Simulation Study of the Impact of Traps in GaN Substrates on the Electrical Characteristics of AlGaN/GaN HEMTs with Thin Channel Layers

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Research Article

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Editor-in-Chief 
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Dear Editor,

Please find enclosed our manuscript entitled “Simulation Study of the Impact of Traps in GaN Substrates on the Electrical Characteristics of AlGaN/GaN HEMTs with Thin Channel Layers,” which we request you to consider for publication as original article in Journal of Computational Electronics

Our paper describes a novel way to design gallium nitride (GaN) high electron mobility transistors (HEMTs). Because GaN HEMTs are valuable in everyday radio-frequency (RF) systems, such as radar and satellite communications, and enhanced performance is needed for advanced systems, improving their design is a great advantage. Native GaN substrates have potential for HEMTs because they have a homo-epitaxial growth layer with a low defect density. We have studied the effects of trap concentration in the GaN substrates and how a trade-off relationship develops.

We have investigated how traps in a GaN substrate affect GaN HEMTs by a device simulation. We focus on the trade-off relationship that exists between leaks, transient response and low-frequency small-signal-gain that hinders RF performance. Our results confirm that an AlGaN back-barrier structure is highly effective for minimizing leakage and improving trade-off performance in GaN substrates.

This manuscript has not been published elsewhere and is not under consideration by another journal. We have approved the manuscript and agree with submission to Journal of Computational Electronics. There are no conflict of interest to declare.

We believe that the findings of this study are relevant to the scope of your journal and will be of interest to its readership.

Sincerely,

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Simulation Study of the Impact of Traps in GaN Substrates on the Electrical Characteristics of AlGaN/GaN HEMTs with Thin Channel Layers

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Abstract
GaN substrates are promising candidates for GaN high electron mobility transistors (HEMTs) due to their epitaxial layer growth with a low defect density. In this study, technology computer-aided design simulations were executed to design the GaN HEMTs on semi-insulating GaN substrates with thin channel layers. Traps in the GaN substrates played a role in suppressing drain-leakage currents, although degrading transient responses changed the bias from off to on-state for the 0.02-μm thin channel layer. A trade-off relationship between the drain-leakage current and transient response is occurred by changing the trap concentration in the GaN substrates. The AlGaN back-barrier structure has been found to be highly effective in suppressing the drain-leakage current in low-trap-concentration GaN substrates. The trade-off relationship improved by adopting the back-barrier layers, and the maximum drain current decreased. The drain-current reduction was compensated by increasing the A1 content in the barriers without degrading the trade-off relationship. Therefore, for GaN HEMTs that have low-trap-concentration GaN substrates combined with the back-barrier layer, a high-Al-content barrier have characteristics that are favorable for the trade-off relationship in the case of thin channel layers. Moreover, the traps in GaN substrates were found to affect low-frequency S21, which is important for linearity of the power amplifier, as critically as the transient responses.

Keywords Gallium nitride (GaN) high electron mobility transistor (HEMT), GaN substrate, simulation, thin channel, transient response, drain-leakage current, low frequency S parameter

1 Introduction
GaN high electron mobility transistors (HEMTs) are promising candidates for high-power and high-frequency radio-frequency (RF) systems such as radar, satellite communications, and base stations because GaN semiconductors feature highly critical electric fields and a high saturation velocity [1-3]. Although RF amplifiers that use GaN HEMTs have already been commercialized, advanced systems require increased performance. It is possible to improve the RF performances of GaN HEMTs, which can be achieved by exploiting the III-Nitride semiconductors' intrinsically excellent physical properties.

GaN HEMTs have traditionally used AlGaN/GaN epitaxial layers that are grown on SiC or Si substrates. The lattice-mismatched substrates cause crystal defects to be introduced because of hetero-epitaxial growth. Defects in the epitaxial layers are known to strongly affect the electrical characteristics as electron traps [4-9]. The AlGaN/GaN heterostructures with many threading dislocation densities have a large gate-leakage current [4]. The traps in the buffer layer and at the semiconductor's surface degrade transient-response characteristics such as current collapse, drain-lag and gate-lag [5-9]. For GaN HEMTs on SiC substrates, the suppressed trap effect requires a thick GaN buffer layer with a thickness of around 1 μm because of the decreased number of defects that have been introduced from the difference of the lattice constants between the GaN and SiC substrates [7]. However, adopting a thick GaN epitaxial layer has the disadvantage of increased drain-leakage currents, which are a limiting factor for the high-frequency operation of GaN HEMTs with a short gate length. Intentionally introducing the traps into the GaN buffer layer is a way to decrease the drain-leakage current [7]. Therefore, the traps play a role in reducing the drain-leakage current and degradation of the transient responses. This trade-off restricts the performances of the GaN HEMTs that have been fabricated on the lattice-mismatched substrates.

