Effects of acceptors in a Fe-doped buffer layer on breakdown characteristics of AlGaN/GaN high electron mobility transistors with a high-k passivation layer

Yuuki Kawada, Hideyuki Hanawa, and Kazushige Horio

Faculty of Systems Engineering, Shibaura Institute of Technology, Saitama 338-8570, Japan

Received June 16, 2017; accepted August 18, 2017; published online September 13, 2017

We analyze off-state breakdown characteristics of AlGaN/GaN high electron mobility transistors (HEMTs) with a Fe-doped buffer layer where a deep acceptor located above the midgap is included. It is shown that by introducing a high-k passivation layer, the breakdown voltage \( V_{BR} \) improves as in a case with an undoped semi-insulating buffer layer. In the Fe-doped case, \( V_{BR} \) becomes a little higher in the case where the passivation layer’s relative permittivity \( \varepsilon_r \) is rather higher when the energy levels determining the Fermi level are set equal in the two buffers. It is also shown that when the energy level of deep acceptor is deeper, \( V_{BR} \) becomes higher in the region where \( \varepsilon_r \) is high. This occurs because the leakage current via the buffer layer becomes smaller. © 2017 The Japan Society of Applied Physics

Recently, AlGaN/GaN high electron mobility transistors (HEMTs) are accepting great attention because of their applications to power microwave devices and switching devices.\(^1,2\) Their breakdown voltages are, however, much lower than those theoretically estimated. In order to enhance the breakdown voltage, introducing a field plate is well known to be attractive.\(^3–5\) But the field plate increases the parasitic capacitance, resulting in degrading the high-frequency characteristics. As a different way to improve the breakdown voltage, in our previous work, we presented a structure having a passivation layer with high permittivity. And the calculated results indicated that the breakdown voltage was improved significantly.\(^6,7\) In the analysis, it was assumed that in an undoped semi-insulating buffer layer, a deep donor above the midgap compensated a deep acceptor below the midgap. On the other hand, recently, Fe- and C-doped semi-insulating buffer layers are often used, and their related levels act as deep acceptors.\(^8–12\) Particularly, the Fe-related level is considered to be located above the midgap. Therefore, it is interesting to analyze the case having a Fe-doped buffer layer and compare the results with the case having the undoped semi-insulating buffer layer.\(^13,14\) In this work, we analyze the off-state breakdown characteristics of AlGaN/GaN HEMTs with a Fe-doped buffer layer in which a deep acceptor located above the midgap is included, and studied how the breakdown characteristics are affected by the deep acceptors.

A device structure analyzed here is shown in Fig. 1. The gate length and the gate-to-drain distance is 0.3 and 1.5 \( \mu \text{m} \), respectively. The passivation layer’s thickness is 0.1 \( \mu \text{m} \). We vary the relative permittivity of the passivation layer \( \varepsilon_r \) as a parameter. Here, we adopt a Fe-doped semi-insulating buffer layer, where the Fe-related level (\( E_{DA} \)) is set to 0.5–0.6 eV below the bottom of conduction band.\(^8,12\) The Fe-related level is a deep acceptor.\(^8,12\) The deep acceptors act as electron traps. The deep-acceptor density \( N_{DA} \) is \( 10^{17} \text{cm}^{-3} \).

Basic equations are Poisson’s equation having the ionized deep-acceptor density term and electron and hole continuity equations which include a carrier loss rate via the deep acceptor and an impact ionization rate.\(^7,15–17\) The carrier generation rate by impact ionization \( G \) is expressed as

\[
G = (\alpha_n|J_n| + \alpha_p|J_p|)/q,
\]

where \( J_n \) and \( J_p \) are the electron and hole current densities, respectively. \( \alpha_n \) and \( \alpha_p \) are the electron and hole ionization rates, respectively, and given by

\[
\alpha_n = A_n \exp(-B_n/|E|),
\]

\[
\alpha_p = A_p \exp(-B_p/|E|).
\]

Here \( E \) is the electric field. The coefficients \( A_n, B_n, A_p, \) and \( B_p \) are the fitting parameters and are obtained from Ref. 18, as in Refs. 5 and 7. The basic equations are solved numerically in two dimensions.

