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Citation	Applied Physics Letters, 83(14), 2952-2954 https://doi.org/10.1063/1.1616648
Issue Date	2003-10-06
Doc URL	http://hdl.handle.net/2115/5540
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Type	article
File Information	APL83-14.pdf

APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 14 6 OCTOBER 2003

Suppression of current collapse in insulated gate AlGaN/GaN heterostructure field-effect transistors using ultrathin Al_2O_3 dielectric

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(Received 20 May 2003; accepted 12 August 2003)

We investigated effects of electronic states at free surfaces of AlGaN/GaN heterostructure field-effect transistors (HFETs) on the inner current transport at the heterointerfaces. The analysis on transient currents for the air-exposed and H_2-plasma-treated devices showed that N-vacancy-related near-surface traps play an important role in current collapse in AlGaN/GaN HFETs. An Al_2O_3-based surface passivation scheme including an N_2-plasma surface treatment was proposed and applied to an insulated-gate HFET. A large conduction-band offset of 2.1 eV was achieved at the $Al_2O_3/Al_{0.3}Ga_{0.7}N$ interface. No current collapse was observed in the fabricated Al_2O_3 insulated-gate HFETs under both drain stress and gate stress. *© 2003 American Institute of Physics.* [DOI: 10.1063/1.1616648]

Although significant progress has been achieved in the GaN-based high-power/high-frequency electronic devices, surface-related problems still need an immediate solution. In particular, so-called current collapse effects not only degrade microwave output performance but also impede reliable operation of the GaN-based power devices. The current collapse phenomena have often been observed in Schottky-gate AlGaN/GaN heterostructure field-effect transistors (SG HFETs) under both gate stress[1–6] and drain stress.[2,5,7] Some models based on the electron trapping by surface states have been proposed.[6,7] However, the mechanism for the current collapse is not clarified as yet.

In this letter, we report on passivation effects of the Al_2O_3-based insulated-gate (IG) structure on current collapse in AlGaN/GaN HFETs. Although SiN_x films have been used to mitigate the surface problems on the GaN-based devices,[4–9] it can be argued that its band gap ($E_G \sim 5$ eV) and dielectric constant ($\epsilon \sim 7$) are not suitable for utilization as a gate barrier to $Al_xGa_{1-x}N$ (e.g., $E_G \sim 4.1$ eV and $\epsilon \sim 9$ for $x = 0.3$). In this aspect, Al_2O_3 has an advantage over SiN_x for the application to IG-type AlGaN/GaN HFETs, due to its larger band gap and higher dielectric constant. For understanding the collapse mechanism and optimizing passivation process, the dynamic response of surface states was investigated in terms of transient currents in gateless HFETs.

The AlGaN/GaN heterostructures used in the present study are schematically shown in Fig. 1. The structure consists of undoped GaN, undoped $Al_xGa_{1-x}N$, Si-doped $Al_xGa_{1-x}N$, and undoped $Al_xGa_{1-x}N$ layers, all grown by metalorganic vapor phase epitaxy on c-plane sapphire or 6H-SiC substrate. The Al content x ranged from 0.28 to 0.30. Typical values of the electron concentration and mobility of the samples at room temperature were 1.1×10^{13} cm^{-2} and 900 $cm^2/V\,s$, respectively. As an ohmic contact, a Ti/Al/Ti/Au layered structure was formed on the surface of GaN/AlGaN, followed by annealing in N_2 ambient at 800 °C for 2 min.

A gateless HFET structure with a drain–source spacing of 4 μm, shown in Fig. 1(a), was prepared to investigate the correlation between the surface electronic states and inner current transport. The surface of the gateless device was subjected to H_2 plasma and N_2 plasma excited using an electron cyclotron resonance (ECR) source with a microwave power of 50 W. The process temperature and time were 280 °C and 1 min, respectively. The Al_2O_3-based surface passivation structure was fabricated through the following *in situ* steps: The AlGaN surface was treated in the ECR N_2 plasma at 280 °C for 1 min. An Al layer with a nominal thickness of 3 nm was then deposited by molecular-beam deposition on the AlGaN surface at RT in the molecular-beam-epitaxy growth chamber. Subsequently, the top Al layer was oxidized using ECR-excited O_2 plasma at RT for 5 min. Finally, the sample was annealed at 700 °C for 10 min under UHV condition. Through this *in situ* process, an Al_2O_3 IG HFET structure schematically shown in Fig. 1(b) was fabricated.