Semi-insulating GaN substrates are promising native candidates in GaN HEMTs for RF applications [3]. The homoepitaxial method of growing GaN layers on GaN substrates is expected to achieve not only low defect density but also the thin channel layer that is desirable for a high-frequency operation with a short gate length. The AlGaN/GaN epitaxial layers that were grown on GaN substrates have either low reverse leakage currents or a high electron mobility compared to the epitaxial layers that were grown on the lattice-mismatched substrates [10], [11]. Many papers reported on GaN HEMTs fabricated on GaN substrates [12-25]. A high power density of 9.4 W/mm at 10 GHz was demonstrated by operating with a high drain bias of 50 V [13]. A remarkable current-collapse reduction was obtained using GaN HEMTs with an extremely low dislocation density on GaN substrates [16-19, 22]. Additionally, a degradation of the direct current (DC) and dynamic performances after 3-MeV proton irradiation became lower using metal-insulator-semiconductor HEMTs on the GaN substrates [20]. An excellent high power-added-efficiency of 82.8% at 2–3 GHz was demonstrated recently using GaN substrates with a reduced Si contamination at the interface for the epitaxial layers [25]. The reported results indicate that GaN substrate usage improves DC
and RF performances.

GaN substrates for a high-frequency RF amplifier are required to have high resistance to suppress parasitic conduction loss at RF operations. GaN semiconductors can increase the resistance by introducing iron (Fe) or carbon (C) atoms, which create the deep level in the GaN bandgap [26-29]. The traps capture the conducting electrons and release them after a long characteristics time, so with the deep levels, the traps increase the resistivity but degrade the transient response that affects the RF performances. When the gate length for the high-frequency operation shortens, that reduced thickness of the epitaxial layers effectively suppresses the drain-leakage current [30]. The transient response from the off-to-on state bias worsens as the thin channel layers decrease [31]. These simulation results show that precise control of the traps is necessary for obtaining the GaN HEMTs’ maximum performance on a GaN substrate. However, the traps’ impacts on a GaN substrate for GaN HEMTs with thin channel layers are not clear.

In this paper, a technology computer-aided design (TCAD) simulation investigates the traps’ effects for GaN HEMTs on a GaN substrate. We focused on the trade-off relationship between the drain-leakage current and the transient response from off-to-on state bias (corresponding to current collapse), when the trap concentration in the GaN substrate and channel-layer thickness change. Moreover, the power gain ($S_{21}$) in the small signal response is calculated in a low-frequency range. The low-frequency dispersions in the gain destroy the linearization of GaN HEMTs and cause long-term memory effects on RF systems such as a Doherty power amplifier in cellular base stations [32-34].

2 Device structures and simulation conditions

2.1 Device structures of GaN HEMTs on GaN substrates

The simulation was performed by using the Atlas of Silvaco device simulators in TCAD [35]. Figure 1 shows a schematic-cross sectional GaN HEMT structure on GaN substrates for the simulation. The epitaxial layers include the buffer, channel, and barrier located on the GaN substrates. The buffer, channel, and GaN substrate layers contain common acceptor traps. For the trap parameters, the energy level below the conduction band and the capture cross section were fixed at 0.6 eV and $5.0 \times 10^{-15}$ cm$^2$ for all GaN layers and the substrate, respectively [36]. Approximately 0.6 eV for the trap’s energy level is a common value for the experimental results and is observed for the GaN grown on not only SiC but also GaN substrates [8, 9, 27, 36-40]. The trap concentration of the channel layer was fixed to be at as low as $1.0 \times 10^{15}$ cm$^{-3}$ [37]. The Al content and barrier layers’ thickness were 0.2 and 10 nm, respectively. The channel-layer thickness was changed from 0.02 to 1.0 μm because it is an important parameter for the short-channel effect. This study used two kinds of barrier layers: one is the GaN buffer layer, which is usually used for traditional GaN HEMTs, and the other is an AlGaN back-barrier layer, which aims to confirm two-dimensional electron gas (2DEG) to the channel layer and improve the short-channel effects [41-43]. The Al content of the back-barrier layers was 0.08. Both buffer layers had the same trap concentration of $2.0 \times 10^{15}$ cm$^{-2}$ and thickness of 0.1 μm. The GaN substrates were fixed to be as thick as 100 μm, which is similar to a realistic value. However, the trap concentration of GaN substrates was changed from $10^{15}$ to $10^{16}$ cm$^{-3}$. Heavily doped thin layers were located under the source and drain electrodes to ensure the ohmic characteristics (not shown in Fig. 1). The gate had a T-shaped structure, and its length and work function were 0.6 μm and 5.0 eV, respectively. The distances from the source to the gate electrodes and from the gate to the drain electrodes were 0.6 and 2.0 μm, respectively. Additionally, the gate width was 1 mm.

