A simulation study of the impact of traps in the GaN substrate on the electrical characteristics of an AlGaN/GaN HEMT with a thin channel layer

Toshiyuki Oishi1 · Kaito Ito1

Received: 24 March 2021 / Accepted: 8 October 2021 / Published online: 26 October 2021
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract
Gallium nitride (GaN) substrates are promising candidates for GaN high-electron-mobility transistors (HEMTs) because of their epitaxial layer growth with low defect density. We perform device simulations to study the influence of substrate acceptor traps in GaN HEMTs on semiinsulating GaN substrates with a thin (0.02 μm) channel layer. When the trap concentration in the GaN substrate increases at a constant channel trap concentration of 1.0 × 10^{15} \text{ cm}^{-3}, the drain leakage current decreases but the transient response worsens. These phenomena result from an increase of the conduction-band energy due to ionized acceptor traps with negative charge. For GaN buffer structures, we obtain moderate suppression of the drain leakage current (1.7 × 10^{-9} \text{ A/mm}) and a good transient response (with a normalized drain current of 0.86 at 1 ms for the transient response from the off- to on-state condition) at a substrate trap concentration of 5.0 × 10^{15} \text{ cm}^{-3}. The aluminum gallium nitride (AlGaN) back-barrier structure is highly effective for suppressing the drain leakage current at a low trap concentration of 1.0 × 10^{15} \text{ cm}^{-3} in GaN substrates. Although its maximum drain current is decreased, this structure exhibits a low drain leakage current (4.7 × 10^{-11} \text{ A/mm}) and a high normalized drain current (0.95) in the transient response. Increasing the Al content in the barriers of the GaN HEMT structure increases its maximum drain current to 1.2 \text{ A/mm}, whereas the drain leakage current and transient response are well maintained. Moreover, the traps in the GaN substrate affect the low-frequency $S_{21}$, which is important for the linearity of power amplifiers, and the characteristics of $S_{21}$ are similar to those of the transient responses.

Keywords Gallium nitride (GaN) · High-electron-mobility transistor (HEMT) · GaN substrate · Device simulation · Thin channel · Transient response · Drain-leakage current · Low-frequency $S$ parameter

1 Introduction

Wide-bandgap materials such as GaN and diamond are expected to enable the realization of electronic devices (transistors and diodes) with performance beyond conventional devices that use silicon (Si) and gallium arsenide (GaAs) [1–5]. In particular, GaN high-electron-mobility transistors (HEMTs) are promising candidates for high-power and high-frequency radiofrequency (RF) systems such as radar, satellite communications, and base stations because GaN semiconductors feature highly critical electric fields and a high saturation velocity [3–5]. Although RF amplifiers that use GaN HEMTs have already been commercialized, advanced systems require increased performance. The RF performance of GaN HEMTs can be improved by exploiting the intrinsic physical properties of group III nitride semiconductors. Conventionally, GaN HEMTs have used AlGaN/GaN epitaxial layers grown on silicon carbide (SiC) or Si substrates. Lattice-mismatched substrates cause crystal defects because of heteroepitaxial growth. Defects in the epitaxial layers can significantly affect the electrical characteristics by acting as electron traps [6–12]. AlGaN/GaN heterostructures with threading dislocations exhibit high gate leakage currents [6]. The traps in the buffer layer and on the semiconductor surface degrade the transient response characteristics, such as the current collapse, drain lag, and gate lag [9–11]. For GaN HEMTs on SiC substrates, suppression of this trap effect requires the use of a thick GaN buffer layer with a thickness of approximately 1 μm, because of the reduction in the...
number of defects introduced by the difference in the lattice constants between the GaN and SiC substrates [11]. However, adopting a thick GaN epitaxial layer suffers from the disadvantage of increasing the drain leakage currents, which can limit the high-frequency operation of GaN HEMTs with a short gate length. Globally, traps are introduced into the GaN buffer layer to decrease the drain leakage current [9]. Therefore, the traps play a role in reducing the drain leakage current and degrading the transient response.

Semiinsulating GaN substrates are promising candidates for use in GaN HEMTs for RF applications [12]. The homoepitaxial method of growing GaN layers on GaN substrates is expected to achieve a low defect density and thin channel layer, which is desirable for high-frequency operation with a short gate length. AlGaN/GaN epitaxial layers grown on GaN substrates have low reverse leakage currents and high-electron mobility when compared with epitaxial layers grown on lattice-mismatched substrates [13, 14]. Many studies have reported GaN HEMTs fabricated on GaN substrates [15–27]. One study demonstrated a high power density of 9.4 W/mm at 10 GHz with a high drain bias of 50 V [15]. Other work obtained a remarkable reduction in the current collapse by using GaN HEMTs with an extremely low dislocation density on GaN substrates [18–21, 24]. Also, in one study, the degradation of the direct-current (DC) and dynamic performance was reduced after irradiation with 3-MeV protons of metal–insulator–semiconductor HEMTs on GaN substrates [22]. Recently, another study demonstrated an excellent high-power-added efficiency of 82.8% at 2–3 GHz by using GaN substrates with reduced Si contamination at the interface of the epitaxial layers [27]. The results indicated that the use of a GaN substrate improved both the DC and RF performance.

GaN substrates for high-frequency RF amplifiers must have a high resistance to suppress the parasitic conduction loss that occurs during RF operation. The resistance of GaN semiconductors can be increased by introducing iron (Fe) or carbon (C) atoms, which create traps in the GaN bandgap [28–31]. When the gate length is reduced for high-frequency operation, the reduced thickness of the epitaxial layers effectively suppresses the drain leakage current [32]. The traps in GaN substrates worsen the transient response from the off- to on-state bias as the channel-layer thickness decreases [33]. However, previous studies used Fe trap concentrations above $10^{17}$ cm$^{-3}$ [27, 32, 33]. Therefore, the trap effects in a GaN substrate with a low trap concentration are not clear.

In this study, we conduct device simulations to investigate the effects of traps in a GaN substrate for GaN HEMTs. We focus on the relationship between the drain leakage current and the transient response from the off- to on-state bias (corresponding to current collapse) when the trap concentration in the GaN substrate and the channel layer thickness change. Moreover, we calculate the power gain ($S_{21}$) in the small-signal response in the low-frequency range. The low-frequency dispersion in the gain destroys the linearity of GaN HEMTs and causes long-term memory effects in RF systems, such as Doherty power amplifiers for cellular base stations [34–36].

