Extrinsic Electrons and Carrier Accumulation in $Al_xIn_{1-x}Sb$/InSb Quantum Wells: Well-Width Dependence

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Abstract. Hall coefficient (R_H) and magnetoresistance (MR) effects were studied at room temperature and 77 K for undoped quantum well (QW) structures of InSb sandwiched by $Al_{0.1}In_{0.9}Sb$ alloy grown by molecular beam epitaxy on GaAs substrates. As the result of two-carrier analyses of R_H, it was found that the sheet density of the extrinsic electrons at room temperature decreases with the increase of the well width above 100 nm. At 77 K the electrons extended in the QW show the negative longitudinal MR in magnetic fields parallel to the QW, which originates in specular boundary scattering in the classical orbits at the walls of barriers.

A quantum well (QW) structure of InSb with $Al_xIn_{1-x}Sb$ barriers has been considered to be an ideal system for electronic device applications such as magnetic sensors and high-speed transistors. In this QW structure, an $Al_xIn_{1-x}Sb$ barrier layer is often selectively δ-doped in order to supply the carriers to the QW [1]. This is not due to absence of extrinsic carriers but due to the small mobility of existing extrinsic electrons accumulated at the hetero-interface even when neither InSb nor the barrier region is intentionally doped. In the undoped InSb QW structures, two sources of extrinsic electrons are expected: deep donors in the barrier layers and shallow donors in InSb. The electrons falling into the QW from the deep donors will result in the band bending near the interface, producing the accumulation layer.

Classical size effects of magnetoresistance (MR) in semiconductors arising from the boundary scattering in the quasi-ballistic regime have been studied in the QWs [2], the ion-beam exposed channels of two-dimensional electron systems [3] and the quantum dots [4]. In the case of specular boundary scattering (SBS), negative MR appears, which originates in the suppression of the backward scattering of electrons by impurities under a magnetic fields because of the cyclotron motion. SBS requires that the length scale of roughness at the boundary is much smaller than the Fermi wavelength λ_F. Our InSb QW satisfies this condition.

In order to investigate the transport properties of the extrinsic electrons of InSb QWs, we have measured the Hall coefficient (R_H) and MR. InSb QWs were sandwiched by $Al_{0.1}In_{0.9}Sb$ alloys grown on GaAs(100) substrates by molecular beam epitaxy. The samples were capped by a 6 nm-thick GaAs layer [5]. The lattice mismatch between the QW and the barriers is 0.5 %. The Hall and MR measurements for the QWs with different well widths ($L_w = 15 \sim 300$ nm) were performed under the magnetic fields (B) up to 1.5 T at room temperature (RT) and 77 K. The sample parameters for various L_w at 77 K are given in Table 1.

At RT the carrier concentration for our InSb QWs is larger than the intrinsic one ($= 2.0 \times 10^{16}$ cm^{-3}) in bulk InSb indicating that there are extrinsic carriers. Moreover, the B-dependence of R_H for $L_w = 30$ nm as shown in the inset in Fig.1(a) indicates the two-carrier conduction, while for $L_w = 200$ nm R_H is almost independent of B at RT. As regards the two carriers, we assume that one is the electron with high mobility which is extended in the QW and the other is the accumulated one with low mobility at the hetero-interface. Although there is not much difference in the sheet resistance between InSb QWs and InSb films grown directly on GaAs, the electron mobility of InSb QWs in thin regions of less than 0.5 μm was significantly higher compared with InSb films on GaAs substrates [5]. These results indicate that there is a low-mobility layer at the hetero-interface. Fig.1(a) show the L_w-dependence of the sheet density of the extended electrons (n_w) and the accumulated ones (n_{ac}) estimated by the two-carrier analysis. It is found that n_w at RT increases and n_{ac} decreases gradually as L_w increases. We obtained the sheet density of extrinsic electrons ($n_{w(ex)}$) at RT estimated by subtracting the one of intrinsic electrons (n_i) from n_w as shown in the left hand of Fig.1(a). The decrease in $n_{w(ex)}$ at RT with the increase of L_w above 100 nm is quite anomalous. This is different from the increase behavior followed by the saturation of $n_{w(ex)}$ found in InAs QWs reported in our previous paper [2]. The difference between them is the depth of the QW. It is shallow for InSb QWs, whereas it is deep for InAs QWs. There is a possibility that more electrons in InSb QWs with increasing L_w return to deep donors and the band bending near the interface becomes smaller. Therefore, a crossover from two-carrier conduction to one-carrier one is considered to be observed as shown in the inset in Fig.1(a).