2.2 Simulation conditions

The DC characteristics, transient response, and small-signal $S$ parameters were calculated without a self-heating effect, and some figures of merit were selected to study the trade-off relationships. The typical simulation results are shown in Fig. 2. Figure 2(a) shows the drain current ($I_{DS}$) that depends on the drain voltage ($V_{DS}$). The drain current at $V_{DS} = 40$ V and $V_{GS} = 2$ V had a maximum value and was adopted as the figure of merit ($I_{DSMAX}$) for $I_{DS}$. Figure 2(b) shows $I_{DS}$ calculated as a function of gate voltage ($V_{GS}$). Because the pinch-off voltage is approximately −1 V, GaN HEMTs are in the off-state condition at $V_{GS} = −5$ V. The drain-leakage currents increase as $V_{DS}$ increases from 10 to 40 V. We adopted $I_{DS}$ at the off-state condition ($V_{DS} = 40$ V and $V_{GS} = −5$ V) as a figure of merit for the drain-leakage current. This is called $I_{DSOFF}$, and $I_{DSOFF}$ is $3.0 \times 10^{-7}$ A/mm in Fig. 2(b). Depending on the time, in the transient responses, $I_{DS}$ was calculated when $V_{DS}$ and $V_{GS}$ were changed from the off-state bias ($V_{GSOFF} = −5$ V) to the on-state bias ($V_{DSP} = 5$ V and $V_{GSP} = 0$ V). Figure 1(c) shows the normalized $I_{DS}$ as a function of time. The start $V_{DS}$ in the off-state bias ($V_{DSOFF}$) was 20 or 40 V. $I_{DS}$ was normalized by DC value at the on-state bias. The normalized $I_{DS}$ was below the DC value until approximately 1 ms. The $I_{DS}$ capturing the electron in the deep levels was small. The normalized $I_{DS}$ increased to the DC value after 1 ms, and reached the DC values at 0.1 s. The characteristic time of the trap was evaluated using the Schockley–Read–Hall defect model [44]. Because the characteristic time for the trap energy level was 41 ms, the changes in $I_{DS}$ in Fig. 2(c) result from the traps. The normalized $I_{DS}$ for $V_{DSSQ} = 40$ V was lower than that for $V_{DSSQ} = 20$ V. The normalized $I_{DS}$ at 1 ms for $V_{DSSQ} = 40$ V was adopted as a figure
3 Simulation results and discussion

3.1 Dependence on channel thickness

The thin channel layer is useful for high-frequency operations. This section discusses the effects of the traps in GaN substrates by calculating channel-thickness dependence. Figure 3 shows the \( I_{DS} - V_{GS} \) curves and transient-response characteristics as a function of channel thickness for relatively high trap concentration of \( 2.0 \times 10^{16} \text{ cm}^{-3} \) in the GaN substrates. The channel thickness was changed from 0.02 to 1.0 \( \mu \text{m} \). Figure 3(a) shows how \( I_{DS} \) depends on \( V_{GS} \) at high \( V_{DS} \) of 40 V. Under the on-state condition, \( I_{DS} \) has characteristics that are similar for all channel thicknesses, because 2DEG is located on the channel side of the hetero interface, between the barrier and channel layer, and the electron concentration in 2DEG is almost independent of the channel thickness. In subthreshold regions, \( I_{DS} \) decreases drastically when the channel-layer thickness decreases from 1.0 to 0.1 \( \mu \text{m} \). Under the pinch-off voltage for a channel-layer thickness less than 0.1 \( \mu \text{m} \), \( I_{DS} \) is almost the same as the very low value of \( 10^{-10} \text{ A/mm} \). Therefore, GaN HEMTs with a thin channel layer effectively suppress the drain-leakage current. Figure 3(b) shows the transient responses from the off-state bias (\( V_{DS} = 40 \text{ V}, V_{GS} = -10 \text{ V} \)) to the on-state bias (\( V_{DS} = 5 \text{ V}, V_{GS} = 0 \text{ V} \)). Normalized \( I_{DS} \) increases from 1 ms and reaches the DC value for all channel-layer thicknesses. When the channel-layer thickness is thinner, the normalized \( I_{DS} \) below 1 ms decreases. Therefore, traps in the GaN substrate have a negative effect on the transient response for the thin channel layer, although the trap concentration is constant. As shown in Figs. 3(a) and (b), GaN HEMTs with a thin channel layer are found to effectively suppress the drain-leakage current but are worse for the transient response.