Transient current measurements were made on the gateless HFETs. Firstly, drain stress ranging from 9 to 15 V was applied to the devices for 50–300 s. Next, the transient currents were recorded after returning the drain voltage to the quiescent bias of 0.5 V. Figure 2 shows an example of transient currents at RT observed in the gateless device exposed to H_2 plasma. The current showed an initial fast transient followed by highly nonexponential recovering transient. For the device with air-exposed surface, a similar transient with a rather small amplitude was observed. In addition, both de-

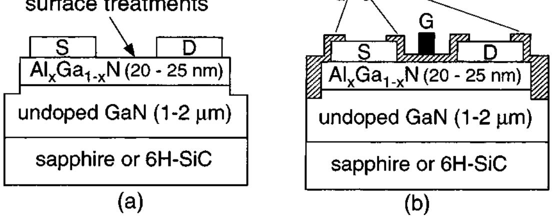

FIG. 1. Schematic illustrations of (a) gateless HFET and (b) Al_2O_3 IG HFET.

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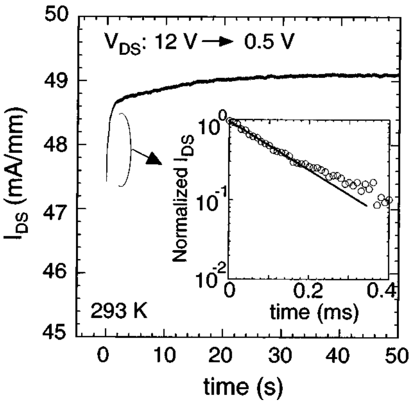

FIG. 2. Transient currents observed in the gateless HFET exposed to H_2 plasma at 280 °C for 1 min.

vices showed an increase in transient amplitude with the drain stress. On the other hand, no transient was observed in current for the N_2-plasma-treated device and the Al_2O_3-passivated device. If thermal effects are dominant for the current transients, then all gateless devices would show almost the same transient behavior in drain currents, independent of surface treatments. However, the present results indicated that the current transients seem to be caused by trapping and detrapping of electrons by surface states, thereby reflecting the difference in surface electronic properties.

Figure 3 shows measured temperature dependence of the time constant of the initial fast transient as a function of the inverse temperature. The same Arrhenius-type temperature dependence with an activation energy ΔE of 0.37 eV was obtained for the air-exposed and H_2-plasma-treated devices. Note that the activation energy was calculated by taking into account the temperature correction factors. Thus, a deep level with the signature plot shown in Fig. 3 plays a dominant role in the transient in drain currents. Mizutani *et al.*[10] have very recently detected a similar surface trap in AlGaN/GaN HFETs from low-frequency noise measurement. On the other hand, slow and nonexponential response seems to be typical of electron emission from a surface state continuum that includes a wide range of time constants.

A detailed x-ray photoelectron spectroscopy (XPS) analysis showed that a serious depletion of N atoms was found at the AlGaN surfaces for the samples with the H_2-plasma treatment. During the process, highly active hydrogen radicals can react with the AlGaN surface to form volatile NH_x products. For the air-exposed device, it is expected that natural oxidation leads to escape of N atoms in the NO_x form as well as partial formation of Al oxide and Ga oxide. Such surface reactions will introduce N vacancy and related defects in the near-surface region of AlGaN. Thus, the most likely candidate for the observed 0.37 eV deep level seems to be N vacancy, or a complex related to N vacancy. Such near-surface trap and surface states could be filled with electrons injected from the channel during the application of a large drain stress. This could form a "virtual gate" with a negative charge at the free AlGaN surface.[11] After switching the drain voltage to the quiescent bias of 0.5 V, the emission of the trapped electrons from the surface electronic states resulted in the transient in the drain current, as shown in Fig. 2.

