Normally-Off Operation of Lateral Field-Effect Transistors Fabricated from Ultrapure GaN/AlGaN Heterostructures

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The presence of a 2D electron gas (2DEG) in GaN/Al$_{1-x}$Ga$_x$N heterostructures with low aluminum mole fraction is found to depend on the residual background impurity concentration in the GaN/AlGaN layer stack. At a residual donor level of $2 \times 10^{16}$ cm$^{-3}$, a 2DEG is absent at 300 K in dark environment. Such a 2DEG can be generated at the GaN/AlGaN interface either by illumination with ultraviolet light or by applying an electrostatic potential. The latter results in inherently normally-off switching characteristics of lateral field-effect transistors.

1. Introduction

Group-III nitrides and their heterostructures have become key elements in energy-saving daily life applications, such as white solid-state lighting[1] and short wavelength lasers for data storage concepts.[2] Single-interface gallium nitride/aluminum gallium nitride (GaN/AlGaN) heterostructures feature a highly mobile electron channel with mobilities exceeding 2000 cm$^2$ (V s)$^{-1}$ at room temperature.[3] Combined with the large bandgap of 3.4 eV and the associated high critical breakdown field strength as well as thermal and chemical stability of this compound material, GaN-based devices increasingly emerge in high-frequency and power applications.[4,5]

The aforementioned mobile channel at the GaN/AlGaN interface is a 2D electron gas (2DEG) in close proximity to the surface (10–50 nm) with record low-temperature electron mobility in excess of $10^5$ cm$^2$ (V s)$^{-1}$.[6] Due to polarization changes at the GaN/AlGaN interface, a confinement potential is formed[7] which is usually flooded with electrons. One possible source of these charges is surface states, from which the electrons are transferred into the confinement potential.[8] Following this view, in such structures the generation of the 2DEG does not require intentionally introduced donors which would also act as efficient Coulomb scattering centers. However, one disadvantageous consequence of this undesirable existing 2DEG for applications in lateral heterostructure field-effect transistors (HFETs) is the associated normally-on switching characteristics, a drawback for fail-safe device designs.

Technologically, this normally-on characteristics can be converted into the desired normally-off fashion, for example, by an additional recess etch step, an extra p-type GaN or AlGaN layer beneath the gate electrode[4,5] or a hybrid GaN/Si cascode technology approach.[9] but all of which require additional processing efforts and costs.

Recent observations point at the importance of the residual oxygen donor impurity level for the presence of a 2DEG in the GaN/AlGaN stack[10] and the related consequences for lateral FET operation.[11] It is found that for oxygen background levels of $\approx 10^{16}$ cm$^{-3}$ FETs cannot be fully switched off, while at $\approx 10^{17}$ cm$^{-3}$ they operate in depletion-mode (normally-on)[12,13] Here it is demonstrated that at an even lower residual oxygen level of $2 \times 10^{16}$ cm$^{-3}$, lateral FETs exhibit enhancement-mode (normally-off) transfer characteristics.

2. Experimental Section

2.1. Growth of the GaN/AlGaN Heterostructure and Device Fabrication

The nominally undoped GaN/AlGaN layer stack was grown by molecular beam epitaxy (MBE) on a 2 in. insulating GaN substrate at 700 °C. As a first layer, a 1 μm-thick GaN buffer layer was grown, followed by a 16 nm-thick Al$_{0.06}$Ga$_{0.94}$N barrier, which was capped with 3 nm GaN (inset of Figure 1). The growth procedure (reported in detail in ref. [10]) resulted in material with an unintentional oxygen background of $2 \times 10^{16}$ cm$^{-3}$ as analyzed...
by secondary ion mass spectroscopy (SIMS). Oxygen represented a shallow donor with ionization energy of \( \frac{25}{30} \text{meV} \). In reference samples, no difference for the incorporation of oxygen in GaN and Al\(_x\)Ga\(_{1-x}\)N with low aluminum mole fraction (\( x < 0.1 \)) was observed.\(^{13} \) Silicon and carbon were found to be below the SIMS detection limits.

