Negative and Positive Magnetoresistance in Variable-Range Hopping Regime of Undoped Al$_x$In$_{1-x}$Sb/InSb Quantum Wells

S. Ishida[1], T. Manago[1], K. Oto[2], A. Fujimoto[3], H. Geka[4], A. Okamoto[4] and I. Shibasaki[4]

[1]Tokyo University of Science, Yamaguchi, Sanyo-Onoda, Yamaguchi 756-0884, Japan
[2]Department of Physics, Faculty of Science, Chiba University, Inage, Chiba 263-8522, Japan
[3]Applied Physics, Osaka Institute of Technology, 5-16-1,Asahi, Osaka 535-8585, Japan
[4]Asahi Kasei Corporation, Fuji, Shizuoka 416-8501, Japan

Abstract. Low-temperature magnetoresistance (MR) in the variable-range hopping (VRH) regime of undoped Al$_x$In$_{1-x}$Sb/InSb quantum wells was studied. The low-*T* resistance shows that the two dimensional (2D) Mott VRH crossovers to Efros-Shklovskii (ES) VRH due to the Coulomb interaction with lowering *T*. The anisotropic negative MR in weak magnetic fields was explained by the quantum interference in the VRH. The in-plane positive MR in higher fields found in ES VRH regime was attributed to the spin-Zeeman effect that suppresses the hops between singly occupied states in the presence of intra-state correlation. As for the orbital MR subtracted from perpendicular MR, in deeply insulating regime the negative MR saturates above a characteristic field followed by an exponential increase of the positive MR in agreement with the quantum interference and the subsequent shrinkage of wave functions with increasing field, while in barely insulating regime of the 2D metal-insulator (MI) transition a large negative MR inexplicable survives even in the extremely high magnetic-fields.

Quantum wells (QWs) of InSb confined byAl$_x$In$_{1-x}$Sb ($x = 0.1$) barriers have long received much attention for the study of magneto-quantum transport [1]. In such QWs, existing extrinsic electrons accumulated at the hetero-interface even in undoped samples exhibit extraordinarily small mobility, suggesting that the carriers fall into the strongly localized states of a band-tail.

In the insulating regime of the two-dimensional (2D) metal-insulator (MI) transition investigated until now in Si-MOSFETs [2] and Al$_x$Ga$_{1-x}$As/GaAs HEMTs [3], the variable-range hopping (VRH) resistance of the form $\rho = \rho_0 \exp(T_0/T)^{p}$ was found with a *T*-independent prefactor ρ_0, where $p = 1/3$ in the Mott VRH [4] and $p = 1/2$ in the Efros-Shklovskii (ES) VRH [5] in the appearance of Coulomb gap around the Fermi level. In the VRH, the quantum interference among alternative scattering paths in hops [6, 7] yields a weak-field negative magnetoresistance (MR) due to the orbital origin, while the spin-Zeeman effect in the presence of intra-state correlation results in a positive MR in higher fields [8]. In the present work, we study the magneto-transport properties of undoped $Al_xIn_{1-x}Sb$/InSb QWs (x = 0.1) in the 2D-VRH regime under the magnetic fields up to 12 T in both $B_\perp$ and $B_{//}$-configurations down to 0.4 K. The QW structures consisting of $Al_xIn_{1-x}Sb$ buffer/barrier (700 nm), InSb (L_w) and $Al_xIn_{1-x}Sb$ barrier (50 nm) layers (x = 0.1) with a cap layer of GaAs 6nm thick were grown on GaAs(100) substrates by MBE. The lattice mismatch between the QW and the barriers is 0.5%. The well widths are L_w = 30 and 70nm with the sheet carrier density of n_s = 3 and 5 × 10^{11} cm^{-2}, respectively. In the magnetic fields parallel to the 2D plane, we measured both cases of (B//I) and (B⊥I), confirming no anisotropy between these configurations.

