

Resonant tunneling effect and tunneling magnetoresistance in GaMnAs quantum-well double-barrier heterostructures

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We have investigated the d^2I/dV^2 - V characteristics and tunneling magnetoresistance (TMR) in the GaMnAs quantum-well (QW) double-barrier heterostructures, and compared them with those of the GaMnAs-based single-barrier heterostructure. We obtained a relatively high TMR ratio of 126.5% in the single-barrier heterostructure at 2.6 K. The value of d^2I/dV^2 and the TMR ratio of this single-barrier heterostructure monotonically approached zero with increasing the bias voltage. On the other hand, in the double-barrier structures, oscillatory behaviors were seen in the negative bias region of d^2I/dV^2 - V curves. With increasing the QW width, these peaks shifted to a smaller voltage and the period of the oscillation became short. This means that these oscillatory behaviors are induced by the resonant tunneling effect mediated by holes tunneling through the GaMnAs QW. Also, we observed that TMR is increased at these resonant peak bias voltages in the double-barrier heterostructures.

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1 Introduction Ferromagnetic-semiconductor heterostructures containing GaMnAs are hopeful candidates for future spintronic devices. Large tunneling magnetoresistance (TMR) of 75% (8.0 K) and 290% (0.39 K) were observed in the GaMnAs-based single-barrier heterostructures [1, 2]. Also, the GaMnAs-based quantum heterostructures are expected to realize new functions by combining TMR and the quantum-size effect (resonant tunneling effect). For example, large enhancements of TMR up to ~800% [3] and to more than ~10⁶% [4] are expected to be obtained in GaMnAs-based resonant tunneling diode (RTD) structures. In magneto-optical measurements of the GaMnAs quantum well (QW) heterostructures, blue shifts of the magneto-optical spectra have been observed, suggesting the existence of the quantum-size effect in GaMnAs [5, 6]. However, there are no reports on the clear observation of the resonant tunneling effect in ferromagnetic-semiconductor quantum heterostructures [4, 7, 8]. We investigated the d^2I/dV^2 - V characteristics and TMR in the GaMnAs-QW double-barrier heterostructures with various QW thicknesses, and compared them with those of the GaMnAs-based single-barrier heterostructure. We clearly observed the resonant tunneling effect and the TMR increase induced by it in the GaMnAs-QW double-barrier heterostructures. In this paper, we present these experimental results.

2 Growth and measuring methods The GaMnAs-QW double-barrier heterostructures investigated here are composed of Ga_{0.95}Mn_{0.05}As(20 nm)/ GaAs(1 nm)/ Al_{0.5}Ga_{0.5}As(4 nm)/ GaAs(1 nm)/ Ga_{0.95}Mn_{0.05}As QW (d nm)/ GaAs (1 nm)/ AlAs (4 nm)/ GaAs:Be(Be: 1×10^{18} cm⁻³) with various d from 3.8 to 20 nm. These heterostructures were grown on p -GaAs(001) substrates by molecular-beam epitaxy (MBE). The 1-nm-thick spacer layers were inserted in order to prevent the Mn diffusion into the barrier

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layers and to smooth the surface. The GaAs:Be, AlAs, and the lowest GaAs spacer layers were grown at high temperatures of 600, 550, and 600 °C, respectively. The GaMnAs layers were grown at low temperature of 225 °C, and the GaAs/ AlGaAs/ GaAs barrier layers were grown at 205 °C. In these structures, TMR occurs by tunneling of holes between the ferromagnetic GaMnAs top electrode and the ferromagnetic GaMnAs QW. Also, we grew a single-barrier heterostructure composed of Ga_{0.95}Mn_{0.05}As(20 nm)/ GaAs(1 nm)/ AlAs(2 nm)/ GaAs(1 nm)/ Ga_{0.95}Mn_{0.05}As (20 nm)/ GaAs:Be (100 nm)/ *p*-GaAs(001) as a reference sample. The growth conditions used for the growth of this single-barrier structure were the same as those used for the double-barrier structure. After the growth, circular mesa diodes with 200 μm in diameter were fabricated by chemical etching. We spin-coated an insulating negative resist on the sample, opened a contact hole with 180 μm in diameter on the top of the mesa, and fabricated a metal electrode by evaporating Au on this surface. In the following measurements, the bias polarity is defined by the voltage of the top GaMnAs electrode with respect to the substrate. The schematic band diagrams when positive and negative biases are applied to the double-barrier structure are shown in Figs. 1(a) and (b), respectively. The following tunneling transport measurements were carried out in a cryostat cooled at 2.6 K with a conventional two-terminal direct-current (DC) method. dI/dV - V and d^2I/dV^2 - V characteristics were derived mathematically from the data of the I - V characteristics measured at every 5 mV. The results of the bias dependence of TMR were obtained mathematically from the data of I - V characteristics measured in parallel and antiparallel magnetizations. I - V characteristics in both parallel and antiparallel magnetizations were obtained at zero-magnetic field.