Small pieces of the 2 in. wafer were used for further device processing. Hall bars and transistor test structures were lithographically defined and mesa structures patterned in a reactive ion etch step using chlorine-based plasma. Ti/Al/Ni/Au stacks annealed at 800 \( \degree \text{C} \) in nitrogen atmosphere for 30 s served as ohmic contacts. For transistors, the entire surface (including contacts, mesa, and etched regions) was covered with 27 nm Al\(_2\)O\(_3\) by atomic layer deposition. A 100 nm-thick Ti/Au film served as gate electrode. To electrostatically access the device channel in the vicinity of the source and drain, these ohmic contact stacks were partially covered by the gate electrode (Figure 2).

### 2.2. Measurement Routines

Capacitance versus gate–source voltage \( C(V_{GS}) \) measurements were carried out by sweeping a quasistatic DC bias voltage modulated with an AC signal with a frequency of 20 kHz and with an amplitude of 30 mV using an Agilent B1505A Power Device Analyzer equipped with a capacitance measurement unit. The DC bias voltage at the gate electrode was swept in the direction from lower to higher voltages with a staircase-like sweep pattern and a rate of approximately 0.5 V s\(^{-1}\). Depth profiles of the charge carrier density were extracted by applying the data transformation according to Ambacher et al.\(^{21} \) after subtracting a constant offset capacitance. This offset capacitance accounted for the direct overlap of the gate and ohmic contacts in the FET devices. Transfer \( I_D(V_{GS}) \) characteristics and two-terminal \( I_{DS}(U_{DS}) \) data were obtained with the same device analyzer.

A \(^3\)He cryostat equipped with a superconducting magnet (up to 15 T) was used for low-temperature magneto-transport studies. The sample photoexcitation at 325 nm wavelength was realized with the fiber-coupled output of a He–Cd laser. The large distance of \( \approx 20 \text{mm} \) between the bare fiber end (numeric aperture = 0.22) and the sample surface enabled a good uniformity of both the illumination and the resulting 2DEG density as confirmed by the onset of Shubnikov–de Haas (SdH) oscillations. The photoexcitation power was attenuated by optical filters and then measured at the fiber input. The fiber optical transmission amounted to \( \approx 80\% \). Magneto-transport data were recorded using a low-frequency lock-in technique.

### 3. Results and Discussion

Hall bars processed from the ultrapure GaN/Al\(_{0.06}\)Ga\(_{0.94}\)N heterostructure show insulating behavior at 300 K and in dark environment, i.e., the two-terminal resistance is larger than
50 MΩ and currents measured with a parameter analyzer below 1 V source-drain voltage \( U_{SD} \) are within the noise level. When illuminated with ambient light (e.g., from fluorescent ceiling lamps) however, the longitudinal Hall bar conductivity increases by three orders in magnitude, manifesting the formation of a conductive channel (Figure 1). The ambient light must possess a spectral component below 400 nm wavelength; mere visible light does not yield changes in the electrical conductivity. The influence of illumination on the conductivity at 300 K is reversible. When the ultraviolet (UV) light is blanked, the conductivity drops and finally vanishes within minutes or hours, depending on the opaqueness of the cover used. If the housing is absolutely light-tight, the conductivity fades away within 10 min. The question regarding the nature of the conducting channel remains. In the next paragraphs, the 2D character will be unambiguously demonstrated.

The 2D nature of the conductive channel was verified in low-temperature magneto-transport measurements under steady UV laser excitation. From the SdH oscillations in the longitudinal resistance of a Hall bar at 0.5 K, the 2D electron density can be extracted by assigning the corresponding Landau-level filling factors (Figure 3). Three important conclusions can be drawn: first, the observed SdH oscillations are characteristic to 2D systems. On top of this, the longitudinal resistance at magnetic fields of about 10 T reaches zero. This concludes that the conductive channel does not only possess a 2D component, rather this 2D channel is the only conduction path in the layer stack at low temperature. Second, the extracted 2D electron density of \( 2.5 \times 10^{12} \text{ cm}^{-2} \) at low excitation power matches well with previously reported values in such type of heterostructure.\(^6\) Finally, when varying the excitation power over almost five orders in magnitude, the 2D density only changes by 20%, manifesting a tremendous channel robustness.

