APPLIED PHYSICS LETTERS VOLUME 84, NUMBER 4 26 JANUARY 2004

Surface passivation effects on AlGaN/GaN high-electron-mobility transistors with SiO_2, Si_3N_4, and silicon oxynitride

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(Received 16 September 2003; accepted 25 November 2003)

Surface passivation effects were studied on AlGaN/GaN high-electron-mobility transistors (HEMTs) using SiO_2, Si_3N_4, and silicon oxynitride (SiON) formed by plasma enhanced chemical vapor deposition. An increase of I_{Dmax} and g_{mmax} has been observed on the passivated (SiO_2, Si_3N_4 and SiON) HEMTs when compared with the unpassivated HEMTs. About an order of magnitude low I_{gLeak} and three orders of magnitude high I_{gLeak} was observed on Si_3N_4 and SiO_2 passivated HEMTs, respectively, when compared with the unpassivated HEMTs. The increase of I_{gLeak} is due to the occurrence of surface related traps, which was confirmed by the observation of kink and hysteresis effect on dc and ac $I_{\mathrm{DS}}-V_{\mathrm{DS}}$ characteristics, respectively. Though the Si_3N_4 passivated HEMTs show better dc characteristics, the breakdown voltage (BV_{gd}) characteristics are not comparable with SiO_2, SiON passivated and unpassivated HEMTs. The SiON is also a very promising candidate as a surface passivant for AlGaN/GaN HEMTs because it shows better BV_{gd} with low hysteresis width and small I_D collapse than Si_3N_4 passivated HEMTs. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1642276]

In recent years, there has been intense development of AlGaN/GaN high-electron-mobility transistors (HEMTs) as candidates for high power and high temperature applications at microwave frequencies. Recently researchers have demonstrated impressive AlGaN/GaN microwave power HEMTs as high as 11.7 W/mm.[1] The performance of these devices are limited by trapping effects through drain-current collapse.[2] Much attention has been focused on the reduction of surface states using different passivation dielectrics.[3–8] The Si_3N_4 and SiO_2 shown to be able to mitigate the effects of these states.[3,5,6,9] Kikkawa *et al.*[10] demonstrated free of current collapse and g_m dispersion by surface-charge controlled HEMTs by Si_3N_4. More than one order of magnitude higher gate leakage currents (I_{gLeak}) after SiO_2 and Si_3N_4 passivation were found earlier.[11,12] On the other hand slightly lower I_{gLeak} after passivation with Si_3N_4 were reported recently.[5] Due to the occurrence of deep traps, SiO_2 passivated HEMTs show slow switching speed with high breakdown voltage (BV_{gd}).[13] There is no report available for the surface passivation studies on AlGaN/GaN HEMTs with SiON. In this letter, we are reporting the surface passivation studies of SiO_2, Si_3N_4, and SiON on AlGaN/GaN HEMTs. In addition, unpassivated HEMTs are also compared with the passivated HEMTs.

The AlGaN/GaN heterostructure was grown on 2-in.-diameter sapphire substrate using metalorganic chemical vapor deposition (Nippon Sanso SR2000). The device structure and the growth conditions were published elsewhere.[14] After the device isolation with BCl_3 plasma reactive ion etching, SiO_2, Si_3N_4, and SiON dielectrics with a thickness of ~100 nm were deposited at 300 °C by plasma enhanced chemical vapor deposition (PECVD). Refractive indices of the deposited SiO_2, Si_3N_4, and SiON are 1.47, 1.88, and 1.58, respectively. The XPS spectra revealed the deposited SiO_2 and Si_3N_4 dielectrics[3] were slightly silicon rich and SiON was slightly nitrogen rich. The source drain ohmic contacts were formed after etching the dielectrics with optimized buffered HF solution using Ti/Al/Ni/Au (20/72/12/40 nm) metals followed by lamp annealing at 775 °C for 30 s. The samples contact resistances were in the range between 1.25 and 1.77 Ω mm. The gate metal Pd/Ti/Au (40/20/60 nm) was formed by conventional lithography.[2]

The inset of Fig. 1 shows the schematic diagram of the surface passivated HEMTs. The dielectric layers: (i) source-gate gap, (ii) gate-drain gap, and (iii) isolated region were covered. To observe the effect of surface passivation, unpassivated AlGaN/GaN HEMTs were also fabricated on the same wafer. The dc characteristics were carried out on the HEMTs using Agilent 4156c semiconductor parameter analyzer under dark and white-light illumination. To observe the drain current (I_D) collapse of the devices, ac $I_{\mathrm{DS}}-V_{\mathrm{DS}}$ characteristics were carried out at different drain sweep voltages ($V_{\mathrm{DS}}=0-8$, 0–12, 0–15, 0–20, 0–25, and 0–30 V) using Tektronix 370A curve tracer.[2]

