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Room-temperature mobility above $2200 \text{ cm}^2/\text{V}\cdot\text{s}$ of two-dimensional electron gas in a sharp-interface AlGaIn/GaN heterostructure

Jr-Tai Chen,^{a)} Ingemar Persson, Daniel Nilsson, Chih-Wei Hsu, Justinas Palisaitis, Urban Forsberg, Per O. Å. Persson, and Erik Janzén

Department of Physics, Chemistry, and Biology, Linköping University, SE 581 83 Linköping, Sweden

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A high mobility of $2250 \text{ cm}^2/\text{V}\cdot\text{s}$ of a two-dimensional electron gas (2DEG) in a metalorganic chemical vapor deposition-grown AlGaIn/GaN heterostructure was demonstrated. The mobility enhancement was a result of better electron confinement due to a sharp AlGaIn/GaN interface, as confirmed by scanning transmission electron microscopy analysis, not owing to the formation of a traditional thin AlN exclusion layer. Moreover, we found that the electron mobility in the sharp-interface heterostructures can sustain above $2000 \text{ cm}^2/\text{V}\cdot\text{s}$ for a wide range of 2DEG densities. Finally, it is promising that the sharp-interface AlGaIn/GaN heterostructure would enable low contact resistance fabrication, less impurity-related scattering, and trapping than the AlGaIn/AlN/GaN heterostructure, as the high-impurity-contained AlN is removed. © 2015 AIP Publishing LLC.
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The transport properties of AlGaIn/GaN high electron mobility transistor (HEMT) structures have been studied intensively over the last two decades. In the high temperature regime ($>300 \text{ K}$) of interest for most device applications, the mobility of the two-dimensional electron gas (2DEG) formed near the AlGaIn/GaN interface has been theoretically calculated and shown to be ultimately limited by phonon scattering.^{1,2} Nevertheless, in practice, other important scattering mechanisms related to structural imperfections of the materials including alloy disorder and interface roughness could actually influence the 2DEG mobility. Room-temperature 2DEG mobility in the AlGaIn/GaN heterostructure is typically reported in the range from 1300 to $1600 \text{ cm}^2/\text{V}\cdot\text{s}$, depending on the 2DEG density and the Al content of the AlGaIn barrier.^{3,4} By inserting a thin ($1\text{--}2 \text{ nm}$) AlN exclusion layer (AlN_{ex}) at the AlGaIn/GaN interface, the 2DEG mobility can be remarkably increased to $\sim 2200 \text{ cm}^2/\text{V}\cdot\text{s}$.^{5–7} This mobility improvement is associated with better 2DEG confinement near the interface, reducing the penetration of the electron wave function into the AlGaIn barrier, so that the scattering due to alloy disorder is alleviated.⁸ However, the presence of the thin AlN_{ex} layer (or high-Al-content AlGaIn layer) can raise the surface potential in a HEMT structure owing to its wide band gap nature, rendering difficulties in obtaining low ohmic contact resistance,⁹ which is essential for high-frequency applications. Additional recess etching into the AlGaIn barrier for contact metallization processes becomes necessary to reduce the contact resistance.^{10,11} In this work, we show that the 2DEG mobility can be greatly improved in metalorganic chemical vapor deposition (MOCVD)-grown AlGaIn/GaN heterostructures by sharpening the interface, without inserting an AlN_{ex} layer. The effect of different AlGaIn/GaN interface structures on the 2DEG properties is presented, utilizing high-resolution scanning transmission electron microscopy (STEM).

