Gate Control, Surface Leakage Currents and Peripheral Charging in AlGaN/GaN Heterostructure Field Effect Transistors Having Nanometer-Scale Schottky Gates

S. KASAI,[1,2] J. KOTANI,[1] T. HASHIZUME[1] and H. HASEGAWA[1]

1.– Research Center for Integrated Quantum Electronics and Graduate School of Information Science and Technology, Hokkaido University, N13, W8, Kita-ku, Sapporo 060-8628, Japan 2.– E-mail: kasai@rciqe.hokudai.ac.jp

Gate control properties together with gate leakage currents in AlGaN/GaN HFETs with nm-scale Schottky gates were investigated focusing on effects of AlGaN surfaces at the gate periphery. Fabricated AlGaN/GaN HFETs showed unexpectedly small gate length (L_G)-dependence of transconductance, g_m. Comparison of transfer characteristics from theory and experiment, effective L_G in the fabricated devices were found much longer than geometrical size in the order of 100 nm, indicating the formation of virtual gates. Detailed analysis of the gate leakage current behaviors based on a thin surface barrier model showed the presence of strong electric field at the gate periphery. Mechanism of the virtual gate formation was discussed based on the obtained nm-scale Schottky gate behaviors.

Key words: GaN, heterojunction FET (HFET), Schottky gate, gate leakage current, surface state, virtual gate

INTRODUCTION

Recently, extensive research efforts have been made on GaN-based FETs for their near-future applications, such as base stations for mobile communication and wireless-LAN systems and devices for high-power electricity systems, because of their high-power handling capabilities due to large band gaps giving high breakdown voltages and high-density electrons generated at heterointerfaces as well as high-speed performance by the large saturation velocity in high electric field. However, for their practical uses, there are several sever problems, including current collapse and large gate leakage currents relating to both short- and long-term reliabilities. It is also problem that their cut-off frequency is saturated around 100 GHz, even when the gate length is reduced less than 100 nm. Recent researches have revealed that these problems strongly relate to surfaces of GaN-based materials [1-3], however, their mechanisms have not been understood enough yet. The purpose of this paper is to investigate the gate control and gate leakage current in AlGaN/GaN heterostructure FETs (HFETs) with nanometer-scale Schottky gates both experimentally and theoretically, focusing on the effects of AlGaN surfaces at the gate periphery.

EXPERIMENTS

Figure 1 shows a cross-section of a HFET fabricated and characterized in this study. The top AlGaN barrier was 25 nm, including a 10 nm carrier supply layer. Sheet carrier density and mobility of the two-dimensional electrons at room temperature were $1x10^{13}$ cm^{-2} and 1,100 cm^2/Vs, respectively. Schottky gate metal was Ni/Au. Gate length was varied from 130 nm to 1,000 nm. Source and drain Ohmic contacts were formed by depositing Ti/Al/Ti/Au and alloying at 800ºC for 1 min by RTA. No surface passivation was made on the samples. Reference large-area Schottky diodes on bulk AlGaN layer with corbino electrodes were also fabricated. The fabricated samples were characterized by DC current-voltage measurements using an Agilent 4156C semiconductor parameter analyzer. Schottky I-V measurements were also carried out in various temperatures using a low-temperature DC prober system.

RESULTS AND DISCUSSION

DC Characteristics of Fabricated HFETs

A typical drain current-voltage (I_D-V_D) characteristic of the fabricated HFETs is shown in Fig. 2a. All the fabricated devices showed such respectable characteristics. However, they did not show ideal transfer characteristics. Namely, as shown in Fig. 2b, maximum transconductance, $g_{m\ max}$, hardly changed even though the gate length, L_G, was decreased down to 200 nm. One of the possible reason explaining this is the short channel

effect. However, all the fabricated devices had gate length/barrier thickness aspect ratios larger than 5 at least, then no short channel effect was expected to take place. Another responsible mechanism is formation of virtual gates [1-4], where the effective gate length is virtually longer than that of geometrical size due to unintentional charging up of the surface at the gate periphery.

