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AlGaN/GaN metal-oxide-semiconductor heterostructure field-effect transistor with oxidized Ni as a gate insulator

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We fabricated the AlGaN/GaN metal-oxide-semiconductor heterostructure field-effect transistor (MOSHFET) using the oxidized Ni(NiO) as a gate oxide and compared electrical properties of this device with those of a conventional AlGaN/GaN heterostructure field-effect transistor (HFET). NiO was prepared by oxidation of Ni metal of 100 Å at 600 °C for 5 min in air ambient. For HFET and MOSHFET with a gate length of 1.2 μm, the maximum drain currents were about 800 mA/mm and the maximum transconductances were 136 and 105 mS/mm, respectively. As the oxidation temperature of Ni increased from 300 to 600 °C the gate leakage current decreased dramatically due to the formation of insulating NiO. The gate leakage current for the MOSHFET with the oxidized NiO at 600 °C was about four orders of magnitude smaller than that of the HFET. Based on the dc characteristics, NiO as a gate oxide is comparable with other gate oxides. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1811793]

Recent advancements in AlGaN/GaN based heterostructure field-effect transistors (HFETs) have opened the way for their practical applications to high power and high frequency electronic devices.[1–3] However, several significant problems still remain hindering wide range applications of these devices. First, the gate leakage current limiting the operation of HFET is too high.[4] Second, HFETs exhibit current collapse with a high rf input drive on the gate resulting in significantly reducing the rf powers below the values expected from dc.[5,6] AlGaN/GaN metal-oxide-semiconductor HFETs (MOSHFETs) using the gate oxide such as $Ga_2O_3(Gd_2O_3)$,[7] SiO_2,[8–10] MgO,[11] Sc_2O_3,[12] and insulators such as AlN[13] and Si_3N_4[14,15] offer lower gate leakage current and greater voltage swings than conventional HFETs. In addition, the gate oxide can also be used for surface passivation, mitigating the current collapse that occurs in unpassivated devices due to traps between the gate and drain regions.

Recently, Ho *et al.*[16,17] successfully developed a contact to *p*-type GaN with a specific contact resistance lower than $1\times10^{-4}\ \Omega\ cm^2$ using an oxidizing Ni/Au(100/50 Å). They attributed the low resistance ohmic contact to the formation of *p*-NiO. However, it is estimated that the hole concentration of oxidized Ni is less than $1\times10^{16}\ cm^{-3}$. In addition, the perfect NiO crystal is an insulator of which band gap and dielectric constant are 4.0 eV and 11.9, respectively.[17] The dielectric constant of NiO is much larger than that of $SiO_2(\varepsilon=3.9)$, $Si_3N_4(\varepsilon=7.5)$, and $MgO(\varepsilon=9.8)$ and comparable to $Sc_2O_3(\varepsilon=14.5)$. Therefore, NiO can act as a gate insulator for MOSHFET. In view of process point, moreover, using oxidized NiO has two advantages compared to other gate oxides. The one is free from the plasma exposure that can damage the device property due to the direct exposure of plasma to active region during the oxide deposition.[18–21] The other is a relative clean interface between AlGaN and gate oxide because Ni metal is deposited at very high vacuum of about 10^{-7} Torr. However, there is no work about NiO gate insulator for MOSHFET.

In this letter, we report on the fabrication of the AlGaN/GaN MOSHFET with NiO insulating layer and present dc characteristics of the devices. NiO was prepared by oxidation of Ni metal of 100 Å at 600 °C for 5 min in air ambient. For a gate length of 1.2 μm, the maximum drain currents were about 800 mA/mm for both devices. The gate leakage current for the MOSHFET with the oxidized NiO at 600 °C was about four orders of magnitude smaller than that of the HFET. Based on the dc characteristics, NiO as a gate oxide is comparable with other gate oxides.[8,12,14]

The AlGaN/GaN HFET structures were grown by metalorganic chemical vapor deposition on *c*-plane Al_2O_3 substrates. The layer structure had a 2-μm-thick semi-insulating GaN buffer followed by a 500-Å-thick unintentionally doped $Al_{0.28}Ga_{0.72}N$ layer. The Hall mobility and sheet carrier density were 720 $cm^2/V\ s$ and $7.4\times10^{12}\ cm^{-2}$, respectively. Two device structures with and without NiO gate insulator layer were fabricated. The device dimensions are gate length (L_g) of 1.2 μm, gate width (W_g) of 20 μm, and source-drain separation of 2.7 μm. Figure 1 shows a cross-sectional schematic diagram of the MOSHFET with NiO gate insulator. The device fabrication started with device isolation. A BCl_3 based inductively coupled plasma system was used to define the mesa. Ohmic metals consisted of thermal deposited

