Molecular beam epitaxy of high mobility In_{0.75}Ga_{0.25}As for electron spin transport applications

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The authors describe the molecular beam epitaxy of relaxed, nominally undoped In_{0.75}Ga_{0.25}As–In_{0.75}Al_{0.25}As quantum well structures grown on InP substrates. The maximum two-dimensional electron density is 2 \times 10^{13} \text{ cm}^{-2}, with a peak mobility of 2.2 \times 10^{5} \text{ cm}^{2} \text{ V}^{-1} \text{ s}^{-1} at 1.5 \text{ K}. In high magnetic field, the electron g-factor was shown to have a magnitude of 9.1 \pm 0.1 at Landau-level filling factor of 4. The Rashba coefficient, determined from the analysis of the magnetoresistance at high Landau-level filling factor (>12), is 1 \times 10^{-11} \text{ eV m}. The mobility is sufficiently high in these two-dimensional electron gases that spin-orbit effects are observed up to 4.2 \text{ K}. The interface asymmetry, defined as the difference between the wavefunction penetration into the upper and lower In_{0.75}Al_{0.25}As quantum barriers, makes no contribution to the Rashba spin-orbit coupling parameter in this system. Quantum wires defined in these two-dimensional electron gases using insulated, split surface gates show clear quarter-integer quantized conductance plateaux at exactly 0.25(2e^2/h) and 0.75(2e^2/h) in nonequilibrium transport. In_{0.75}Ga_{0.25}As may have important application as an alternative field effect transistor channel to silicon, and the large electronic g-factor and Rashba spin-orbit coupling parameter make this material combination suitable for exploring spin related phenomena in one-dimensional systems. © 2009 American Vacuum Society. [DOI: 10.1116/1.3156736]

I. INTRODUCTION

The Landé spin g-factor, g, of a system is a measure of the magnetic moment per unit angular momentum. The spin-splitting energy in an applied magnetic field (B) is then given by \( g \mu_B B \), where \( \mu_B \) is the Bohr magneton. In GaAs, the bare g-factor is \( |g| = 0.44 \), although this is enhanced to an effective value, \( |g^*| \), both by heterostructure confinement and sheet electron density variations. \( |g| \) is a substantially larger for In_{Ga_{1-x}}As \( (n_s) \) variations. \( |g| \) is of interest due to the fact that as \( x \) is increased they exhibit narrower band-gap energies, decreasing effective masses, and reduced Schottky barriers at a metal-semiconductor interface. For these reasons alone, InGaAs has been widely proposed as a channel material in III-V complementary metal-oxide semiconductor devices. However, these high-\( |g| \) materials also play an important role in the present spintronic devices, where the ability to selectively manipulate electrons with opposite spin polarity, either through variable g-factor or via the Rashba spin-orbit coupling effect, is of fundamental importance. The combination of several III-V materials into one heterostructure could lead to devices within which \( |g| \) is gate tunable.

The Rashba spin-orbit coupling that removes the spin degeneracy in zero applied magnetic field has, for InAs and In_{0.75}Ga_{0.25}As, been quantified previously but, to date, not for the 75% indium alloy. The Hamiltonian describing the Rashba spin-splitting energy is given by \( \hat{H}_{\text{Rashba}} = \alpha (\sigma \times \mathbf{k}) \cdot \mathbf{n} \), where \( \alpha \) is the material-dependent Rashba coefficient, \( \sigma \) is a vector of the Pauli spin matrices, \( \mathbf{k} \) is the electron wave vector in the plane of the confining potential, and \( \mathbf{n} \) is a unit vector parallel to the growth axis of the quantum well (QW). In a system with a Fermi wave vector of \( k_F \) the spin-splitting energy is then \( 2\alpha |k_F| \). This effect has been measured here as a carrier-density imbalance between the two spin subbands at low applied magnetic field.

In this article, we describe the growth and characterization of high-quality In_{0.75}Ga_{0.25}As and demonstrate its potential suitability as a constituent element of spintronic devices.
One-dimensional (1D) transport measurements are also presented, which show the suitability of \( \text{In}_{0.75}\text{Ga}_{0.25}\text{As} \) for ballistic transport studies where electron-electron interaction effects are significant. The \( \text{In}_{0.75}\text{Ga}_{0.25}\text{As} \) material system may also be applicable for use in 1D spintronic devices where strong spin-orbit interaction effects are expected to reveal new physics.\(^{11,12}\)

