Improved microwave and noise performance of InAlAs/InGaAs metamorphic high-electron-mobility transistor with a liquid phase oxidized InGaAs gate without gate recess

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The metal-oxide-semiconductor metamorphic high-electron-mobility transistor (MOS-MHEMT) with an oxide grown by liquid phase oxidation on the InGaAs capping layer without a gate recess exhibits a lower leakage current density with suppressed impact ionization, better microwave characteristics, and improved high frequency noise performance compared to the conventional MHEMT with a recessed gate. The improved high frequency performance is due to the lower gate-source and gate-drain capacitances of the InAlAs/InGaAs MOS-MHEMT. Reduced surface recombination and impact ionization may also contribute to the improved frequency response, noise performance, and associated gain. © 2010 American Institute of Physics. [doi:10.1063/1.3430569]

The gate leakage current of the metamorphic high-electron-mobility transistor (MHEMT) is higher than that of the conventional HEMT due to its high indium mole fraction. The conduction band discontinuity (ΔE_c) is only 0.52 eV for the In0.52Al0.48As/In0.53Ga0.47As layers. The high aluminum content in the In0.52Al0.48As Schottky layer also generates more surface states to further induce a gate leakage issue. Moreover, the narrow energy-gap high-indium-content InGaAs channel is typically accompanied by impact ionization, which brings about high gate leakage current and current instability. Therefore, the output conductance, breakdown voltage, and output power are degraded, and this is harmful to high-power and low-noise applications. The kink effect associated with surface treatment or impact ionization could be overcome by employing an insulator to form a metal-oxide-semiconductor (MOS) structure to suppress surface states and increase the barrier height. However, a reliable and economical oxide film on the Schottky layer is still required. In addition, the gate-recess process also creates surface states which generate parasitic capacitances that degrade device performance.

A simple and selective liquid phase oxidation (LPO) on GaAs operated at low temperature (30–70 °C) has been proposed and investigated. Our previous works have reported on the preliminary study of the oxide film composition and the dc characteristics of the InAlAs/InGaAs MOS-MHEMT. Improved microwave performance of the same structure with an oxidized InAlAs gate has been achieved, and the improved results were attributed to parasitic capacitances; however, it was less pronounced that what is observed. Low frequency noise measurement, which is also a commonly used method to investigate MOS interface properties of MOS-MHEMTs and surface treatment properties of HEMTs, has been extensively studied in InGaAs-based devices. However, only a few studies have been devoted to the detailed characterization of microwave behavior, especially in InGaAs-based devices. Even less attention has been paid to the high frequency noise between the high-indium-content MOS-HEMT and HEMT. In this paper, microwave performance and the high frequency noise of the InAlAs/InGaAs MOS-MHEMT with an oxidized InGaAs gate without gate recess is presented and discussed to further understand the role of the gate oxide.

The MHEMT structure is grown by metalorganic chemical vapor deposition on a semi-insulating GaAs substrate. The structure is composed of a metamorphic buffer layer, a 30 nm In0.53Ga0.47As channel layer, a 10 nm undoped In0.52Al0.48As spacer layer, a Si d-doping layer, a 30 nm undoped In0.52Al0.48As Schottky layer, and a 10 nm In0.53Ga0.47As cap layer with a silicon doping density of 5 × 10^16 cm^-3. The measured room-temperature Hall mobility and sheet carrier concentration were ~7000 cm^2/Vs and ~2 × 10^{12} cm^-2, respectively. The device isolation was accomplished by mesa wet etching down to the buffer layer. Ohmic contacts were made with Au/Ge/Ni alloy (84:12:4 by weight) deposited by evaporation, and then patterned by a lift-off processes, followed by rapid thermal annealing at 300–340 °C for 30–60 s. The gate recess was etched with a citric buffer etchant for the referenced MHEMT. For MOS-MHEMT fabrication, the wafers were immersed in the LPO growth solution to generate the gate oxide directly at 50 °C. The LPO can convert the 10-nm-thick In0.53Ga0.47As capping layer into the oxide film without gate recess. Finally, the gate electrode was formed by a lift-off process with Au. The gate dimension and the drain-to-source spacing are 0.65 × 200 μm^2 and 3 μm, respectively.

Figure 1 shows the three-terminal off-state breakdown and on-state breakdown for MOS-MHEMT and the referenced MHEMT. The off-state breakdown voltage is defined as the maximum V_DS where the pinched-off device reaches a drive current density of 1 mA/mm. The on-state voltage is defined as the maximum V_Ds with half of the saturation drain current density of the device. The on-state breakdown voltage is dominated by impact ionization in the InGaAs channel, and the off-state breakdown voltage is believed to

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be dependent on a combination of thermionic-field emission of electrons from the metal gate to the Schottky layer and impact ionization in the InGaAs channel. When the gate bias is as low as the pinch-off voltage, some carriers still pass through the InGaAs channel. In our previous study, the MOS-MHEMT has a smaller subthreshold swing than the referenced one for the same VDS. Therefore, it appears that MOS-MHEMT has a smaller subthreshold swing than the various VDS for the MOS-MHEMT and referenced MHEMT. The VDS swept from 2.5 to 4 V in 0.5 V per step.

In the MOS-MHEMT, however, the electrical field in the gate-to-drain region at a fixed VDS and VGS is smaller than that of the referenced MHEMT due to the high barrier height between the gate metal and the Schottky layer. This results in a smaller channel electric field, and therefore a smaller impact ionization effect that is beneficial to the output conductance.