The remainder of this manuscript is organized as follows:

- **Section 2** describes the GaN HEMT structures and simulation methods, such as the model and calculation conditions.
- **Section 3** presents the results and discussion, as follows:
  - (a) **Section 3.1** shows that the transient response is strongly degraded for a channel layer thinner than 0.1 μm.
  - (b) **Section 3.2** describes the effects of traps in the GaN substrate of GaN HEMTs with channel layers as thin as 0.02 μm. A low trap concentration effectively improves the transient response. Combining a low trap concentration of $1.0 \times 10^{15}$ cm$^{-3}$ and the AlGaN back-barrier layer improves the drain leakage current, transient response, and small-gain magnitude, although the maximum drain current is decreased.
  - (c) **Section 3.3** shows that increasing the aluminum (Al) content in the barrier layer increases the maximum drain current without degrading the other characteristics.

- **Section 4** concludes this paper.

### 2 The device structures and simulation conditions

#### 2.1 The device structure of the GaN HEMT on a GaN substrate

Figure 1 and Table 1 present a schematic cross-sectional structure and the parameters of the GaN HEMT, respectively. The epitaxial layers (including the buffer, channel, and barrier) are placed on a GaN substrate. The thickness of the barrier and buffer layer is 10 nm and 0.1 μm, respectively. The channel layer thickness is 0.02 μm, whereas the channel layer thickness is varied from 0.02 to 1.0 μm in Sect. 3.1. We fix the GaN substrate to a thickness of 100 μm, which is approximately equal to that of realistic GaN HEMTs. We cover the surface with a silicon nitride (SiN) passivation layer with a thickness of 0.2 μm. The gate has a T-shaped structure, with bottom and head length of 0.6 and 1.0 μm, respectively. The distances from the source to the gate electrodes and from the gate to the drain electrodes are 0.6 and 2.0 μm, respectively. The Al content of the barrier layer is 0.2. The gate width is set to 1 mm.
two-dimensional devices [40]. For the GaN HEMT structure shown in Fig. 1, the potential and current density are determined by solving the Poisson, carrier continuity, and transport equations self-consistently. Equations (1) and (2) show the Poisson and carrier continuity equations:

$$\text{div}(\epsilon \nabla \psi) = -\rho,$$

$$\frac{\partial n}{\partial t} = \frac{1}{q} \text{div}(\overline{J_n}) - R_n, \quad \frac{\partial p}{\partial t} = \frac{1}{q} \text{div}(\overline{J_p}) - R_p.$$  (2)

In Eq. (1), $\epsilon$, $\psi$, $\rho$, and $\nabla$ are the permittivity, electrostatic potential, space charge density, and gradient operator, respectively. In Eq. (2), $q$ is the magnitude of the electron charge, $n$ and $p$ are the electron and hole concentration, $\overline{J_n}$ and $\overline{J_p}$ are the electron and hole current density, and $R_n$ and $R_p$ are the recombination rates for electrons and holes. $\overline{J_n}$ and $\overline{J_p}$ in Eq. (2) are applied in a drift–diffusion model that is expressed as

$$\overline{J_n} = -qn\mu_n\nabla\phi_n, \quad \overline{J_p} = -qp\mu_p\nabla\phi_p.$$  (3)

In Eq. (3), $\mu_n$ and $\mu_p$ are the electron and hole mobilities, while $\phi_n$ and $\phi_p$ are the quasi-Fermi potentials for electrons and holes, respectively. In the transient response calculation, the traps do not reach equilibrium immediately. This effect is taken into account by solving the following differential rate equation using the Shockley–Read–Hall recombination model:

$$\frac{dN_{iA}}{dt} = N_{iA} \left\{ v_n\sigma_n \left[ n(1 - F_{iA}) - gF_{iA} n_i \exp \left( \frac{E_i - E_i}{kT_L} \right) \right] - v_p\sigma_p \right\}.$$  (4)

In Eq. (4), $N_{iA}$ is the ionized trap density for acceptor traps, $v_n$ and $v_p$ are the thermal velocity for electrons and holes, and $\sigma_n$ and $\sigma_p$ are the capture cross-sections for electrons and holes. $F_{iA}$, $g$, $n_i$, $E_i$, $k$, and $T_L$ are the probability of ionization for acceptor traps, the degeneracy factor for traps, the intrinsic carrier concentration, the trap energy level, the intrinsic Fermi level, the Boltzmann constant, and the lattice temperature, respectively. The lattice temperature was constant at 300 K, and the self-heating effect was not considered. The lattice temperature increased because of self-heating, which reduces the drain current and improves the transient response. Although the self-heating effect should be considered in future work, the current results without self-heating are useful for studying the effects of traps in GaN substrates for GaN HEMTs with thin channel layers.

Table 2 lists the physical parameters used in the simulations. We adopt the parameter values based on our previous simulation of GaN HEMTs with a thick channel layer [41, 42]. The gate work function for the Schottky barrier is 5.0 eV. The spontaneous and piezoelectric polarization
The physical parameters of the GaN HEMT structure

| Parameter                              | Value          |
|----------------------------------------|----------------|
| Gate metal work function                | 5.0 eV         |
| Polarization charge density at AlGaN–GaN interface | $7 \times 10^{12}$ cm$^{-2}$ |
| Background doping concentration         | $1 \times 10^{12}$ cm$^{-3}$ |
| Channel acceptor traps:                |                |
| Energy level below $E_c$                | 0.6 eV         |
| Concentration                          | $1 \times 10^{15}$ cm$^{-3}$ |
| Capture cross-section                   | $5 \times 10^{-15}$ cm$^{2}$ |
| Buffer acceptor traps:                 |                |
| Energy level below $E_c$                | 0.6 eV         |
| Concentration                          | $1 \times 10^{15}$ cm$^{-3}$ |
| Capture cross-section                   | $5 \times 10^{-15}$ cm$^{2}$ |
| GaN substrate acceptor traps:          |                |
| Energy level below $E_c$                | 0.6 eV         |
| Capture cross-section                   | $5 \times 10^{-15}$ cm$^{2}$ |

are modeled as fixed charges of $7.0 \times 10^{12}$ cm$^{-2}$ at the barrier–channel interface. We ignore the polarization charge at the passivation–barrier interface [43]. Heavily doped thin layers are present under the source and drain electrodes to ensure ohmic characteristics (not shown in Fig. 1). The depth of the heavily doped layer was as shallow as 1 nm from the surface of the channel to prevent leakage between the heavily doped layers at the source and drain. The background doping concentration for all the semiconductor layers was $2.0 \times 10^{12}$ cm$^{-3}$, which is less than the trap concentration, to clarify the trap effect.