**II. GROWTH DETAILS**

The growth of this material system was first reported in Ref. 13. The samples here were grown in a Veeco MOD GEN II solid-source molecular beam epitaxy chamber. A 700 nm \( \text{In}_{0.75}\text{Al}_{0.25}\text{As} \) buffer was grown on a semi-insulating InP (001) substrate. The indium mole fraction was linearly graded from \( x=0.52 \) to \( x=0.85 \) to promote relaxation of the overlying active region. A 300 nm \( \text{In}_{0.75}\text{Al}_{0.25}\text{As} \) bottom barrier was then grown, followed by a 30 nm \( \text{In}_{0.75}\text{Ga}_{0.25}\text{As} \) cap. The growth temperature throughout was 440 °C, calculated using a kSA BandiT system.\(^{14}\) The maximum growth rate was 1.3 \( \mu \)m/h and the V/III ratio of beam-equivalent pressures was \( \sim 30 \). The whole structure was grown without intentional doping, although a background deep donor at a density of \( \sim 1 \times 10^{10} \) cm\(^{-3} \) is present in the \( \text{In}_{0.75}\text{Al}_{0.25}\text{As} \).\(^{13}\) The devices measured here have polyimide insulated surface gates, which can fully deplete or enhance \( n_e \). The dilute two-dimensional electron gases (2DEGs) formed in the \( \text{In}_{0.75}\text{Ga}_{0.25}\text{As} \) exhibit very high electron mobility (\( \mu = 2.2 \times 10^5 \) cm\(^2\)/Vs) with a low sheet electron density (1.6 \times 10^{11} \) cm\(^{-2} \) at 1.5 K. Growth conditions and electron transport in these structures have been optimized previously.\(^{15}\)

**III. LANDÉ SPIN G-FACTOR MEASUREMENTS**

Shubnikov–de Haas measurements were made in a 12 T cryostat between 1.5 and 4.2 K. The coincidence method was used to induce Landau-level crossings and enable calculation of \( |g^*| \) in these 2DEGs.\(^{16}\) In situ rotation enabled control of the relative angle (\( \theta \)) between the 2DEG and the magnetic field. These nonperpendicular magnetic fields were used to vary the ratio between the Zeeman energy (\( g^* \mu_B B_T \)) and the cyclotron energy (\( h e B_L / m^* \)), where \( B_T \) is the total applied field, \( B_L \) is the field component perpendicular to the 2DEG (with \( B_L = B_T \cos \theta \)), and \( m^* \) is the electron effective mass. As \( \theta \) is increased from zero, the first crossing of the spin-split peaks in the oscillatory magnetoresistance corresponds to a unity ratio of Zeeman energy to cyclotron energy. \( |g^*| \) can hence be determined from \( \theta, B_T, \) and \( m^* \). The value of the effective mass has been measured by cyclotron resonance to be 0.039\( m_e \), where \( m_e \) is the free electron mass.\(^{17}\)

The longitudinal magnetoresistance (\( R_{xx} \)) is plotted in Fig. 1 as a function of perpendicular magnetic field at 1.5 K with a carrier density of \( 1.4 \times 10^{11} \) cm\(^{-2} \). The rotation angle is \( 0^\circ \) at the bottom trace and \( 82.3^\circ \) at the upper trace. At \( 82.3^\circ \) there is still sufficient perpendicular magnetic field to resolve the resistance peak in the Shubnikov–de Haas oscillations, annotated by \(*\), between filling factors \( \nu = 4 \) and \( \nu = 3 \). As the applied magnetic field becomes more parallel to the plane of the 2DEG, crossings of spin-split peaks in \( R_{xx} \) can be resolved at \( \nu = 4 \) (at \( \sim 1.5 \) T) and \( \nu = 6 \) (at \( \sim 1.0 \) T). The well-defined coincidence for \( \nu = 4 \) gives a value of \( |g^*| = 9.1 \pm 0.1 \). The crossing at \( \nu = 6 \) is not as well resolved (it is broadened over a larger angular range) and yields a value of \( |g^*| = 8.1 \pm 0.3 \). These values agree with previous transport studies.\(^{17}\) The reduction in \( |g^*| \) at higher filling factor is consistent with a decrease in electron-electron exchange interactions.\(^{18}\)

