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Effects of buffer compensation strategies on the electrical performance and RF reliability of AlGaN/GaN HEMTs

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ABSTRACT

The effects of buffer compensation strategies on the electrical performance and RF reliability of AlGaN/GaN HEMTs have been studied by means of static and dynamic I–V measurements, drain-current transient spectroscopy, XRD, and RF stress tests. Devices equipped with C-doped and Fe-doped GaN buffer feature improved sub-threshold behaviour (lower source-to-drain leakage current, and lower DIBL) and improved RF reliability. As a drawback, devices equipped with Fe- and C-doping experience higher dynamic current dispersion, ascribed to higher concentration of the deep levels E2 (0.56 eV/10^{-15} cm^2) and E4 (0.84 eV/10^{-14} cm^2).

1. Introduction

GaN-based HEMTs are excellent candidates for next-generation high-power microwave applications. Nevertheless, due to the spontaneous n-type conductivity of GaN crystals, devices equipped with unintentionally-doped GaN buffer experience detrimental short-channel effects, undermining both the device performances and their long-term stability. Technological solutions involve the introduction of carbon and/or iron species, which compensate the unintentional donors, render the GaN buffer layer semi-insulating, and improve the confinement of electrons in the 2DEG. Nevertheless, the incorporation of foreign impurities and the related growth conditions may give rise to enhanced crystallographic defect density and enhanced parasitic charge-trapping phenomena. Within this work, we comprehensively investigate the static and dynamic parasitic effects related to the GaN-buffer design, and we discuss the implications on the RF performance and reliability.

2. Experimental details

Devices under test belong to fourteen wafers differing mainly for GaN buffer design. HEMTs were fabricated using the same process steps and layout, with a 0.5 μm Ni/Au gate; they were grown on silicon carbide substrate and they adopt an AlGaN/GaN heterostructure with nominal 25% Al concentration and 23 nm AlGaN thickness, but with different buffer compensation, including either no doping (type I), 3×10^{17} cm^{-3} C-doping (type II), 2×10^{17} cm^{-3} Fe-doping (type III), or 10^{18} cm^{-3} Fe and 10^{18} cm^{-3} C co-doping (type IV).

The performed analysis includes (i) static, double-pulsed, and Load-Pull characterizations, devoted to the evaluation of static- and dynamic-performances, (ii) Drain-Current Transient Spectroscopy (DCTS), performed to identify the involved deep-trap-levels and related defect-states, and (iii) X-ray diffraction (XRD), employed to gather

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auxiliary information on the crystallographic defectiveness of the samples under test.

3. Static I–V analysis

The parasitic conductivity of GaN buffer strongly impact on the subthreshold behaviour of AlGaN/GaN HEMTs. Fig. 1 shows the I_G–V_G and I_S–V_G characteristics acquired on four representative samples equipped with unintentionally doped (u.i.d.), 3×10^{17} cm^{-3} C-doped, 2×10^{17} cm^{-3} Fe-doped, and 10^{18} cm^{-3} Fe- and 10^{18} cm^{-3} C-doped buffer. Devices equipped with u.i.d. buffer feature remarkable source-to-drain leakage current and high Drain-Induced Barrier Lowering (DIBL) effect, which are proofs of high parasitic buffer conductivity, poor carrier confinement, and poor pinch-off properties. Source-to-drain leakage-current and DIBL can be gradually mitigated by the adoption of acceptor-like carbon and iron doping, which compensate the spontaneous n-type of u.i.d. buffer [1–3]. Good subthreshold behaviour is achieved with doping concentration equal to or greater than 10^{18} cm^{-3}. In the following, the side effects of buffer doping on the dynamic performance of the devices are reported.

4. Pulsed I–V and drain current transient spectroscopy

To investigate the impact of different buffer-compensation strategies on the dynamic performance of the devices under test, double pulsed I_D–V_D measurements [4] have been performed. Dynamic current dispersion has been evaluated in the quiescent bias point (V_{GQ};V_{DQ}) = (−6 V;25 V). Results reveal that wafers adopting iron- and/or carbon-doped buffer show, on average, higher current dispersion than those adopting u.i.d. buffer (Fig. 2).

In order to identify the roots of enhanced charge-trapping and related current dispersion effects, the devices under test have been submitted to drain current transient spectroscopy [5]. Fig. 3 depicts drain-current recovery transients performed on representative devices equipped with u.i.d., 3×10^{17} cm^{-3} C-doped, and 10^{18} cm^{-3} Fe-10^{18} cm^{-3} C-doped buffers, subjected to 100 s-long semi-on-state stress (V_{GF};V_{DF}) = (V_{TH} + 0.5 V;25 V). Distinct electron detrapping processes are observed in the different samples. By performing the measurements at different base-plate temperature, we characterized the thermal-activation of these detrapping processes, gathering the activation-energy and the apparent capture cross-section of involved deep-levels. The detected deep-levels, labelled E2, E3, E4 and E5 can be mainly ascribed to III-nitride defects. Similar results have been reported in several research works on deep-level transient spectroscopy in (Al)GaN layers [6–9].