Figure 4 shows two-dimensional (2D) plots of the current density at the off-state bias (\( V_{DS} = 40 \text{ V}, V_{GS} = -5 \text{ V} \)) for 0.02-, 0.7-, and 1.0- \( \mu \text{m} \) channel thicknesses. In the case of a thin 0.02- \( \mu \text{m} \) channel layer, the current density is extremely low for all regions between the source and drain. The drain-leakage currents flow from the drain to the source through the region of merit of the transient response. The power gain (\( S_{21} \)) in the \( S \) parameters was calculated as an on-state bias (\( V_{GS} = 0 \text{ V} \)). Figures 2(d) and (e) show the real and imaginary parts of \( S_{21} \) for a low-frequency range. The real parts of \( S_{21} \) increase monotonically from 100 to 1000 Hz. However, the imaginary part of \( S_{21} \) has a zenith that is caused by the traps, and the peak frequency corresponds to the region of increasing \( I_{DS} \) in the real parts of \( S_{21} \). As a figure of merit of \( S_{21} \), the peak magnitude in the imaginary part at \( V_{DS} = 40 \text{ V} \) was adopted.
under the gate for the thick 0.7- and 1.0-μm channel layers, and become larger for the thicker channel. As shown in Figs. 4(b) and (c), the depletion layer, which extends from the gate electrode, is considered to reduce the electrons within the 0.2-μm thickness. Therefore, the 0.02-μm channel-layer thickness is sufficient thin to suppress the drain-leakage current that flowed under the gate. A larger drain-leakage current flows for a thicker channel layer because of a wider space for the current flow under the gate.

Figure 5 shows 2D plots of the ionized trap density at 1ms in the transient response for channel thickness of (a) 0.02, (b) 0.7, and (c) 1.0 μm. Bias is changed from off state (V_{DS} = 40 V and V_{GS} = −10 V) to on state bias (V_{DS} = 5 V and V_{GS} = 0 V). Trap concentration of GaN substrates (N_{TSUB}) is $2 \times 10^{16}$ cm$^{-3}$.

3.2 Effects of the trap concentration in GaN substrates for GaN HEMTs with thin channel layers

This section discusses the characteristics of GaN HEMTs with a thin 0.02-μm GaN channel layer that was simulated by changing the trap concentration in the GaN substrates. Additionally, we investigate for GaN HEMTs both with and without an AlGaN back-barrier layer. Figure 6 shows the I_{DS}-V_{GS} curves, transient response, and imaginary parts of S_{21} for a normal GaN HEMT structure without a back-barrier layer. The trap concentration in the GaN substrates was changed from $10^{15}$ to $10^{16}$ cm$^{-3}$. As shown in Figs. 6(a) and (b), both the drain-leakage current and I_{DS} at 1 ms in the transient response decrease when the trap concentration increases. For a high trap concentration of $10^{16}$ cm$^{-3}$, the drain-leakage current can be suppressed, although the transient response degrades; that is, the normalized I_{DS} is as small as 0.78 times the DC value. However, in the case of a lower trap density, the transient response has better characteristics, although the drain-leakage current has larger values. Both the moderate suppression of the drain-leakage current and positive transient response are satisfied for the $5.0 \times 10^{15}$ cm$^{-3}$ trap concentration, although it seems that there is room for an improved transient response. Figure 6(c) shows the imaginary parts of S_{21} at the on-state bias (V_{DS} = 40 V and V_{GS} = 0 V). The peak frequencies for the different trap concentrations in the GaN substrates are almost
Fig. 6 (a) $I_{DS}$-$V_{GS}$ curves, (b) transient response from off-state to on-state bias, (c) imaginary parts of $S_{21}$ in low frequency region as parameters of trap concentrations in GaN substrates ($N_{TSUB}$). Channel thickness is as thin as 0.02 μm.

Fig. 7 Two-dimensional plots of current density at off-state bias for substrate trap concentration of (a) $10^{16}$, (b) $3 \times 10^{16}$ and (c) $5 \times 10^{16}$, and (d) $10^{17}$ cm$^{-3}$. Channel thickness is 0.02 μm. $V_{DS}$ and $V_{GS}$ are 40 and −5 V, respectively.

Fig. 8 Depth profiles of (a) conduction band energy ($E_c$), (b) electron concentration ($n_e$) and (c) ionized trap density ($n_{TI}$) under gate edge of drain side at 1 ms in transient response for various trap concentration in GaN substrates ($N_{TSUB}$). Position is defined distance from hetero interface. Bias is changed from off-state ($V_{DS} = 40$ V and $V_{GS} = −10$ V) to on-state bias ($V_{DS} = 5$ V and $V_{GS} = 0$ V). Channel thickness is 0.02 μm.

the same because peak frequency corresponds to the characteristics time which is dominated by the trap energy level and capture cross section. The peak magnitudes decrease as the trap concentrations in the GaN substrates decrease because the signal response is attributed by traps in the GaN substrates.