Calculated drain output characteristics for \( \varepsilon_r = 7 \) and \( \varepsilon_r = 30 \) are essentially similar, as shown in Ref. 19. The drain currents for \( \varepsilon_r = 30 \) become a little lower because the effective gate length becomes longer due to the extended depletion region at the drain side of the gate. When the gate voltage \( V_G \) is 0 V and the drain voltage \( V_D \) is 40 V, the drain current for \( \varepsilon_r = 30 \) becomes lower by about 10% than that for \( \varepsilon_r = 7 \). Figure 2 shows calculated drain current–drain voltage (\( I_D–V_D \)) characteristics and gate current–drain voltage (\( I_G–V_D \)) characteristics as a parameter of passivation layer’s relative permittivity \( \varepsilon_r \). Here, \( E_C – E_{DA} = 0.5 \text{ eV} \) and the gate voltage is \( -8 \text{ V} \). These are off-state characteristics. In the cases where \( \varepsilon_r \) is relatively low (\( \leq 10 \)), the drain currents increase suddenly, reaching the breakdown. In these cases, the impact ionization of carriers determines the breakdown voltage. On the other hand, in the cases where \( \varepsilon_r \) is relatively high (\( \geq 30 \)), the drain currents reach a critical value (1 mA/\( \mu \text{m} \)) before the sudden increases. In these cases, the leakage current via the buffer layer determines the breakdown voltage. Here, the breakdown...
voltage is defined as a drain voltage when the drain current becomes 1 mA/mm. Anyway, the breakdown voltage increases as $\varepsilon_r$ becomes high. Here, it should be mentioned that the thickness of space-charge region in the buffer layer is about 0.1 µm under equilibrium when $N_{DA} = 10^{17}$ cm$^{-3}$, but it becomes about 2.6 µm at the drain side when $V_D = 350$ V. It is comparable to the buffer layer thickness used here. Therefore, it should be noted that the buffer leakage current may depend on the buffer layer thickness.

Figure 3 shows a comparison of electric field profiles along the AlGaN/GaN heterojunction interface between the two cases where $\varepsilon_r$ is different. When $\varepsilon_r$ is 7, the increase in the drain voltage is entirely applied along the drain edge region of gate, resulting in the breakdown around $V_D = 80$ V (Fig. 2). However, when $\varepsilon_r$ is 30, the electric field around the drain edge region of gate is weakened as seen in Fig. 3(b). The peak of electric field is about 2 MV/cm at $V_D = 100$ V. When $V_D$ increases more, the high electric field region extends toward the drain, and the electric field at the gate edge of drain becomes high at $V_D = 200$ V. Finally, the peak of electric field at the drain edge region of gate becomes about 3 MV/cm at $V_D = 304$ V. This voltage is the breakdown voltage in this case.

Figure 4 shows the breakdown voltage $V_{br}$ versus $\varepsilon_r$ relationships for the two cases with different types of buffer layers. In the undoped semi-insulating buffer layer, the energy level of deep donor ($E_{DD}$) is considered to be equal to $E_{DA}$ in the Fe-doped semi-insulating buffer layer. The deep-acceptor densities are both $10^{17}$ cm$^{-3}$. The breakdown voltage is almost equal when $\varepsilon_r$ is low ($\leq 10$), but it becomes a little higher in the case of Fe-doped buffer layer in the region where $\varepsilon_r$ is high. This is attributed to the fact that the Fermi level in the bulk region is a little away from the conduction

Fig. 2. Calculated (a) off-state $I_D$-$V_D$ characteristics and (b) on-state $I_D$-$V_D$ characteristics of AlGaN/GaN HEMT's with a Fe-doped semi-insulating buffer layer having a deep acceptor above the midgap. $E_C - E_{DA} = 0.5$ eV and $N_{DA} = 10^{17}$ cm$^{-3}$. The gate voltage $V_G$ is $-8$ V.

Fig. 3. Electric field profiles along the AlGaN/GaN interface with different $\varepsilon_r$. $V_G = -8$ V. (a) $\varepsilon_r = 7$, (b) $\varepsilon_r = 30$.

Fig. 4. Breakdown voltage versus $\varepsilon_r$ relationships between the two cases with Fe-doped and undoped semi-insulating buffer layers. Here, $E_{DA}$ is equal to $E_{DD}$. 

Jpn. J. Appl. Phys. 56, 108003 (2017) Y. Kawada et al.
band in the case with Fe-doped buffer layer,\textsuperscript{13)} which leads to the lower buffer leakage current. Therefore, the breakdown voltage determined by buffer leakage current becomes higher.

Figure 5 shows \(I_D-V_D\) characteristics in the case where \(E_{DA}\) is 0.56 eV below the bottom of conduction band. This is a little deeper than that shown in Fig. 2(a). It is seen that the sudden increases in drain currents when \(\varepsilon_i\) is relatively low are similar to the cases shown in Fig. 2(a). However, when \(\varepsilon_i\) becomes high (\(\geq 30\)), the curves show similar features and the drain currents reach a critical value (1 mA/mm) without indicating abrupt increases. Here, the buffer leakage currents come to determine the breakdown voltages, and these buffer leakage currents becomes lower than the cases shown in Fig. 2(a).

