Shubnikov–de Haas and Hall oscillations in InAs-$Ga_{1-x}In_xSb$ superlattices

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(Received 26 February 1993)

We report a quantum transport investigation of n-type InAs-$Ga_{1-x}In_xSb$ superlattices. Our data display Shubnikov–de Haas oscillations in the diagonal conductivity accompanied by plateaulike inflections in the Hall conductivity. Correlation of the oscillation periods with carrier densities obtained from mixed-conduction analyses of the nonoscillating conductivity components implies that the electron effective mass is nearly isotropic. Because of the large miniband width (> 150 meV), one can rule out the conventional quantum Hall effect as the source of the structure in the Hall conductivity. It is instead attributed to a high density of localized states at the bottom of each Landau level, resulting from interface-roughness-induced potential fluctuations.

We have studied the quantum transport properties of a series of n-type InAs-$Ga_{1-x}In_xSb$ strain-layer superlattices. The Shubnikov–de Haas oscillations in the diagonal conductivity (σ_{xx}) are found to be accompanied by oscillatory features of comparable magnitude in the Hall conductivity (σ_{xy}).

InAs-$Ga_{1-x}In_xSb$ superlattices have recently received a great deal of attention because of their potential as long wave infrared (LWIR) detector materials.[1] It has been demonstrated that large absorption coefficients are obtained in the appropriate spectral region when the InAs well thickness (d_W) and the $Ga_{1-x}In_xSb$ barrier thickness (d_B) are on the order of those employed in the present work:[2–6] $d_W = 39$ Å and $d_B = 25$ Å. Both thicknesses are less than in most other superlattice systems to have received extensive study, particularly with regard to in-plane transport.

These small d_W and d_B have important consequences for the superlattice's electrical properties. First, because the InAs quantum wells are thin, we expect interface roughness scattering to be much more prominent than in most other heterostructure systems. The mobility for that mechanism scales approximately as $\mu_{\rm IRS} \propto d_W^6$,[7] although the relation can be modified somewhat due to nonparabolicity effects in narrow-gap superlattices.[8] A d_W^6 dependence has already been confirmed for InAs-AlSb single quantum wells,[9] in which interface roughness dominates the mobility for any $d_W \leq 100$ Å. Since the relevant InAs-$Ga_{1-x}In_xSb$ well thicknesses for detector applications are considerably less than 100 Å, it is not surprising that the electron mobilities tend to be relatively low. To our knowledge, no previous study of this system has reported μ_n greater than ≈ 6000 cm^2/Vs at *any* temperature, and the low-temperature mobilities have generally been much smaller, displaying activation behavior with decreasing T.[5] Such low mobilities have made it more difficult to achieve the condition $\mu_n B \gg 1$, which is required if Shubnikov–de Haas oscillations are to be observed. Beyond the effect on the net mobility, random potential fluctuations produced by the rough interfaces may also lead to significant localization of the low-energy electron states. For an InAs quantum well of average thickness 39 Å, we estimate that a variation of the well width by one monolayer should shift the quantized energy levels by ≈ 15 meV. One expects energy fluctuations of that magnitude to lead to the localization of a significant number of electron states at the bottom of each Landau level. Consequences for the magnetic-field variation of the Hall conductivity will be discussed below.

The thinness of the $Ga_{1-x}In_xSb$ barriers has similarly important ramifications due primarily to the resulting strength of the energy dispersion along the growth axis $E(k_z)$. In the usual limit $d_B \gg L_e$, where $L_e = [\hbar^2/2m_B(\Delta E_C - E)]^{1/2}$ is the wave-function penetration depth into the barriers, m_B is the electron effective mass in the barrier material and ΔE_C is the conduction-band offset, a Kronig-Penney one-band calculation[10] yields the familiar form