The AlGaIn/GaN HEMT structures were grown on $2 \times 2 \text{ cm}^2$ 4H-semi-insulating (SI) SiC substrates in a hot-wall MOCVD system at a pressure of 50 mbar in a mixture of N_2 and H_2 as the carrier gases. Details of the hot-wall MOCVD reactor and the complete HEMT structure growth process have been presented elsewhere.^{7,12} A series of AlGaIn/GaN HEMT samples were grown to investigate the structural details in various AlGaIn/GaN interfaces and their effects on the 2DEG properties. The series consists of three $\sim 28\text{-nm}$ -thick $\text{Al}_{0.17}\text{Ga}_{0.83}\text{N}/\text{GaN}$ HEMT samples, denoted S1–S3. The growth conditions were identical for the three HEMT samples, except for the condition during the transition from the GaN layer to the AlGaIn layer. Three different interface structures of the AlGaIn/GaN heterostructure were specifically prepared. The samples S1 and S2 are the AlGaIn/GaN heterostructures without and with inserting a nominal 2-nm -thick AlN_{ex} layer at the interface. The AlN_{ex} layer growth at a rate of $\sim 3.5 \text{ nm/min}$ was carried out with our standard recipe,⁷ a TMAI flow of 0.7 ml/min ($31.5 \mu\text{mol/min}$) together with a NH_3 flow of 21 l/min (2000 sccm). For the sample S3, the heterostructure was grown with the aim to obtain a sharp interface. Thus, a low flow rate of TMAI, 0.23 ml/min ($10.4 \mu\text{mol/min}$), together with the NH_3 flow of 21 l/min for 13 s was introduced to the growth zone right after the GaN growth. Besides, it is worth pointing out that a 200-nm -thick intrinsic GaN spacer layer grown at 1080°C with residual C, Si, and O concentrations below the SIMS detection limit of $\sim 1 \times 10^{16} \text{ cm}^{-3}$ was used in all the HEMT structures to prevent possible trapping effects and ionized impurity scattering that can adversely affect 2DEG mobility.¹² The samples were characterized by mercury-probe capacitance-voltage (CV) measurements to extract the pinch-off voltage. A contactless eddy-current technique and a Leighton (LEI 1610) contactless mobility system were performed to measure the sheet resistance (R_s) and the 2DEG density and the mobility, respectively. Afterwards, STEM was employed to analyze the interfacial structures of the three samples. Table I summarizes the electrical properties of the three HEMT samples.

^{a)} Author to whom correspondence should be addressed. Electronic mail: jrche@ifm.liu.se.

TABLE I. Summary of the electrical properties of the samples S1, S2, and S3.

HEMT sample	S1	S2	S3
Interface	No AlN _{ex}	AlN _{ex}	Sharpened
2DEG mobility (cm ² /V·s)	1669	2190	2154
2DEG density (cm ⁻²)	6.34×10^{12}	7.8×10^{12}	6.50×10^{12}
Rs (Ω/sq)	612	330	450
Pinch-off voltage (V)	-3.0	-4.2	-3.1

Comparing the samples S1 and S2, it is clear to see that the 2DEG mobility was greatly enhanced from 1669 to 2154 cm²/V·s, as expected, with insertion of the AlN_{ex} layer. However, the 2DEG density and the pinch-off voltage were also increased, indicating that the thickness and the polarization contributed from the AlN_{ex} layer are not negligible. On the other hand, the sample S3 exhibits almost identical electrical properties as sample S1, except for a very high mobility, up to 2140 cm²/V·s. This mobility improvement leads to 36% reduction of Rs, from 612 Ω/sq of S1 to 450 Ω/sq of S3. To rule out the possibility that the difference observed in the mobility might be associated with different levels of dislocation scattering,¹³ high-resolution x-ray diffraction rocking curve measurements were carried out. The crystalline quality of the three samples was found similar. The rocking curves of the GaN (002) and (102) peaks in full width of half maximum for the three HEMT samples are all similar, ~120 and ~200 arcsec, respectively. Therefore, in order to clarify the mechanism of the enhanced mobility exhibited from S3, cross-sectional STEM was then performed on the three HEMT samples to access the structural characteristics in the AlGaIn/GaN interface region. Prior to the analysis, the STEM samples were prepared by standard polishing and argon ion milling procedures. The imaging was performed using the double aberration corrected Linköping Titan³ 60–300 (S)TEM equipped with a monochromated high brightness Schottky field emission gun operating at 300 kV. Energy dispersive x-ray (EDX) measurements were performed with a Super-X EDX spectrometer and STEM images were acquired using a high angle annular dark field (HAADF) detector.

