AlGaN/GaN HEMTs on SI-GaN Substrates up to Ka-Band Frequencies

CNF Project # 370-89

Principal Investigator(s): Lester F. Eastman
User(s): Jonathan Felbinger, M.V.S. Chandra

Affiliation(s): School of Electrical and Computer Engineering, Cornell University
Primary Research Funding: ONR MURI subcontract from UCSB; Group 4 Labs, LLC
Contact: lfe@iiiv.tn.cornell.edu, felbinger@cornell.edu

Abstract:

The electrical and thermal performance of AlGaN/GaN devices on GaN substrate is examined. GaN-on-GaN high electron mobility transistors (HEMTs) with 150 µm periphery yielded a power density of 3.12 W/mm at 28 GHz. Thermal resistance in ungated test structures on GaN and SiC substrates is compared. The GaN-on-GaN devices demonstrate good electrical and thermal performance for K\textsubscript{a} band applications.

Introduction:

The homoepitaxial growth of AlGaN/GaN HEMTs on semi-insulating (SI) GaN substrates eliminates the dense dislocation matrix at the buffer-substrate interface present for other choices of substrate, commonly SiC, Si, or sapphire. The uniformity of the material mitigates threading dislocations and mismatch in thermal expansion coefficients typically stemming from the non-homogeneous buffer-substrate interfaces. HEMTs fabricated on bulk GaN substrates have experimentally demonstrated 10 W/mm large-signal performance at 10 GHz and good reliability [1]. In this work, the K\textsubscript{a} band and thermal performance of AlGaN/GaN-on-GaN devices is presented.

Summary of Research:

Bulk SI-GaN substrate was grown via HVPE at Kyma Technologies. AlGaN/GaN epitaxial layers were grown by metal oxide chemical vapor deposition (MOCVD) atop GaN and SiC substrates. 200Å Al\textsubscript{0.25}Ga\textsubscript{0.75}N was grown atop 2.4 µm regrown GaN on 374 µm-thick GaN. The epitaxial layers on 370 µm-thick SiC substrate were comprised of 200Å Al\textsubscript{0.26}Ga\textsubscript{0.74}N atop 1.5 µm GaN. Devices on SI-GaN and SiC substrates were fabricated in parallel at the Cornell NanoScale Science and Technology Facility. A standard Ti/Al/Mo/Au ohmic recipe was used, including a post-deposition anneal. Mesa isolation was achieved after ohmic contact anneal via an ICP etch. After passivation with ~ 85 nm PECVD SiN\textsubscript{x}, Ni/Au gates with field-plate extensions were patterned [2]. The devices were characterized electrically and thermally.

The AlGaN/GaN HEMTs on SI-GaN demonstrated exceptionally good performance. Transfer length method measurements revealed a contact resistance of 0.13Ω-mm and a sheet resistance of 440Ω/sq. Of note, the I-V curves exhibited reduced negative output resistance in saturation compared to HEMTs on other substrates.

Figure 1: Quasi-dc (solid) and 200 ns pulsed (hollow) off-state (circular; \( V_{GS} = 0V, V_{DS} = 0V \)) and drain-lag (square; \( V_{GS} = 20V, V_{DS} = -7V \)) performance of a 2 \times 100 \times 0.1 µm (FP), 50 µm pitch AlGaN/GaN-on-GaN HEMT.
The devices exhibit a sharp pinch-off characteristic at \(-5\, V_{gs}\). The usual \(-5\, V_{ds}\) knee voltage with a drain current of 1050 mA/mm at \(+1\, V_{gs}\) was observed. The unity-current-gain frequency \(f_T\) was at 46.4 GHz for a 100 nm gate with field plate extension. The gate leakage current is moderately high, at 182 \(\mu A/mm\), which is an order of magnitude greater than that observed for similar devices on SiC.

Compared to dc characteristics, 200 ns pulsed off-state and drain-lag measurements for devices on bulk GaN indicate low dispersion, predicting good microwave performance (Figure 1). Large-signal measurements were completed at 18 and 28 GHz. At 18 GHz, a \(2 \times 75 \times 0.1 \, \mu m\) HEMT with 12 \(\mu m\) pitch between gate centers driven at 22 dBm and biased at 20V and 511 mA/mm output 3.41 W/mm with 29.5% PAE. At 28 GHz, a similar device with 25 \(\mu m\) pitch driven at 22 dBm biased at 20V and 562 mA/mm output 2.54 W/mm with 16.8% PAE; when driven to 24 dBm, the HEMT output 3.12 W/mm with 18.3% PAE.

The surface temperature in the active region of ungated, mesa-isolated, 80-\(\mu m\)-wide devices was measured via scanning thermal microscopy (SThM). The peak operating temperature rise, averaged over several line scans, versus dissipated dc power was measured. To first-order, the temperature rise was a linear function of dissipated power; from this relationship, the thermal resistance was extracted for devices of various gap between the ohmic contacts. The thermal resistance of such devices on SI-GaN was observed to be slightly less than that of identical structures on SiC (Figure 2.)

Thermal resistance was estimated via a finite-difference method [3]; for the structures on bulk GaN, analytic cylindrical-spherical and prolate spheroidal models were developed. The modeled thermal resistance on SiC substrate does not account for the thermal boundary resistance (TBR) resulting from a dense dislocation matrix at the interface between the GaN epitaxy and the SiC substrate; for similar test structures, TBR has been demonstrated to contribute an additional 30% to the thermal resistance [4].

The inclusion of TBR explains the experimentally-observed comparable thermal resistance for devices on bulk GaN and SiC substrates. Particularly for the shorter gaps, the electrical probes may be acting as a heat sink, lowering the thermal resistance.

The HEMTs fabricated on SI-GaN substrate demonstrated very little dc-rf dispersion consistent with good power performance up to K_a band. Despite the superior thermal conductivity of bulk SiC, the heterointerface between the buffer and the substrate impedes phonon propagation; thus, similar thermal resistance was observed for devices on GaN and SiC substrates. The outlook for HEMTs on SI-GaN substrates includes potential reliability enhancements based on reduced defect density and the elimination of epi-substrate thermal expansion mismatch.

References:


Figure 2: Thermal resistance of 80 \(\mu m\)-wide GaN-on-GaN and GaN-on-SiC devices: experimentally observed (SThM) and calculated by finite-difference models.