$$E(k_z) \approx E_0 - \frac{1}{2} W \cos(k_z d), \tag{1}$$

which implies that the effective mass in the superlattice is highly anisotropic: $m_z \gg m_x$. Here $W \propto e^{-d_B/L_e}$ is the width of the miniband, E_0 is its midpoint energy, and $d \equiv d_W + d_B$ is the superlattice period. However, when $d_B \approx L_e$ as in the present example, Eq. (1) is inappropriate and the one-band formalism gives a dispersion relation which approaches the unperturbed bulk form. We have confirmed that for an InAs-$Ga_{0.75}In_{0.25}Sb$ superlattice with the relevant layer thicknesses, an eight-band $\mathbf{k}\cdot\mathbf{p}$ calculation employing the transfer-matrix formalism[11] also yields nearly isotropic electron effective masses: $m_x \approx 0.025m_0$, $m_z \approx 0.030m_0$. While the in-plane result may be compared with the experimental magneto-optical value $m_x \approx 0.031m_0$,[5] there has apparently been no previous determination of m_z. The eight-band calculation also predicts that in contrast to Eq. (1), $E(k_z)$ is relatively parabolic over most of the miniband, whose width exceeds 150 meV. One consequence of this particularly pronounced miniband dispersion is that the quantum Hall effect, a fundamentally two-dimensional phenomenon, should not be observable.

Three InAs-$Ga_{0.75}In_{0.25}Sb$ superlattices were grown by molecular-beam epitaxy at Columbia University. Substrates were semi-insulating [100] InP, and the growth sequence for each structure consisted of a 1-μm-thick GaSb buffer layer, followed by the alternating layers of InAs and $Ga_{1-x}In_xSb$ (50 periods), and then a 200-Å-thick GaSb cap. Magnetotransport measurements were performed as a function of magnetic field ($B = 0-7$ T) and temperature ($T = 1.6-300$ K), using the Van der Pauw technique. In all cases, the current flow was in the plane of the superlattice and the magnetic field was along the growth axis.

All of the unintentionally doped samples were found to be n type, with net donor concentrations between 8.0×10^{16} cm^{-3} and 2.7×10^{17} cm^{-3}. Table I lists low-temperature electron densities and mobilities obtained from mixed-conduction analyses of the nonoscillating conductivity components σ_{xx}^0 and σ_{xy}^0. For samples 1 and 2, the table also gives the zero-temperature extrapolation of the energy gap, as determined from the temperature dependence of the intrinsic carrier density.[5] An accurate determination of E_g^0 could not be made for sample 3, in part because of the higher background carrier concentration. Also complicating the analysis for that superlattice was the presence of a second electron species, which may have occupied either the buffer layer or the substrate [but probably not one of the quasi-two-dimensional (quasi-2D) interfaces regions, because the net areal density of 9.2×10^{12} cm^{-2} was too high]. That carrier did not contribute to the quantum oscillations because of its low mobility, 3500 cm^2/Vs. The mixed-conduction analyses indicated that samples 1 and 2 each contained only a single type of electron with a sharply defined mobility.

Low-temperature mobilities for all three superlattices were in the range 7700–1.1×10^4 cm^2/Vs, which is somewhat higher than any reported previously for the InAs-$Ga_{1-x}In_xSb$ system. In part this may be due to a different interface roughness correlation length resulting from the growth conditions, but it is probably also related to the higher carrier concentrations in the present samples (e.g., n was only 4×10^{15}–5×10^{16} cm^{-3} in the superlattices studied by Omaggio *et al.*[5]). Since interface roughness dominates the scattering, we do not expect the additional ionized impurities present in our samples to have any appreciable influence on the scattering rate. On the contrary, the additional electrons provide enhanced screening of the roughness-induced potential fluctuations. Furthermore, a lowest-order estimate suggests that $\approx 10^{16}$ cm^{-3} electrons are required before the Fermi energy becomes larger than the typical magnitude of the fluctuations. We therefore expect a percolation-type metal-insulator transition in the low-temperature limit, which is qualitatively consistent with the experimental observations when the present and previous[5] results for different n are compared.

