresistance (TMR) in epitaxially grown Fe/MgO/GeFe. This is the first observation of TMR using group-IV FMS.

We grew Fe/MgO/$Ge_{0.935}Fe_{0.065}$/Ge:B (B: 4×10^{19} cm^{-3}) on a p^+Ge (001) substrate by MBE. The thickness (d) of the MgO barrier was changed from 3 nm to 9 nm by moving the main shutter in front of the sample surface during the growth. Single-crystal diffraction patterns were observed by reflection high energy electron diffraction during the growth of all the layers. Figure 1 shows the transmission electron microscopy (TEM) lattice image of the trilayer structure. The MgO and Fe layers are epitaxially grown on $Ge_{1-x}Fe_x$ (x = 6.5%).

After the growth, an Al film was deposited as an electrode, and square-shaped mesa diodes were fabricated by photolithograpy and Ar-ion etching. Figure 2 shows the d dependence of the resistance-area product (RA). The RA increases exponentially with d. This indicates that the MgO layer works as a tunnel barrier. The barrier height at 3.5 K is estimated to be 35 meV using the Wentzel–Kramers–Brillouin (WKB) approximation. For this estimation, we assumed the electron rest mass in the MgO layer. Figure 3 shows the TMR curves observed in the tunnel junction with d = 3 nm. Jumps of the resistance at ±7 mT in the major loops (red and blue curves) correspond to the change of the magnetization direction of the Fe layer. In the minor loop (green curve), the anti-paralleled magnetization configuration is stable at H = 0. This is a typical feature of TMR.

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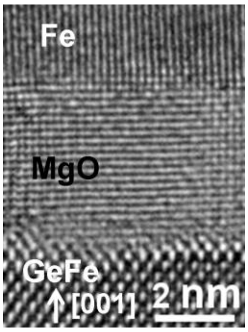

Fig. 1 TEM lattice image of the sample projected along the Ge[110] axis.

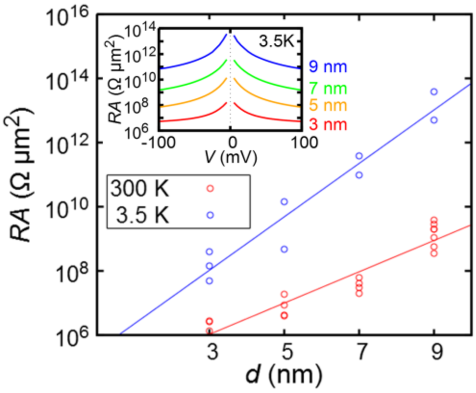

Fig. 2 MgO thickness (d) dependence of RA at 3 mV for 300 K and 5 mV for 3.5 K. The inset shows the RA of the junctions versus bias voltage (V) at 3.5 K.

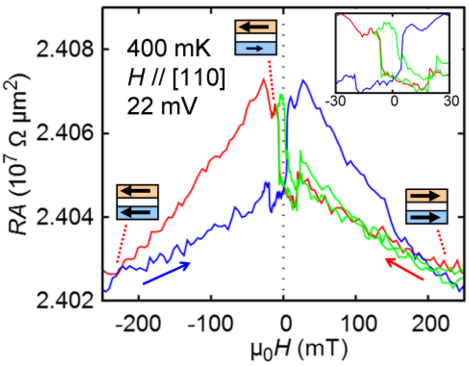

Fig. 3 TMR curves observed in the tunnel junction with d = 3 nm. The bias voltage is 22 mV. The red and blue curves are major loops. The green curve is the minor loop.

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