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Spin-dependent Resonant Tunneling in III-V-based Ferromagnetic-Semiconductor Quantum Heterostructures

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1. Introduction

Ferromagnetic - semiconductor quantum heterostructures are good model systems for future quantum devices with spin degrees of freedom. Especially, fully epitaxial GaMnAs-based quantum heterostructures are a material system ideal for investigating the spin-dependent resonant tunneling effect. Here, successful detection of the spin-dependent resonant tunneling effect in GaMnAs double-barrier quantum-well (QW) heterostructures is reviewed. From quantitative analyses of the quantum levels formed in the GaMnAs QWs, some new insights into the band structure in the vicinity of the Fermi level of GaMnAs were derived. In this presentation, current understanding of these results is also discussed.

2. Experimental results[1]

The resonant tunneling diode (RTD) junctions used in the experiments are composed of GaMnAs (20 nm) / GaAs (1 nm)/ AlGaAs (4 nm) / GaAs (1 nm)/ GaMnAs (d = 3.8 - 20 nm) / GaAs (1 nm)/ AlAs (4 nm) / GaAs:Be on p+GaAs(001) substrates, which were grown by low-temperature molecular-beam epitaxy (LT-MBE). The schematic device structure is shown in Fig. 1.

Figure 2(a) shows d^2I/dV^2-V characteristics of these junctions in parallel magnetization at 2.6 K. Oscillations whose peak voltages depend on d were observed in the negative bias region of all the curves. With increasing d, these peaks shift to smaller voltages and the period of the oscillation becomes short. Such oscillatory behavior has not been observed in GaMnAs-based single-barrier magnetic tunnel junctions, indicating that these oscillations are induced by resonant tunneling effect. The peaks HHn and LHn (n=1, 2, 3 ···) are assigned to resonant tunneling through the nth level of the heavy hole (HH) band and light hole (LH) band in the GaMnAs QW, respectively, as will be described later. Figure 2(b) shows the bias dependence of the TMR ratio of these junctions at 2.6 K with a magnetic field applied in plane along the [100] direction, where the TMR ratios are normalized by the maximum value of TMR in each curve shown in the parenthesis. TMR oscillations can be seen in the negative bias region of all the curves. With increasing d, the TMR peaks (except for that near zero bias) shift to smaller voltages as is the case of the d^2I/dV^2-V characteristics shown in Fig. 2(a), which indicates that these TMR increases are induced by the resonant tunneling effect.

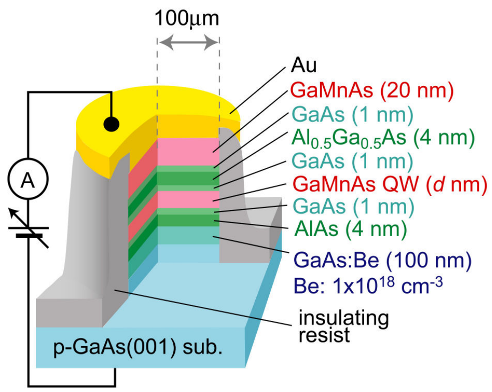

Fig. 1 Schematic device structure of the $Ga_{0.95}Mn_{0.05}As$(20 nm)/ GaAs(1 nm)/ $Al_{0.5}Ga_{0.5}As$(4 nm)/ GaAs(1 nm)/ $Ga_{0.95}Mn_{0.05}As$(d nm)/ GaAs(1 nm)/ AlAs(4 nm)/ GaAs:Be (100 nm) RTD junction examined in this study.

3. Discussion

The quantum levels of GaAs/ AlGaAs(4 nm)/ GaMnAs(d nm)/ AlAs(4 nm)/ GaAs were calculated by the transfer matrix method[2] with the 4×4 Luttinger-Kohn $k{\cdot}p$ Hamiltonian[3] and the p-d exchange Hamiltonian.[4] The valence band lineup assumed in this calculation is shown in Fig. 3(a). Figure 3 (b) shows the calculated result of the resonant-peak bias voltage at $k_{\parallel}$=0, where $k_{\parallel}$ is the wave vector parallel to the film plane. The calculated results are shown as small points (curves). Figure 3(b) also shows the experimental peak voltages assigned to HH and LH quantum levels observed in the d^2I/dV^2-V curves in parallel magnetization by solid rectangles and triangles, respectively. Here, the peak voltages are expressed in the absolute values. Although there is a little deviation between the experimental and calculated results, the experimental results are well fitted by the present model. This result means that the resonant tunneling effect in the GaMnAs QW is strongly associated with its valence band feature.

In these analyses, it is found that the Fermi level position should be assumed in the bandgap for explaining the obtained quantum levels in the GaMnAs QWs. This result contradicts the mean-field Zener model[4] commonly used for describing GaMnAs, where the Fermi level is assumed to exit in the valence band. Our result suggests that a more appropriate model may be needed for perfect understanding of the GaMnAs heterostructures.