We set the GaN substrate as a semiconductor material with traps. The buffer, channel, and GaN substrate layers contain common acceptor traps. For the trap parameters, we fix an energy level below the conduction band and a capture cross-section of 0.6 eV and $5.0 \times 10^{-15}$ cm$^{2}$, respectively, for all the GaN layers and the substrate [44]. A trap energy level of approximately 0.6 eV is a common value from experimental results. The variation of the trap energy mainly affects the transient response and the imaginary part of $S_{21}$. When the trap energy level becomes large, the recovery time of the DC current in the transient response becomes slow. In the imaginary part of $S_{21}$, the signal peak moves to lower frequency. In this study, we focus on the effects of the substrate trap concentration for a fixed trap energy level. A trap energy of around 0.6 eV was observed for GaN grown on both SiC and GaN substrates [10, 11, 29, 44–47]. The trap concentration of the channel layer is fixed at $1.0 \times 10^{15}$ cm$^{-3}$ [45]. The trap concentration of the GaN substrates is varied from $10^{15}$ to $10^{16}$ cm$^{-3}$. The GaN and AlGaN buffer layers have the same trap concentration of $1.0 \times 10^{15}$ cm$^{-3}$. We carefully construct the mesh structure to make it thin at the interfaces of the layers. Also, we locate the mesh points at the interface between the different materials and the doping concentration.

### 2.3 The simulation conditions

We calculated the DC characteristics, transient response, and small-signal $S$ parameters; Figure 2 shows typical simulation results. Figure 2a shows the drain current ($I_{DS}$) as a function of the drain voltage ($V_{DS}$). $I_{DS}$ reaches its maximum value at $V_{DS} = 40$ V and $V_{GS} = 2$ V, which is denoted as $I_{DSMAX}$. Figure 2b shows the $I_{DS}$ calculated as a function of the 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 current increases as $V_{DS}$ is increased from 10 to 40 V. We define the drain leakage current $I_{DSOFF}$ to be the value of $I_{DS}$ in the off-state condition ($V_{DS} = 40$ V and $V_{GS} = -5$ V). In Fig. 2b, $I_{DSOFF} = 3.0 \times 10^{-3}$ A/mm.

In the transient response, we calculate $I_{DS}$ when changing $V_{DS}$ and $V_{GS}$ from the off-state bias ($V_{GSQ} = -5$ V) to the on-state bias ($V_{DSP} = 5$ V and $V_{GSP} = 0$ V). Figure 2c shows the normalized $I_{DS}$ as a function of time. The starting value of $V_{DS}$ in the off-state bias ($V_{DSQ}$) is 20 or 40 V. The DC value at the on-state bias is applied to normalize $I_{DS}$, which is below the DC value until approximately 1 ms. The normalized $I_{DS}$ increases to the DC value after 1 ms and reaches the DC value at 0.1 s.

The characteristic time of the trap is evaluated by using the Shockley–Read–Hall defect model [48]. Because the characteristic time for the trap in Table 2 is 41 ms, the changes in $I_{DS}$ in Fig. 2c result from the traps. The normalized $I_{DS}$ for $V_{DSQ} = 40$ V is lower than that for $V_{DSQ} = 20$ V. The normalized $I_{DS}$ at 1 ms for $V_{DSQ} = 40$ V is evaluated to study the transient response. The power gain ($S_{21}$) described using the $S$ parameter is calculated as an on-state bias ($V_{GS} = 0$ V). Figure 2d and e show the real and imaginary parts of $S_{21}$ in the low-frequency range. The real part of $S_{21}$ increased gradually from 100 to 1000 Hz. However, the imaginary part of $S_{21}$ shows a peak caused by the traps, and the peak frequency corresponds to the region of increasing $I_{DS}$ in the real part of $S_{21}$. The peak magnitude in the imaginary part of $S_{21}$ is evaluated at $V_{DS} = 40$ V to study its effects on the power gain.

### 3 The simulation results and discussion

#### 3.1 The dependence on the channel thickness

A thin channel layer is useful for high-frequency operation. In this section, we discuss the effects of the traps in the GaN substrate by calculating the channel thickness dependence. Figure 3 shows the $I_{DS}–V_{GS}$ curves and the transient response characteristics as a function of the channel thickness for a relatively high trap concentration of $2.0 \times 10^{16}$ cm$^{-3}$ in the GaN substrate. The channel thickness is varied from 0.02 to
Figure 2 shows the calculations of the typical characteristics, showing (a) the $I_{DS}-V_{DS}$ curves, (b) the $I_{DS}-V_{GS}$ curves, (c) the transient response from the off- to on-state bias, and (d) the real and (e) the imaginary parts of $S_{21}$ in the low-frequency region. The channel thickness and trap concentration of the GaN substrate are 1.0 μm and $2 \times 10^{16} \text{ cm}^{-3}$, respectively.

1.0 μm. Figure 3a shows $I_{DS}$ as a function of $V_{GS}$ at a high $V_{DS}$ of 40 V. In the on-state condition, $I_{DS}$ shows similar characteristics for all the channel thicknesses because the 2DEG is located on the channel side of the heterointerface between the barrier and the channel layer, and the electron concentration in the 2DEG is almost independent of the channel thickness.

In the subthreshold region, $I_{DS}$ decreases significantly when the channel layer thickness is decreased from 1.0 to 0.1 μm. Below the pinch-off voltage for a channel layer thickness of less than 0.1 μm, $I_{DS}$ 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 3b shows the transient response from the off-state bias ($V_{DS} = 40 \text{ V}$ and $V_{GS} = -10 \text{ V}$) to the on-state bias ($V_{DS} = 5 \text{ V}$ and $V_{GS} = 0 \text{ V}$). The normalized $I_{DS}$ increases from 1 ms and reaches a DC value for all the channel layer thicknesses. When the channel layer thickness is reduced, the normalized $I_{DS}$ up to 1 ms decreases. Therefore, the traps in the GaN substrate have a negative effect on the transient response of the thin channel layer, even when the trap concentration is constant. As shown in Figs. 3a, b, GaN HEMTs with a thin channel layer effectively suppress the drain leakage current but worsen the transient response.