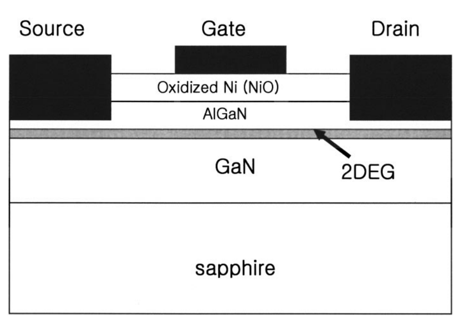

FIG. 1. Schematic diagram of NiO/AlGaN/GaN MOSHFET structure.

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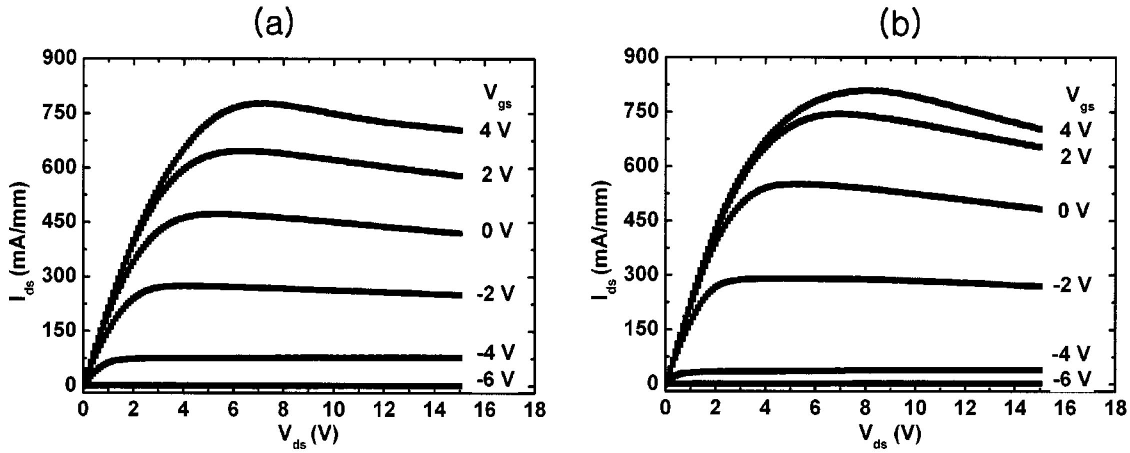

FIG. 2. Drain-source current (I_{ds}) characteristics of the (a) NiO/AlGaN/GaN MOSHFET and (b) AlGaN/GaN HFET with L_g=1.2 μm and W_g=20 μm as a function of drain-source voltage (V_{ds}). The gate-source voltage (V_{gs}) was varied from 4 to −6 V in steps of −2 V.

Ti/Al/Ni/Au(250/1100/300/1200 Å) and annealed at 800 °C for 30 s using rapid thermal annealing in a N_2 ambient. The ohmic contact characteristics of the Ti/Al/Ni/Au were investigated by transmission line method . For the oxidized Ni layer Ni metal of 100 Å was deposited on AlGaN layer using e-beam evaporator at about 10^{-7} Torr between ohmic contacts and then standard lift-off procedures were used to remove the metal's outside patterns. Ni oxidation was performed with a thermal treatment from 300 to 600 °C for 5 min in an air ambient. As the annealing temperature increased the oxidized Ni layer changed into transparency from dark color, which revealed the transformation of Ni layer into NiO. Thermal evaporated Ni/Au gate contacts were employed on both the HEFTs and MOSHFETs. Current–voltage measurements were performed using a parameter analyzer (HP 4155A).

Figure 2 shows the drain current (I_{ds}) versus drain-source voltage (V_{ds}) characteristics of MOSHFET and HFET for different values of gate-source voltage (V_{gs}) at room temperature. As shown in Fig. 2, for both devices the maximum drain current of about 800 mA/mm was comparable and the negative resistance characteristics due to self-heating were shown for higher gate biases. Good pinch off properties were observed at gate biases of about −5.9 and −5.0 V for MOSHFET and HFET, respectively. The higher pinch off voltage in MOSHFET compared with that of HFET is considered to be due to the addition of NiO insulating layer. For a higher gate bias, however, MOSHFET is well modulated more than HFET due to NiO.