**IV. DETERMINATION OF THE RASHBA COEFFICIENT**

This relatively large absolute value of Landé spin \( g \)-factor in the \( \text{In}_{0.75}\text{Ga}_{0.25}\text{As} \) material system means that the Zeeman-splitting transport regime dominates down to \( \sim 0.5 \) T, with spin-orbit coupling effects only quantifiable at fields lower than this. At 0.5 T the Zeeman energy is 0.26 meV, compared to a Rashba spin-orbit coupling energy of 2.2 meV. To preclude this complication and allow sensitive magnetotransport measurements to be made in fields of less than 0.5 T, a magnetic field modulation coil was built to surround the sample in a second cryostat with a temperature ranging from 1.7 K to approximately 77 K. In this way, alternating magnetic fields with peak magnitude of 10 mT were generated at audio frequencies and hence the contribution from the Zeeman splitting could be minimized through analysis of Landau-level filling factors greater than 12, i.e., the Shubnikov–de Haas region for \( B < 0.5 \) T. To reduce electron-heating effects, source-drain currents were typically 100 nA or lower, while electrical signals were measured using Stanford SR830 lock-in amplifiers.
The asymmetric background doping in this material system and the QW heterojunctions with the pinning of the Fermi energy at the surface of the structure create a built-in electric field perpendicular to the 2DEG. The magnitude of this structural inversion asymmetry can be tuned via application of a gate bias and results in the creation of two spin subbands of unequal carrier density in zero applied magnetic field.\textsuperscript{10} In this regime, Shubnikov–de Haas oscillations in $R_{xx}$ show a characteristic beating structure at a low applied magnetic field.\textsuperscript{19} As a consequence of this, anomalous structure in $R_{xx}$ is also seen in high mobility GaAs–AlGaAs heterostructures with no Rashba spin-orbit coupling effects measurable in $R_{xx}$.

The Rashba coupling constant was determined both in enhancement and depletion modes with an insulating surface gate. Under positive gate bias, $\alpha=1 \times 10^{-11} \text{ eV m}$, with $1.4 \leq n_s \leq 1.9 \times 10^{11} \text{ cm}^{-2}$, shown as the $\bullet$ data points in Fig. 3. The $\blacksquare$ data points show that under negative gate bias where $n_s < 1.4 \times 10^{11} \text{ cm}^{-2}$, $\alpha$ is reduced to $0.7 \times 10^{-11} \text{ eV m}$ at $n_s = 1 \times 10^{11} \text{ cm}^{-2}$. This is the lowest carrier density at which $\alpha$ has been determined in any III-V system using this technique.

Wavefunction penetration into the In$_{0.75}$Al$_{0.25}$As barriers, i.e., the interface asymmetry, makes no contribution to $\alpha$ in this system. Figure 3 shows the wavefunction asymmetry (dashed line), which is parametrized as the difference in the wavefunction probability at the bottom QW interface, $\psi_{(b)}^2$, and the top QW interface, $\psi_{(t)}^2$. This was calculated from a self-consistent wavefunction solution to the confining potential and depletion modes with an insulated surface gate. The $\bullet$ are data from ungated devices, while $\blacklozenge$ represents a series of four individual data points with different gate voltages in the enhancement mode (at 0.50, 0.75, 1.00, and 1.25 V) but illuminating the device after every gate voltage change to maintain a constant carrier density of $1 \times 10^{11}$ cm$^{-2}$. This has a similar effect to backgating the device. The fact that the four data points are identical is another demonstration that an interface contribution to $\alpha$ is not significant in this material system.

V. 1D CHANNELS IN In$_{0.75}$Ga$_{0.25}$As–In$_{0.75}$Al$_{0.25}$As

Surface split gates were used to define a 1D channel in the In$_{0.75}$Ga$_{0.25}$As by selectively depleting electrons from certain...
areas of the 2DEG\textsuperscript{21,22} below the electrostatic gates [Fig. 4(a)]. As a consequence of the near absence of a Schottky barrier at the surface of the In\textsubscript{0.75}Ga\textsubscript{0.25}As capping layer, these gates needed to be insulated. However, in order to achieve well-defined 1D channels with good control over the quantum confinement, it was important to keep this insulating film as thin as possible. For this purpose, polyimide films with thickness of \( \sim 50\) nm were used. Defined by e-beam lithography, the split gates used here were separated by 500 nm and were 400 nm long [Fig. 4(b)]. Maximum leakage current through the polyimide was 1.4 nA, which, although higher than ideal, still allowed successful resolution of features in the 1D conductance. As negative bias is applied to the split gates, the effective channel width is reduced to form a 1D quantum wire. This confinement splits the sub-band energy levels of the 2DEG into a series of quantized 1D states, each separated in conductance by \( 2e^2/h \).\textsuperscript{21,22} This is manifested as a series of plateaux in the channel conductance at integer values of this conductance quantum. For spin non-degenerate systems, additional plateaux are observed at odd-integer multiples of \( e^2/h \).