Figure 4 shows two-dimensional (2D) plots of the current density at the off-state bias ($V_{DS} = 40 \text{ V}$ and $V_{GS} = -5 \text{ V}$) for channel thicknesses of 0.02, 0.7, and 1.0 μm. In the case of a thin channel layer with a thickness of 0.02 μm, the current density is extremely low in all regions between the

\begin{align*}
\text{(a)} & \quad \begin{array}{c}
\text{V}_{\text{GS}} = 2 \text{ V} \\
\text{V}_{\text{DS}} = 40 \text{ V}
\end{array} \\
\text{(b)} & \quad \begin{array}{c}
\text{V}_{\text{GS}} = 0 \text{ V} \\
\text{V}_{\text{DS}} = 20 \text{ V}
\end{array} \\
\text{(c)} & \quad \begin{array}{c}
\text{V}_{\text{GS}} = 0 \text{ V} \\
\text{V}_{\text{DS}} = 10 \text{ V}
\end{array} \\
\text{(d)} & \quad \begin{array}{c}
\text{V}_{\text{GS}} = 40 \text{ V} \\
\text{V}_{\text{DS}} = 20 \text{ V}
\end{array} \\
\text{(e)} & \quad \begin{array}{c}
\text{V}_{\text{GS}} = 40 \text{ V} \\
\text{V}_{\text{DS}} = 10 \text{ V}
\end{array}
\end{align*}
source and drain. The drain leakage current flows from the drain to the source through the region under the gate for the thick channel layers with thickness of 0.7 and 1.0 μm, and becomes larger for the thicker channel. As shown in Figs. 4b, c, the depletion layer, which extends from the gate electrode, is considered to reduce the electrons within a thickness of 0.2 μm. Therefore, the channel layer thickness of 0.02 μm is sufficiently thin to suppress the drain leakage current that flows under the gate. A larger drain leakage current flows for a thicker channel layer because of the wider space for the current to flow under the gate.

Figure 5 shows 2D plots of the ionized trap density at 1 ms in the transient response for channel thicknesses of 0.02, 0.7, and 1.0 μm. For the thinner channel layer, the ionized traps with a high density in the GaN substrates are extended to a wider area between the source and drain. The ionized traps with negative charges increase the conduction-band energy and decrease the drain current, as shown in Fig. 5a. Figures 3a and 4 show that the drain leakage current can be suppressed for a channel-layer thickness of less than 0.1 μm because the thin channel prevents current flow in the area under the gate electrode. However, the thin channel layer degrades the transient response dramatically, as shown in Fig. 3b, because the GaN substrate with a high trap concentration approaches the 2DEG in the channel layer. It thus becomes necessary to investigate a GaN substrate with a lower trap concentration for GaN HEMTs with thin channel layers.

### 3.2 The effects of traps in the GaN substrate for a GaN HEMT with a thin channel layer

This section discusses the influence of the GaN substrate traps on the characteristics of GaN HEMTs with a thin GaN channel (0.02 μm) by changing the trap concentration in the GaN substrate. GaN HEMTs with and without an AlGaN back-barrier layer are further investigated. Figure 6 shows the \( I_{DS}-V_{GS} \) curves, the transient response, and the imaginary part of \( S_{21} \) for a GaN HEMT structure with a GaN buffer layer. The trap concentration in the GaN substrate

![Fig. 4](image1)

![Fig. 5](image2)
is varied from $10^{15}$ to $10^{16}$ cm$^{-3}$. As shown in Figs. 6a, b, the drain leakage current and $I_{DS}$ at 1 ms in the transient response decrease when the trap concentration is increased. For a high trap concentration of $10^{16}$ cm$^{-3}$, the drain leakage current can be suppressed, although the transient response is degraded (the normalized $I_{DS}$ is as small as 0.78, at 1 ms). However, in the case of a lower trap density, the transient response has better characteristics but the drain leakage current has larger values. When the GaN substrate trap concentration is $5.0 \times 10^{15}$ cm$^{-3}$, $I_{DS_{OFF}}$ and the normalized $I_{DS}$ in the transient response are $1.7 \times 10^{-9}$ A/mm and 0.86, respectively. Although this result is good, there is room for improvement in the characteristics.

Figure 6c shows the imaginary part 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 the same because the peak frequency corresponds to the characteristic time, which is dominated by the trap energy level and the capture cross-section. The peak magnitudes decrease as the trap concentration in the GaN substrate is reduced because the signal response is attributable to the traps in the GaN substrate.

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 substrate. The depletion region spreads into the GaN substrate through the channel and buffer layers because of the thin channel layer of 0.02 μm. The current flows in the GaN substrate, as shown in Fig. 7a, because a trap concentration as low as $10^{15}$ cm$^{-3}$ insufficiently suppresses the leakage current. When the

![Figure 6 and 7 images](image-url)
trap concentration in the GaN substrate is increased, the leakage current decreases. Figure 7a′–d′ shows zoomed-in plots around the channel layers of Fig. 7a–d. In the channel region, the current flowing from the drain to the source is suppressed for all the considered values of the trap concentration because the depletion layer penetrates the buffer layers.

Figure 8 shows the conduction-band energy, the electron concentration, and the ionized trap density under the gate edge at the drain side at 1 ms in the transient response from the off- to on-state bias. The origin of the position axis is the surface of the barrier layer. The conduction-band energy in the substrate increases as the trap concentration in the GaN substrate is increased. As shown in Fig. 8b, the region with the highest electron concentration in the buffer and substrate thins as the trap concentration in the GaN substrate is increased. Figure 8c illustrates that the ionized trap density in the GaN substrate increases as a function of the trap concentration. As shown in Fig. 8a, c, when the trap concentration in the GaN substrate is increased, the increase in the ionized traps with a negative charge contributes to a rise in the conduction-band energy in the buffer and substrate. This conduction-band energy decreases the electron concentration in the buffer and substrate, and the drain leakage current decreases. This result indicates that the normalized $I_{DS}$ at 1 ms decreases because the ionized traps with higher concentration increase with higher trap concentrations in the GaN substrate. This mechanism, in which the ionized traps in the GaN substrate lift the conduction-band energy, is similar to the suppression of the drain leakage current. Therefore, a trade-off occurs between the drain leakage current and the transient response. Also, such a relationship appears between the drain leakage current and the low-frequency $S_{21}$, which degrades as the trap concentration in the GaN substrate is increased.

