Improved Thermal Stabilities in Normally-off GaN MIS-HEMTs
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GaN based power transistors, with the merit of operating at elevated junction/ambient temperature and high switching frequency, are suitable for high-performance compact power converters. For the GaN transistors with metal–insulator–semiconductor (MIS) structure, their high temperature stability can be hindered by the challenges of $V_{TH}$ instability originating from the thermal electron emission of trap states at the dielectric/III-N interface [1,2]. To address this issue, a thinned barrier layer is proposed to bring the deep interface traps below the Fermi level at pinch-off so that they become inactive [2]. In this work, the normally-off MIS-HEMTs featuring a partially recessed (Al)GaN barrier were realized by a fluorine-plasma implantation/etch technique. The partially recessed barrier leads to improved thermal stability, while the fluorine implantation can convert the device from D-mode to E-mode without completely removing the barrier and sacrificing the high mobility heterojunction channel [3].

The schematic cross-section of the normally-off MIS-HEMT is shown in Fig. 1. Both the fluorine ion implantation and gate recess were carried out using CF$_4$ plasma. By properly adjusting the power level of the RF source driving the fluorine plasma, we are able to obtain two desirable results: 1) a well-controlled slow dry etching for gate recess; and 2) effective shallow implantation of fluorine ions into the AlGaN barrier. Fluorine plasma implantation at a higher RF power level of 200 W resulted in a well-controlled slow etching process with an etching rate of 2-nm/min. Meanwhile, a lower RF power of 150 W only induced insignificant etching of the barrier layer [4]. After 6 minutes of F-implantation/etch, a recess depth of ~12 nm and a smooth etched surface were obtained. After removing another 22-nm AlGaN by a digital etching [5], 20-nm Al$_2$O$_3$ was deposited by ALD with an in-situ nitridation process [6].

The proposed MIS-HEMT exhibits a threshold voltage ($V_{TH}$) of +0.6 V at a drain current of 10 $\mu$A/mm, a maximum drive current of 730 mA/mm, an on-resistance of 7.07 $\Omega$·mm (Fig. 2), and a hysteresis of ~0.3 V between the up- and down- $V_{GS}$-sweep with a relatively fast sweeping rate (0.7 V/s). Three-terminal off-state breakdown measurement of a MIS-HEMT with $L_{GD} = 15 \mu$m yields a breakdown voltage of 703 V at a drain leakage of 1 $\mu$A/mm with the substrate grounded (Fig. 3(a)).

Fig. 3(b) shows the temperature ($T$)-dependent transfer characteristics of a MIS-HEMT. When temperature increases from 25 °C to 200 °C, an increase of 3 orders of magnitude is observed in the OFF-state drain leakage due to increased buffer leakage, while the drain current exhibits an decrease (e.g. from 240 mA/mm to 200 mA/mm at $V_{GS} = 4$ V). By using a current criteria of $I_{DS}$ of 10 $\mu$A/mm, $V_{TH}$ shifted by 0.5 V negatively.

The dynamic properties of fabricated MIS-HEMTs were evaluated by high-drain-bias transient switching test and on-wafer hard switching measurement performing at temperature ranging from 25 °C to 200 °C (Fig. 4). A dynamic $R_{ON}$ degradation ($\times$1.58) for an OFF-state drain bias stress of 600 V (Fig. 5(a)) indicates effective suppression of current collapse for the room-temperature operation of proposed MIS-HEMTs. At elevated temperatures, the degradation of dynamic $R_{ON}$ for $V_{DS}$ stress up to 200 V is suppressed (Fig. 5(b)). During the hard switching test under high-frequency and high-temperature conditions (Fig. 5(c)), the increase of dynamic $R_{ON}$ is less than 18% and shown negligible temperature dependence.

Switching time = 0.1 ~ 1 s

\( R_{on} @ I_{on} > 110 \text{ mA/mm} \)

OFF-state: \( V_{gs} = 0 \text{ V} \)

ON-state: \( V_{gs} = 7 \text{ V}, V_{ds} = 1.2 \text{ V} \)

\( \Delta V_{th} \sim 0.3 \text{ V} \)

\( V_{ds} = 10 \text{ V} \)

OFF-state: \( V_{gs} = -1 \text{ V} \)

ON-state: \( V_{gs} = 6 \text{ V}, V_{ds(on)} = 1.2 \text{ V} \)

\( \Delta V_{th} \sim 0.5 \text{ V} \)

\( V_{gs} = 10 \text{ V} \)

25 °C to 200 °C

25 °C/step