The low-temperature resistance of our samples appears to follow the form $\rho = \rho_0 \exp(T_0/T)^p$ accompanied by the crossover from p = 1/3 in the Mott VRH to p = 1/2 in the ES VRH with lowering T, which is evidently shown in Fig. 1 where ρ in the unit of quantum resistance h/e^2 (25.9 kΩ) is plotted versus $T^{-1/3}$ in (a) and $T^{-1/2}$ in (b). The prefactor appears to be $\rho_0 = \rho_M \sim h/e^2$ in the Mott VRH, and $\rho_0 = \rho_{ES} \sim 2h/e^2$ in the ES VRH. The values of ρ_M and ρ_{ES} are about two times what are obtained on 2D electron systems (2DES) in Si-MOSFETs [2] and δ-doped $Al_xGa_{1-x}As$/GaAs hetero-structures [3]. The fits of $\rho(T)$ in Fig. 1 (a) to the Mott VRH law yield ξ from the Mott temperature $T_0 = T_M$ = $13.8/(\pi k_B g \xi^2)$ as well as $R_h = R_M = (1/3)\xi(T_0/T)$, where

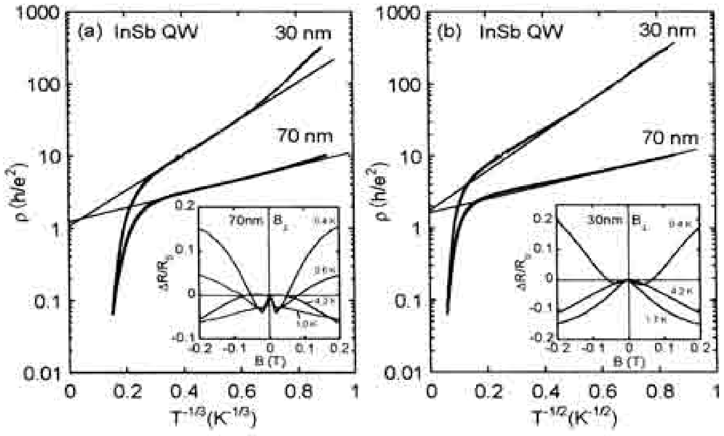

Fig. 1. Resistance plotted in the unit of h/e^2 versus $T^{-1/3}$ down to 1.4 K in (a) and $T^{-1/2}$ in (b). Insets: $\Delta\rho/\rho(0)$ depicted in low $B_\perp$- and low T- regions for L_w = 30 and 70nm in (a) and (b), respectively.

k_B is the Boltzmann constant, $g = m^*/(\pi\hbar^2)$ the 2D density of states, R_h the average hopping length and ξ the localization length: $\xi \sim$ 290 nm and $R_M \sim$ 130 nm at 4.2 K for L_w = 70nm. Also, the fits of ρ in Fig. 1 (b) to the ES VRH law yield $R_h = R_{ES} = (1/4)\xi(T_{ES}/T)$, $R_{ES} \sim$ 53 (92) nm at 4.2 (1.4) K with $\xi \sim$ 69 nm for L_w = 30nm (for L_w = 70 nm, $R_{ES} \sim$ 125 nm at 1.4 K).

The inset of Fig. 1 (a) and (b) depicts $\Delta\rho/\rho(0) = [\rho(B_\perp) - \rho(0)]/\rho(0)$ in $B_\perp$-configuration for L_w = 70 and 30nm, respectively. The low-field negative MR growing with lowering T arises from the quantum interference due to orbital origin in the VRH. Theories [6, 7] predict that the $B_\perp$-field suppresses destructive interference among the alternative scattering paths from initial to final state in a long-range hop leading to negative MR and its field dependence is determined by the flux $\Phi = B_\perp A$ penetrating an area A in which phase coherence is maintained. The area A is that of an ellipse of width $(R_h\xi)^{1/2}$ and length R_h. As a result, the negative MR grows with $B = B_\perp$ proportionally to B^2 in vanishing fields and linearly with B in moderate-field region, followed by the saturation around B_s when $\Phi = B_s A = h/e$ corresponding to the flux quantum. This implies that for moderate magnetic fields $-\Delta\rho/\rho(0) \quad BA = R_h^{3/2}(T, B)\xi^{1/2}(B)B$, and for vanishing fields $-\Delta\rho/\rho(0) \quad (BA)^2 = R_h^3(T, B)\xi(B)B^2$. Since $R_h = R_{ES} \quad T^{-1/2}$ in ES VRH, theory predicts that $-\Delta\rho/\rho(0) = f_1(T)B \quad T^{-3/4}B$ in moderately weak fields and $-\Delta\rho/\rho(0) = f_2(T)B^2 \quad T^{-3/2}B^2$ in extremely weak fields [10] assuming that R_h and ξ are nearly independent of B, which was confirmed from fits to the detailed data of $\Delta\rho/\rho(0)$ in ES VRH regime. Further, we also confirmed the relations $f_1(T) \quad T^{-1/2}$ and $f_2(T) \quad T^{-1}$ in Mott VRH regime, being consistent with $R_h = R_M \quad T^{-1/3}$ in this regime. In an ideal 2D system, there should be no negative MR in $B_{//}$-configuration [9]. Nevertheless, we observe it for $B_{//}$ [10] possibly because of a finite thickness of the accumulation layer and (or) a background concentration of shallow donors in the QW.

