I. INTRODUCTION

Two-dimensional electron gases (2DEGs) formed in high indium-content In$_{x}$Ga$_{1-x}$As exhibit advantages over their analogs in the Al$_{y}$Ga$_{1-y}$As/GaAs system, and could lead to the realization of various spintronic and high-speed devices. These benefits include a high effective g factor, a low effective electron mass, a large spin-orbit coupling constant, and an almost nonexistent Schottky barrier at the metal-semiconductor interface, resulting in such junctions being highly transmissive. This last property has led to advances in the development of innovative hybrid superconductor-semiconductor devices.

For In$_{x}$Ga$_{1-x}$As-based high electron mobility transistors (HEMTs), the 2DEG is usually formed in an In$_{x}$Ga$_{1-x}$As quantum well (QW) with In$_{y}$Al$_{1-y}$As barriers. Electron transport is limited by four types of scattering center: remote-ionized dopants, background impurities, alloy disorder, and interface roughness. Electron transport in In$_{0.53}$Ga$_{0.47}$As, lattice matched to InP, is limited by alloy-disorder scattering. As the indium composition of the QW is increased, the electron mobility $\mu$ also increases, reaching a maximum at $x = 0.75$ due to a reduction in this scattering mechanism. An InAlAs buffer with graded composition is used to alter the lattice parameter from that of the substrate to that of the active device layers. Such buffers produce near-complete lattice relaxation in subsequent layers. This means that surfaces will be flatter, reducing interface-roughness scattering and increasing electron mobility.

To observe certain effects at low magnetic fields, it may be beneficial to reduce the number of filled Landau levels. For example, the critical field at which spin splitting is observed reduces with the electron density $n$. A 2DEG with $\mu > 100 000$ cm$^2$/V s but with low $n$ has been demonstrated. Based on a GaAs substrate with a step-graded InAlAs buffer, the 2DEG was confined in an In$_{0.75}$Ga$_{0.25}$As QW. The entire heterostructure was undoped, thereby removing the source of remote-ionized-dopant scattering. It was shown that the 2DEG electrons probably originate from a donor state $0.12–0.15$ eV below the In$_{0.75}$Al$_{0.25}$As-barrier conduction-band minimum. Figures of $\mu = 215 000$ cm$^2$/V s and $n = 2.84 \times 10^{11}$ cm$^{-2}$ at 1.4 K are reported and spin splitting is observed in the Shubnikov–de Haas (SdH) oscillations close to 2.5 T.

This work seeks to further extend the low-carrier-density limit for which a 2DEG with $\mu > 100 000$ cm$^2$/V s can be formed. Mismatch is lower between In$_{0.75}$Ga$_{0.25}$As and InP substrates than GaAs. Therefore, for the same composition gradient, the thickness of the graded buffer necessary to achieve equivalent lattice relaxation can be reduced. If the 2DEG indeed consists of electrons deriving from a deep-level state in the In$_{0.75}$Al$_{0.25}$As barriers, it is proposed that a thinner buffer (i.e., bottom barrier) may result in fewer carriers. The effect of growth temperature and crystallographic orientation on $n$ and $\mu$ in such a 2DEG is investigated.

II. EXPERIMENT

In$_{0.75}$Ga$_{0.25}$As HEMTs were grown in a Veeco Mod. GEN-II solid-source molecular beam epitaxy system on semi-insulating (100) InP substrates. The V/III ratio of beam-equivalent pressures was maintained at $\sim 30$, with a maximum growth rate of $\sim 1.3 \mu$m/h. Such growth conditions are typical for this material system and have been optimized elsewhere. Five growth temperatures were investigated: 470 °C (523 °C), 440 °C (483 °C), 410 °C (439 °C), 380 °C (373 °C), and 350 °C (312 °C), measured using an optical pyrometer. The values in parentheses were measured simultaneously with a KSA BandiT system, which uses the...
substrate band-edge wavelength to calculate absolute temperature. Growth temperatures quoted throughout this work refer to those measured by pyrometer. During the epitaxy of each sample, the growth temperature was kept constant.

The InP substrate was heated under As$_4$ to desorb the native oxide and after a short degas, 50 nm of lattice-matched In$_{0.52}$Al$_{0.48}$As was grown. For simplicity, a linearly graded In$_{0.1}$Al$_{0.9}$As buffer was grown to achieve maximal relaxation of the device heterostructure. In order to achieve the same composition gradient as in Ref. 9, the 700 nm buffer was graded in two stages. Over the first 500 nm, the indium mole fraction was ramped from $x=0.52$ to $x=0.75$, while during the last 200 nm, the In content was further increased to $x=0.85$. Taking into account partial relaxation through misfit dislocations in the initial sections of the buffer, this second stage was designed to achieve a lattice constant at the surface comparable to that of unstrained In$_{0.75}$Ga$_{0.25}$As and thereby promote minimally strained growth of subsequent layers.