Figure 7 shows the 2D plots of the current density at the off-state bias ($V_{DS} = 40$ V and $V_{GS} = −5$ V) for various trap concentrations in the GaN substrates. The depletion region spreads into the GaN substrate through the channel and buffer layers because of the thin 0.02-μm channel layer. In the channel region, the current flows from the drain to the source suppress in all cases of trap concentrations. The current flows in the GaN substrate, as shown in Fig. 7(a), because traps as low as $10^{15}$ cm$^{-3}$ are not sufficient to suppress the leakage current. When the trap concentrations in the GaN substrates increase, the leakage current decreases. Figure 8 shows the conduction band energy, electron concentration, and ionized trap density under the gate edge of the drain side at 1 ms in the transient responses from the off-state bias ($V_{DS} = 40$ V and $V_{GS} = −10$ V) to the on-state bias ($V_{DS} = 5$ V and $V_{GS} = 0$ V). The origin of the position axis is the barrier layer’s surface. The conduction-band energy in the substrate increases when the trap concentration in the GaN substrates increases. As shown in Fig.8(b), the region with the highest electron concentration in the buffer and
and imaginary parts of the low-frequency $S_{21}$

The back-barrier layers are extremely effective in suppressing the drain-leakage current even for the low $10^{15}$-cm$^{-3}$ trap concentration. When the trap concentration in the GaN substrates increases, the transient responses and low-frequency $S_{21}$ characteristics degrade, which are results that are similar to those of the structures without the back-barrier, as shown in Fig. 6(b) and (c). Therefore, back-barrier layers are considered not to have a large impact on the transient response and low-frequency $S_{21}$.

Figure 10 shows the 2D plots of the current density at the off-state bias ($V_{DS} = 40$ V and $V_{GS} = -5$ V) for GaN HEMTs with the back-barrier layer. The scale is the same as that in Fig. 7 for GaN HEMTs without back-barrier layers. The leakage current does not flow for all of the trap-concentration cases. The back-barrier layers are extremely effective in suppressing the drain-leakage current even for the low $10^{15}$-cm$^{-3}$ trap concentration in the GaN substrates. Figure 11 shows the conduction-band energy, electron concentration, and ionized trap density under the gate edge of the drain side at 1 ms in the transient responses from the off-state to on-state biases. The origin of the position axis is the surface of the barrier layer (the same as Fig. 8). The conduction-band energy in the GaN substrate increases when the trap concentration in the GaN substrates increases. The growth of the conduction-band energy causes the conduction-band energy to rise at the surface of the channel layer. This growth indicates that the normalized $I_{DS}$ at 1 ms in the transient responses decreases as the trap concentration in the GaN substrates increases, as shown in Fig. 9(b). Figure 11(b) shows the electron-concentration profiles for various trap concentrations in the GaN substrates.
concentrations in GaN substrates. The electron concentration is extremely low in the buffer and GaN substrates compared with that in Fig. 8(b) for the GaN HEMTs without the back-barrier structure. This low concentration in the GaN substrates results in the suppression of the drain-leakage current. Figure 11(c) shows the ionized trap density as a function of the position in the depth position. The traps in the GaN substrates ionize almost all traps close to the buffer layer. Because the ionized traps have a negative charge, there are additional negative charges for higher trap concentrations in GaN substrates, which results in the higher energy level for the conduction band.

The figures of merit for the back-barrier structure are compared with one another for the structure with no back-barrier. Figure 12(a) shows $I_{DSMAX}$ as a function of the trap concentration in GaN substrates. $I_{DSMAX}$ does not depend on the trap concentration in the GaN substrates for the structures both with and without the back-barrier layers. GaN HEMTs with the back-barrier layer have smaller $I_{DSMAX}$ because the back barrier raises the conduction band energy at the channel’s surface. Figure 12(b) shows the normalized $I_DS$ at 1 ms in the transient responses that depend on the trap concentration in the GaN substrates. The GaN HEMTs, both with and without the back-barrier layer, have similar values and tendencies where the normalized $I_DS$ at 1 ms decreases as the
trap concentration in GaN substrates increases. Figure 12(c) shows the $I_{\text{DSOFF}}$ ($I_{\text{DS}}$ at the off-state bias ($V_{\text{DS}} = 40 \text{ V}$ and $V_{\text{GS}} = -5 \text{ V}$]) both with and without the back-barrier layers. $I_{\text{DSOFF}}$ is decreased by applying the back-barrier layers. The drain-leakage current improves dramatically at the $10^{15}$-cm$^{-3}$ low-substrate trap concentration. Figure 12(d) shows the peak magnitudes in the imaginary parts of $S_{21}$ as a function of the trap concentration in GaN substrates. The back-barrier layers make the peak magnitude small. As shown in Fig. 12(b) and (d), the transient response and low-frequency $S_{21}$ do not change much with or without the back-barrier layers. Therefore, the back-barrier layers contribute toward the suppression of the drain-leakage current rather than the improvement of the transient response and low-frequency $S_{21}$.