The insertion of a back-barrier between the channel layer and the substrate in a GaN HEMT is known to lift the conduction band [37–39]. Therefore, the GaN buffer layer is replaced by a back-barrier layer to suppress the drain leakage current. The back-barrier layer contains traps with the same concentration of $2.0 \times 10^{15}$ cm$^{-3}$ as in the GaN buffer layer.

Figure 9 shows the $I_{DS}$–$V_{GS}$ curves, the transient response, and the imaginary part of the low-frequency $S_{21}$ for the GaN HEMTs with a back-barrier layer. The trap concentration in the GaN substrate is changed from $10^{15}$ to $10^{16}$ cm$^{-3}$, As shown in the $I_{DS}$–$V_{GS}$ characteristics in Fig. 9a, the drain leakage current is suppressed sufficiently to $4.7 \times 10^{-11}$ A/mm even for the low trap concentration of $10^{15}$ cm$^{-3}$. On the other hand, the transient response and the low-frequency $S_{21}$ characteristics exhibit similar properties to those shown in Fig. 6b, c. The normalized $I_{DS}$ is as large as 0.95, at 1 ms, for the low GaN substrate trap concentration of $10^{15}$ cm$^{-3}$. Therefore, we do not consider the back-barrier layer as having a great impact on the transient response or the 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 the GaN HEMT with a back-barrier layer. The scale is linear for the current density. The drain leakage current is suppressed for all the trap concentrations in the GaN substrate, corresponding to the $I_{DS}$–$V_{GS}$ curves shown in Fig. 9a. Moreover, the distribution of the current density is almost the same. The back-barrier layer is extremely effective for suppressing the drain leakage current, even for a trap concentration of $10^{15}$ cm$^{-3}$ in the GaN substrate.

![Fig. 8](image-url) The depth profiles of a the conduction-band energy, b the electron concentration, and c the ionized trap density under the gate edge at the drain side at 1 ms in the transient response for various trap concentrations in the GaN substrate ($N_{TSUB}$). Position is defined as the distance from the heterointerface. The bias is changed from the off-state ($V_{DS} = 40$ V and $V_{GS} = -10$ V) to the on-state bias ($V_{DS} = 5$ V and $V_{GS} = 0$ V). The channel thickness is 0.02 μm.
Figure 11 shows the conduction-band energy, the electron concentration, and the ionized trap density under the gate edge on the drain side at 1 ms in the transient response from the off- to on-state bias. The origin of the position axis is the surface of the barrier layer, as in Fig. 8. The conduction-band energy in the GaN substrate increases as the trap concentration increases. The channel thickness is 0.02 μm.

Figure 10: The two-dimensional plots of the current density for the AlGaN back-barrier structure with a trap concentration in the GaN substrate of a $10^{15}$ cm$^{-3}$, b $3 \times 10^{15}$ cm$^{-3}$, c $5 \times 10^{15}$ cm$^{-3}$, and d $10^{16}$ cm$^{-3}$. The channel thickness is 0.02 μm. $V_{DS}$ and $V_{GS}$ are 40 V and −5 V, respectively.

Figure 11: The depth profiles of a the conduction-band energy, b the electron concentration, and c the ionized trap density under the gate edge on the drain side in the transient response with an AlGaN back-barrier for various trap concentrations in the GaN substrate ($N_{TSUB}$). The time in the transient response is at 1 ms. Position is defined as distance from the heterointerface. The bias is changed from the off-state ($V_{DS} = 40$ V and $V_{GS} = -10$ V) to the on-state bias ($V_{DS} = 5$ V and $V_{GS} = 0$ V). The channel thickness is 0.02 μm.

The $I_{DS} - V_{GS}$ curves, the transient response from off- to on-state bias, and the imaginary part of $S_{21}$ at low frequencies as functions of the trap concentration in the GaN substrate ($N_{TSUB}$) for a GaN HEMT with an AlGaN back-barrier layer. The channel thickness is 0.02 μm.
concentration in the GaN substrate is increased. The growth of the conduction-band energy that causes the conduction-band energy to rise at the surface of the channel layer indicates that the normalized $I_{DS}$ at 1 ms in the transient responses decreases as the trap concentration in the GaN substrate is increased, as shown above in Fig. 9b. Figure 11b shows the electron concentration profiles for various trap concentrations in the GaN substrate. The electron concentration is extremely low in the buffer, and in the GaN substrate compared with that in Fig. 8b for the GaN buffer layer. This low concentration in the GaN substrate suppresses the drain leakage current. Figure 11c shows the ionized trap density as a function of depth. The traps in the GaN substrate ionize almost all the traps close to the buffer layer. Because ionized traps have a negative charge, a higher trap concentration in the GaN substrate has additional negative charges, resulting in a higher energy level for the conduction band.

We compared the characteristics of the back-barrier structure with those of the GaN buffer layer. Figure 12a shows $I_{DSMAX}$ as a function of the trap concentration in the GaN substrate. $I_{DSMAX}$ does not depend on the trap concentration in the GaN substrate for the structures with the GaN buffer or AlGaN back-barrier. The GaN HEMT with a back-barrier layer exhibits a smaller $I_{DSMAX}$ because the back-barrier raised the conduction-band energy at the surface of the channel. Figure 12b shows the normalized $I_{DS}$ at 1 ms in the transient response as a function of the trap concentration in the GaN substrate. The normalized $I_{DS}$ at 1 ms shows similar values and tendencies for the GaN buffer and AlGaN back-barrier. As shown in Fig. 12c, $I_{DSOFF}$ decreased when using the back-barrier layer. The drain leakage current improves dramatically at the low substrate trap concentration of $10^{15}$ cm$^{-3}$. Figure 12d shows the peak magnitudes in the imaginary part of $S_{21}$ as a function of the trap concentration in the GaN substrate. The use of the back-barrier layer decreases the peak magnitude. As shown in Fig. 12b, d, the transient response and the low-frequency $S_{21}$ did not change significantly when using the GaN buffer versus the AlGaN back-barrier layer. Therefore, the back-barrier layer contributes to the suppression of the drain leakage current rather than the improvement of the transient response and the low-frequency $S_{21}$.