The present samples also differ from InAs-$Ga_{1-x}In_xSb$ superlattices studied previously in that their low-temperature magnetotransport coefficients exhibited quantum oscillations. These were analyzed by fitting the nonoscillating component $\sigma_{ij}^0(B)$ to a smooth polynomial expansion, and then extracting the oscillating component from the net conductivity: $\Delta\sigma_{ij}(B) \equiv \sigma_{ij}(B) - \sigma_{ij}^0(B)$. Figures 1–3 plot the normalized results $\Delta\sigma_{xx}/\sigma_{xx}^0$ and $\Delta\sigma_{xy}/\sigma_{xy}^0$. Following a discussion of the Shubnikov–de Haas oscillations in σ_{xx} for all three samples, we will comment on the oscillations in σ_{xy}.

The $\Delta\sigma_{xx}/\sigma_{xx}^0$ curve in Fig. 1 displays three clear maxima and minima. From the approximate relation[12] $\Delta\sigma_{xx}(B) \propto e^{-2\pi/\mu_n B}$, the decay of the amplitudes with increasing B^{-1} implies $\mu_n \approx 1.0 \times 10^4$ cm^2/Vs, which is consistent with the Hall result. In a three-dimensional (3D) semiconductor whose mass is isotropic in the $\hat{x}$-$\hat{y}$ plane, the carrier concentration is related to the oscillation period ΔB^{-1} by the expression[12]

$$n = \frac{1}{3\pi^2}\left(\frac{2e}{\hbar \Delta B^{-1}}\right)^{3/2}\left(\frac{m_z}{m_x}\right)^{1/2}, \tag{2}$$

where the Landau levels are taken to be spin degenerate, an assumption which will be reexamined below. In the present study the carrier concentration is known independently from the mixed-conduction analysis, whereas the mass ratio has not previously been characterized experimentally for the InAs-$Ga_{1-x}In_xSb$ system. We have therefore used the oscillation period to estimate m_z/m_x, even though the uncertainty is relatively high (perhaps 30%) because the mass ratio enters Eq. (2) only as a

TABLE I. Well and barrier thicknesses, Hall density and mobility, zero-temperature extrapolation of the energy gap, and mass anisotropy ratio (from the Shubnikov–de Haas period) for the three InAs-$Ga_{0.75}In_{0.25}Sb$ superlattices.

Sample No.	d_W (Å)	d_B (Å)	n (cm^{-3})	μ_n (cm^2/Vs)	E_g^0 (meV)	m_z/m_x
1	39	25	8.0×10^{16}	9400	72	1.2
2	39	25	1.4×10^{17}	7700	65	1.0
3	39	25	2.7×10^{17}	1.1×10^4		1.0

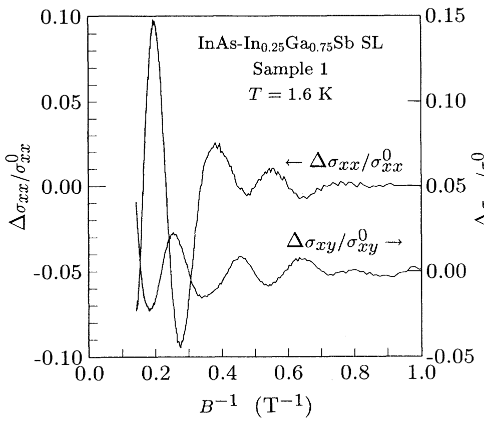

FIG. 1. Oscillating components of the diagonal (left scale) and Hall (right scale) conductivities, normalized to the nonoscillating components, vs inverse magnetic field for sample 1 at $T = 1.6$ K.

