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Nanostructured GaN Transistors: Pushing the Limits of Linearity and Reliability

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Abstract

In this talk, we present new technologies to push the limits of performance, linearity and reliability in GaN-based devices. To drastically enhance the performance of both transistors and diodes, novel GaN-based devices based on three-dimensional nanostructures are proposed. In transistors, nanostructured gate contacts offer an excellent control over electrons in the channel. This was used to demonstrate high-voltage, normally-off AlGaN/GaN HEMTs, with significant reduction in leakage current and improved sub-threshold slope. Such nanostructures were also applied to sub-100 nm short-channel InAlN/GaN HEMTs to yield a flat transconductance (g_m) even at high drain current, with very flat current gain cutoff frequency (f_T) as a function of gate voltage. In Schottky diodes, nanostructured anode contacts were developed to improve its turn-on characteristics as well as to reduce its reverse-bias leakage current by nearly 4 orders of magnitude.

In the second half of the talk, we also address another major challenge of GaN-based devices: the current collapse when devices are operated under pulsed conditions. We will present results identifying ambient moisture as the previously unrecognized cause of current collapse in AlGaN/GaN HEMTs. The use of hydrophobic passivation was found to prevent dc-to-RF dispersion and improve long-term reliability.

1. Introduction

The large breakdown field, high electron mobility and capability of high-temperature operation of GaN-based devices would enable smaller, higher efficiency power devices. However several major challenges need to be addressed for this material system to be widely adopted. For example, most of the GaN-based high-voltage transistors are based on AlGaN/GaN HEMTs, which are intrinsically normally-on devices. While normally-off devices are required for power electronics, it is very challenging to develop high-performance normally-off GaN power transistors.

First of all, low on-resistance (R_{on}) is difficult to be achieved with conventional normally-off GaN technologies based on plasma treatments or gate recess, which degrade channel mobility. Although the channel R_{on} can be reduced by shrinking the normally-off gate length, the OFF-state drain leakage current poses another challenge. Low leakage current is an important requirement for normally-off GaN transistors since they have to hold high voltages at the drain with V_{gs} = 0 V.

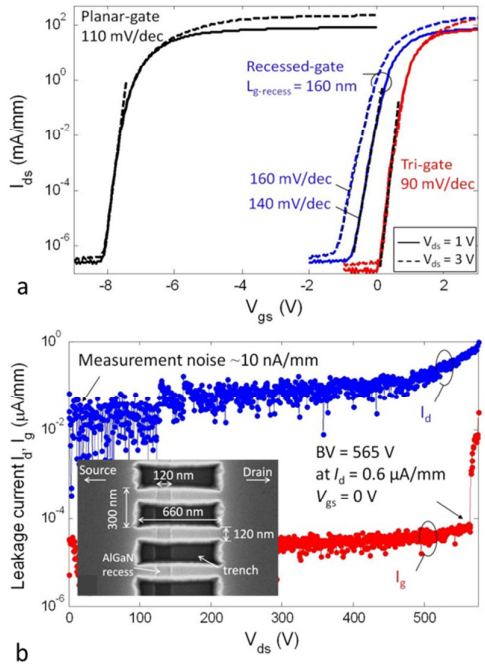

Figure 1 – (a) I_{DS} versus V_{GS} curves comparing the planar-gate to the trigate AlGaN/GaN HEMTs. (b) Leakage current versus V_{DS} showing the large breakdown voltage of 565 V at 0.6 μA/mm. (Inset) Top-view SEM image of the trigate structure.

In this talk, we demonstrate three-dimensional (3D) nanoscaled stripes patterned under the gate contact, which combined to a sub-micron gate recess (trigate structure), resulted in normally-off GaN transistors with a breakdown voltage as high as 565 V at very low drain leakage current of 0.6 μA/mm. This trigate structure also showed an on/off current ratio of more than 8 orders of magnitude with a sub-threshold slope of 86 ± 9 mV/decade. We extended this concept to high frequency GaN-based HEMTs. A major challenge in these devices is the strong non-linear behavior of short-channel GaN HEMTs. Their extrinsic transconductance (g_m) quickly drops after reaching its peak value. In this talk, we demonstrate that nanoscaled 3D channel region applied to sub-100 nm gate length GaN HEMTs can provide both high linearity and large breakdown voltage. As shown in Figure 2, the nanowire channel device with L_g = 80 nm, presents a much flatter extrinsic transconductance than the planar device because of the relatively larger current drivability of its source access region. The extrinsic g_m of the nanowire channel device is larger than that of the planar device because of lower source access resistance due to the larger effective width of its source access region and surrounding side gate effect. This shows that the intrinsic

GaN device with proper source design can support such high current density. Another advantage of the proposed structure is the potential to support high breakdown voltage while maintaining high linearity. As the linear source resistance is achieved without removing access region, the gate-to-drain region can be scaled based on the target breakdown voltage.

