Student Paper

OFF-State Drain Leakage Reduction for InAlN/GaN HEMTs Using a HCl and O_2-Plasma Two-Step Treatment

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The GaN high electron mobility transistor (HEMT) with InAlN barrier has shown promising characteristics for applications in radio frequency amplifiers and power switches[1]. However, high off state leakage due to reverse bias gate leakage often limits its applications. The poor quality unintentionally formed oxide on the InAlN surface has been speculated to be one of the culprits. Various methods have been reported to reduce the leakage current [2~5]; both thermal oxidation [3] and O_2 plasma treatments[4,5] have been reported to effectively suppress leakage current. Here we show that a HCl and O_2-plasma two-step treatment, which removes oxides and oxidizes the surface, respectively, is instrumental in reducing drain leakage as well as variations among devices.

The HEMT wafer used was grown by IQE and consists of InAlN(7.3nm)/AlN(1nm)/GaN(10nm) /InGaN(3.3nm) on SiC substrate. The device schematic and process flow is shown in Fig 1. Source/drain contacts were made by depositing Ti(20 nm)/Al(100 nm)/Ni(40 nm)/Au(40 nm) and annealing at 890℃ in forming gas. Mesa isolation was achieved by reactive ion etch (RIE). All devices presented here are on the same sample, which went through the identical process flow except the surface treatment prior to gate metal deposition of Ni(40 nm)/Au(100 nm). O_2 plasma treatment was carried out in RIE using a 30 sccm O_2 flow at 20 mTorr and a RF power of 30 W and 75 V self bias. 1:1 HCl:DI was used.

The I_D-V_{GS} curve comparison (Fig 2) among devices with different surface treatment clearly shows reduced leakage current with the two-step treatment. The off state drain current and threshold voltage V_{th} (extracted using constant current method at 1mA/mm) of devices in the saturation region with different gate lengths are shown in Fig 3, suggesting that the drain leakage is largely independent of gate length but closely related with V_{th}. More than 10 devices were tested for each treatment with the gate length ranging from 1 μm to 20 μm, and the leakage and threshold voltage data are shown in Fig 4. The HCl + O_2 plasma two-step treatment renders the lowest off state drain leakage current as well as leakage variation among different devices. We also observe that the leakage current seems to minimize near a HCl treatment of 10 s or a O_2 treatment near 10 min. This may be due to the effectiveness of HCl in removing III-oxides and the saturation nature of O_2 plasma oxidation [6]. The statistics of measured drain leakage is shown in Fig 5. The average drain leakage current was calculated by excluding the maxima and minima. It shows that the HCl +O_2 plasma treatment leads to about 100 times smaller average drain leakage and standard deviation than those of the non-treated devices. The relative standard deviation for the devices with the HCl + O_2 plasma treatment is also about 20% smaller. The two-step treatment is expected to remove some InAlN barrier, thus inducing changes in V_{th} and gate capacitance. Indeed, V_{th} is observed to increase, accompanied by a reduction in drain leakage (Fig 2-4), which could be partly owing to the reduced channel charge after gate recess thus reduced electric field under the gate. The CV measurements show that the gate capacitance for the devices with HCl treatment is 2.3% higher than that of devices without treatment (from 0.794 $\mu F/cm^2$ to 0.812 $\mu F/cm^2$). This corresponds to 0.22 nm reduction in barrier thickness when a relative dielectric constant of 9 is used for calculation. Digital etching[6] test on the same epitaxial structure shows an etch depth of 10 nm after 8 cycles of 30 s HCl and 5 min O_2 plasma treatments, resulting in a etch depth of 1.25 nm per cycle. This along with larger capacitance with HCl treatment confirms the effectiveness of HCl in removing oxide on InAlN. Furthermore, 1D Poisson simulations also suggest that the gate Schottky barrier height increases from 1.40 eV to 1.58 eV after the two-step treatment. The split CV measurements show that, with the HCl and O_2 plasma treatment, both the 2DEG charge density and mobility decrease slightly (1.28×10^{13} cm^{-2} versus 1.37×10^{13} cm^{-2}, 840 $cm^2/V\cdot s$ versus 921 $cm^2/V\cdot s$).