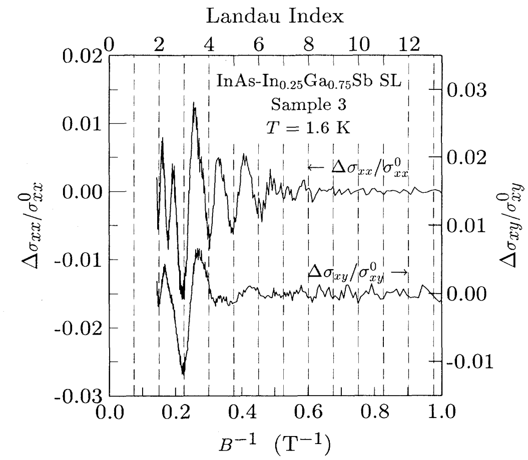

FIG. 3. Oscillating components of the diagonal and Hall conductivities vs inverse magnetic field for sample 3.

square root. The results listed in Table I ($m_z/m_x \approx 1.2$ for sample 1 and ≈ 1.0 for samples 2 and 3 discussed below) confirm the theoretical prediction of a nearly isotropic effective mass in InAs-Ga$_{1-x}$In$_x$Sb superlattices with layer thicknesses relevant to LWIR devices. This finding has important implications for detectors, since the growth direction mass governs both the tunneling noise (which has an inverse exponential dependence on $m_z^{1/2}$) (Ref. 13) and collection efficiency (which relies on the growth-direction transport of minority carriers).

Figures 2 and 3 show the analogous results for $\Delta\sigma_{xx}/\sigma_{xx}^0$ in samples 2 and 3. It is evident that the oscillation periods for the three samples decrease as expected with increasing carrier concentration. In Figs. 2 and 3, the top scale corresponds to the number of Landau levels i which would be fully occupied at a given inverse magnetic field if one assumes spin degeneracy, $m_z = m_x$, and a Shubnikov–de Haas phase factor[14] of 1/2. With these assumptions, most of the minima in $\Delta\sigma_{xx}$ fall on integer values of i. Also apparent from Figs. 2 and 3 is that in these two superlattices, the spin splitting has been resolved at the highest magnetic fields. Figure 2 shows minima not only at the integers 2 and 3 corresponding to complete Landau levels, but also at $1\frac{1}{2}$ and $2\frac{1}{2}$. Similarly, Fig. 3 shows $\Delta\sigma_{xx}$ minima not only at all integers from 2 to 6, but also at $2\frac{1}{2}$. This is not surprising since for fields in the range 5–7 T, the spin splitting is ≈ 10 meV if we take the g factor in the superlattice to be comparable to that in bulk InAs.[15]

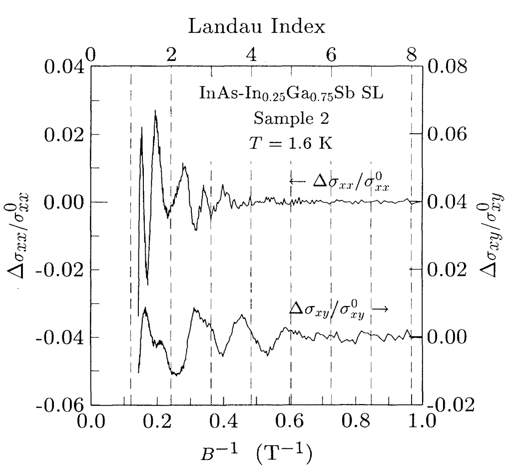

FIG. 2. Oscillating components of the diagonal and Hall conductivities vs inverse magnetic field for sample 2.

We next consider the quantum features in the Hall conductivity, which appear as plateaulike inflections in $\sigma_{xy}(B)$. From the normalized plots in Figs. 1–3, it is evident that $\Delta\sigma_{xy}/\sigma_{xy}^0$ displays oscillations which are of comparable magnitude to those in $\Delta\sigma_{xx}/\sigma_{xx}^0$. While only two Hall minima are resolvable in Fig. 3, the $\Delta\sigma_{xy}/\sigma_{xy}^0$ oscillations in Figs. 1 and 2 actually extend to higher inverse field than the corresponding Shubnikov–de Haas data. Most of the half-integer (spin-splitting) oscillations in the diagonal conductivity are not accompanied by minima in the Hall conductivity, although there is a weak feature in $\Delta\sigma_{xy}$ corresponding to $1\frac{1}{2}$ in Fig. 2. Note also that whereas the $\Delta\sigma_{xy}$ and $\Delta\sigma_{xx}$ oscillations for sample 3 are nearly in phase, the Hall minima for the other two samples are shifted to higher B^{-1} relative to the Shubnikov–de Haas minima.