Analysis of Gate Control Characteristics

To study the gate characteristics in detail, simulation of the transfer characteristics based on two-dimensional (2D) potential calculation were carried out and compared with the experimental curves. Theoretical drain current was computed using a standard drift current formula in a linear region. Here, carrier concentration was obtained from the calculated potential. In this potential simulation, AlGaN surface Fermi level was assumed to be pinned completely at the charge neutrality energy level, E_{CNL}. Experimental curves were measured by using small drain voltage of 0.2 V to obtain the drain current in the linear region so as to eliminate the effect of potential modulation by the drain voltage. For examples, experimental curves for the devices with gate lengths of 400 nm and 130 nm are plotted with thick solid lines in Figs. 3a and 3b, respectively. Theoretical curves for various gate lengths are also plotted in the figures and the theory clearly showed that g_m values increase by the decrease of the gate length. In Fig. 3c, we compared the experimental and theoretical $g_{m\,max}$ as a function of gate length. This plot clearly shows the degradation of g_m

in the fabricated devices and it becomes remarkable when the gate length is less than 500 nm.

From Fig. 3, the fabricated devices were found to behave just like having longer gate lengths than those of geometrical sizes, as schematically shown in Fig. 4a. The observed behavior indicates the formation of virtual gate. [1-4] In order to see this point clearly, the values of effective gate length, L_{Geff}, were estimated. The procedure for estimation is as follow. In Figs. 3a and 3b, we picked out cross points of experimental I_D-V_G curve with theoretical one for each gate length. The gate length of a theoretical curve at each cross point was taken as the effective gate length at the corresponding gate voltage. Then, the effective gate length changed depending on the gate voltage. Estimated effective gate lengths for the fabricated devices with L_G = 130 nm, 400nm and 1000 nm are summarized in Fig. 4b. From this figure, it can be clearly seen that the effective gate lengths are much longer than geometrical size and they depend on the gate voltage in all devices. With decrease of the gate voltage, the effective gate length increased monotonically. This trend was common in all fabricated devices. Figure 4c shows virtual gate extension, ΔL_{Geff}, as a function of the gate voltage. In this figure, we could find that the values of the virtual gate extensions were almost same for all devices as well as their voltage dependences, even thought the geometrical gate lengths were different each other. These results clearly suggest that the Schottky gate periphery plays important roles in the observed anomalous gate control characteristics.

Anomalous Behaviors in nm-Scale Schottky Gates on HFETs and Their Analysis

Thus, detailed investigation was made on characteristics of the nm-scale Schottky gates on the HFETs. Figures 5a and 5b show measured I-V-T characteristics of the reference large size AlGaN Schottky diode and a 200 nm-Schottky gate on a HFET, respectively, plotted by circles and boxes. The measurement temperature was varied from 300 K to 150 K. From these plots, both samples were found to have very large reverse currents together with small temperature dependencies as compared with those predicted from conventional thermionic emission (TE) theory for standard Schottky interfaces. Especially, the HFET Schottky gate showed anomalously large leakage current both in forward and reverse biases together with a shoulder component in the low forward region, which was never seen in the reference large-size diodes.

To analyze the obtained results, the theoretical I-V-T curves were computed based on a thin surface barrier (TSB) model [5,6] using an one dimensional potential simulation and computation of tunneling coefficient by WKB approximation.[6] Calculated I-V-T curves are plotted also in Figs. 5a and 5b by solid lines. The key features of the TSB model are summarized in Fig. 5c. In this model, high-density donor-like defects due to nitrogen vacancy (V_N) near the surface form a thin surface barrier region.[5,6] The surface defect distribution in the depth direction decays exponentially. The thickness of the surface defect region is characterized by a parameter, λ. The TSB enhances electron tunneling in the

surface region and the total current transport though the Schottky interface is controlled by thermionic field emission (TFE). TSB parameters to fit the experimental data in Fig. 5a are also schematically shown in Fig. 5c. In the case of the large-size bulk Schottky diode, the TSB model reproduced experiment curves quite well in both forward and reverse bias regions including their temperature dependence. This confirms the TSB model is responsible for the gate leakage currents in the large-size Schottky diodes. On the other hand, in the case of the nm-scale Schottky gate HFETs, only forward currents in the high bias region could be reproduced by the theory. Increase of over all currents compared with the large-size diodes was due to thinning of top AlGaN barriers by high-density donor doping and polarization effects in the AlGaN/GaN heterostructures by the simulation. However, the current component in the reverse bias region as well as the current shoulder in the low forward bias could not be reproduced, even when the TSB parameters were varied. Then, the discrepancies from the theory were also brought by the gate peripheral effect in the nm-scale Schottky gates.