Figure 13 illustrates the relationship between the electrical characteristics. $I_{DSOFF}$ and the normalized $I_{DS}$ at 1 ms are correlated, as shown in Fig. 13a. $I_{DSOFF}$ increases when the normalized $I_{DS}$ at 1 ms increases. $I_{DSOFF}$ for the back-barrier (a) (b) (c) (d)

Fig. 12  a $I_{DS}$, b the normalized $I_{DS}$ at 1 ms in the transient response, c the drain leakage current, and d the peak magnitude of the imaginary part of $S_{21}$ as functions of the trap concentration in the GaN substrate ($N_{TSUB}$). Back-barrier 2 has 0.22 times the Al content of back-barrier 1. The channel thickness is 0.02 μm

© Springer
layer decreases at the same normalized $I_{DS}$ at 1 ms in the transient response. As shown in Fig. 13b, the peak magnitudes of $S_{21}$ correlate with the transient response because these effects result from the traps in the GaN substrate. The GaN HEMT with a back-barrier layer shows good $S_{21}$ values for the same transient response. As shown in Fig. 13c, $I_{DSOFF}$ decreases as the $S_{21}$ values decrease. The back-barrier layer is used to obtain a low drain leakage current.

3.3 The characteristics of the GaN HEMT with a back-barrier layer and a barrier layer with high Al content

In Sect. 3.2, it is shown that the back-barrier structure can improve the normalized $I_{DS}$ in the transient response and the $S_{21}$ signal at low frequency with a low drain leakage current. However, as shown in Fig. 12a, the maximum drain current decreases when the back-barrier layer is adopted. In this section, a GaN HEMT with a high Al content in the barrier layer is studied, to increase the maximum drain current.

Figure 14 shows the characteristics of the GaN HEMTs with an Al content of 0.22 in the barrier layer. The structure is the same as that simulated in Sect. 3.2, except for the Al content of the barrier. The trap concentration in the GaN substrate is as low as $10^{15}$ cm$^{-3}$. We adopt a back-barrier layer to reduce the drain leakage current. In the $I_{DS}$-$V_{DS}$ curves shown in Fig. 14a, the maximum drain current of 1.2 A/mm is obtained at $V_{DS} = 40$ V and $V_{GS} = 2$ V. The drain leakage current is suppressed below $10^{-10}$ A/mm for $I_{DS}$ in the off-state condition, as shown in Fig. 14b. Because these curves in a subthreshold region do not depend on $V_{DS}$, the back-barrier layer is useful for suppressing the drain leakage current. Figure 14c shows the transient $V_{DSQ}$ response for 20 and 40 V. The normalized $I_{DS}$ at 1 ms is as high as 0.98, even with a high $V_{DSQ}$ of 40 V. Figure 14d shows the imaginary part of $S_{21}$ in the low-frequency region. The peak magnitudes decrease as $V_{DS}$ is increased from 10 to 40 V. Figures 12 and 13 include the data for GaN HEMTs with a high Al content of 0.22 and a back-barrier layer (named back-barrier 2). The maximum $I_{DS}$ becomes as large as that of the GaN HEMT without the back-barrier layer, as shown in Fig. 12a. However, the drain leakage current and the transient response retain almost the same values as those of the GaN HEMT with the back-barrier layers. The peak magnitude in the imaginary part of $S_{21}$ is slightly higher, as shown in Fig. 12d.

Figure 15 shows the characteristics when the gate length is varied from 0.5 to 0.05 $\mu$m for the GaN HEMT with a back-barrier and high-Al-content barrier layer. Figure 15a shows how $I_{DS}$ depends on $V_{DS}$ at $V_{GS} = 2$ V. As the gate length is decreased, the maximum $I_{DS}$ increases from 1.3 to 1.6 A/mm. Figure 15b shows $I_{DS}$ versus $V_{GS}$ for a high $V_{DS} = 40$ V. When the gate is shortened length from 0.5 to 0.05 $\mu$m, the slope in the subthreshold region increases. However, the drain leakage current below $V_{GS} = −3$ V is suppressed below $5 \times 10^{-6}$ A/mm, even for 0.05 $\mu$m. The transient response at a high $V_{DSQ}$ of 40 V shows good characteristics, being approximately 0.98 at 1 ms for all the gate lengths, as shown in Fig. 15c. Figure 15d shows the imaginary part of $S_{21}$ in the low-frequency region at the on-state bias. The peak magnitudes increase as the gate length is decreased from 0.5 to 0.25 $\mu$m. Below a gate length of 0.25 $\mu$m, the peak magnitudes are almost the same at 0.3, which is not extremely large when compared with that in Fig. 12 or 13. Figure 15e shows the threshold voltage as a function of the gate length. The threshold voltage—defined as the voltage extrapolated from the point
Conclusions

We investigate the GaN HEMT on a GaN substrate with a thin channel layer in terms of the drain leakage current, the transient response from the off- to on-state bias, and the low-frequency $S_{21}$ using device simulations. We calculate the dependence on the channel layer thickness for a relatively high trap concentration of $2 \times 10^{16}$ cm$^{-3}$ in the GaN substrate. A channel thickness of less than 0.1 μm suppresses the drain leakage current and degrades the transient response. This result indicates that a thin channel layer is not preferable for RF applications in the case of a GaN substrate with high trapped concentration. The transient response is degraded because of the ionized traps in the GaN substrate. In the case of the GaN HEMT with a thin channel layer of 0.02 μm thickness, a moderate trap concentration of $5.0 \times 10^{15}$ cm$^{-3}$ in the GaN substrate results in good characteristics with $I_{DSOFF}$ and a normalized $I_{DS}$ in the transient response of $1.7 \times 10^{-9}$ A/mm and 0.86, respectively. The drain leakage current flows in the GaN substrate, although the depletion layer extending from the gate suppresses the current in the channel layer. We adopt an AlGaN back-barrier layer with an Al content of 0.08 to suppress the drain leakage current in the GaN substrate. Using the back-barrier layer at a low trap concentration of $10^{15}$ cm$^{-3}$ in the GaN substrate significantly decreases the drain leakage current, by seven orders.