The quantum Hall effect has often been observed in InAs-GaSb and InAs-AlSb single[16–19] and multiple[20] quantum wells. Those data display plateaus at quantized values of the Hall conductivity,

$$\sigma_{xy}(B) = 2\mathcal{N}_W i \frac{e^2}{h}, \tag{3}$$

where $\mathcal{N}_W$ is the number of quantum wells conducting in parallel. In order for the plateaus to be ideally flat [and for $\sigma_{xx}(B)$ to approach zero], a key requirement is that there be energy gaps containing only localized states between the successive Landau levels separated by the cyclotron energy $\hbar\omega_c$. This condition is easily satisfied in single and multiple quantum wells populated by quasi-2D electrons, and even in superlattices as long as the energy dispersion approaches a quasi-2D character at high magnetic fields, i.e.,[21,22]

$$W \ll \hbar\omega_c \, . \tag{4}$$

However, the present superlattices represent the *opposite* limit of a system exhibiting strong 3D dispersion. One can never hope to satisfy Eq. (4) since the miniband width is still an order of magnitude larger than the cyclotron energy at $B = 7$ T.

Thus the oscillatory features in the Hall data from Figs. 1–3 cannot be interpreted by direct analogy to the quantum Hall effect for quasi-2D systems because the dispersion along the growth axis is far too great for energy gaps containing only localized states to develop between the Landau levels. Examination of the σ_{xy} data confirms that the spacing of the plateaulike inflections is much less than the value predicted by Eq. (3). Our results are probably more closely related to the observation of Hall oscillations in a number of bulk 3D semiconductors,[23–25] including InAs.[26] Generally, those studies have obtained relative amplitudes $\Delta R_H/R_H^0$ which are factors of 5–100 smaller than for the Shubnikov–de Haas oscillations of the resistivity.

Mani has pointed out that if a high concentration of localized states leads to the formation of quasimobility gaps at the bottom of each Landau level, one expects the Hall resistivity to display periodic structure even in a 3D system.[25] He showed using a simplified model that, although there are conducting states present at all energies, the occurrence of a high fraction of localized states at some energies will lead to plateaulike inflections in $\sigma_{xy}(B)$. Since the large random potential fluctuations caused by interface roughness in the present InAs-$Ga_{1-x}In_xSb$ superlattices should be expected to produce particularly strong localization, it is not surprising that $\Delta\sigma_{xy}/\Delta\sigma_{xx}$ from our data (often on the order of unity) is generally much larger than the ratios observed in bulk semiconductors (typically ≤ 0.2).[23,24,26]

Summarizing, magnetotransport measurements on a series of n-type InAs-$Ga_{1-x}In_xSb$ superlattices with thin wells and barriers have led to the observation of Shubnikov–de Haas oscillations in σ_{xx} accompanied by oscillations in σ_{xy}. Correlation of the oscillation period with electron densities obtained from a mixed-conduction analysis of the nonoscillating conductivity components implies that in contrast to most multiperiod quantum structures studied previously, the electron effective mass is nearly isotropic. Spin splitting of the high-field oscillations of $\sigma_{xx}(B)$ is also observed in two of the samples. The features in $\sigma_{xy}(B)$ are attributed to the presence of localized states at the bottom of each Landau level, which are particularly pronounced in this system because of the large potential fluctuations due to interface roughness.

We gratefully acknowledge Richard Miles for several valuable discussions of the InAs-$Ga_{1-x}In_xSb$ system. We also thank L. R. Ram-Mohan and Quantum Semiconductor Algorithms for the use of superlattice band-structure software. This research was supported in part by SDIO/IST and in part by the Office of Naval Research.

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