Figure 1 shows the good pinchoff $I_{\mathrm{DS}}-V_{\mathrm{DS}}$ characteristics of unpassivated and passivated 15-μm-AlGaN/GaN HEMTs. Table I shows the dc parameters of unpassivated and passivated HEMTs. The device dimensions are: $W_g=15\ \mu$m, $L_{sd}=11\ \mu$m, $L_{sg}=5\ \mu$m, and $L_g=1.5\ \mu$m. An increase in the maximum drain current ($I_{D\,\max}$) and extrinsic transconductance ($g_{\mathrm{m\,max}}$) of ~19% and 8% for SiO_2, 19% and 6% for Si_3N_4, and 11% and 2% for SiON passivated

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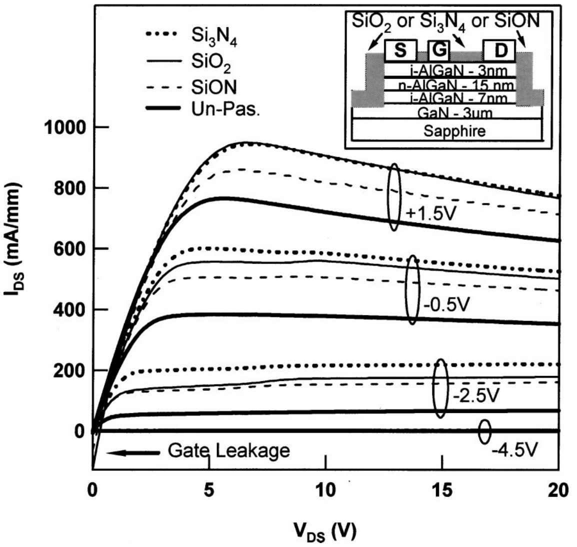

FIG. 1. dc I_{DS}–V_{DS} characteristics of Si_3N_4, SiO_2, SiON passivated and unpassivated AlGaN/GaN HEMTs on sapphire substrate: $V_G=+1.5$ V, $\Delta V_G=-2.0$ V. Inset is a schematic diagram of passivated AlGaN/GaN HEMTs.

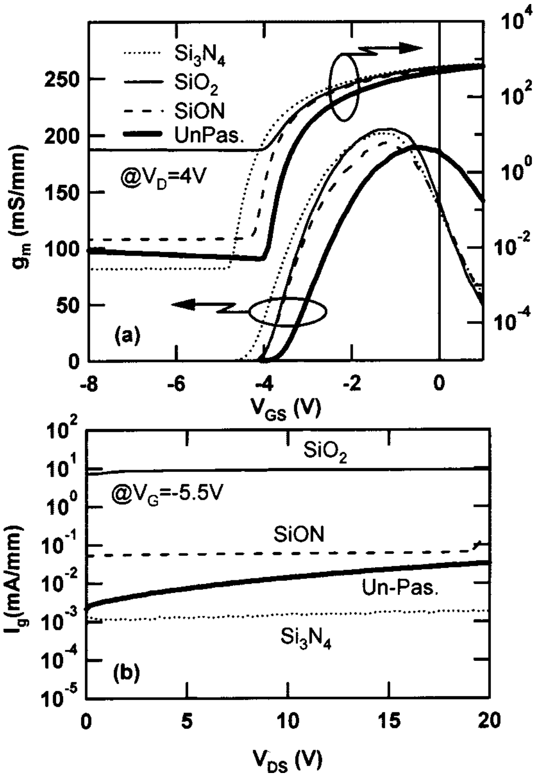

FIG. 2. (a) Transfer characteristics of Si_3N_4, SiO_2, SiON passivated and unpassivated AlGaN/GaN HEMTs measured at $V_D=4$ V, (b) I_g–V_{DS} characteristics of passivated and unpassivated HEMTs measured at subthreshold regime ($V_G=-5.5$ V).