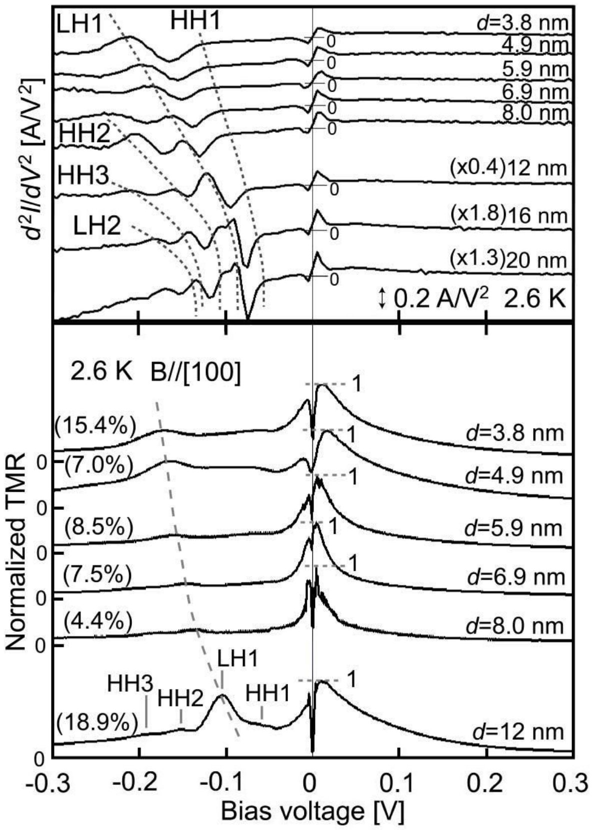

Fig. 2 (a) d^2I/dV^2-V characteristics of $Ga_{0.95}Mn_{0.05}As$(20 nm)/ GaAs(1 nm)/ $Al_{0.5}Ga_{0.5}As$(4 nm)/ GaAs(1 nm)/ $Ga_{0.95}Mn_{0.05}As$(d nm)/ GaAs(1 nm)/ AlAs(4 nm)/ GaAs:Be(100 nm) RTD junctions with various QW thicknesses d in parallel magnetization at 2.6 K. Numbers in the parentheses express the magnification ratio for the vertical axis. (b) Bias dependence of TMR with various QW thicknesses d when a magnetic field was applied in plane along the [100] direction at 2.6 K, where the TMR ratios are normalized by the maximum value of TMR in each curve shown in the parenthesis.

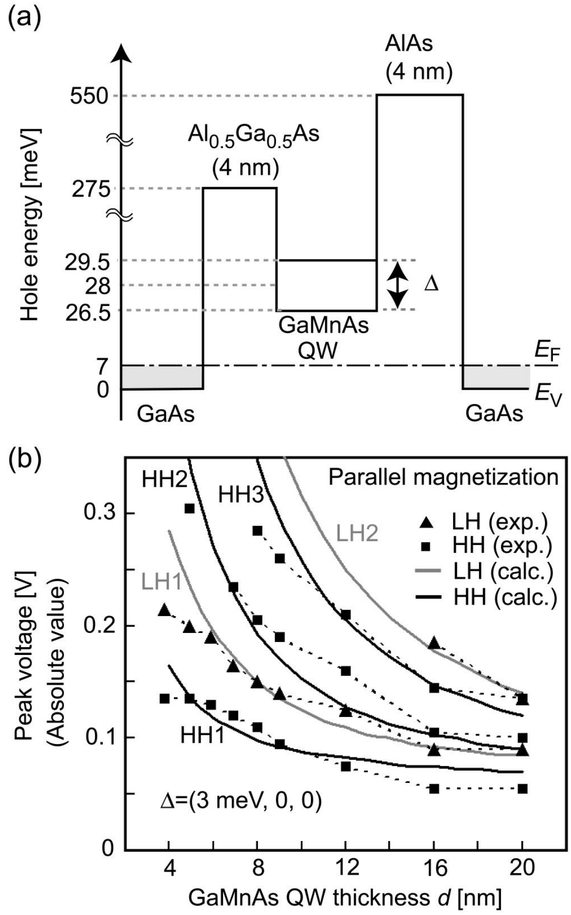

Fig. 3 (a) Valence-band structure assumed in our calculation of the quantum levels in GaAs/ $Al_{0.5}Ga_{0.5}As$(4 nm)/ GaMnAs(d nm)/ AlAs(4 nm)/ GaAs. E_F, E_V, and Δ mean the Fermi level, the valence band edge, and the spin-splitting energy of the light-hole band of the GaMnAs QW at the Γ point, respectively. (b) Calculated and experimentally obtained resonant peak voltage *vs.* the GaMnAs QW thickness d. The solid rectangles and triangles denote the experimentally obtained resonant-peak voltages assigned as HH and LH quantum levels in the d^2I/dV^2-V characteristics 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)/ $Ga_{0.95}Mn_{0.05}As$(d nm)/ GaAs(1 nm)/ AlAs(4 nm)/ GaAs:Be(100 nm) RTD junctions in parallel magnetization, respectively. Here, these voltages are expressed in the absolute values. The small points (curves) denote the calculated resonant voltages.

4. Conclusion

We have observed the resonant tunneling effect and TMR increase induced by it in GaMnAs-QW double-barrier heterostructures with the QW thickness from 3.8 to 20 nm, indicating highly coherent tunneling occurs in these heterostructures. The observed quantum levels of the GaMnAs QWs were successfully explained by the coherent tunneling model with the valence-band $k{\cdot}p$ model and the p-d exchange interaction. In these analyses, it is found that the Fermi level position should be assumed in the bandgap in the GaMnAs QWs, which contradicts the mean-field Zener model commonly used for describing GaMnAs, where the Fermi level is assumed to exit in the valence band. This result suggests that a more appropriate model might be needed for perfect understanding of the GaMnAs heterostructures.

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