Figure 13 illustrates the trade-off relationships between the figures of merit. Figure 13(a) shows $I_{\text{DSOFF}}$ versus normalized $I_{\text{DS}}$ at 1 ms in the transient responses. $I_{\text{DSOFF}}$ increases when the normalized $I_{\text{DS}}$ at 1 ms increases. This correlation indicates that there is a trade-off relationship between $I_{\text{DSOFF}}$ and normalized $I_{\text{DS}}$ at 1 ms and that the back-barrier layer can ease this trade-off relationship. As shown in Fig. 13(b), the peak magnitudes of $S_{21}$ correlate with the transient responses because these effects result from the traps in GaN substrates. GaN HEMTs with a back-barrier layer have good $S_{21}$ values for the same transient response. As shown in Fig. 13(c), $I_{\text{DSOFF}}$ improves (decreases) as the $S_{21}$ values degrade, i.e., there is a trade-off relationship. Both the low-drain-leakage current and small magnitude of imaginary $S_{21}$ parts are obtained using the back-barrier layers.

### 3.3 Characteristics of GaN HEMTs with a back-barrier layer and a barrier layer with high Al content

In the previous section, the back-barrier structures can reduce the negative effects of small $I_{\text{DS}}$ in the transient responses and the large $S_{21}$ signal at a low frequency, and the low drain-leakage current continues. However, as is evident from Fig. 12(a), the maximum drain current decreased by adopting the back-barrier layer. In this section, GaN HEMTs that have a high Al content in the barrier layer have been studied to increase the maximum drain current.

Figure 14 shows the characteristics of the GaN HEMTs with 0.22 Al content in the barrier layer. The structure is the same as that calculated in Section B, except for the barrier’s Al content. The trap concentration in the GaN substrates is as low as $10^{15}$ cm$^{-3}$ to obtain a satisfactory transient response and low-frequency $S_{21}$. The back-barrier layer is adopted to reduce the drain-leakage current. From 14(a) of the $I_{\text{DS}}$–$V_{\text{DS}}$ curves, the maximum 1.2 A/mm drain current is obtained at $V_{\text{DS}} = 40 \text{ V}$ and $V_{\text{GS}} = 2 \text{ V}$. The drain-leakage current is suppressed to be lower than $10^{-10}$ A/mm for $I_{\text{DS}}$ in the off-state condition, as shown in the $I_{\text{DS}}$–$V_{\text{GS}}$ curves of Fig. 14(b). As these curves in a subthreshold region do not depend on $V_{\text{DS}}$, the back-barrier layer is useful in suppressing the drain-leakage current. Figure 14(c) shows the transient responses for $V_{\text{DSQ}}$ of 20 and 40 V. The normalized $I_{\text{DS}}$ at 1 ms is as high as 0.98 even if there is high $V_{\text{DSQ}}$ of 40 V. Figure 14(d) shows the imaginary parts of $S_{21}$ in the low-frequency region. The peak magnitudes decrease as $V_{\text{DS}}$ increases from 10 to 40 V. Figures 12 and 13 include the data for GaN HEMTs with the 0.22 high Al content and back-barrier layer (called back-barrier 2). The maximum $I_{\text{DS}}$ becomes as large as GaN HEMTs without the back-barrier layer, as shown in Fig. 12(a). However, the drain-leakage current and transient response maintain almost the same values as the GaN HEMTs with the back-barrier layers. The peak magnitude in the imaginary parts of $S_{21}$ becomes slightly high, as shown in Fig. 12(d). The trade-off relationships between the figures of merit maintain good positions in Fig. 13, in addition to increasing the maximum drain current.