The cross-sectional STEM-HAADF images and the corresponding EDX line profiles across the AlGaIn/GaN interface for the samples S1, S2, and S3 are shown in Fig. 1. Figs. 1(a)–1(c) show the STEM-HAADF images of the samples S1, S2, and S3, respectively, where the dashed lines and the arrows indicate the EDX probing direction and the interfaces, respectively. As seen in Fig. 1(a), the interface of S1 is obscure, suggesting that the elemental composition across the interface is mixed. In contrast, the sample S2 with the nominal AlN_{ex} layer shows a very sharp AlN_{ex}/GaN interface as shown in Fig. 1(b). However, it is clear that the following AlN_{ex}/AlGaIn interface is not as sharp as the AlN_{ex}/GaN interface. Besides, the AlN_{ex} layer thickness was confirmed to be around 2.5 nm by taking the second derivative of the Al-K EDX line profile. Furthermore, comparing Fig. 1(c) with Fig. 1(a), the sample S3 apparently exhibits a sharper AlGaIn/GaN interface than S1. The interface sharpness is more readily visualized by presenting the Al-K EDX

FIG. 1. STEM-HAADF images of the samples (a) S1, (b) S2, and (c) S3, and (d) the EDX spectra of the three samples in the AlGaIn/GaN interface region.

line profile across the interface, starting from the GaN layer and into the AlGaIn or AlN_{ex} layers. The corresponding EDX spectra of the three samples are shown in Fig. 1(d), with the onset of the interfaces aligned with respect to each other to facilitate comparison. For the samples S1 and S3, though both exhibit the same heterostructure, their Al profiles are quite different as shown. The Al profile from the GaN to the AlGaIn in S1 requires ~2.0 nm to reach the level at the average concentration of the AlGaIn layer, while the transition in S3 is comparably abrupt and requires less than 1.0 nm to the Al level of the AlGaIn. We propose that this is the explanation for the recorded mobility difference as seen between the samples S1 and S3. This proposal is further supported by the fact that the high-mobility sample S2 also exhibits an abrupt Al transition at the interface of AlN_{ex}/GaN.

In principal, a sharp-interface AlGaIn/GaN heterostructure would enable better carrier confinement as a result of the abrupt conduction band offset, which is supposed to give rise to the same effect on the 2DEG mobility as the insertion of an AlN_{ex} layer into the heterostructure. To confirm this scenario, a multi-carrier mobility-spectrum measurement¹⁴ was performed in the Lehigh system on the three HEMT samples, the analysis of which can resolve individual carrier mobilities, densities, and their contributions to the conductivity in multi-carrier materials. The mobility spectrum gives an idea of the mobility distributions of various fractions of the free electrons. The analysis result is shown in Fig. 2. The pink, red, and blue spectra represent the mobility distributions of the 90%, 50%, and 10% of the free electrons, respectively. Obviously, S2 and S3 have much higher peak mobility than S1. More importantly, S1 shows a broader mobility distribution than S2 and S3. This evidences that the carrier confinement in sharp-interface S2 and S3 is similar and indeed better than that in S1, consequently

FIG. 2. Multi-carrier mobility distributions of the samples S1, S2, and S3.

leading to higher mobility. We found that this experimental work is in good agreement with a theoretical calculation¹⁵ predicting that when the width of the AlGaIn/GaN heterointerface is reduced from 2 nm to 0.5 nm, the amount of electron gas located in GaN would be considerably increased, so that the 2DEG experiences less alloy disorder and/or interface roughness scattering.

Clearly, the introduction of the low-flow-rate TMAI to the growth zone during the growth transition from the GaN to the AlGaIn was the key process to abruptly raise the Al content. It is likely that the TMAI flow can surpass the residual Ga in the gas phase or on the growth surface, thus the Ga incorporation is suppressed to a certain extent during the interface transition. The influence of the residual Ga can be also observed on the nominal AlN_{ex} layer, because in fact the AlN_{ex} layer is a high Al-content AlGaIn layer instead of a pure AlN layer. Such influences from the residual elements could result in a memory effect, which leads to a gradual and diffuse elemental transition at the interface like the AlGaIn/GaN interface of S1 and the AlGaIn/AlN_{ex} interface of S2. This has been a common phenomenon seen in MOCVD growth processes. Now, the proposed method for interface sharpening seems to be an effective process route.