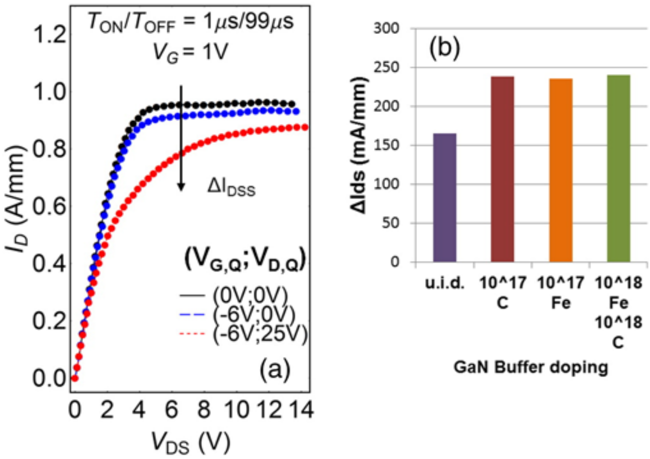

Fig. 2. (a) Representative double-pulse I_D–V_D measurement, showing the collapse of drain-current when the devices are exposed to off-state. (b) Wafers adopting iron- and/or carbon-doped buffer experience, on average, higher current dispersion (ΔI_{DSS} extracted at (V_G,V_D) = (1 V,$V_{D,KNEE}$)) than those adopting u.i.d. buffer.

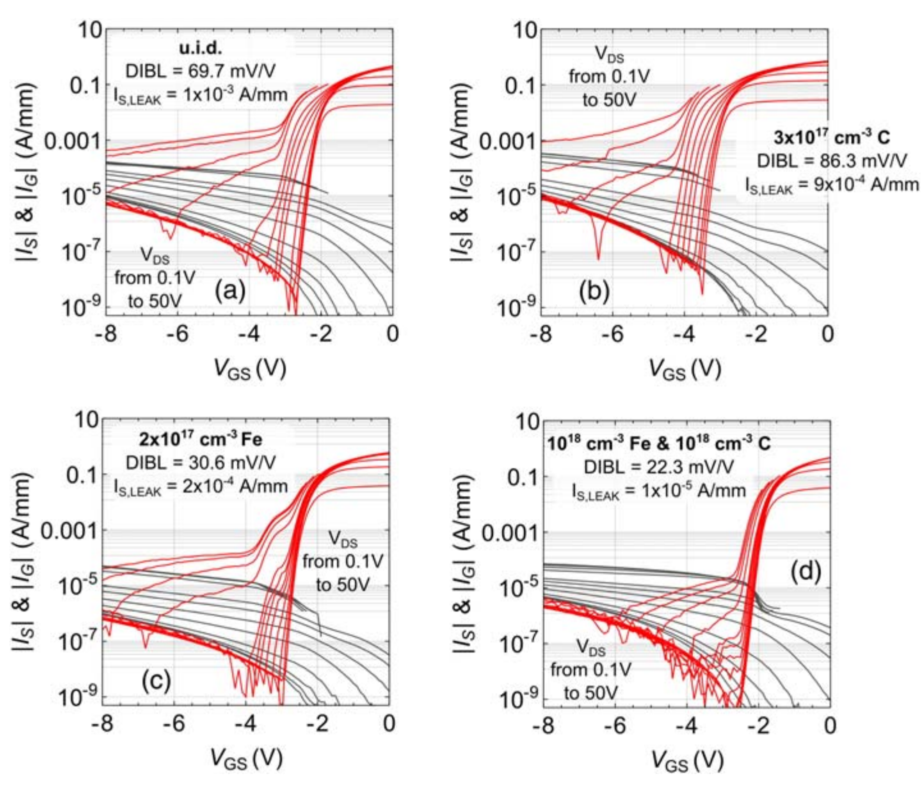

Fig. 1. Static I_G–V_G and I_S–V_G characteristics of representative samples equipped with unintentionally doped (u.i.d.), 3×10^{17} cm^{-3} C-doped, 2×10^{17} cm^{-3} Fe-doped, and 10^{18} cm^{-3} Fe- and 10^{18} cm^{-3} C-doped buffer. V_{DS} is stepped from 0.1 V to 50 V. Current compliance has been set at 0.1 A/mm to avoid device degradation. Strong subthreshold issues (high source-to-drain leakage-current, and high DIBL effects) are detected in u.i.d. buffer, and are mitigated by the introduction of carbon and iron compensating species.