Growth was then interrupted for 5 min under an As$_4$ overpressure. This was allowed to stabilize the following effusion cell cooling prior to growth of the remainder of the structure. This long pause had the benefit of allowing surface smoothing to occur, albeit with the disadvantage that impurities might congregate at this interface. 50 nm of In$_{0.75}$Al$_{0.25}$As was then grown, followed by a 30 nm In$_{0.75}$Ga$_{0.25}$As QW, a 120 nm In$_{0.75}$Al$_{0.25}$As top barrier, and finally a 10 nm In$_{0.75}$Ga$_{0.25}$As cap. No layers were intentionally doped.

Standard wet-etch lithographic techniques were used to define a Hall bar, with annealed AuGeNi Ohmic contacts. In order to investigate any electron transport anisotropy, Hall bars were fabricated both parallel and perpendicular to the [011] axis. An optically transparent 7 nm thick NiCr gate was positioned above the channel. Due to the low metal-In$_{0.75}$Ga$_{0.25}$As Schottky barrier, with a quoted height of 0.031 eV, films of polyimide, 300–500 nm thick, were used to insulate the gate from the channel.

III. RESULTS AND DISCUSSION

The In mole fraction of the QW in these samples was measured using x-ray diffractometry (XRD) to be $x=0.73\pm0.01$. In order to assess the extent of strain relaxation in these layers, a reciprocal space map of the (2 2 4) XRD reflection was compared with the (0 0 4) reflection. Relaxation of 90%–95% was inferred for these samples, with residual strain anisotropy found to be less than 1%. Atomic force microscopy (AFM) images of the sample surfaces are shown in Fig. 1.

In common with a previous study, surface roughness decreases as the growth temperature is reduced. The root-mean-square roughness is reduced from 7.23 nm on the hottest-grown sample to 3.49 nm for the sample grown at 350 °C. The samples grown at 410 °C have definite striations running parallel to the [01-1] direction. However, these are not apparent in the coolest samples, whose surfaces display little superstructure. The average feature height on the surface comparable to that of unstrained In$_{0.75}$Ga$_{0.25}$As and residual strain anisotropy found to be less than 1%. Atomic force microscopy (AFM) images of the sample surfaces are shown in Fig. 1.

FIG. 1. (Color online) $15\times15$ μm$^2$ AFM images reveal significant variation in surface roughness with growth temperature. As an aid to comparison, the $z$-axis scale on each image is 30 nm.

410 °C samples was 2.59±1.60 nm. The length of these features was measured to be 0.34±0.11 μm in the [011] direction and was 1.60±0.42 μm along [01-1] giving a length-to-width ratio of approximately 5.

A trace showing representative SdH oscillations in the longitudinal resistivity of a 2DEG appears as Fig. 2. For the data shown, the electron density, calculated from the gradient had negligible effect on the overall electron density. In fact, sustained illumination reduced the electron density, calculated from the gradient had negligible effect on the overall electron density. In fact, sustained illumination reduced n slightly, adversely affecting the transport characteristics. Gate bias was used to control $n$ in the channel and the response can be conveniently modeled by treating the gate/polyimide/channel system as a simple capacitor, which gives $dn/dV=\varepsilon_0\varepsilon_r/e$.$\ell$. The relative dielectric constant of the HD Microsystems polyim-
ide used here was $\varepsilon_r=2.9$. So, for a polyimide thickness of $t=450$ nm, gate response is calculated to be $dn/dV=0.356 \times 10^{11}$ cm$^2$/V. This is in good agreement with the experimental value of $dn/dV=0.385 \times 10^{11}$ cm$^2$/V at low gate voltage.

Electron density was varied from 2DEG “pinchoff” up to the onset of gate leakage ($I>10$ nA). Magnetotransport measurements were performed at various gate voltages to allow $\mu$ as a function of $n$ to be plotted for each sample (Fig. 3). For each curve, $\mu$ saturates at high $n$. Single peaks in all FFTs of the SdH oscillations show single subband population. The saturation in $\mu$ at elevated $n$ cannot therefore be attributed to intersubband scattering. The gradient of the curves from the two median samples grown at 410 °C gives a power-law dependence of $\alpha=0.48$. An earlier study indicates that transport is thus limited by background-impurity (BI) scattering. This result is in good agreement with previous work into scattering in these undoped structures. For $n<2 \times 10^{11}$ cm$^{-2}$, $\mu$ is shown to be limited by BI scattering. It is only at higher $n$ that the contribution due to alloy-disorder scattering becomes significant. BI scattering is therefore likely to be responsible for limiting peak mobility in these samples.

The 5 min growth interruptions necessitated by the need to cool the indium cell are very long and therefore need optimization to minimize the deleterious effect of background-impurity incorporation at the buffer surface. However, short interruptions to group III fluxes at a heterojunction also allow surface migration of adsorbed species. Although the extent of this is dependent on growth conditions, this migration can lead to a lengthening of the monolayer-high terraces and smoother interfaces. This in turn results in increased mobility via reduced interface-roughness scattering. In future, two In cells will negate the need for such interruptions, thus permitting an investigation into whether they provide any net benefit.