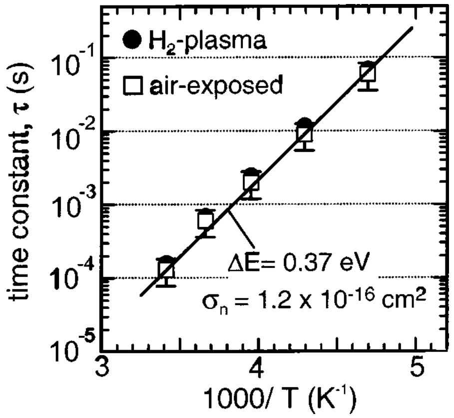

FIG. 3. Temperature dependence of the time constant of the dominant fast current transient in the gateless HFET.

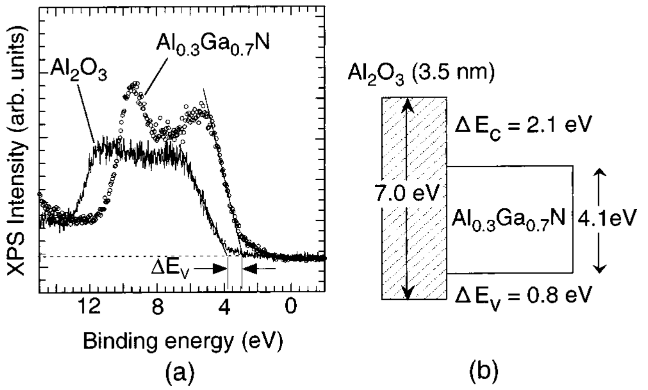

FIG. 4. (a) XPS valence-band spectra of the AlGaN surface before and after the passivation and (b) band alignment at the Al_2O_3/AlGaN interface.

No depletion of N atoms was observed on the N_2-plasma-treated AlGaN surface. This is consistent with the finding that the gateless HFETs with the N_2-plasma treatment showed no current transient. It is likely that the present ECR N_2-plasma treatment partially recovers or terminates the N-vacancy-related surface defects, leading to reduction of surface-defect traps and surface states on AlGaN.[9] For practical surface passivation of devices, however, one needs a protective layer against chemical reaction or charge transfer. Thus, we have developed a surface passivation scheme with a combination of ECR N_2-plasma treatment and formation of thin Al_2O_3 layer, and applied it to the IG HFET shown in Fig. 1(b).

Figure 4(a) shows the XPS valence-band spectra of the AlGaN surface before and after the passivation process. After the passivation, a drastic change in the spectrum appeared, reflecting the formation of the Al oxide layer. The valence band offset ΔE_v was estimated to be 0.8 eV from the energy difference between the leading edges of the valence-band spectra. A separate XPS analysis showed[12] that the composition of the Al oxide was very close to Al_2O_3 and that the energy gap E_G of the Al oxide was 7.0 eV. It was also shown that the thickness of the Al_2O_3 layer was 3.5 nm. As a result, we obtained a large conduction-band offset of 2.1 eV at the Al_2O_3/AlGaN interface, as shown in Fig. 4(b). Such band structure is desirable for insulated gate application to AlGaN/GaN HFETs. Indeed, the Al_2O_3 IG structure led to more than three orders reduction of leakage currents as

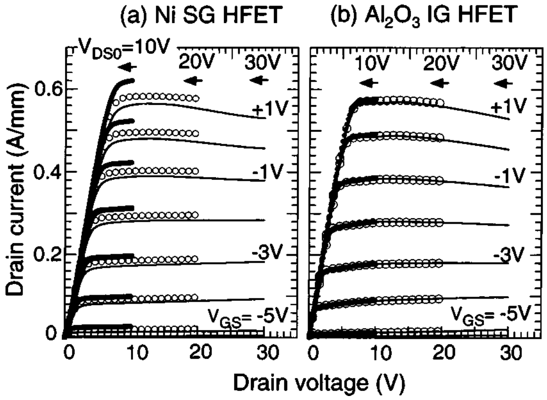

FIG. 5. Drain $I-V$ characteristics of the fabricated Ni SG and Al_2O_3 IG HFETs under various drain-stress voltages.

compared to the conventional Ni Schottky-gate HFETs.