Figure 3 shows the measured unity-current-gain cutoff frequency, fT, and the maximum oscillation frequency, fmax, at the maximum transconductance gm of the referenced MHEMT and MOS-MHEMT. The fT and fmax of MHEMT (MOS-MHEMT) are 14 (30) GHz and 29 (60) GHz, respectively. The gate-source capacitance, Cgs, and gate-drain capacitance, Cgd, extracted from S-parameters of the MOS-MHEMT (Cgs=0.458 pF and Cgd=0.022 pF) are lower than those of the referenced MHEMT (Cgs=0.784 pF and Cgd=0.056 pF) at the VGS with maximum gm. The inset shows the microwave characteristics versus the gate length of the MOS-MHEMT. The fT can be calcuated via the expression:

\[
f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})(1 + g_d R_S)} = \frac{g_m}{2\pi C_{gs}}
\]

or

\[
f_T = \frac{v_s}{2\pi L},
\]

where \( g_{ds} \) is the output conductance, \( R_S \) is the source resistance, \( n_{ch} \) is the electron sheet density in the 2DEG channel, \( v_s \) is the saturation velocity, \( q \) is the elementary charge, and \( L \) is the gate length. The \( R_S \) is composed of contact resistances and resistances of the different parts of the epilayer within the gate-source region. Using Eqs. (1) and (2), the \( C_{gs} \) can be approximated by

\[
C_{gs} = qL \frac{dn_{ch}}{dV_{GS}}
\]

A smaller \( C_{gs} \) accompanies a smaller rate of change of \( dn_s/dV_{GS} \), which leads to a higher mobility added by increasing the gate voltage to further enhance the microwave performance. Similar results have also been observed on AlGaN/GaN MOS-HEMTs. However, a smaller \( C_{gs} \)

**FIG. 1.** (Color online) Comparison of the three-terminal off-state and on-state breakdown for the MOS-MHEMT and referenced MHEMT.

**FIG. 2.** (Color online) Comparison of the gate current density vs VGS at various VDS for the MOS-MHEMT and referenced MHEMT. The VGS swept from 2.5 to 4 V in 0.5 V per step.

**FIG. 3.** (Color online) Comparison of microwave characteristics at maximum \( g_m \) with \( V_{TH}=3 \) V measured from 0.45 to 50 GHz. The inset shows the microwave characteristics vs gate length for the MOS-MHEMT.
would degrade the $g_m$. The improved microwave performances in Fig. 3 show the existence of a smooth surface after LPO without gate recessing, which is superior to that of the CA-based etchant. Therefore, a compromise between these parameters (especially higher mobility, smaller $C_{gs}$ and $C_{gd}$) still increases the $f_i$ and $f_{max}$ from Eq. (1).

Figure 4 shows the comparison of noise performances measured over a frequency range from 1.2 to 7.2 GHz at a $V_{DS}$ of 2 V and a drain current of 10 mA. The minimum noise figure, $NF_{min}$, of the MHEMT (mos-MHEMT) increased from 1.76 (2.51) dB at 1.2 GHz to 5.64 (3.20) dB at 7.2 GHz. The associated gain of the MHEMT (mos-MHEMT) decreased from 20.16 (24.20) dB at 1.2 GHz to 7.18 (11.52) dB at 7.2 GHz. Showing that the introduced LPO-grown oxide does not degrade MOS-MHEMT performance. However, the higher $NF_{min}$ may be due to probe pad resistances during the measurement for both devices. Reducing probe pad resistances achieves the de-embedding noise figure. Major noise sources of HEMTs are attributed to thermal noise, shot noise, hot-electron noise, and generation-recombination noise.22 Equation (4) is a semipirical equation for thermal noise, expressed by model elements including resistances (i.e., channel and parasitic access resistances) related to low-noise device performance.21

$$NF_{min} \approx 1 + 2 \pi C_g f K_F \sqrt{\frac{R_S + R_G}{R_m}},$$

(4)

where $f$ is operating frequency, $K_F$ is a frequency-dependent constant related to the material parameters, and $R_G$ is the gate resistance. The $R_G$ depends on the gate dimension and resistance of the gate material. Long oxidation time ($\approx$ 1 h) degrades the contact resistance therefore the $R_S$ is a little higher. For MOS-MHEMT, a compromise between the dominant $C_{gs}$ and the term in the square root reduces the $NF_{min}$ even the ratio $(R_S + R_G)/g_m$ is increased, i.e., the smaller $C_{gd}$ benefits the $NF_{min}$ from Eq. (4). The Schottky barrier related to the gate leakage (shot noise) also plays an important role for low-noise applications. As mentioned above, due to the suppressed gate leakage current or impact ionization effect in Fig. 2, improved noise performance is expected. This result is consistent with the viewpoint of Ref. 18. On the other hand, hot-electron noise due to energetic random electron motion, associated with ultrafast kinetic dissipation processes, is within the conduction band, which may result in impact ionization effect. However, the suppressed impact ionization reduces the hot-electron noise. Furthermore, defects at the metal-semiconductor interface can increase the ideal factor and also produce traps which can contribute to low-frequency and microwave noise.23 The LPO can satisfy dangling bonds to reduce the surface recombination centers and suppress the electron trapping within the surface states. Consequently, a smaller $C_{gs}$, a suppressed gate leakage current/impact ionization effect, and reduced interface traps are beneficial to the noise performance and associated gain for the MOS-MHEMT.

In this work, we fabricated InAlAs/InGaAs MHEMTs with a LPO oxidized gate without gate recess. Smaller $C_{gs}$ and $C_{gd}$ suppressed impact ionization, and reduced surface states contribute to the improved microwave behavior and noise performance. Therefore, MOS-MHEMT makes the proposed low-temperature LPO oxidized gates suitable for high-speed and low-noise applications.

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