Polarization-Graded HEMTs for Improved Johnson's Figure of Merit

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AlGaN/GaN-based HEMTs have demonstrated excellent power and speed performance [1,2], making them promising for RF and mm-wave applications. The use of polarization grading presents an additional device design concept that shows great potential in enhancing linearity, noise, and power performance in mm-wave applications [3,4]. This concept was also previously applied to lower-frequency RF power applications, but at unscaled device dimensions [5]. In this work, we investigate compositionally-graded HEMTs, which can enhance device breakdown (V_{BD}) through lateral electric field engineering, while maintaining high device cut-off frequency (f_T) via device scaling and channel profile engineering. We compare the impact of channel polarization engineering with gate electrostatic engineering using a gate mini-field plate (mini-FP). The gate-connected mini-FP, while effective at managing the gate-to-drain peak electric field, imposes additional parasitic capacitances that affect device speed. Through 2D physics-based simulations in Synopsys Sentaurus TCAD and comparison to experiment, we demonstrate that polarization grading of the channel enhances V_{BD} while preserving high f_T, resulting in a Johnson's figure of merit (JFOM = f_T x V_{BD}) that is ~2.4x that of a conventional HEMT, a significant improvement compared to the 1.25x improvement from using a mini-FP.

Laterally-scaled, 50 nm gate-length conventional HEMTs (with and without a 50 nm gate integrated mini-FP) and graded-channel T-gate HEMTs were evaluated (Fig. 1). The simulations use a custom LO-phonon aware transport model [6], and have been validated against measured DC characteristics [3,7] (Fig. 2); their accuracy in capturing RF performance (i.e. f_T, f_{max}) was also shown previously [8]. As seen in Fig. 3, the polarization discontinuity at the AlGaN barrier/GaN channel in the conventional abrupt-junction HEMT results in a δ-function sheet charge ($1.27x10^{13}$ cm^{-2}) at the interface (Fig.3 (b)). Conversely, in the graded-channel structure, with Al composition graded linearly over 6 nm thickness, the polarization charge is distributed between an interfacial sheet charge density of $6.2x10^{12}$ cm^{-2} and a volumetric density of $1.2x10^{19}$ cm^{-3} (following $\rho = -\nabla \cdot \vec{P}$). This distributes the mobile charge, creating a 3D charge slab rather than a 2DEG, resulting in a flatter g_m profile (Fig. 4). Also, LO phonon coupling in III-Ns [6,9] results in a carrier-density dependent v_{sat}, which is enhanced in the polarization-graded structure due to the reduced local charge density. This allows graded-channel devices to attain high f_T that is maintained across a wide I_d range [8], (Fig. 5). Peak f_T of 183 GHz, 179 GHz, and 168 GHz were extracted for the graded-channel, HEMT, and mini-FP HEMT devices, respectively. Furthermore, the reduced interface charge in the graded channel spreads out the E-field lines, lowering the channel peak lateral field. This is evidenced by a 23% reduction in peak E_x in the graded channel, compared to a 5% reduction with a 50 nm mini-FP at V_{ds}=10V (Fig. 5). As a result, the graded-channel device exhibits a V_{BD} of 43 V, an increase of ~ 25V over the HEMT (Fig. 6). This enhanced V_{BD} and f_T yield a high JFOM of 7.8 THz-V for the graded structure, compared to 3.2 and 4.0 THz-V for the HEMT and HEMT with mini-FP, making graded-channel HEMTs very promising for mm-wave applications.

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