The comparison of \(V_{br}\) versus \(\varepsilon_i\) relationships with different \(E_{DA}\) is shown in Fig. 6. In the cases where \(\varepsilon_i\) is low (\(\leq 10\)), the two curves are almost the same. But, in the case where \(E_{DA}\) is deeper, the breakdown voltage is rather higher in the high \(\varepsilon_i\) region. This occurs because the buffer leakage current is lower in the case of deeper \(E_{DA}\), as shown in Figs. 2(a) and 5. This lower current is originated from the higher electron barrier at the channel-buffer interface in the case of deeper \(E_{DA}\).

In summary, we have analyzed off-state breakdown characteristics of AlGaN/GaN HEMTs with a Fe-doped semi-insulating buffer layer where a deep acceptor above the midgap is considered (\(E_C - E_{DA} = 0.5 \text{ eV}\)). It has been shown that by introducing a high-\(k\) passivation layer, the breakdown voltage improves as in a case with an undoped semi-insulating buffer layer (\(E_C - E_{DD} = 0.5 \text{ eV}\)). In the Fe-doped case, the breakdown voltage becomes a little higher in the region where the relative permittivity of the passivation layer is high. It has also been shown that when the energy level of deep acceptor is deeper, the breakdown voltage becomes higher in the high-\(k\) region. This is due to the fact that the buffer leakage current becomes smaller in this case due to the higher energy barrier between the channel and the buffer layer.

\textsuperscript{1)} U. K. Mishra, L. Shen, T. E. Kazior, and Y.-F. Wu, \textit{Proc. IEEE} \textbf{96}, 287 (2008).
\textsuperscript{2)} N. Iboda, Y. Niyama, H. Kamiyashiki, Y. Sato, T. Nomura, S. Kato, and S. Yoshida, \textit{Proc. IEEE} \textbf{98}, 1151 (2010).
\textsuperscript{3)} S. Karmalkar and U. K. Mishra, \textit{IEEE Trans. Electron Devices} \textbf{48}, 1515 (2001).
\textsuperscript{4)} E. Babat-Treidel, O. Hilt, F. Brunner, V. Sidorov, J. Würfl, and G. Tränkle, \textit{IEEE Trans. Electron Devices} \textbf{57}, 1208 (2010).
\textsuperscript{5)} H. Onodera and K. Horio, \textit{Semicond. Sci. Technol.} \textbf{27}, 085016 (2012).
\textsuperscript{6)} H. Hanawa and K. Horio, \textit{Phys. Status Solidi A} \textbf{211}, 784 (2014).
\textsuperscript{7)} H. Hanawa, H. Onodera, A. Nakajima, and K. Horio, \textit{IEEE Trans. Electron Devices} \textbf{61}, 769 (2014).
\textsuperscript{8)} M. Silvestri, M. J. Uren, and M. Kuball, \textit{Appl. Phys. Lett.} \textbf{102}, 073501 (2013).
\textsuperscript{9)} G. Verzellesi, L. Morassi, G. Meneghesso, M. Meneghini, E. Zanoni, G. Pozzovivo, S. Lavanga, T. Detzel, O. Härbelin, and G. Caratala, \textit{IEEE Electron Device Lett.} \textbf{35}, 443 (2014).
\textsuperscript{10)} S. Gustafsson, J.-T. Chen, J. Bergsten, U. Forsberg, M. Thorsell, E. Janzén, and N. Rosman, \textit{IEEE Trans. Electron Devices} \textbf{62}, 2162 (2015).
\textsuperscript{11)} J. Hu, S. Stoffels, S. Lenci, G. Groeseneken, and S. Decoutere, \textit{IEEE Electron Device Lett.} \textbf{37}, 310 (2016).
\textsuperscript{12)} Y. S. Puzyrev, R. D. Schrimpf, D. M. Fleetwood, and S. T. Pantelides, \textit{Appl. Phys. Lett.} \textbf{106}, 053505 (2015).
\textsuperscript{13)} R. Tsurumaki, N. Noda, and K. Horio, \textit{Microelectron. Reliab.} \textbf{73}, 36 (2017).
\textsuperscript{14)} Y. Kawada, H. Hanawa, and K. Horio, \textit{Proc. TechConnect World Conf.}, 2017, Vol. 4, p. 31.
\textsuperscript{15)} K. Horio and K. Satoh, \textit{IEEE Trans. Electron Devices} \textbf{41}, 2256 (1994).
\textsuperscript{16)} K. Horio, A. Wakabayashi, and T. Yamada, \textit{IEEE Trans. Electron Devices} \textbf{47}, 617 (2000).
\textsuperscript{17)} Y. Mitani, D. Kasai, and K. Horio, \textit{IEEE Trans. Electron Devices} \textbf{50}, 285 (2003).
\textsuperscript{18)} C. Bulutay, \textit{Semicond. Sci. Technol.} \textbf{17}, L59 (2002).
\textsuperscript{19)} H. Hanawa, Y. Satoh, and K. Horio, \textit{Microelectron. Eng.} \textbf{147}, 96 (2015).