For growth temperatures below 410 °C, peak $\mu$ is reduced from 221 000±6000 to 47 000±900 cm$^2$/V s at 350 °C as growth becomes less stoichiometric. Above 410 °C, however, peak $\mu$ is also reduced, with just 65 000±1300 cm$^2$/V s measured at 470 °C. This is due to lower $n$ and increasingly poor surface morphology. This is shown in Fig. 4, where a Gaussian fit to these data indicates that for high $\mu$, growth temperature is close to optimal at 410 °C. Over the same growth temperature range, peak electron density decreases exponentially from ($3.44\pm0.04$) $\times 10^{11}$ cm$^{-2}$ at 350 °C to ($0.98\pm0.02$) $\times 10^{11}$ cm$^{-2}$ at 470 °C.

Magnetotransport measurements at 400 mK yield a peak electron mobility, for the 410 °C samples, of $\mu=227\ 000\pm5000$ cm$^2$/V s. With negative gate bias it was possible to reduce $n$ to 8.0 $\times 10^{10}$ cm$^{-2}$ while still measuring $\mu>100\ 000$ cm$^2$/V s for these same samples. Indeed, just above pinchoff, values of $n=5.15\times10^{10}$ cm$^{-2}$ and $\mu=44\ 000$ cm$^2$/V s were measured.

The 2DEGs grown at 410 °C agree exactly with the highest peak electron mobilities published to date for such structures. It is important to note, however, that this peak $\mu$ has been achieved with an electron density as low as 1.36 $\times 10^{11}$ cm$^{-2}$; that is, with a twofold reduction in $n$ compared with that earlier work. The only major difference in growth conditions is that the V/III ratio during growth of those earlier samples was lower, at $\sim12$. The employment of a thinner InAlAs buffer appears to have been successful in reducing $n$. This supports the conclusion that a trap in the In$_{0.75}$Al$_{0.25}$As is the source of the 2DEG electrons. The decrease in electron-electron screening which has occurred as a result of this lowering of $n$ has not affected overall electron mobility. The use of a superlattice below a step-graded buffer to trap impurities and dislocations in future samples may lead to yet higher electron mobility.

To investigate transport anisotropy in these samples, Hall bars were fabricated parallel to two orthogonal crystal axes: [011] and [01-1]. $\mu$ versus $n$ curves for two such Hall bars taken from a sample grown at 410 °C are shown in Fig. 5. The curves are approximately colinear at low electron densities. However, $\mu$ saturates more quickly at high $n$ for devices fabricated parallel to [01-1] and in this direction, for similar values of $n$, $\mu$ is reduced by 10%. This anisotropic behavior was representative of all samples measured and is in agreement with previous observations. Surface features on these samples, as measured by AFM (see Fig. 1), are shown to be five times longer in the [01-1] direction. Structural anisotropy has been noted in similar material systems and explained by differing group III reaction rates between...
the cation- and anion-terminated step edges in these orthogonal directions.21 As peak $n$ is reached, the Fermi wavelength ($\lambda_F$) reaches a minimum of $\approx 60$ nm. At high $n$, $\lambda_F$ is sufficiently small that electrons moving parallel to [01-1] experience enhanced interface-roughness scattering compared to those traveling orthogonally.20 Hence, at least in the regime where $n > 1.5 \times 10^{11}$ cm$^{-2}$, it is proposed that the high-$\mu$ direction for devices is parallel to [011].

IV. CONCLUSIONS

The growth temperature for undoped In$_{0.75}$Ga$_{0.25}$As QW HEMTs on InP has been optimized at 410 °C. Insulated gate response has been shown to be in good agreement with theory in the limit of low applied bias. Electron mobility saturates at high $n$ and peak values of $\mu = 221,000$ cm$^2$/V s at $n = 1.36 \times 10^{11}$ cm$^{-2}$ are reported here. This peak $\mu$ is in excellent agreement with the highest values previously published. It is argued therefore that this is the fundamental peak electron mobility for these devices, a limit set by alloy-disorder and background-impurity scattering.

However, this work demonstrates that the electron density required to achieve this maximum value can be significantly reduced. The use of a thinner graded buffer has more than halved the peak electron density supporting the hypothesis that the 2DEG electrons originate within the InAlAs. That, in combination with low background-impurity incorporation, has resulted in these low-$n$/high-$\mu$ systems. For values of $n > 8.0 \times 10^{10}$ cm$^{-2}$ electron mobilities of $\mu > 100,000$ cm$^2$/V s are achieved. Electron transport is isotropic below $n > 1.5 \times 10^{11}$ cm$^{-2}$. Above this, the high-$\mu$ direction for such devices is parallel to [011] and is attributed to anisotropic surface morphology.


FIG. 5. (Color online) $\mu$ as a function of $n$ for Hall bars fabricated parallel to [011] and [01-1].