HEMTs, respectively, were observed when compared with the unpassivated HEMTs. Figure 2(a) shows the transfer characteristics of passivated and unpassivated HEMTs. Though, the $I_{D\,\max}$ and $g_{m\,\max}$ increased due to the surface controlled effect,[10] the rise in gate-leakage current (I_{gLeak}) was observed[11,12] except Si_3N_4 passivated HEMTs.[5] Figure 2(b) shows the I_{gLeak} of unpassivated and passivated HEMTs measured at subthreshold regime ($V_G=-5.5$ V). Two terminals I_{gLeak} were also measured on Schottky diode and the results were similar to the results of three terminals I_{gLeak}. About an order of magnitude low I_{gLeak} and three orders of magnitude high I_{gLeak} was observed on Si_3N_4 and SiO_2 passivated HEMTs, respectively, when compared with the unpassivated HEMTs. Similar behavior was observed for drain leakage current [see Fig. 2(a)]. The rise in I_{gLeak} for the SiO_2 and SiON passivated devices results in a significant output conductance, which was observed by other authors[11,12] and would have implications for increased rf noise. The surface related traps with activation energy of 0.2 eV accounted for the I_{gLeak} mechanism.[14]

The I_D collapse behavior was realized using ac I_{DS}–V_{DS} characteristics.[2] Inset of Fig. 3 shows the output resistance [ratio of knee voltage (V_{knee}) and $I_{D\,\max}$] of passivated and unpassivated HEMTs for different V_{DS}. The I_D reduction with the increase of V_{DS} up to 30 V was high for SiO_2 passivated HEMTs when compared with the other dielectric passivated and unpassivated HEMTs (see Table I). The observation of high I_D collapse in SiO_2 passivated HEMTs are due to the effect of surface related traps, which was confirmed by the occurrence of hysteresis in ac I_{DS}–V_{DS} measurements. The V_{knee} variation at a particular I_D is high for SiO_2 passivated HEMTs, very little variation has been observed in unpassivated HEMTs. The device output power (P_{out}) was calculated with: $P_{\mathrm{out}}=(V_{DS}-V_{\mathrm{knee}})(I_D/2)$ by fixing the $V_{DS}=30$ V.[2] Highest P_{out} was observed on Si_3N_4 passivated HEMTs. SiO_2 passivated HEMTs exhibited lowest P_{out}. Bernat *et al.*[15] were also observed similar behavior with SiO_2 passivation. The hysteresis (looping) effects were observed on both the passivated and unpassivated HEMTs. Relatively high P_{out} with low I_D collapse and hysteresis width (V_{hys}) was observed on SiON passivated HEMTs when compared with unpassivated HEMTs. Maximum V_{hys} (2.27 V) was observed at $V_G=+1.5$ V for SiO_2 passivated HEMTs (see Table I) which indicates the existence of traps. The carrier trapping effects were confirmed using dark and white-light illuminated dc characteristics.[2] Figure 3 shows

TABLE I. Device dc parameters of SiO_2, Si_3N_4, and SiON passivated and unpassivated AlGaN/GaN HEMTs on sapphire substrate.

Parameters	$I_{D\,\max}$ (mA/mm)	$g_{m\,\max}$ (mS/mm)	$(I_{dI}-I_{dd})/I_{dI}$ (%) @$V_D=4.45$ V and $V_G=-1.5$ V	V_{th} (V)	V_{th} Vari. (%)	V_{hys} (V) @30 V	I_{dAC} Reduc. (%) @$V_G=+1.5$ V and $V_D=30$ V	V_{knee} Vari. (%)	BV_{gd} (V)	P_{out} (W/mm)
Un-Pas.	766	189	7.00	−3.67	1.89	0.68	0.89	6.80	112	4.39
SiO_2	949	205	8.33	−4.19	5.80	2.27	6.83	40.2	132	3.60
Si_3N_4	943	201	6.91	−4.41	1.59	0.70	2.39	19.2	56	4.72
SiON	860	193	8.18	−4.07	3.00	0.08	1.51	20.4	108	4.36

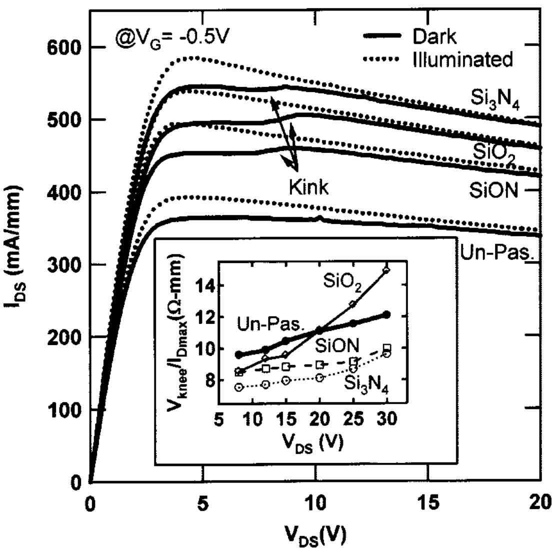

FIG. 3. dc I_{DS}–V_{DS} characteristics of Si_3N_4, SiO_2, SiON passivated and unpassivated AlGaN/GaN HEMTs measured at $V_G = -0.5$ V under dark and white-light illumination. Inset is $V_{knee}/I_{D\,max}$ vs drain sweep voltages (V_{DS}=0–8, 0–12, 0–15, 0–20, 0–25, and 0–30 V) measured from ac I_{DS}–V_{DS} characteristics.

