Improved Linearity and Reliability in GaN MOS-HEMTs Using nanolaminate La2O3/SiO2 Gate Dielectric

Wang-Cheng Shih1, Hisang-Hua Hsu1, Yu-Xiang Huang1, Tai-Wei Lin1, Chia-Hsun Wu2, Yueh-Chin Lin3, Jer-Shen Maa4, Edward Yi Chang2,3,6, Kuniyuki. Kakushina5 and Hiroshi. Iwai5,6

1Institute of Photonic System, National Chiao-Tung University (NCTU).
2001 Ta Hsueh Road, Hsinchu 30010, Taiwan, R.O.C.
Phone: +886-9-3030-8298 E-mail: sshihiwntw@gmail.com
2Institute of Materials Science and Engineering, National Chiao-Tung University (NCTU).
3Institute of Lighting and Energy Photonics, National Chiao-Tung University (NCTU).
4Institute of Electronics Engineering, National Chiao-Tung University (NCTU).
5Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology.
J2-68, 4259 Nagatsuta, Midori-ku, Yokohama 226-8502, Japan
6International college of Semiconductor Technology, National Chiao-Tung University (NCTU).

Abstract—Improved device property for linear power applications has been discussed in this study. We have compared the La2O3/SiO2 AlGaN/GaN MOS-HEMTs with other La2O3-based (La2O3/HfO2, La2O3/CeO2 and single La2O3) MOS-HEMTs. It was found that forming lanthanum silicate films can not only improve dielectric quality but also can improve device characteristics. The improved gate insulating, reliability and linearity by 8-nm La2O3/SiO2 MOS-HEMT was demonstrated.

1. Introduction
GaN metal-oxide-semiconductor high-electron-mobility transistors (MOS-HEMTs) has been intensively investigated due to its larger voltage swing, high breakdown field and lower gate leakage current, as compared with the conventional Schottky HEMTs[1,2]. Among the dielectric materials, La2O3 is one of the attractive due to its high dielectric constant, large bandgap and better thermal stability[3]. However, it is chemically unstable in air by reacting with CO2 to form La2(CO3)3 or absorbing water to form La(OH)3. Recently, some research have been focused on the properties of lanthanum silicate films, which was found to be much more inert with respect to hydroxide and carbonate formation, and less likely to contain oxygen deficiencies[1,4]. SiO2 is hydrophilic and has large energy band offset with GaN, we believed that forming lanthanum silicate films can not only improve dielectric quality and stability but also can further improve device reliability, linearity and other dc property. Thus in this study, we fabricated the AlGaN/GaN MOS-HEMTs with 8 nm nano-laminate La2O3/SiO2 gate dielectrics and compared with other kinds of La2O3-based MOS-HEMTs (La2O3/HfO2, La2O3/CeO2 and single La2O3) and Schottky-gate HEMTs. The improved linearity and reliability had been demonstrated in La2O3/SiO2 MOS-HEMTs.

2. Device fabrication and measurement
The samples used in this study were grown on silicon substrate by MOCVD. It includes 1μm GaN buffer, 25nm undoped AlGaN barrier and 10nm undoped GaN cap layer. The fabrication processes started from the device isolation by ICP mesa etching using Cl2 gases. The etching depth was 200nm. Then, the multilayer metal of Ti/Al/Ni/Au was deposited using E-Gun evaporator and annealed by rapid thermal annealing (RTA) system at 800°C for 60 sec in N2 ambient to form Ohmic contact, and the spacing of source-drain was 20μm. Four kinds of 8 nm nanolaminate La2O3-based film(La2O3/SiO2, La2O3/HfO2, La2O3/CeO2 and single La2O3) was deposited by molecular beam deposition (MBD) as the gate dielectric, the thickness has been checked by transmission electron microscopy (TEM). Fig.1 shows the schematic diagram of the stacked La2O3-based MOS-gate structure. Afterward, a post–deposition annealing (PDA) was carried out at 600°C in N2 ambient for 5 minutes. Finally, Ni/Au gate metal was deposited by E-Gun evaporator, and the gate length used was 2μm. The conventional HEMTs were fabricated for comparison which had same process steps except for gate dielectric deposited. Agilent E5270B device analyzer was used for DC characteristic and the reliability test. Intermodulation characteristic were measured by HP8753D network analyzer.