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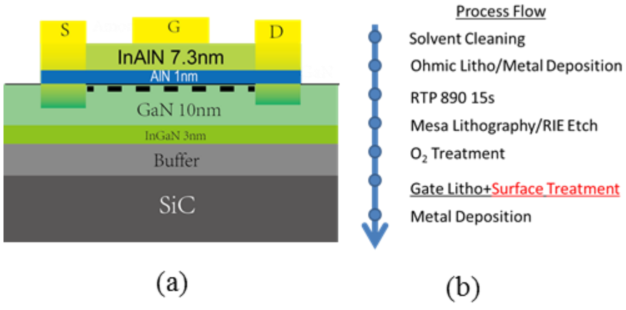

Figure 1 (a) Schematic and (b) process flow of InAlN/GaN HEMTs. Dashed line indicates the 2DEG.

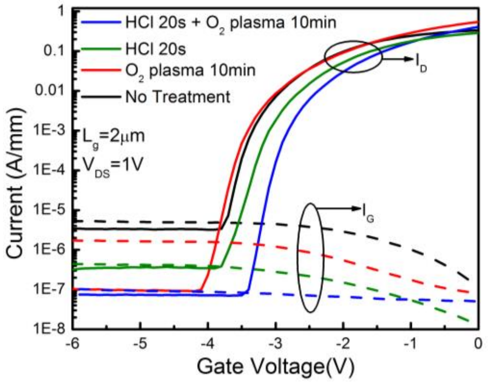

Figure 2 Transfer curve comparison between devices with different surface treatments. HCl + O_2 plasma treatment renders lowest leakage in both drain and gate.

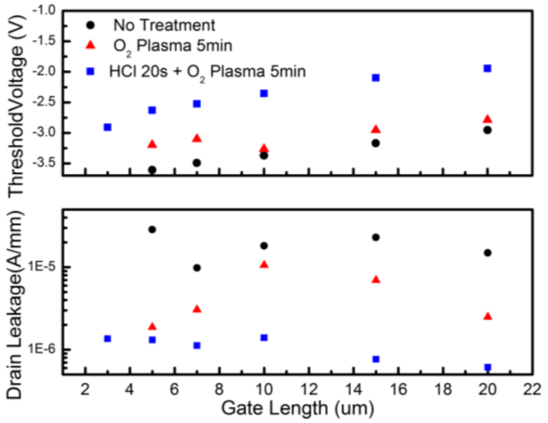

Figure 3 Threshold voltage (Top) and off state drain leakage (bottom) vs. gate length for different surface treatments. Drain leakage mainly stems from the gate-drain reverse biased Schottky junction.

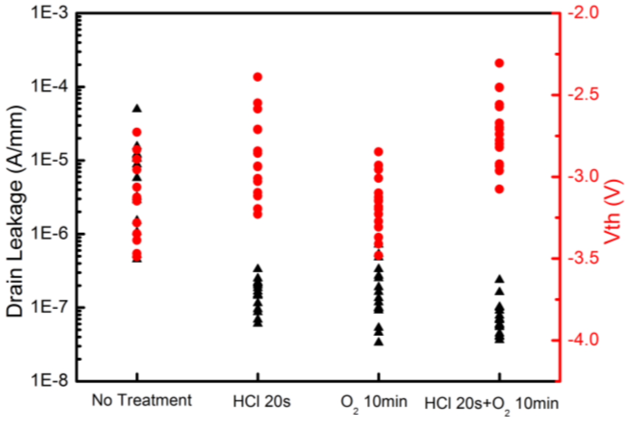

Figure 4 Comparison of off state drain leakage (black triangles) and threshold voltage (red circles) for devices with different surface treatments. The HCl+O_2 plasma two-step treatment leads to the lowest leakage and highest V_{th}. Gate length of devices shown here range from 1 to 20 μm.

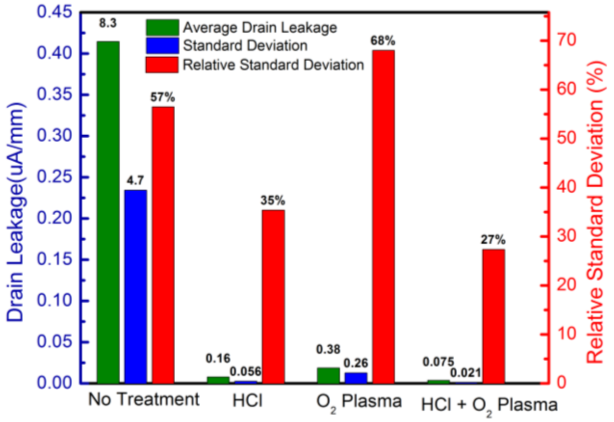

Figure 5 Average drain leakage currents and their absolute and relative standard deviations for devices with various surface treatments prior to gate metal deposition.