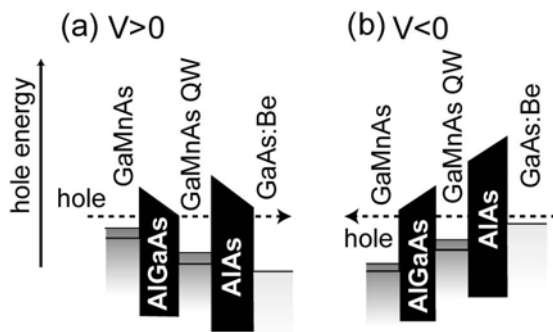


Fig. 1 Schematic band diagrams of the GaMnAs-QW double-barrier heterostructure when the bias polarity is (a) positive and (b) negative. Here, the 1-nm-thick GaAs spacer layers are omitted for simplicity.

3 Results Figures 2 shows (a) dI/dV - V , (b) d^2I/dV^2 - V characteristics and (c) bias dependence of TMR observed in the GaMnAs/ AlAs/ GaMnAs single-barrier heterostructure (reference sample) at 2.6 K. In (a), solid and dotted curves correspond to the data in parallel and antiparallel magnetizations, respectively. The values of dI/dV and d^2I/dV^2 monotonically change with increasing the bias voltage $|V|$ except for those near zero bias. The sharp features near zero bias correspond to the zero-bias anomaly which is usually observed in GaMnAs-based heterostructures [9]. These results of the monotonical changes in dI/dV and d^2I/dV^2 are different from those observed in metal-based magnetic tunnel junctions, where inelastic scattering peaks of magnons and phonons have been usually observed [10, 11]. The inset of (c) shows the magnetic field dependence of the tunnel resistance at 2.6 K observed in this sample with a magnetic field applied in plane along the [100] direction and with a bias voltage of 1 mV. We can see a typical TMR curve with a relatively high TMR ratio of 126.5%. Here, TMR is defined as $(R_{AP}-R_P)/R_P$, where R_P and R_{AP} are the tunnel resistances ($=V/I$) for parallel and antiparallel magnetization, respectively. We can see that the TMR value rapidly decreases with increasing the bias voltage. The bias voltage V_{half} , at which the TMR ratio is reduced by half, was 14 mV in this sample.

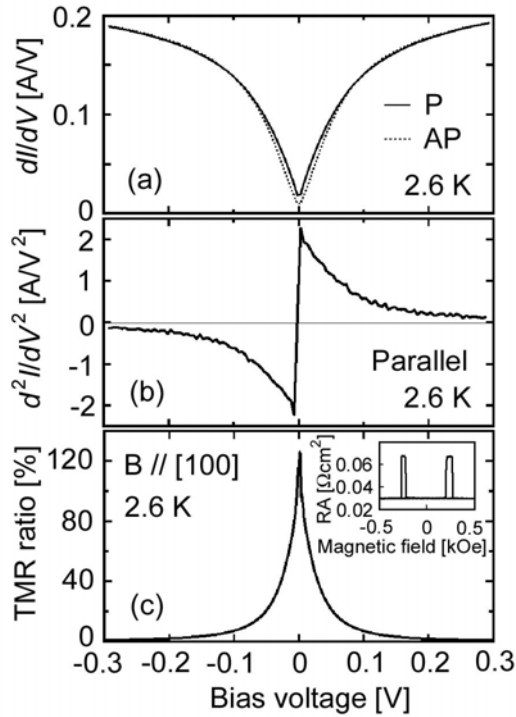


Fig. 2 (a) dI/dV - V and (b) d^2I/dV^2 - V characteristics of the GaMnAs/ AlAs/ GaMnAs single-barrier heterostructure (reference sample) at 2.6 K. In (a), the solid and dotted curves correspond to the parallel and antiparallel magnetizations, respectively. (c) Bias dependence of TMR of this sample at 2.6 K, when the magnetic field was applied in plane along the [100] axis. The inset shows the magnetic field dependence of the resistance-area product (RA) observed in the GaMnAs single-barrier heterostructure at 2.6 K with a bias voltage of 1 mV. Typical TMR curve with a relatively high TMR ratio of 126.5% was obtained.