To find the origin of such anomalous characteristics in the nm-scale Schottky gates on HFETs, temperature dependence of the ideality factors in forward bias, n_f, were evaluated. As shown in Fig. 5b, the forward currents had two components, the one was the current in the high bias region that could be reproduced by the TSB model, and another was the shoulder current component in the low bias region having a rather slow slope. Then ideality factors for each component were evaluated for various temperatures and the results

are shown in Fig. 6. Solid lines in the figure show the theoretical curves based on the TFE model for various specific energy [7], E_{00},

$$E_{00} = qh(N_D/\varepsilon_S m_e^*)^{1/2}/4\pi, \qquad (1)$$

where h is Plank's constant, N_D is effective donor concentration, ε_S and m_e^* are dielectric constant and electron effective mass in the AlGaN. Figure 6 shows that experimental data for two current components followed the theoretical curves well, which confirmed that the both current components were controlled by the TFE transport. This result also indicated the existence of higher electric fields than that deduced from the standard Schottky barrier potential. Then, effective donor concentrations were calculated from Eq. (1), assuming a standard Schottky barrier, and the maximum electric field, E_{max} at the interface were computed using a simple formula, $E_{max} = \{2qN_D(\phi_{Bn}-E_C+E_F-V_G)/\varepsilon_S\}^{1/2}$, where ϕ_{Bn} is Schottky barrier height for n-type AlGaN. Using ϕ_{Bn} = 1.3 eV from the result in Fig. 5a, calculated maximum fields together with the effective donor concentrations from Eq. (1) are summarized in Table I. The field strengths of 2 MV/cm and 5 MV/cm for current components in high and low bias regions, respectively. The one-dimensional (1D) potential calculation based on the TSB model indicates the existence of maximum field of 2.4 MV/cm in vertical (depth) direction, which was very close to the value from the temperature dependence of the ideality factor in the high biases. This clarifies that the

current component in the high bias is controlled by the TSB. On the other hand, the current in the low bias region indicated the presence of anomalously large electric field as compared with that expected from the TSB model in the present layer structure.

Thus, the region having the large field region was sought in the calculated 2D potential at $V_G = -1$ V, as shown in Fig. 7a. Then, strong lateral field was found to exist at the gate periphery as indicated by an arrow in the figure. To see it more clearly, the lateral electric field at AlGaN top surface was picked up and plotted in Fig. 7b. From the simulation result, the maximum field about 4 MV/cm was obtained just at the gate periphery. This value was close to the value of 5 MV/cm estimated from the temperature dependence of the ideality factor in the low bias region as in Table I, rather the vertical field of 2 MV/cm by the TSB. These results clarifies that the anomalous leakage currents in the nm-sized Schottky gates are caused by the strong lateral field at the gate periphery as schematically shown in Fig. 8. The lateral maximum field from the calculated potential somewhat deviated from the values estimated from the leakage current, however, this seems to come from a simple estimate of the field from the leakage current using several approximations. Here, it should be noted that such strong lateral field at gate periphery was produced only when the AlGaN surface Fermi level was assumed completely pinned at the charge neutrality energy level, E_{CNL}, then the existence of high-density surface states resulted in such anomalies in nm-scale Schottky gates on GaN-based HFETs.

Model for Virtual Gate Formation

All the results obtained above consistently indicated that the anomalies in both gate control and gate current characteristics for the fabricated HFETs were controlled by the gate periphery. Here, it should be noted that the strong surface Fermi level pinning on AlGaN surfaces and high-density V_N-related deep donors unique in GaN-based materials strongly relate to the observed phenomena. In addition, although the other III-V semiconductor HFETs also show the virtual gate effect caused by the strong surface Fermi level pinning,[8] the effect is not so remarkable as in GaN-based HFETs. Considering these facts, a possible model for the virtual gate formation is deduced, schematically shown in Fig. 9. Figure 9a shows the band diagram at the initial stage of negative gate voltage application. In first, the strong lateral electric field with a thinned barrier is produced by a large potential difference between the gate metal and the strongly pinned AlGaN surface, and a large number of electrons are injected laterally from the gate to the AlGaN surface at the gate periphery. This results in an anomalous gate leakage currents in the low bias region.