3. Results and discussions
3.1 DC measurements
Fig.2(a) shows the dc transfer characteristics for the studied devices, it was observed that the maximum drain current (I_DMAX) of La2O3/SiO2 MOS-HEMTs is the highest, the improved gate insulating property was shown in Fig 2(b). The reduction of gate leakage current of La2O3/SiO2 MOS-HEMTs is due to the larger bandgap of lanthanum silicate films. Table.1 shows the result of measurement. The larger gate-voltage swing (GVS), breakdown voltage (BV) and better subthreshold slope (SS) was observed in La2O3/SiO2 MOS-HEMTs. However, the threshold voltage (VTH) of La2O3/SiO2 MOS-HEMTs was relatively negative due to its lower dielectric constant as compared with others.
Fig. 2 (a) dc transconductance, (b) $I_G-V_G$ characteristics of the studied devices.

Table 1 Comparison measured data of studied devices.

<table>
<thead>
<tr>
<th>Material</th>
<th>$g_{m0}$ (mA/V)</th>
<th>$I_{th}$ (μA)</th>
<th>$V_{TH}$ (V)</th>
<th>$V_{GS}$ (V)</th>
<th>$I_{SS}$ (A/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>La$_2$O$_3$/SiO$_2$</td>
<td>705</td>
<td>139</td>
<td>-4.00</td>
<td>3.05</td>
<td>200</td>
</tr>
<tr>
<td>La$_2$O$_3$/HfO$_2$</td>
<td>672</td>
<td>138</td>
<td>-3.45</td>
<td>2.75</td>
<td>200</td>
</tr>
<tr>
<td>La$_2$O$_3$/CeO$_2$</td>
<td>567</td>
<td>106</td>
<td>-3.9</td>
<td>2.3</td>
<td>470</td>
</tr>
<tr>
<td>La$_2$O$_3$ CeO$_2$</td>
<td>533</td>
<td>130</td>
<td>-3.5</td>
<td>2.8</td>
<td>425</td>
</tr>
<tr>
<td>La$_2$O$_3$</td>
<td>587</td>
<td>146</td>
<td>-3.05</td>
<td>2.15</td>
<td>325</td>
</tr>
</tbody>
</table>

Fig. 3 Comparison of current degradation and proportion after high voltage stress.

Table 2 Comparison measured data of studied devices.

<table>
<thead>
<tr>
<th>Material</th>
<th>Before stress</th>
<th>After 3 hours stress</th>
<th>$\Delta C_g$</th>
<th>$\Delta I_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>La$_2$O$_3$/SiO$_2$</td>
<td>0.672</td>
<td>0.722</td>
<td>11.12</td>
<td>11.78</td>
</tr>
<tr>
<td>La$_2$O$_3$/HfO$_2$</td>
<td>1.05</td>
<td>1.14</td>
<td>12.86</td>
<td>13.44</td>
</tr>
<tr>
<td>La$_2$O$_3$/CeO$_2$</td>
<td>0.674</td>
<td>0.81</td>
<td>20.6</td>
<td>21.44</td>
</tr>
<tr>
<td>La$_2$O$_3$ CeO$_2$</td>
<td>0.766</td>
<td>18.02</td>
<td>Fail</td>
<td>Fail</td>
</tr>
</tbody>
</table>

The reliability test was executed under drain-source voltage ($V_{DS}$) of 200V and gate-source voltage ($V_{GS}$) of -5V for 3 hours. Fig. 3 shows La$_2$O$_3$/SiO$_2$ MOS-HEMTs had only 1.2% current degradation after high voltage stress and Table 2 also shows the stability of gate capacitance, which were due to the improvement of gate dielectrics quality and gate insulating characteristics. The larger breakdown voltage and better reliability of La$_2$O$_3$/SiO$_2$ MOS-HEMTs showed a great potential for power applications.

3.3 Intermodulation characteristics

Fig. 4 IP3 versus $I_{DS}$ curves for studied device, the test frequency is 2GHz and $V_{DS}$=20V

Since the larger output current and wider GVS, the maximum third-order intercept (IP3) value of La$_2$O$_3$/SiO$_2$ MOS-HEMTs was 22.16 dBm and showed totally higher than other devices versus different $I_{DS}$. After 3 hours high voltage stress, La$_2$O$_3$/SiO$_2$ MOS-HEMTs also showed less degradation of IP3 value. The result was shown in fig. 4.

4. Conclusions

The 8nm molecular beam deposited nano-laminate La$_2$O$_3$/SiO$_2$ MOS-HEMTs was compared with the same thickness of La$_2$O$_3$/HfO$_2$, La$_2$O$_3$/CeO$_2$ and La$_2$O$_3$ MOS-HEMTs. The improved output current, gate insulating, reliability and linearity was demonstrated in this study which showing the great potential of La$_2$O$_3$/SiO$_2$ MOS-HEMTs for high-linearity power applications.

Acknowledgements

This work was sponsored by National Chung-Shan Institute of Science & Technology, Taiwan, under Grant No. CSIST-0101-V108 (104)

References