Figure 5 shows comparison of drain $I-V$ characteristics between the SG and the Al_2O_3 IG HFETs with device size of 1.0 μm×60 μm under various drain-stress voltages. The solid lines, open circles and dotted lines correspond to the $I-V$ sweeps with the initial drain stress V_{DS0} of 30, 20, and 10 V, respectively. As shown in Fig. 5(a), the SG HFET showed pronounced drain-stress-dependent current collapse, very similar to the reported data.[2,5] This can be explained by the electron injection into surface states under high drain voltages, as mentioned earlier. On the other hand, all the $I-V$ sweeps traced the same line at the given gate voltage for the Al_2O_3 IG HFET, as shown in Fig. 5(b), indicating the significant effects of the present Al_2O_3-based passivation structure.

As one of the methods of investigating manifestation of current collapse or rf dispersion under gate stress, we compared pulsed mode $I-V$ characteristics between conventional Ni SG and Al_2O_3 IG HFETs.[2,4,5] The result is shown in Fig. 6. In the dc mode, a sweep of the gate voltage was made statically from -8 to $+1$ V with a sweeping rate of 0.05 V/s. In the pulse-mode measurements, on the other hand, we set -8 V for the base line of the gate pulse form. The gate voltage was then increased to $+1$ V with a pulse width of 0.5 ms and a 5% duty cycle, as indicated in the inset of Fig. 6.

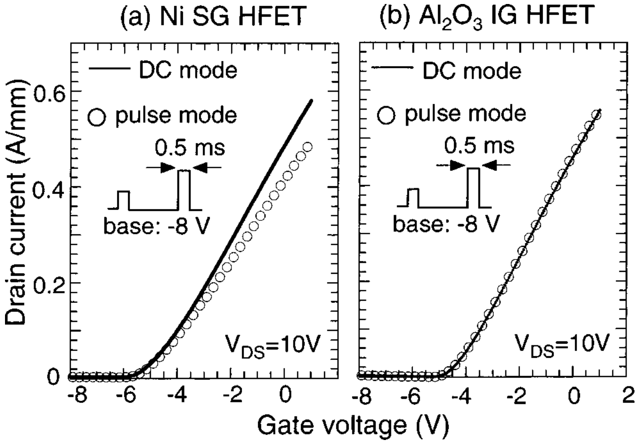

FIG. 6. $I_{DS}-V_{GS}$ characteristics measured under the dc-mode and the pulse-mode gate sweepings.

As shown in Fig. 6(a), large differences in drain currents between the dc- and pulse-mode methods were observed for the Ni SG HFETs.[2,4–6] The gate stress induced electron injection into surface states in the region between gate and drain, causing the virtual gating effects on the AlGaN surface. The serious gate leakage currents observed in the SG HFETs can assist such electron injection.[11] Even after increasing gate voltage in the pulse form, this virtual gating effects continue and reduce the two-dimensional electron gas density due to the base line of -8 V, causing a serious current collapse. As shown in Fig. 6(b), on the other hand, no current collapse was observed for the Al_2O_3 IG HFET. The present Al_2O_3-based passivation process including ECR N_2-plasma treatment can reduce surface states. In addition, the Al_2O_3 IG structure remarkably decreased gate leakage currents. Thus, our Al_2O_3-based IG and surface passivation structure is very effective in suppressing current collapse in AlGaN/GaN HFETs.

In summary, the analysis on the transient currents in the gateless AlGaN/GaN HFETs showed that the N-vacancy-related near-surface trap is one of the possible origins for current collapse. To suppress the current collapse, the Al_2O_3-based surface passivation scheme including the N_2-plasma treatment was applied to the insulated-gate type GaN/AlGaN HFET. No current collapse was observed in the fabricated Al_2O_3 IG HFETs under both drain stress and gate stress, indicating a remarkable advantage of the Al_2O_3-based passivation for reliability improvement of AlGaN/GaN HFETs.

This work was partly supported by 21C COE Project on "Meme-Media Based Next Generation ITs" and grant-in-aid for Scientific Research (B) (No. 14350155) from the Ministry of Science, Education, Sports, and Culture, Japan.

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