We also investigate the GaN HEMT with a higher Al content of 0.22 in the barrier layer. The GaN HEMT has a high $I_{DS}$ value of 1.2 A/mm, a low drain leakage current of $4.7 \times 10^{-11}$ A/mm, a high normalized $I_{DS}$ of 0.97 in the transient response,
and a low magnitude of 0.18 in the low-frequency $S_{21}$. Finally, it is confirmed that this structure can operate with a short gate length of 0.05 μm despite the threshold voltage decrease. Also, the GaN substrate traps affect the low-frequency $S_{21}$. The imaginary part of $S_{21}$ increases with the trap concentration in the GaN substrate, showing a tendency similar to that in the transient response.

Acknowledgements This work was supported by MEXT “Research and development of next-generation semiconductor to realize energy-saving society” Program (grant no. JP1005357).

Funding This method is based upon work supported by Ministry of Education, Culture, Sports, Science, and Technology.

References

1. Saremi, M., et al.: Analysis of the reverse I-V characteristics of diamond-based PIN diodes. Appl. Phys. Lett. 111, 043507 (2017). https://doi.org/10.1063/1.4986756
2. Saremi M.: Modeling and Simulation of the Programmable Metallization Cells (PMCs) and Diamond-Based Power Devices. Dissertation of Doctor of Philosophy, Arizona State University, USA 2017. https://repository.asu.edu/items/44124. Accessed 3 June 2021
3. Coffie, R. L.: High power high frequency transistors: a material’s perspective. In high-frequency GaN Electronic Devices, Editors, P. Fay, D. Jena, P. Maki, AG, Switzerland: Springer Nature, (2020). ch. 2, pp. 5–41
4. Mishra, U.K., et al.: AlGaN/GaN HEMTs—an overview of device operation and applications. Proc. IEEE 90, 1022–1031 (2002). https://doi.org/10.1109/JPROC.2002.1021567

Fig. 15 a The $I_{DS}$−$V_{DS}$ curves, b the $I_{DS}$−$V_{GS}$ curves, c the transient response from the off- to on-state bias, and d the imaginary part of $S_{21}$ at low frequency as functions of the gate length. e The pinch-off voltage as a function of the gate length. The GaN HEMT has an AlGaN back-barrier and a high-Al-content barrier with a thin channel layer. The channel thickness and the trap concentration of the GaN substrate are 0.02 μm and $10^{15}$ cm$^{-3}$, respectively.
5. Amano, H: GaN as A Key Material for Realizing Internet of Energy. CSW2019, May 2019, MoPLN1-1, https://www.csw-jpn.org/wp-content/uploads/2019/01/CSW2019_Abstract_AMANO.pdf.

6. Kaun, S.W., et al.: Effects of threading dislocation density on the gate leakage of AlGaN/GaN heterostructures for high electron mobility transistors. Appl. Phys. Express 4, 024101 (2011). https://doi.org/10.1143/APEX.4.024101

7. Binari, S.C., et al.: Trapping effects and microwave power performance in AlGaN/GaN HEMTs. IEEE Trans. Electron Devices 48, 465–471 (2001). https://doi.org/10.1109/65.906437

8. Vetrty, R., et al.: The impact of surface states on the DC and RF characteristics of AlGaN/GaN HFETs. IEEE Trans. Electron Devices 48, 560–566 (2001). https://doi.org/10.1109/65.906451

9. Uren, M.J., et al.: Buffer design to minimize current collapse in GaN/AlGaN HFETs. IEEE Trans. Electron. Devices 59, 3327–3333 (2012). https://doi.org/10.1109/TED.2012.2216535

10. Bisi, D., et al.: Deep-level characterization in GaN HEMTs-Part I: advantages and limitations of drain current transient measurements. IEEE Trans. Electron Devices 60, 3166–3175 (2013). https://doi.org/10.1109/TED.2013.2279021

11. Tripathi, D.C., et al.: Insight into buffer trap-induced current saturation and current collapse in GaN RF heterojunction field-effect transistors. IEEE Trans. Electron Devices 67(5460), 5465 (2020). https://doi.org/10.1109/TED.2020.3034062

12. Frayssinet, E., et al.: High electron mobility in AlGaN/GaN heterostructures grown on bulk GaN substrates. Appl. Phys. Lett. 77, 2551–2553 (2000). https://doi.org/10.1063/1.1318236

13. Liu, C., et al.: Ultralow reverse leakage current in AlGaN/GaN lateral Schottky barrier diodes grown on bulk GaN substrate. Appl. Phys. Express 9, 031001 (2016). https://doi.org/10.15677/APEX.9.031001

14. Khan, M.A., et al.: GaN–AlGaN heterostructure field-effect transistors on bulk GaN substrates. Appl. Phys. Lett. 76, 3807–3809 (2000). https://doi.org/10.1063/1.126788

15. Chu, K.K., et al.: 9.4-W/mm power density AlGaN–GaN HEMTs on free-standing GaN substrates. IEEE Electron Device Lett. 25, 596–598 (2004). https://doi.org/10.1109/LED.2004.833847

16. Storm, D.F., et al.: Microwave power performance of MBE-grown AlGaN/GaN HEMTs on HVPE GaN substrates. Electron. Lett. 42, 663–665 (2006). https://doi.org/10.1049/el:20060648

17. Storma, D.F., et al.: Microwave performance and structural characterization of MBE-grown AlGaN/GaN HEMTs on low dislocation density GaN substrates. J. Cryst. Growth 305, 340–345 (2007). https://doi.org/10.1016/j.jcrysgro.2007.04.003

18. Anderson, T.J., et al.: Effect of reduced extended defect density in MOCVD grown AlGaN/GaN HEMTs on native GaN Substrates. IEEE Electron Device Lett. 37, 28–30 (2016). https://doi.org/10.1109/LED.2015.2502221

19. Handa, H., et al.: High-speed switching and current-collapse-free operation by GaN gate injection transistors with thick GaN Buffer on bulk GaN substrates. In IEDM Tech. Dig. (2016). https://doi.org/10.1109/IEDM.2016.7838387

20. Alshehied, M., et al.: Low-dispersion, high-voltage, low-leakage GaN HEMTs on native GaN substrates. IEEE Trans. Electron Devices 65, 2939–2947 (2018). https://doi.org/10.1109/TED.2018.2832280

21. Wojtasik, W., et al.: AlGaN/GaN high electron mobility transistors on semi-insulating Ammonio-GaN substrates with regrown ohmic contacts. Micromachines 9, 546–559 (2018). https://doi.org/10.3390/mi9110546

22. Zhang, D., et al.: Reliability improvement of GaN devices on free-standing GaN substrates. IEEE Trans. Electron Devices 65, 3379–3387 (2018). https://doi.org/10.1109/TED.2018.2848971

23. Ando, Y., et al.: Improved operation stability of Al₂O₃/AlGaN/ GaN MOS high-electron-mobility transistors grown on GaN substrates. Appl. Phys. Express 12, 024002 (2019). https://doi.org/10.7567/1882-0786/aafded

24. Kumazaki, Y., et al.: Remarkable current collapse suppression in GaN HEMTs on free-standing GaN Substrates. In BCICTS2019, Nov. 2019, 10b.2, https://doi.org/10.1109/BCICTS45179.2019.8972742.

