Zirconium dioxide dielectric for gallium nitride high-mobility transistors

US-based researchers claim record positive threshold for normally-off operation.

The Naval Research Laboratory (NRL) and University of Maryland in the USA claim a record positive threshold voltage of +3.9V for a gallium nitride (GaN) metal-oxide-semiconductor high-electron-mobility transistor (MOS-HEMT) [Travis J. Anderson et al, Appl. Phys. Express, vol9, p071003, 2016]. The team used zirconium dioxide (ZrO_2) as a gate dielectric insulator. The positive threshold means that the transistor had normally-off or 'enhancement-mode' operation.

Normally-off transistors are particularly desired in power applications, giving fail-safe operation and more efficient power consumption. The high-power radio frequency (RF) and power switching characteristics of such devices could lead to power amplifier (PA), monolithic microwave integrated circuit (MMIC) and voltage conversion applications.

Using a MOS gate structure significantly reduces gate leakage current, improving reliability and reducing off-state power consumption. ZrO_2 has a high dielectric constant of 25, a large bandgap of 7.8eV, and a high breakdown voltage in the range 15–20MV/cm.

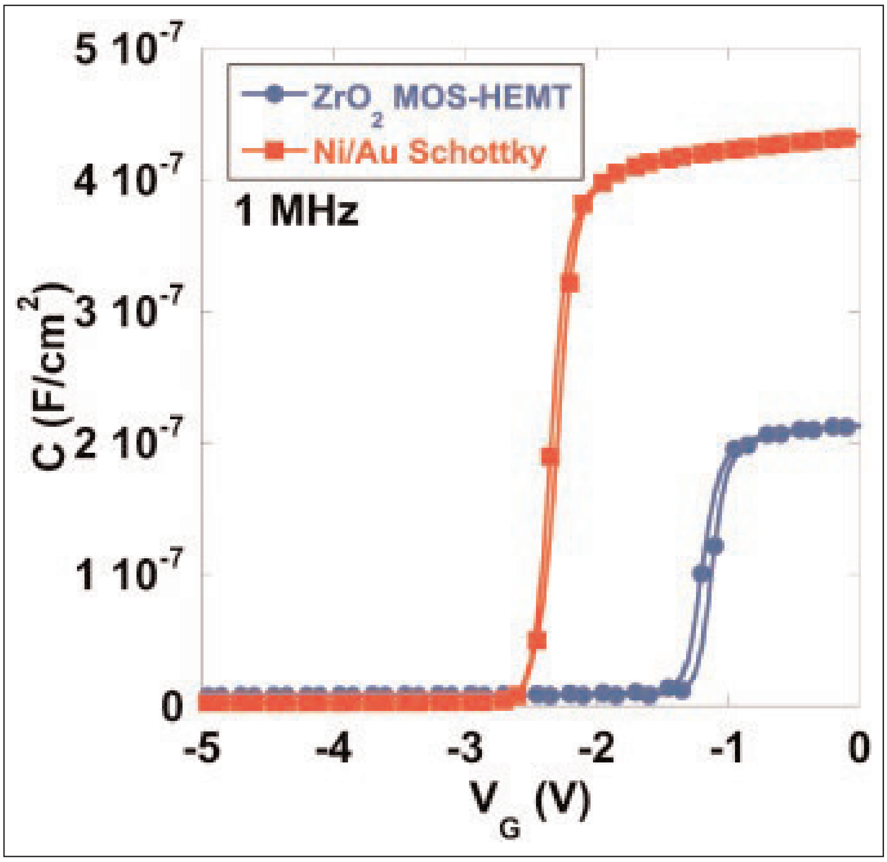

Figure 1. Capacitance–voltage characteristics of Schottky-gated HEMT and ZrO_2 MOS-HEMTs.

The III-nitride heterostructure was grown on high-resistivity silicon with a ~2μm nucleation/transition/GaN-buffer, followed by an 18nm $Al_{0.26}Ga_{0.74}N$ barrier and a 2nm GaN cap. Fabrication began with standard mesa isolation, titanium/aluminium/nickel/gold ohmic metal deposition and annealing, and titanium/gold metal overlay deposition.

Two types of gate were fabricated: a standard Schottky HEMT with nickel/gold gate and plasma-enhanced silicon nitride (PECVD SiN_x) passivation; and a MOS-HEMT with full recessing through the AlGaN barrier, 20nm of atomic layer deposition (ALD) ZrO_2 gate insulation and a nickel/gold electrode. A ZrO_2 MOS-HEMT without recessing was also produced.

The ALD precursors were zirconium(IV) tert-butoxide (ZTB) and deionized water. The researchers comment that no previous ZrO_2 GaN MOS-HEMT has used ZTB precursor. Usually, tetrakis(dimethylamino)zirconium is employed. An advantage of ZTB is that its structure already contains some oxygen, which should lead to higher-quality ZrO_2 films. The ALD cycle consisted of 0.2-second ZTB and 0.03-second dionized water doses separated by 20-second nitrogen purges, giving ~0.07nm/cycle growth.