Figure 15 shows the characteristics when the gate length was changed from 0.5 to 0.05 μm for the GaN HEMTs with the back-barrier and high-Al-content barrier layers. Figure 15(a) shows how $I_{\text{DS}}$ depends on $V_{\text{DS}}$ at $V_{\text{GS}} = 2 \text{ V}$. The maximum $I_{\text{DS}}$ increases from 1.3 to 1.6 A/mm as the gate length decreases. Figure 15(b) shows $I_{\text{DS}}$ versus $V_{\text{GS}}$ of the high $V_{\text{DS}}$ of 40 V. When the gate length is shortened from 0.5 to 0.05 μm, the slopes in the subthreshold region increase, and the drain-leakage current occurs in the low $V_{\text{GS}}$ because of the short-channel effects. However, the drain leakage current below $V_{\text{GS}} = -3 \text{ V}$ is suppressed to be lower than $5 \times 10^{-6}$ A/mm, even for 0.05 μm, which is the shortest gate length. The transient responses at high $V_{\text{DSQ}}$ of 40 V have good characteristics, with around 0.98 at 1 ms for all gate lengths, as shown in Fig. 15(c). Figure 15(d) shows the imaginary parts of $S_{21}$ in the low-frequency region at the on-state bias ($V_{\text{DS}} = 40 \text{ V}$).
and $V_{GS} = 0 \text{ V}$). The peak magnitudes increase as the gate length decreases from 0.5 to 0.25 $\mu$m. Below the 0.25-$\mu$m gate length, the magnitudes of the peak are almost the same at 0.3, which is not extremely large, as compared with that in Fig. 12 or 13. Figure 15(e) shows the threshold voltage depending on the gate length. Threshold voltage is defined as the voltage extrapolated from the point with the maximum slope of the $I_{DS}-V_{GS}$ curves at $V_{DS}$ of 40 V and decreases rapidly from the 0.1-$\mu$m gate length. Therefore, GaN HEMTs on the GaN substrates with the back-barrier layer and the high Al content barrier layer apply to the short gate length effectively.
4 Conclusion

In this work, the GaN HEMT structures on GaN substrates with thin channel layers were investigated in terms of the trade-off relationship between the drain-leakage current, transient response from the off-state bias to the on-state bias, and low frequency $S_{21}$ using TCAD simulations. The dependence on the channel-layer thickness was calculated for a relatively high trap concentration of $2 \times 10^{16} \text{cm}^{-3}$ in the GaN substrates. The drain-leakage current was suppressed at less than the channel thickness of 0.1 $\mu$m, and the transient response are degraded. This finding indicates that the thin channel layer is not preferable for RF applications in the case of GaN substrates with a high trap concentration. Because the transient responses degraded owing to the presence of ionized traps in the GaN substrates, dependencies on the trap concentration were calculated for the GaN HEMTs with a 0.02-$\mu$m thin channel layer. The low trap concentration of $10^{15} \text{cm}^{-3}$ in the GaN substrates improves both the transient response and low-frequency $S_{21}$ characteristics. The drain-leakage current of $10^{-3} \text{A/mm}$ is extremely large at high $V_{DS}$ of 40 V because of the leaks in the GaN substrates, which indicates that a satisfactory trade-off relationship cannot be obtained just by adopting the low trap concentration in GaN substrates for GaN HEMTs with a thin channel layer. To suppress the drain-leakage current without increasing the trap concentration, the AlGaN back-barrier layer is adopted. A significantly decreased drain-leakage current by seven orders is obtained by the back-barrier layer rather than the buffer layers, especially at a low trap concentration of $10^{15} \text{cm}^{-3}$ in GaN substrates. For the back-barrier layer, the weak point is the deceased maximum drain current. We investigated how the GaN HEMTs increase the AI content from 0.20 to 0.22 in the barrier layers. The GaN HEMTs have high $I_{DS}$ and good trade-off relationships between the drain-leakage current, transient response, and low-frequency $S_{21}$. Finally, we confirmed that this structure can operate for a short gate length of 0.05 $\mu$m despite the threshold-voltage decrease.

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Figures

Figure 1

Schematic cross-sectional structure of GaN HEMTs on GaN substrates for simulation.
Figure 2

Typical characteristics calculated. (a) $I_{DS} - V_{DS}$ curves, (b) $I_{DS} - V_{GS}$ curves, (c) transient response from off to on-state bias, and (d) real and (e) imaginary part $S_{21}$ in low frequency region. Channel thickness and trap concentration of GaN substrates are 1.0 $\mu$m and $2 \times 10^{16}$ cm$^{-3}$, respectively.
Figure 3

(a) $I_D - V_{DS}$ curves and (b) transient response as parameters of channel thickness ($d_{CHA}$). Trap concentration of GaN substrates is $2 \times 10^{16}$ cm$^{-3}$.

Figure 4

Two-dimensional plots of current density at off-state bias for channel thickness of (a) 0.02, (b) 0.7, and (c) 1.0 μm. $V_{DS}$ and $V_{GS}$ are 40 and −5 V, respectively. Trap concentration of GaN substrates is $2 \times 10^{16}$ cm$^{-3}$.

Figure 5

Two-dimensional plots for ionized trap density at 1ms in transient response for channel thickness of (a) 0.02, (b) 0.7, and (c) 1.0 μm. Bias is changed from off state ($V_{DS} = 40$ V and $V_{GS} = −10$ V) to on state bias ($V_{DS} = 5$ V and $V_{GS} = 0$ V). Trap concentration of GaN substrates ($N_{TSUB}$) is $2 \times 10^{16}$ cm$^{-3}$.
Figure 6

(a) $I_D S - V_{GS}$ curves, (b) transient response from off-state to on-state bias, (c) imaginary parts of $S_{21}$ in low frequency region as parameters of trap concentrations in GaN substrates ($N_{TSUB}$). Channel thickness is as thin as 0.02 μm.

