Observation of the quantum size effect in Fe quantum wells detected by holes injected from a p-type Ge semiconductor electrode

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Double-barrier magnetic tunnel junctions (DBMTJs) with a ferromagnetic quantum well (QW) are promising for future quantum spintronics devices. The quantized energy levels in ferromagnetic QWs are half metallic and thus are expected to increase tunnel magnetoresistance (TMR) [1]. In the DBMTJs, the TMR ratio can be modulated by a bias voltage, which will bring new functionalities to spintronic devices. Until now, in the studies on the double-barrier metal-based MTJs, metal layers have been used for carrier injection [2 – 6]. However, neither negative differential resistance nor TMR enhancement have been reported for DBMTJs. Here, we use a semiconductor (SC) electrode to inject carriers to Fe QWs. SCs have a small Fermi surface and the carriers have small in-plane wave vectors compared with metals. Thus, each subband in the Fe QW will be detected separately when injecting carriers from SCs, which will enhance resonant tunneling and improve the spin-polarization of the tunneling current in the Fe QWs.

In this study, we grew DBMTJs composed of Co (20 nm)/ Fe (20 nm)/ MgO (3 nm)/ Fe QW (d nm)/ MgO (2 nm)/ Ge:B (85 nm) on a p^+-Ge(001) substrate using molecular beam epitaxy. The thickness d of the Fe QW layer is varied from 4.1 to 8.1 nm, and the boron doping concentration in Ge:B is 4×10^{19} cm^{-3}. Figure 1 shows the TMR curves measured for the DBMTJ with d = 5.8 nm at 297 K and at 3.5 K at a bias voltage V = -10 mV, where holes are injected from the Ge:B layer into the Fe QW and with a magnetic field H along the [100] direction in the film plane. The TMR ratio was 151 % at 297 K and 279 % at 3.5 K. A high TMR ratio was obtained when holes were injected from the Ge:B layer to the DBMTJ. Figure 2 shows the $d^2I/dV^2 - V$ curves of the DBMTJs with various d. We observed oscillations in the $d^2I/dV^2 - V$ curves. One can see that dips or peaks are continuously shifted with d (see the same color arrows, which are assigned to the same resonant level). Using the phase accumulation model, the dip positions are well reproduced by the resonant levels in the Fe QW detected by holes in the Ge:B layer. We have successfully observed the quantum size effect using holes injected from the p^+-Ge layer into the Fe QWs for the first time. This work was partly supported by Giants-in-Aid for Scientific Research and Spintronics Research Network of Japan .

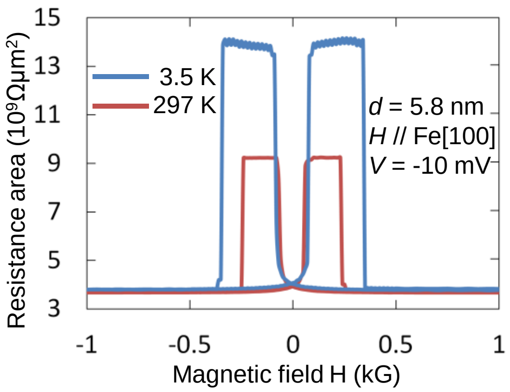

Fig. 1 TMR curves of the DBMTJ with d=5.8 nm when the bias voltage V is -10 mV, where holes are injected from the p^+-Ge substrate into the Fe QW. The red line represents the data at 279 K and the blue line at 3.5 K.

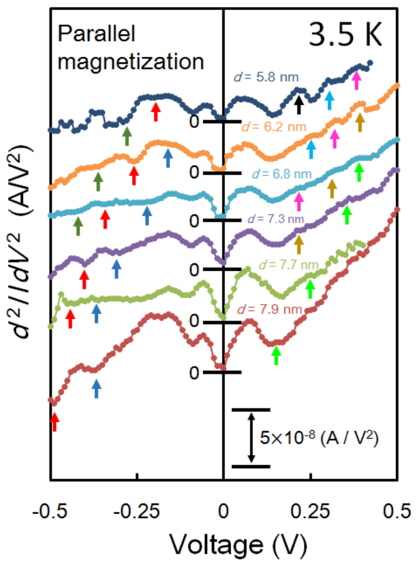

Fig. 2 $d^2I/dV^2 - V$ curves of DBMTJs with various d. The oscillations are observed both at positive and negative bias voltages.

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