Table 1. Sample parameters for InSb QWs at 77 K, where R_s is the sheet resistance, μ_w (μ_{ac}) the mobility of the extended (accumulated) electrons and L_0 the mean free path.

L_w (nm)	R_s ($10^4\Omega$)	n_w (10^{11}cm^{-2})	n_{ac} (10^{11}cm^{-2})	μ_w (10^3cm^2/Vs)	μ_{ac} (cm^2/Vs)	λ_F (nm)	L_0 (nm)	B_s (T)	d_{eff} (nm)
15	14	1.9	1.0	0.23	5.0	87	1.7		
30	13	2.2	0.99	0.22	2.3	81	1.7		
70	2.9	3.1	1.8	0.70	1.2	68	6.4		
100	2.4	1.3	0.56	2.0	1.5	100	12	0.96	130
150	2.1	1.3	0.18	2.1	20	100	13	0.75	160
200	0.69	1.4	0.90	6.3	1.0	100	39	0.68	180
300	0.58	1.0	0.31	11	3.5	120	56	0.48	220

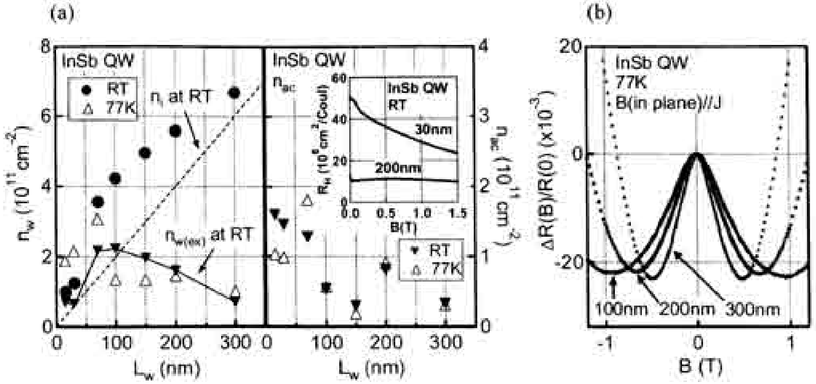

Fig. 1. (a) Left figure: L_w-dependence of the sheet density of the extended electrons (n_w) at RT and 77 K. Broken line represents the sheet density of intrinsic electrons (n_i) at RT. ▼ means the sheet density of extrinsic electrons ($n_{w(ex)}$) estimated by subtracting n_i from n_w. Right figure: L_w-dependence of the sheet density of the accumulated electrons (n_{ac}) at RT and 77 K. Inset: Normalized R_H by L_w for 30 nm and 200 nm at RT. (b) Longitudinal MR under in-plane magnetic fields at 77 K.

The perpendicular MR for InSb QWs at 77 K is positive one proportional to B^2 due to Lorentz force, whereas the longitudinal MR in the parallel fields always starts from the negative one as shown in Fig.1(b), reaching a minimum at the characteristic magnetic field (B_S) followed by the classical positive MR with B^2 dependence with increasing field. As the L_w is wider, the value of B_S shifts to lower fields, arising from SBS in the quasi-ballistic regime at the walls of barriers [3]. Saturation of the negative MR associated with SBS occurs at $B > B_S = 2m_e v_F / ed_{eff}$, where v_F is the electron Fermi velocity and d_{eff} the effective QW width. As for the QW with $L_w \geq 100$ nm, we derived d_{eff} from the cyclotron diameter at B_S and found that d_{eff} is almost equal to L_w as shown in Table 1. These results show that the SBS and the high-mobility electrons extended in the QW play important roles for the negative MR.

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