In this study, we paid attention to the effect of injected electrons at the gate periphery. They have two possible ways after injection; escape from the surface by strong vertical field (in the depth direction) or trapped in the high-density surface states. The laterally injected electron has very high velocity due to the strong lateral field. On the other hand, the energy relaxation time is around 0.1 ps,[9] then electrons travel laterally about 10 nm and

fall to the conduction band edge by loosing their energy. After that, as shown in Fig. 7b, most of them are accelerated by a strong vertical field about 10^6 V/cm which is higher than that in lateral direction of about 10^4 V/cm at 10 nm from the gate edge. On the other hand, there are still some electrons that are trapped by surface states before acceleration by the vertical field. Assuming surface state capture cross section of 1.2×10^{-16} cm^2,[10] thermal velocity of 2.4×10^7 cm/s, the surface state density of 10^{13} cm^{-2} and the surface region thickness of $\lambda \sim 10$ nm from Fig. 5b, the lifetime of electrons in the surface region is estimated to be 35 ps. This value suggests that the most electrons escape from the surface before being trapped by the surface states. However, the small number of electrons trapped in surface states keep staying without recombination, then injected electrons can fill up both the accepter-like surface states and V_N-related deep donors at the gate edge locally in the static case. This is because the surface recombination rate is very small due to the small surface recombination velocity of 5×10^4 cm/s [11] and quite small minority carrier concentration in the wide band gap material. In the next step, electrons increase their numbers in the surface states by current injection at the gate edge start to move laterally through the surface states as shown in Fig. 9b. As the AlGaN has surface state distribution as shown in the right in Fig. 9a,[6,10] the trapped electrons not only ionize the acceptor-like surface states but also neutralize the V_N-related deep donors. Finally, the surface at the gate periphery is charged up in negative and the surface potential rises up to the metal Fermi level as shown in Fig. 9c. This region works as the virtual gate as shown in Fig. 9d.

If the motion of trapped electrons through surface states is controlled by a diffusion process as the virtual gate extension in Si MOSFETs,[12] a diffusion length will give a good index of the virtual gate extension size. The diffusion length was derived from the simple carrier continuous equation in the steady state,

$$D_n \frac{\partial^2 \Delta n(x)}{\partial x^2} - \Delta n(x)/\tau_{emission} - U_S = 0 \qquad (2)$$

where, x is the lateral position in the surface, D_n is the diffusion coefficient in the surface, $\tau_{emission}$ is an emission time from the surface states, and $\Delta n(x)$ is trapped excess electron density in the surface states, and U_S is the surface recombination rate. As mentioned above, the surface recombination is negligible small because of the small surface recombination velocity and the small number of minority carriers in GaN-based materials. Then, the diffusion length, L_S, is given by $(D_n\tau_{emission})^{1/2}$. For simplicity, we only considered a discrete surface state level corresponding to the V_N-related deep donor, even though the surface state distribution has continuous shape. It has been found that the V_N-related surface donor level is 0.37 eV from E_C [4,10] and $\tau_{emission}$ is 1 ms at room temperature [10] for AlGaN surfaces. However, these values gave unreasonably large L_S value to explain the experimental data.

Then, the effect of the strong vertical field which enhanced the emission rate from traps [13] were considered. Taking the Poole-Frenkel type process into account, the trap energy effectively decreases by $(qE/\pi\varepsilon_S)^{1/2}$, where E is the vertical field strength. Using the

vertical field value obtained from the gate leakage current analysis, $\tau_{emission}$ was estimated about 0.15 ns. Also considering the degradation of the diffusion coefficient in the surface by 1/10 order than that in the bulk value, as the mobility degradation in the surface [13], L_S = 220 nm was obtained. This is a reasonably good value for explaining ΔL_G in Fig. 3b. Again, it is noted that the reasons why the virtual gate effect is remarkable in GaN-based FETs are high-density V_N-related surface deep donors increasing the electric field and unintentional electron injection in the surface as well as the small surface recombination due to small surface recombination velocity as compared with GaAs-based materials and small minority carrier density in wide band gap materials. However, for more quantitative explanation of ΔL_G including its gate voltage dependence and the potential shape of the virtual gate regions, further investigation is necessary considering the realistic situation including dynamic carrier transport, charging/discharging processes in continuously distributed surface states, and their potential modulation.

Finally, we mention the effect of the virtual gate on RF characteristics. The most of the electrons trapped in the surface states cannot access directly to the gate metal, therefore the virtual gate mentioned above seems to only respond to the DC signals. However, the region close to the gate edge, the electrons can exchange between the gate metal and surface states by direct tunneling through a very thin potential barrier at the gate periphery, and responds to the high-speed signals. This should also degrade the RF performance. Therefore, the removal of surface states is essentially important for GaN-based FETs to

improve both their performance and reliability.

CONCLUSION

Gate control properties together with gate leakage currents in AlGaN/GaN HFETs with nm-scale Schottky gates were investigated focusing on effects of AlGaN surfaces at the gate periphery. Fabricated AlGaN/GaN HFETs showed unexpectedly small gate length (L_G)-dependence of transconductance, g_m. Comparison of transfer characteristics from theory and experiment, effective L_G in the fabricated devices were found much longer than geometrical size in the order of 100 nm, indicating the formation of virtual gates. Detailed analysis of the gate leakage current behaviors based on a thin surface barrier model showed the presence of strong electric field at the gate periphery. Mechanism of the virtual gate formation was discussed based on the obtained nm-scale Schottky gate behaviors.