Figure 3 shows extrinsic transconductance (G_m) and I_{ds} as a function of V_{gs} for MOSHFET and HFET. The maximum transconductances (G_{mmax}) of MOSHFET were 105 mS/mm which was smaller than 136 mS/mm of HFET in the saturation region of V_{ds}=8 V due to the addition of NiO insulating layer. As can be seen from Fig. 3, the MOSHFET using NiO gate oxide has an advantage of having a larger gate voltage swing and a higher linearity than the HFET. This should lead to smaller intermodulation distortion, to a smaller phase noise, and to a larger dynamic range compared to the HFET.

The gate leakage current properties for MOSHFET at different Ni oxidized temperatures at 5 min in air ambient and HFET are shown in Fig. 4. Above 500 °C the MOSHFETs were observed to have better gate properties than those of HFET. The color of the as-deposited Ni was dark. However, as the oxidation temperature increased Ni metal changed into transparency, which was related to the electrical property of oxidized Ni layer. The inset of Fig. 4 shows the two dominant gate leakage current passes in MOSHFET. The gate leakage current for the MOSHFET at 600°C oxidation temperature was shown to be about four orders of magnitude smaller than that for the HFET at V_{gs}

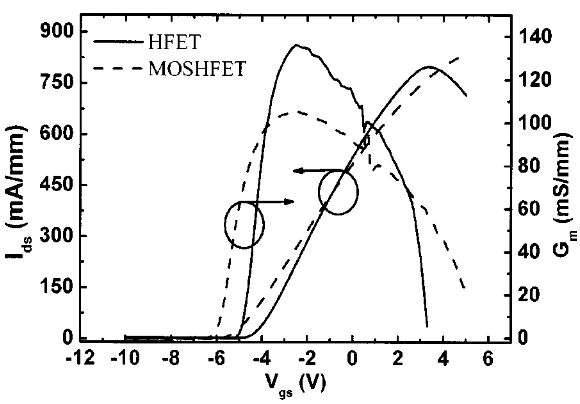

FIG. 3. Extrinsic transconductance (G_m) and I_{ds} characteristics of the NiO/AlGaN/GaN MOSHFET and AlGaN/GaN HFET as a function of gate-source voltage (V_{gs}) at V_{ds}=8 V.

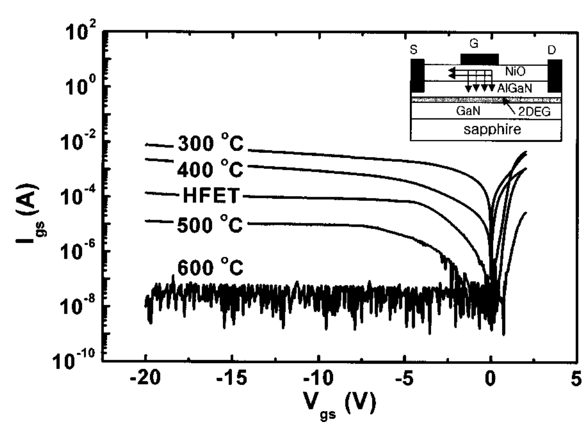

FIG. 4. Gate current comparisons of MOSHFET at different Ni oxidized temperatures and HFET as a function of gate voltage. The device width is 20 μm. The inset shows the gate leakage current passes through the oxidized Ni layer in the MOSHFET.

$=-20$ V. These demonstrate that the oxidized Ni layer on the AlGaN barrier layer suppressed the gate leakage current due to more and more oxidation as the oxidation temperature increased, resulting in improved device characteristics. Further works will continue to understand the material quality and electrical property of oxidized NiO with annealing temperature.

In conclusion, we have fabricated AlGaN/GaN MOSHFET with oxidized NiO gate insulator. The measured characteristics of the MOSHFET showed a good potential of this device for high frequency and high power applications.