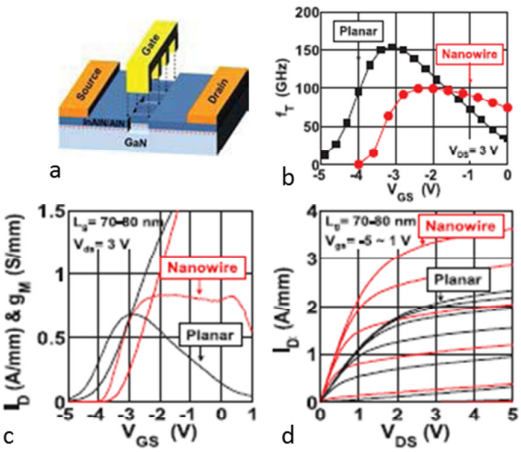

Figure 2 – (a) Schematic of the nanowire short-channel InAlN/GaN HEMT. (b) Current-gain cutoff frequency (f_T) versus V_{GS} showing a flatter response of the nanowire InAlN/GaN HEMT. (c) Comparison of current and transconductance characteristics between the planar and nanowire devices. (d) I_D versus V_{DS} curve for the planar and nanowire devices.

As shown in Figure 2, the nanowire channel device has 35% lower maximum current-gain cutoff frequency (f_T) than the planar device because of the larger fringing capacitance from the side gate and access region, wider than the effective channel region. However, because of its flatter g_m, the f_T drop at high gate bias is significantly suppressed in the nanowire channel device, while a serious degradation of f_T is observed in the planar device. The uniform RF characteristics over a wide range of bias condition in the nanowire devices are very useful to improve the linearity of these devices compared to the traditional GaN HEMTs.

AlGaN/GaN Schottky diodes are another class of power devices that suffer from large reverse-bias leakage current. To correct this, we developed a new 3D anode contact structure (Figure 3), which in contrast to conventional AlGaN/GaN SBDs, forms Schottky contact directly to the two-dimensional electron gas at the sidewalls of the 3D anode structure to improve its turn-on characteristics. In addition, it integrates an insulated trigate MOS structure to reduce its reverse-bias leakage current by more than 3 orders of magnitude (Figure 3b) with a large breakdown voltage. This is among the lowest leakage current reported in lateral AlGaN/GaN SBDs on Silicon substrate.

These 3D nanoscale stripes were fabricated by interference lithography, which is particularly of interest, compared to electron-beam lithography, due to its capability to quickly pattern nanoscaled stripes on large surfaces.

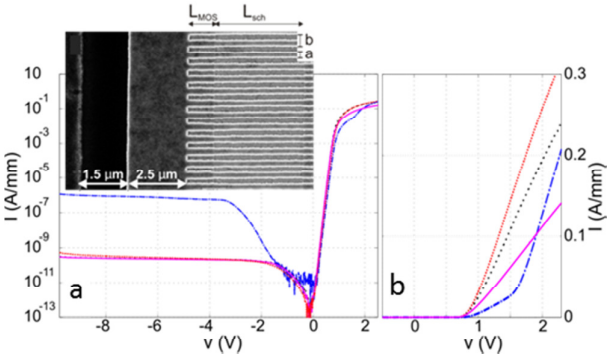

Figure 3 – (a) Top view SEM image of the 3D anode structure. (b) Reverse- and (c) Forward-bias IV characteristics comparing the reference planar to the 3D anode Schottky diode.

In the second part of the talk, we address some of the major reliability issues in GaN-based devices, more specifically the current collapse, or dynamic on-resistance. This is a decrease in maximum drain current as well as an increase in knee voltage and on-resistance when devices are operated under pulsed conditions. Our results identify for the first time that ambient moisture is the main cause of current collapse in AlGaN/GaN HEMTs. The use of hydrophobic passivation was found to prevent dc-to-RF dispersion even when it is not directly in contact with the semiconductor surface. This allows the engineering of multi-stack passivation layers to completely eliminate current collapse (Figure 4).

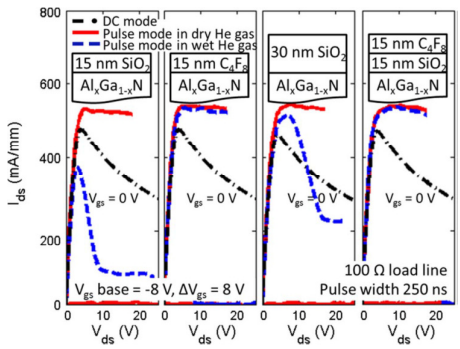

Figure 4 – IV characteristics of different passivation layers combining SiO_2 and C_4F_8 under dry and moist conditions.

Conclusions:

In this work, we present new technologies based on nanostructures that largely reduced leakage current and increased linearity of GaN-based devices. In addition, we discuss the main cause of a major reliability issue in GaN-based devices. These results show how the combination of the unique material properties of GaN, with new nanostructures allows the development of novel devices with state-of-the-art performance.

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