Capacitance–voltage measurements at 1MHz indicated that the MOS-HEMT had lower capacitance (Figure 1). The dielectric constant of the ZrO_2 was estimated at 25. "This indicates that thermal ALD and the ZTB precursor are as effective at producing films with low leakage and a high dielectric constant as plasma-enhanced ALD using amine-based precursors," the team writes.

The measurements also showed a positive threshold

Table 1. Summary of device characteristics.

	Reference HEMT	ZrO_2 MOS-HEMT	Recessed ZrO_2 MOS-HEMT
$I_{D,MAX}$ (A/mm)	0.516	0.482	0.286
I_D @ $V_G = V_T + 4V$ (A/mm)	0.395	0.362	0.274
$g_{m,MAX}$ (mS/mm)	114	92.5	131
V_T (V)	−2.13	−1.43	+3.99
I_G @ $V_G = -5V$ (A)	$1.22x10^{-7}$	$7.41x10^{-13}$	$1.53x10^{-11}$
R_{ON} (Ω-mm)	13.5	14.8	24.0
SS (mV/decade)	191	92.9	187
D_{it} (/cm^2-eV)	$2.03x10^{13}$	$7.00x10^{12}$	$4.87x10^{13}$

voltage shift, "likely the result of excess oxygen in the film, either from excess precursor ligands or from adsorption of water or hydroxyl groups from the background." The team also points out: "most other oxides deposited on GaN suffer from positive charge, resulting in negative V_T shifts."

The resulting devices had comparable DC electrical performance (Table 1). The recessed ZrO_2 MOS-HEMT achieved normally-off behavior with a threshold (V_T) of +3.99V. Although the maximum drain current ($I_{D,MAX}$) was lower than the other devices, the maximum transconductance ($g_{m,MAX}$) was higher (Figure 2). The non-recessed devices had similar on-resistance (R_{ON}).

The subthreshold swing (SS) was used to estimate interface trap densities (D_{it}). The lowest Dit was for the non-recessed MOS-HEMT. "This suggests that the ZrO_2 gate oxide reduces the interface trap density at the AlGaN surface in the gate region," the researchers say.

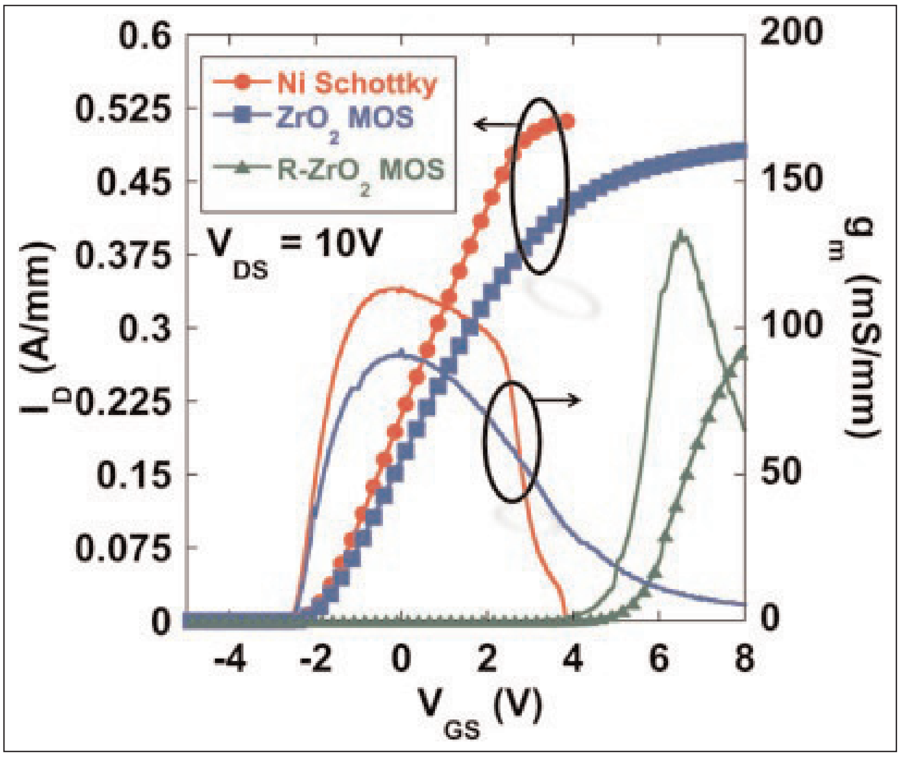

Figure 2. Transfer curves for Schottky-gated HEMT, ZrO_2 MOS-HEMT, and recessed barrier ZrO_2 MOS-HEMT.

The higher D_{it} of the recessed device was probably due to crystal damage from the recess etch process, according to the researchers. They add: "Current collapse was poor in this device structure, as the negative charge in the oxide will enhance the virtual gating effect rather than passivate it. An ideal device structure would implement PECVD SiN_x in the access regions and ZrO_2 under the gate; however, the process steps to enable this are still being developed."

The ZrO_2 reduced gate leakage (I_G) by four orders of magnitude. ■

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