Figure 7

Two-dimensional plots of current density at off-state bias for substrate trap concentration of (a) $10^{15}$, (b) $3 \times 10^{15}$, (c) $5 \times 10^{15}$, and (d) $10^{16}$ cm$^{-3}$. Channel thickness is 0.02 μm. $V_{DS}$ and $V_{GS}$ are 40 and −5 V, respectively.

Two-dimensional plots of current density at off-state bias for substrate trap concentration of (a) $10^{15}$, (b) $3 \times 10^{15}$, (c) $5 \times 10^{15}$, and (d) $10^{16}$ cm$^{-3}$. Channel thickness is 0.02 μm. $V_{DS}$ and $V_{GS}$ are 40 and −5 V, respectively.
Figure 8

Depth profiles of (a) conduction band energy ($E_C$), (b) electron concentration ($n_E$) and (c) ionized trap density ($n_{TI}$) under gate edge of drain side at 1 ms in transient response for various trap concentration in GaN substrates ($N_{TSUB}$). Position is defined distance from hetero interface. Bias is changed from off-state ($V_{DS} = 40$ V and $V_{GS} = -10$ V) to on-state bias ($V_{DS} = 5$ V and $V_{GS} = 0$ V). Channel thickness is 0.02 $\mu$m.

Figure 9

(a) $I_{DS} - V_{GS}$ curves, (b) transient response from off to on-state bias, (c) imaginary $S_{21}$ in low frequency as parameters of trap concentration in GaN substrates ($N_{TSUB}$) for GaN HEMTs with AlGaN back-barrier layers. Channel thickness is 0.02 $\mu$m.
Figure 10

Two-dimensional plots of current density for trap concentration in GaN substrate of (a) $10^{15}$, (b) $3 \times 10^{15}$, (c) $5 \times 10^{15}$ and (d) $10^{16}$ cm$^{-3}$ for AlGaN back-barrier structures. Channel thickness is 0.02 μm. $V_{DS}$ and $V_{GS}$ are 40 and $-5$ V, respectively.

Figure 11

Depth profiles of (a) conduction band energy ($E_C$), (b) electron concentration ($n_E$) and (c) trap ionized density ($n_{TI}$) under gate edge of drain side in transient response for AlGaN back-barrier for various trap concentration in GaN substrates ($N_{TSUB}$). Time in transient response is at 1 ms. Position is defined distance from hetero interface. Bias is changed from off-state ($V_{DS} = 40$ V and $V_{GS} = -10$ V) to on-state bias ($V_{DS} = 5$ V and $V_{GS} = 0$ V). Channel thickness is 0.02 μm.
Figure 12

(a) $I_{DS}$, (b) normalized $I_{DS}$ at 1 ms in transient response, (c) drain-leakage current, and (d) peak magnitude of imaginary $S_{21}$ as function of trap concentration in GaN substrates ($N_{TSUB}$). Back-barrier 2 has a higher 0.22-Al content than that of back-barrier 1. Channel thickness is 0.02 $\mu$m.

Figure 13

Trade-off relationships between (a) drain-leakage current and normalized $I_{DS}$ at 1 ms, (b) peak magnitude in imaginary $S_{21}$ and normalized $I_{DS}$ at 1 ms, (c) drain leakage current and peak magnitude
in imaginary $S_{21}$. Back barrier 2 has higher 0.22-Al content than that of back-barrier 1. Normalized $I_{DS}$ at 1 ms is defined in transient response from off to on-state bias. Channel thickness is 0.02 \( \mu \text{m} \).

**Figure 14**

Characteristics of GaN HEMTs with AlGaN back barrier and 0.22 high-Al-content barrier. (a) $I_{DS}$–$V_{DS}$ curves, (b) $I_{DS}$–$V_{GS}$ curves, (c) transient response from off to on-state bias, (d) real part and (e) imaginary $S_{21}$ in low frequency region. Channel thickness and trap concentration of GaN substrates are 0.02 \( \mu \text{m} \) and $10^{15}$ \( \text{cm}^{-3} \), respectively.
Figure 15

(a) $I_{DS} - V_{DS}$ curves, (b) $I_{DS} - V_{GS}$ curves, (c) transient response from off-to-on-state bias, (d) imaginary $S_{21}$ in low frequency as parameters of gate length. (e) Pinch-off voltage depending on gate length. GaN HEMTs have AlGaN back-barrier and high-Al-content barrier with thin channel layer. Channel thickness and trap concentration of GaN substrates are 0.02 $\mu$m and 10$^{15}$ cm$^{-3}$, respectively.