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REFERENCES

1. R. Vetury, N. Q. Zhang, S. Keller and U. K. Mishra, *IEEE Trans. Electron Devices* 48, 560 (2001).
2. A. M. Wells, M. J. Uren, R. S. Balmer, K. P. Hilton, T. Martin, M. Missous, *Solid-State Electron.* 49, 279 (2005).
3. G. Koley, V. Tilak, L. F. Eastman and M. G. Spencer, *IEEE Trans. Electron Devices* 50, 886 (2003).
4. J. Kotani, S. Kasai, T. Hashizume and H. Hasegawa, *J. Vac. Sci. Technol. B* 23, 1799 (2005).
5. H. Hasegawa and S. Oyama, *J. Vac. Sci. Technol. B* 20,1647 (2002).
6. J. Kotani, H. Hasegawa and T. Hashizume, *J. Vac. Sci. Technol. B* 22, 2179 (2004)
7. S. M. Sie, *Physics of Semiconductor Devices,* 2nd ed. (1981), John Wiley & Sons, New York.
8. A Kameda, S. Kasai, T. Sato, and H. Hasegawa, *Solid-State Electron.* 47, 323 (2003).
9. D. C. Herbert, M. J. Uren, B. T. Hughes, D. G. Hayes, J. C. H. Birbeck, R. Balmer, T. Martin, G.C. Crow, R. A. Aabram, M. Walmsley, R. A. Davies, R. H. Wallis, W. A. Phillips and S. Jones, *J. Phys. Condens. Matter* 14, 3479 (2002).
10. H. Hasegawa, T. Inagaki, S. Ootomo and T. Hashizume, *J. Vac. Sci. Technol. B* 21, 1844 (2003).
11. R. Aleksiejunas, M. Sudzius, T. Malinauskas, J. Vaitkus, K. Harasiunas and S. Sakai,

Appl. Phys. Lett. 83, 1157 (2003).

12. A. S. Grove, *Physics and Technology of Semiconductor Devices*, (1967), John Wiley & Sons, New York.
13. O. Mitroofanov and M. Manfra, *Appl. Phys. Lett.* 84, 422 (2004).
14. S. Hasegawa, I. Shiraki, T. Tanikawa, C. L. Petersen, T. M. Hansen, P. Boggild and F. Grey, *J. Phys. Condens. Matter* 14, 8379 (2002).

Figure captions

Fig. 1. Fabricated device structure.

Fig. 2. (a) Example of measured I_D-V_D curves and (b) g_m-V_G characteristics for devices having various gate lengths.

Fig. 3. Experimental I_D-V_G curve for devices (a) L_G = 400 nm and (b) L_G = 130 nm, respectively. Theoretical curves for various gate lengths are also plotted with thin lines. (c) Gate length dependence of g_m from experiment and theory.

Fig.4. (a) Schematics of virtual gate on an AlGaN/GaN HFET, (b) estimated effective gate length, L_{Geff}, and (c) lateral extension of virtual gate, ΔL_{Geff}, as a function of gate voltage.

Fig. 5. Experimental and theoretical I-V-T curves for (a) a large size AlGaN Schottky diode and (b) a 200 nm-gate AlGaN/GaN HFET. (c) Basic concept of TBS model and assumed parameters.

Fig. 6. Temperature dependences of ideality factors for HFET Schottky gate current components in low bias and high bias regions.

Fig. 7. (a) Contour plot of calculated potential in the HFET and (b) lateral electric field at the AlGaN surface at V_G = -1 V.

Fig. 8. Schematics of Schottky gate leakage current transports at gate periphery.

Fig. 9. Model for formation of a virtual gate, (a) band diagram at the initial condition

under gate voltage application and the AlGaN surface state distribution, (b) half way of electron injection and surface state charging, (c) a band diagram with surface state filling in the steady state and (d) a schematic of the virtual gate formation.

Table I. Estimated E_{00}, N_D and E_{max} from temperature dependence of n_f

	E_{00}	Effective N_D	E_{max} (V_G = 0V)
High bias component	50 meV	1 x 10^{19} cm^{-3}	2 MV/cm
Low bias component	110 mV	8 x 10^{19} cm^{-3}	5 MV/cm