25. Liu, X., et al.: Analysis of the back-barrier effect in AlGaN/GaN high electron mobility transistor on free-standing GaN substrates. J. Alloys and Compd. 814, 152293 (2020). https://doi.org/10.1016/j.jallcom.2019.152293

26. Watanabe, I., et al.: Research and development of GaN-based HEMTs for millimeter- and terahertz-wave wireless communications. In RFIT2020, Sept. 2020. https://doi.org/10.1109/RFT49453.2020.9226221

27. Kumazaki, Y., et al.: Over 80% power-added-efficiency GaN high-electron-mobility transistors on free-standing GaN substrates. Appl. Phys. Express 14, 016502 (2020)

28. Vaudo, R.P., et al.: Characteristics of semi-insulating Fe-doped GaN substrates. Phys. Stat. Sol. (a) 200, 18–21 (2003). https://doi.org/10.1002/pssa.200303273

29. Kordoš, P., et al.: Conductivity and Hall effect of free-standing highly resistive epitaxial GaN:Fe substrates. Appl. Phys. Lett. 85, 5616–5618 (2004). https://doi.org/10.1063/1.1831568

30. Freitas, J.A., et al.: Properties of Fe-doped semi-insulating GaN substrates for high-frequency device fabrication. J. Cryst. Growth 305, 403–407 (2007). https://doi.org/10.1016/j.jcrysgro.2007.03.031

31. Freitas, J.A., et al.: Efficient iron doping of HVPE GaN. J. Cryst. Growth 500, 111–116 (2018). https://doi.org/10.1016/j.jcrysgro.2018.07.030

32. Miyamoto, Y., et al.: Hall effect of free-standing GaN HEMT with a combined thin undoped channel and semi-insulating layer. IEICE Trans. Electron. E103-C, 304–307, (2020). https://doi.org/10.1587/transele.2019FDU0002

33. Ito, K., et al.: Study on effects of GaN trap depth profiles to transient response in GaN HEMTs on GaN substrates by device simulation. In RFIT2020, Sept. 2020. https://doi.org/10.1109/RFIT49453.2020.9226201

34. Nunes, L.C., et al.: A New Nonlinear Model Extraction Methodology for GaN HEMTs Subject to Trapping Effects. In 2015IEEE MTT-S, May 2015. https://doi.org/10.1109/MWSYM.2015.7166977

35. Barradas, F.M., et al.: Compensation of long-term memory effects on GaN HEMT-based power amplifiers. IEEE Trans. Microw. Theory Tech. 65, 3379–3388 (2017). https://doi.org/10.1109/TMTT.2017.2671368

36. Bader, S.J., et al.: Linearity aspects of high power amplification in GaN Transistors. in RFIT2020, Sept. 2020. https://doi.org/10.1109/RFIT49453.2020.9226201

37. Barros, J.F., et al.: Design and analysis of 30 nm T-gate InAlN/GaN HEMTs with AlGaN back-barriers. IEEE Electron Device Lett. 32, 617–619 (2011). https://doi.org/10.1109/LED.2011.2111352

38. Murugandiyana, P., et al.: Design and analysis of 30 nm T-gate InAlN/GaN HEMTs with AlGaN back-barriers for high power microwave applications. Superlattices Microstruct. 111, 045311 (2017). https://doi.org/10.1016/j.spmi.2017.08.002

39. Silvaco, Atlas (2018). Accessed: January 15, 2021. [Online] Available: https://silvaco.com/tacl/
search.ieice.org/bin/summary.php?id=j96-c_8_200. Accessed 7 June 2021
42. Oishi, T. et al.: Simulation Study of Gate Leakage Current under Three-terminal Operation for AlGaN/GaN HEMTs. 10th Topical Workshop on Heterostructure Microelectronics (TWHM 2013) 4–3, Sept. 2–5, 2013 Hakodate, Japan
43. Zagni, N., Chini, A., Puglisi, F.M., Pavan, P., Verzellesi, G.: The effects of carbon on the bidirectional threshold voltage instabilities induced by negative gate bias stress in GaN MIS-HEMTs. J. Comput. Electron. 19, 1555–1563 (2020). https://doi.org/10.1007/s10825-020-01573-8
44. Kanegae, K., et al.: Accurate method for estimating hole trap concentration in n-type GaN via minority carrier transient spectroscopy. Appl. Phys. Express 11(7), 071002 (2018). https://doi.org/10.7567/APEX.11.071002
45. Kanegae, K., et al.: Deep-level transient spectroscopy studies of electron and hole traps in n-type GaN homoepitaxial layers grown by quartz-free hydride-vapor-phase epitaxy. Appl. Phys. Lett. 115, 012103 (2019). https://doi.org/10.1063/1.5098965
46. Looka, D.C., et al.: Identification of donors, acceptors, and traps in bulk-like HVPE GaN. J. Cryst. Growth 281, 143–150 (2005). https://doi.org/10.1016/j.jcrysgro.2005.03.035
47. Bockowskia, M., et al.: Doping in bulk HVPE-GaN grown on native seeds—highly conductive and semi-insulating crystals. J. Cryst. Growth 499, 1–7 (2018). https://doi.org/10.1016/j.jcrysgro.2018.07.019
48. Kompa, G.: Trap centers and trap dynamics. in Basic Properties of III-V Devices—Understanding Mysterious Trapping Phenomena, Kassel, Dutch, Kassel University Press, 2014 pp. 287–300

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.