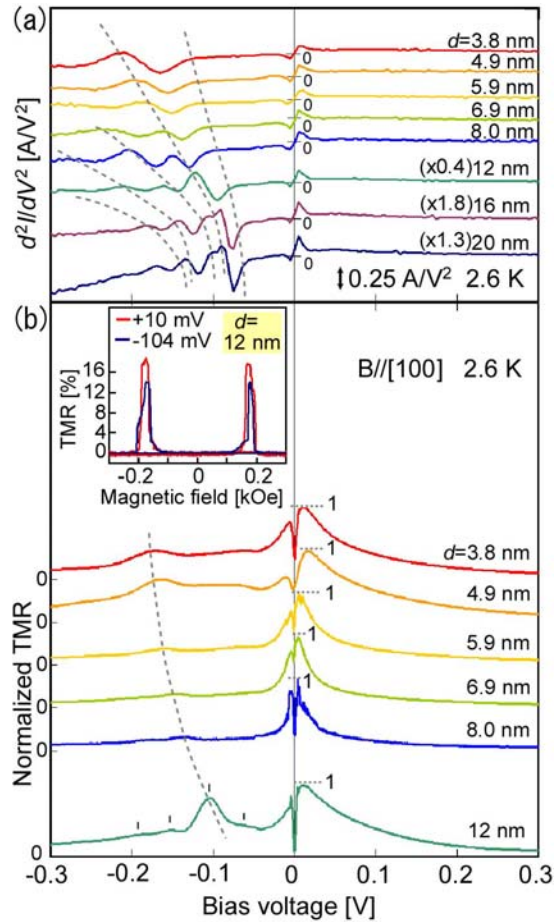


Fig. 3 (a) d^2I/dV^2 - V characteristics of GaMnAs-QW double-barrier heterostructures with various QW thicknesses d in parallel magnetization at 2.6 K. Numbers in the parentheses express the magnification ratio for the vertical axis. (b) Bias dependence of TMR of these junctions at 2.6 K, where the TMR ratios are normalized by the maximum value of TMR in each curve. The inset is the magnetic-field dependence of the tunnel resistance obtained in the junction with $d = 12$ nm when a magnetic field was applied in plane along the [100] direction at 2.6 K with the bias voltages of +10 mV (red curve) and -104 mV (blue curve).

Figure 3(a) shows the d^2I/dV^2 - V characteristics of the GaMnAs-QW double-barrier heterostructures with various d at 2.6 K in parallel magnetization. As well as the single-barrier structure, the zero-bias anomaly is seen near zero bias in all the curves. The most different features are the oscillatory behaviors observed in the negative bias region of all the curves. With increasing d , these peaks shift to the smaller voltage and the period of the oscillation becomes short. This means that these oscillatory behaviors are induced by the resonant tunneling effect mediated by holes tunneling through the GaMnAs QW. Figure

3(b) shows the bias dependence of TMR with a magnetic field applied in plane along the [100] direction. The inset shows the TMR curves observed at 2.6 K in the double-barrier heterostructure with $d = 12$ nm when the bias voltage is +10 mV (red curve) and -104 mV (blue curve), where the TMR ratios are 18.9% and 14.1%, respectively. In contrast to the single-barrier heterostructure, even when the voltage of -104 mV is applied, more than a half of the TMR value obtained at 10 mV is maintained. In the main graph of Fig. 3(b), TMR oscillations can be seen in the negative bias region of all the curves. With increasing d , the TMR peaks shift to a smaller voltage as is the case of the d^2I/dV^2 - V characteristics shown in Fig. 3(a), indicating that these TMR increases are induced by the resonant tunneling effect. Also, Fig. 3(b) indicates that V_{half} can be increased by the resonant tunneling effect. In the negative-bias region of $d = 12$ nm, $|V_{\text{half}}|$ was increased to 124 mV due to the TMR increase at -104 mV, whereas V_{half} in the positive bias was 76 mV. This value is much higher than that obtained in the single-barrier structure mentioned above, and also higher than those reported in GaMnAs-based single-barrier heterostructures which are usually around 50 mV [2, 12, 13]. This result indicates the possibility of controlling the TMR ratio and V_{half} by using the resonant tunneling effect in ferromagnetic-semiconductor quantum heterostructures.

4 Summary We investigated the d^2I/dV^2 - V characteristics and the TMR behaviors in the GaMnAs-QW double-barrier heterostructures, and compared them with those of the GaMnAs-based single-barrier heterostructure. We obtained a relatively high TMR ratio of 126.5% in the GaMnAs single-barrier heterostructure at 2.6 K. The value of the d^2I/dV^2 and the TMR ratio monotonically approached zero with increasing the bias voltage in this single-barrier structure. On the other hand, oscillatory behaviors were observed in the negative bias region of the d^2I/dV^2 - V curves in the double-barrier heterostructures. With increasing d , these peaks shift to smaller voltages and the period of the oscillation becomes short. This means that these oscillatory behaviors are induced by the resonant tunneling effect mediated by holes tunneling through the GaMnAs QW. Also, the TMR increases were observed at these resonant peak bias voltages in the double-barrier heterostructures. These TMR increases induced the enhancement of V_{half} , indicating the possibility that we can control the TMR ratio and V_{half} by using the resonant tunneling effect in ferromagnetic-semiconductor quantum heterostructures.

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