Application of an in-plane source-drain bias (\( V_{sd} \)), parallel to the quantum wire, raises the electrochemical potential of one end of the channel with respect to the other. Assuming that the integer plateau observed at \( V_{sd}=0 \) V is the result of electrons moving in either direction, an increase in \( V_{sd} \) means that electron transport through the 1D channel will be suppressed in one direction, thus halving the conductance.\textsuperscript{23} Within a spin-polarized system, this leads to plateaux at quarter-integer multiples of \( 2e^2/h \). The differential conductance \( G=dI/dV_{sd} \) of these quantum wires was analyzed at 1.5 K using dc bias spectroscopy. Starting at \( -0.1 \) mV, \( V_{sd} \) was raised to \( +4.0 \) mV in 0.05 mV increments with a 1D conductance spectrum taken at each value of \( V_{sd} \) [Fig. 4(c)]. A constant magnetic field of \( B_z=0.6 \) T was applied perpendicular to the 2DEG. This is a technique that is often used to reduce backscattering where there may be impurities present in the quantum wire region.\textsuperscript{22} Traces to the left in Fig. 4(c) show \( G \) for the quantum wire at equilibrium (where \( V_{sd} =0 \) V). The first and second integer plateaux are well resolved. The lack of a half-integer plateau at \( 1.5(2e^2/h) \) when \( V_{sd}=0 \) V indicates that the small applied field is insufficient to spin polarize the system (see discussion in Secs. III and IV). This conclusion is further supported by the fact that as \( V_{sd} \) is increased, quarter-integer plateaux at \( 1.25(2e^2/h) \) or \( 1.75(2e^2/h) \) are not observed. At higher values of \( V_{sd} \), the plateau at \( 1.5(2e^2/h) \) is explained by the contribution of only half of the electrons from the second 1D state, as described previously.

The situation is different where \( G<2e^2/h \). Rather than a similar half-integer plateau developing at \( 0.5(2e^2/h) \) as might be expected, increasing \( V_{sd} \) results in the appearance of quarter-integer plateaux at \( 0.75(2e^2/h) \) and \( 0.25(2e^2/h) \). These would seem to indicate spontaneous spin polarization of the dilute 1D electron system. Similar conductance features, for \( G<2e^2/h \), are often seen in dc bias measurements (\( V_{sd} \neq 0 \) V) on GaAs quantum wires.\textsuperscript{24,25} Measured variously at \( 0.8-0.85(2e^2/h) \) and \( 0.2-0.3(2e^2/h) \), these are believed to be derived from similar electron-electron interaction processes to the well-known “0.7 structure” which is often observed during equilibrium transport (\( V_{sd}=0 \) V).\textsuperscript{28} The “spin-gap model”\textsuperscript{29,30} has been proposed to explain these phenomena in GaAs. This model, which is successful at describing many of the properties of the 0.7 structure, is based on exchange-driven spin polarization. According to this model, the features observed at \( 0.3(2e^2/h) \) and \( 0.85(2e^2/h) \) should, in fact, be the spin-split \( 0.25(2e^2/h) \) and \( 0.75(2e^2/h) \) plateaux, normally observed in large in-plane magnetic fields.

In comparison with those dc bias measurements from GaAs-based systems, what is particularly striking about the plateaux shown in Fig. 4(c), in addition to their clarity and flatness, is the accuracy with which they lie on the expected prefactor values of 0.25 and 0.75. For example, the \( 0.25(2e^2/h) \) plateau agrees exactly with what is expected for a spin-polarized current flowing in only one direction. The fact that these features are resolved unambiguously at \( 0.25(2e^2/h) \) and \( 0.75(2e^2/h) \) may be a direct result of the higher \( |g^*| \) in In\textsubscript{0.75}Ga\textsubscript{0.25}As when compared to GaAs. This material represents an alternative route to exploring the as yet incompletely understood physics of 1D conductance below \( 2e^2/h \).\textsuperscript{31}
VI. CONCLUSIONS

We have demonstrated the growth of high mobility, relaxed In$_{0.75}$Ga$_{0.25}$As QWs. Electronic transport within the resulting dilute 2DEGs was characterized. \[|g^*|\] was calculated from the magnetoresistance to be \(-9\) at 1.5 T. The Rashba spin-orbit coupling constant at high Landau-level filling factor is \(1 \times 10^{-11}\) eV m, with carrier densities of (1.4–1.9) \(\times 10^{11}\) cm\(^{-2}\) and the mobility is sufficiently high in the present devices that spin-orbit effects can be observed in the magnetoresistance up to 4.2 K. Interface asymmetry makes no contribution to the Rashba spin-orbit coupling parameter in this material system. In$_{0.75}$Ga$_{0.25}$As is extremely promising as a candidate for inclusion in future tunable g-factor and spintronic devices. In addition, dc bias spectroscopy of the 1D differential conductance shows quantized conductance plateaux at 0.25 and 0.75 \((2e^2/h)\). The excellent resolution and well-defined conductance values of these plateaux indicate that this high g-factor material system may prove to be useful in determining the origin of electron-electron interactions that currently are not fully understood.

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