To establish a reproducible interface sharpening process, another series of HEMT samples containing a ~21-nm-thick Al_{0.19}Ga_{0.81}N/GaN heterostructure were grown, the interface of which was exposed to a TMAI flow of 0.20 ml/min (9.0 μmol/min) with a NH₃ flow of 2 l/min for varying duration before the AlGaIn growth. Fig. 3 shows the 2DEG density, the mobility, and the pinch-off voltage as a function of the TMAI flow time, measured from this series of HEMT samples. From Fig. 3(a), no explicit increase of the 2DEG density and the pinch-off voltage was observed until the TMAI flow time reached 30 s, suggesting that no distinct

FIG. 3. (a) 2DEG density and pinch-off voltage as a function of the TMAI flow time and (b) 2DEG mobility as a function of the TMAI flow time.

pure AlN or high Al-content AlGaIn interlayer was formed at the interface of AlGaIn/GaN heterostructure when the TMAI flow time of <30 s was applied. The slight increase in the 2DEG density and the pinch-off voltage is likely associated with the additional piezoelectric polarization contributed from the abrupt raise of the Al content at the interface. Moreover, provided that the thickness of AlN growth is linearly proportional to the TMAI flow rate and flow time, the TMAI flow of 0.20 ml/min for 30 s would give rise to approximately a 0.5-nm-thick AlN layer, which is in the same order of a unit cell height of III nitride materials. Thus, the flow time of <30 s should not lead to a formation of a single interlayer. However, the mobility was increased considerably from 1630 to ~2050 cm²/V·s when the TMAI flow time of 15 and 20 s was applied, and then it saturated around 2250 cm²/V·s when the flow time is ≥ 30 s, as shown in Fig. 3(b). Therefore, it appears that a stable interface sharpening process can be realized when a low-flow-rate TMAI is applied. The optimal flow time would depend on the reactor configuration, the wafer size, and so forth.

Finally, the properties of the sharp-interface Al_xGa_{1-x}N/GaN heterostructures with different Al contents of the AlGaIn were investigated. A series of HEMT samples with three different compositions for a 13-nm AlGaIn barrier layer such that $x = 0.20, 0.32$, and 0.45 , respectively, were grown using the interface sharpening recipe of the 20 s TMAI flow time. The 2DEG density was increased from $6.0 \times 10^{12} \text{ cm}^{-2}$

FIG. 4. 2DEG mobility and sheet resistance as a function of the 2DEG density and the corresponding $\text{Al}_x\text{Ga}_{1-x}\text{N}$ composition.

to $1.4 \times 10^{13} \text{ cm}^{-2}$ as a result of the increased Al content in the AlGa_N barrier. Nevertheless, the 2DEG mobility was very high for all the samples, as shown in Fig. 4. The lowest sheet resistance obtained in the series was $225 \text{ } \Omega/\text{sq}$ for the sample with $x = 0.45$ barrier layer. The highest mobility was $2250 \text{ cm}^2/\text{V}\cdot\text{s}$ for the sample with the 2DEG density of $1.0 \times 10^{13} \text{ cm}^{-2}$. This result highlights the importance of the interface sharpness in the 2DEG transport properties.

Furthermore, since it has been shown that the residual impurities in AlGa_N tend to increase with Al content, especially when the growth is not performed at a very high temperature,^{16–18} using a sharp interface instead of inserting an AlN exclusion layer in the AlGa_N/Ga_N heterostructure thus has a great potential of reducing impurity-related scattering and trapping effects. Both effects could adversely influence the 2DEG properties, especially when the hot electrons are injected or pushed into the AlN or high-Al-content AlGa_N exclusion layer during high-field device operations.^{9,19,20}

In summary, a very high 2DEG mobility was achieved in a simple AlGa_N/Ga_N heterostructure by the sharpened interface grown in a MOCVD reactor. Beyond this improvement, it is promising for this type of high-mobility heterostructure to have lower contact resistance and to experience less impurity-related scattering and trapping when operating at high-frequency high-field regimes. Additionally, the interface sharpening method can also be applied to enhance the

carrier confinement in the growth of other heterostructures such as multi-quantum wells in light emitting diode structures.

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