the dc I_{DS}–V_{DS} characteristics of unpassivated and passivated HEMTs measured under dark and white-light illumination. The percentage of increase in I_D under illumination was high for SiO_2 and SiON passivated HEMTs when compared with the Si_3N_4 and unpassivated HEMTs (see Table I). The kink or current slump was high on passivated HEMTs. Similar behavior was observed on Si_3N_4 passivated AlGaN/GaN HEMTs by Ando *et al.*[16] There is no kink observed on unpassivated HEMTs. Due to the occurrence of deep traps, large V_{th} variation with respect to applied V_{DS} was observed for SiO_2 (5.8%) and for SiON (3%) passivated HEMTs. Small I_{gLeak}, small V_{hys}, small V_{th} variation, small kink, small I_D collapse with high P_{out} was observed on Si_3N_4 and unpassivated HEMTs.

Figure 4 shows breakdown voltage (BV_{gd}) characteristics, which were measured on unpassivated and passivated HEMTs at subthreshold regime ($V_G = -5.5$ V) with $L_{gd} = 5.0\ \mu$m and $W_g = 200\ \mu$m. The SiO_2 passivated HEMTs exhibited high BV_{gd} (see Table I) when compared with the passivated (Si_3N_4 and SiON) and unpassivated HEMTs. The observation of low BV_{gd} values on Si_3N_4 passivated HEMTs are due to the occurrence of lateral depletion by shallow traps between gate-drain regions. The observation of high BV_{gd} from SiO_2 passivated HEMTs are due to the formation of deep traps in the SiO_2/AlGaN interface ensure the capture of electrons injected from the gate during turnoff, which depletes the channel vertically instead of laterally.[13] This helps to increase BV_{gd}. But the electrons emit from these deep traps too slowly during turn-on. The enhancement of BV_{gd} (~48%) with low V_{hys} for SiON (80 mV) passivated HEMTs are probably due to the occurrence of both shallow and deep traps when compared with Si_3N_4 passivated HEMTs. The occurrence of very small V_{hys} on SiON passivated HEMTs are an indication to get high switching speed (see Table I). Reasonably good ac and dc characteristics with enhanced BV_{gd} was observed on SiON passivated HEMTs.

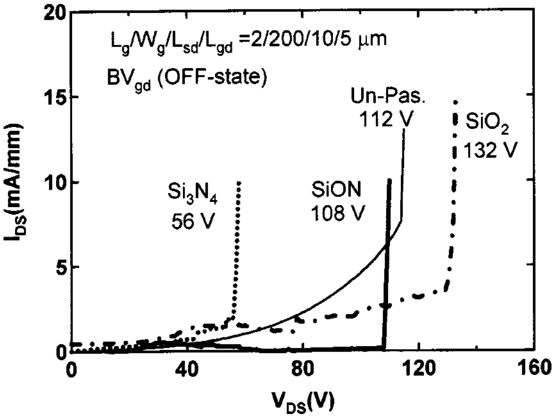

FIG. 4. OFF-state ($V_G = -5.5$ V) breakdown voltage (BV_{gd}) characteristics of Si_3N_4, SiO_2, SiON passivated, and unpassivated AlGaN/GaN HEMTs.

We have demonstrated the surface passivation effects on the performance of AlGaN/GaN HEMTs using PECVD grown SiO_2, Si_3N_4, and SiON. An increase of I_{Dmax} and g_{mmax} has been observed on the passivated (SiO_2, Si_3N_4 and SiON) HEMTs when compared with the unpassivated HEMTs. About an order of magnitude low I_{gLeak} and three orders of magnitude high I_{gLeak} was observed on Si_3N_4 and SiO_2 passivated HEMTs, respectively, when compared with the unpassivated HEMTs. Small increase of I_{gLeak} was observed on SiON passivated HEMTs. Low I_D collapse with low I_{gLeak} was observed on Si_3N_4 passivated AlGaN/GaN HEMTs. The observation of high BV_{gd} on SiO_2 passivated HEMTs are due to the formation of deep traps instead of shallow traps. The SiON is a very promising candidate as a surface passivant for AlGaN/GaN HEMTs because it shows better BV_{gd} with small I_D collapse and V_{hys} than Si_3N_4 passivated HEMTs.

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