Regarding the positive MR in higher fields, we can observe it in both $B_\perp$ and $B_{//}$ for the ES VRH regime. Especially, $\rho_{xx}(B_{//})$ shows a large initial increase with B followed by saturation as shown in Fig. 2. Quite similar results were observed in the insulating δ-doped $Al_xGa_{1-x}As$/ GaAs hetero-structures [11, 12] and also Si MOSFETs [13, 14]. Kurobe and Kamimura [8] proposed that the alignment of electron spins due to the spin-Zeeman effect in the presence of intra-state correlation suppresses the hops between singly occupied states via the Pauli exclusion principle.

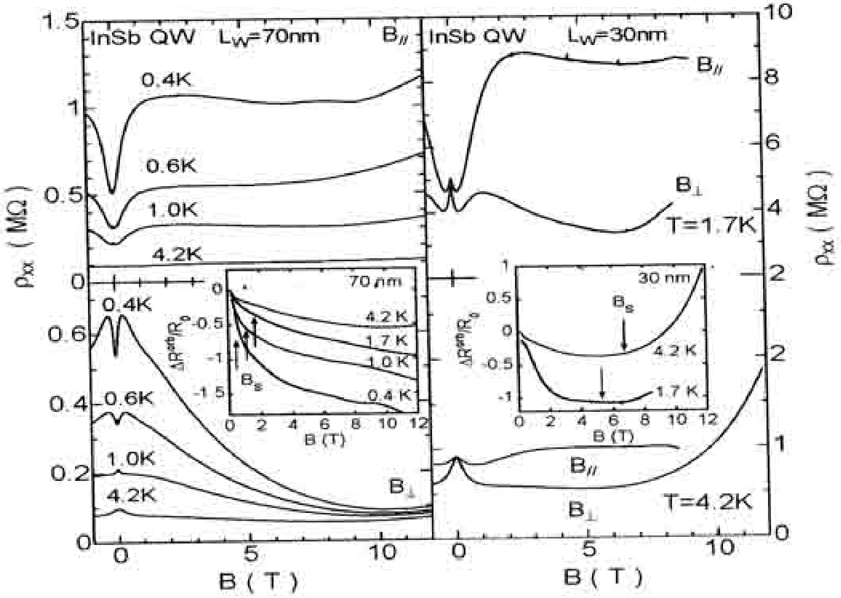

Fig. 2. $\rho_{xx}(B_{//})$ and $\rho_{xx}(B_\perp)$ in high-field region: left-hand panel for L_w = 70nm in low Ts down to 0.4 K and right-hand panel for L_w = 30 nm at 1.7 and 4.2K. Insets: $\Delta R^{orb}(B)/R(0)$ subtracted from $\rho_{xx}(B_\perp)$ for L_w = 70nm in left-hand panel and 30 nm in right-hand panel. The arrows in the insets indicate B_s estimated.

This mechanism yields a linear positive MR that saturates in high B-field when the spins are fully aligned ignoring the energy dependence of ξ, being consistent with the behavior seen in Fig. 2. On the other hand, $\rho_{xx}(B_\perp)$ in Fig. 2 exhibits an apparently complicated feature. Then, the orbital effect was subtracted from $\rho_{xx}(B_\perp) = \sigma_{xx}^{-1}(B_\perp)$ data for $B > 1$ T, simply assuming $\Delta R^{orb}(B)/R^2(0) = \Delta\sigma_{xx}^{orb}(B) = \sigma_{xx}(B_\perp) - \sigma_{xx}(B_{//})$. The results of orbital MR ratio $\Delta R^{orb}(B)/R(0)$ obtained are depicted in the insets of Fig. 2. In the deeply insulating regime (L_w = 30 nm) the negative MR saturates above B_s followed by an exponential increase of the positive MR in agreement with the quantum interference in weak fields and the subsequent shrinkage of wave functions with increasing B [10], while in barely insulating regime of the 2D-MI transition (L_w = 70 nm) a large negative MR inexplicably survives above B_s even in extremely high B-fields.

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