Alternatively to low-temperature magneto-transport measurements, the 2DEG can be identified in charge carrier profiles obtained from capacitance versus gate-source voltage \( C(V_{GS}) \).\(^7\) These \( C(V_{GS}) \) measurements were carried out with lateral FET devices. The absence of the 2DEG in the dark requires an overlap of the gate and source/drain contacts to electrostatically address their surroundings (Figure 2). This processing scheme inevitably requires the deposition of an insulator (e.g., Al₂O₃) after the ohmic contact formation to electrically separate the gate from source/drain. For both cases, under UV illumination and while electrostatically induced in the dark, the electron density peaks at the GaN/AlGaN interface and drops below \( 10^{10} \text{ cm}^{-3} \) after 100 nm (Figure 4). This localized charge distribution is consistent with the low-temperature magneto-transport data and supports the existence of a 2DEG at 300 K.

The possibility to form a conductive channel at the GaN/AlGaN interface under UV illumination or electrostatically in the dark can be exploited for FET operation. Lateral FETs, as shown in Figure 2, operate in enhancement-mode in dark environment at 300 K (Figure 5) with an on-to-off current ratio >\(10^6\). This inherent normally-off operation is attributed to the absence of a 2DEG in the pristine heterostructure. FETs are switched off at 0 V gate voltage; no current can pass from source to drain. By applying positive gate–source voltage however, electrons will accumulate at the GaN/AlGaN interface and switch on the transistors above 1.5 V. Under steady UV illumination, a conductive channel is present and the FETs show normally-on transfer characteristics, i.e., the transistor is not switched off after reducing the gate voltage to zero. A negative gate voltage of \( \approx -1.5 \text{ V} \) is required to turn off the device. A low source–drain current in the FET off-state within the noise limit of the measurement setup implies that the 1 μm-thick GaN buffer layer is highly resistive, even under illumination.

The switching characteristics of FETs and the conductivity change between the dark and under UV illumination point at significantly different Fermi-level positions at the surface in these two regimes. Under UV illumination the heterostructure will be flooded with photoexcited electrons from the valence band and the surface (quasi) Fermi level will be pushed toward the

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**Figure 3.** Low-temperature magneto-transport data recorded under steady homogeneous UV laser illumination of a Hall bar as shown in Figure 1. The SdH oscillations in the longitudinal resistance are characteristic for a 2D electron system; zero values at \( \approx 10 \text{T} \) (at 60 nW excitation) exclude parasitic conduction in competition with the 2DEG. The 2D electron density is extracted from the Landau filling factors and changes only slightly upon varying the excitation power over almost five orders in magnitude.
conduction band edge. As a consequence, the confinement potential formed at the GaN/AlGaN interface due to polarization discontinuities will be populated with electrons. In contrast to the situation under illumination, the surface Fermi level in the dark seems to be pinned deep inside the GaN bandgap, as suggested by the 2.7 V shift (difference) in the threshold voltages under illumination and in the dark (Figure 5). The exact figure of the surface potential in the dark will depend on the structural properties of the surface layers and possible impurities, e.g., carbon acting as a deep acceptor\textsuperscript{[14]} or even some intrinsic defects.\textsuperscript{[15]} Despite the fact that no carbon is found in our MBE material, a residual level below the SIMS detection limit might be present. A thorough computational study on the role of material parameters—in particular the surface potential— influencing the 2DEG density in the presented type of GaN/AlGaN heterostructure is underway.\textsuperscript{[16]}

4. Conclusions

At low residual donor impurity (specifically oxygen) level of $2 \times 10^{16}$ cm$^{-3}$, a 2DEG is absent in GaN/Al$_{0.06}$Ga$_{0.94}$N heterostructures at 300 K in dark environment. A 2DEG populating the native confinement potential resulting from polarization discontinuities at the GaN/AlGaN interface can be induced either optically or electrostatically. Lateral FETs fabricated from the heterostructure operate in enhancement-mode, desired for practical fail-safe applications. The root cause for the absence of a 2DEG seems to be a large surface potential of the GaN cap layer and an associated Fermi level at the channel position far below the conduction band edge. The results manifest that these characteristics enable a future generation of normally-off as well as light-sensitive GaN-based device concepts.
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Conflict of Interest

The authors declare no conflict of interest.

Keywords

molecular beam epitaxy growth, normally-off field-effect transistor, ultra-pure GaN/AlGaN heterostructures, 2D electron gas

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