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[1]K. Kasahara, H. Miyamoto, Y. Ando, Y. Okamoto, T. Nakayama, and M. Kuzuhara, Tech. Dig. - Int. Electron Devices Meet. **2002**, 667 (2002).
[2]R. Quay, R. Kiefer, F. van Raay, H. Massler, S. Ramberger, S. Muller, M. Dammann, M. Schlechtweg, and G. Weimann, Tech. Dig. - Int. Electron Devices Meet. **2002**, 673 (2002).
[3]R. Sandhu, M. Wojtowicz, M. Barsky, R. Tsai, I. Smorchkova, C. Namba, P. H. Liu, R. Dia, M. Truong, D. Ko, J. W. Yang, and M. A. Khan, Tech. Dig. - Int. Electron Devices Meet. **2001**, 940 (2001).
[4]I. Daumiller, C. Kirchner, M. Kamp, K. J. Ebeling, and E. Kohn, IEEE Electron Device Lett. **20**, 448 (1999).
[5]C. Nguyen, N. X. Nguyen, and D. E. Grider, Electron. Lett. **35**, 16 (1999).
[6]E. Kohn, I. Daumiller, P. Schmid, N. X. Nguyen, and C. N. Nguyen, Electron. Lett. **35**, 1022 (1999).
[7]F. Ren, M. Hong, S. N. G. Chu, M. A. Marcus, M. J. Schurman, A. Baca, S. J. Pearton, and C. R. Abernathy, Appl. Phys. Lett. **73**, 3893 (1998).
[8]M. Asif Khan, X. Hu, G. Sumin, A. Lunev, J. Yang, R. Gaska, and M. S. Shur, IEEE Electron Device Lett. **21**, 63 (2000).
[9]G. Simin, A. Koudymov, H. Fatima, J. Zhang, J. Yang, M. Asif Khan, X. Hu, A. Tarakji, R. Gaska, and Michael S. Shur, IEEE Electron Device Lett. **23**, 458 (2002).
[10]D.-W. Chou, K.-W. Lee, J.-J. Huang, H.-R. Wu, Y.-H. Wang, M.-P. Houng, S.-J. Chang, and Y.-K. Su, Jpn. J. Appl. Phys., Part 2 **41**, L748 (2002).
[11]J. Kim, R. Mehandru, B. Luo, F. Ren, B. P. Gila, A. H. Onstine, C. R. Abernathy, S. J. Pearton, and Y. Irokawa, Appl. Phys. Lett. **80**, 4555 (2002).
[12]B. Luo, R. Mehandru, J. Kim, F. Ren, B. P. Gila, A. H. Onstine, C. R. Abernathy, S. J. Pearton, D. Gotthold, R. Birkhahn, B. Peres, R. C. Fitch, N. Moser, J. K. Gillespie, G. H. Jessen, T. J. Jenkins, M. J. Yannuzi, G. D. Via, and A. Crespo, Solid-State Electron. **47**, 1781 (2003).
[13]D.-H. Cho, M. Shimizu, T. Ide, H. Ookita, and H. Okumura, Jpn. J. Appl. Phys., Part 1 **41**, 4481 (2002).
[14]B. M. Green, K. K. Chu, E. M. Chumbes, J. A. Smart, J. R. Shealy, and L. F. Eastman, IEEE Electron Device Lett. **21**, 268 (2000).
[15]X. Hu, A. Koudymov, G. Simin, J. Yang, M. Asif Khan, A. Tarakji, M. S. Shur, and R. Gaska, Appl. Phys. Lett. **79**, 2832 (2001).
[16]J.-K. Ho, C.-S. Jong, C.-N. Huang, C.-Y. Chen, C. C. Chiu, and K.-K. Shin, Appl. Phys. Lett. **74**, 1275 (1999).
[17]J.-K. Ho, C.-S. Jong, C. C. Chiu, C.-N. Huang, K.-K. Shin, L.-C. Chen, F.-R. Chen, and J.-J. Kai, J. Appl. Phys. **86**, 4491 (1999).
[18]K. L. Seaward, N. J. Moll, D. J. Coulman, and W. F. Stickle, J. Appl. Phys. **61**, 2358 (1987).
[19]K. L. Seaward, N. J. Moll, and W. F. Stickle, J. Electron. Mater. **19**, 385 (1990).
[20]R. J. Shul, M. E. Sherwin, A. G. Baca, and D. J. Rieger, Electron. Lett. **32**, 70 (1996).
[21]S. J. Pearton, F. Ren, and C. R. Abernathy, Semicond. Sci. Technol. **8**, 1897 (1993).