Effects of p-GaN Body Doping Concentration on the ON-State Performance of Vertical GaN Trench MOSFETs

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***Abstract*— In this letter, we report the influence of p-GaN body doping concentration on the ON-state performance of vertical GaN trench MOSFETs. Decreasing the p-GaN body doping concentration leads to an enhanced maximum drain current ($I_{D,max}$), reduced specific ON-resistance ($R_{ON,sp}$), but also a decreased threshold voltage (V_{th}), suggesting that the p-GaN doping plays an important role in balancing the V_{th}, $R_{ON,sp}$ and $I_{D,max}$ in vertical GaN trench MOSFETs. Resulting from the tuning of Mg concentration in the p-GaN, we demonstrate high ON-performance including a high $I_{D,max}$ of 2.8 kA/cm^2, a low $R_{ON,sp}$ of 0.87 mΩ·cm^2, a large V_{th} of 4.8 V in a quasi-vertical GaN trench MOSFET on sapphire with a 2.5-μm-thick drift layer, while maintaining a breakdown voltage of 273 V.**

***Index Terms*— Gallium nitride, vertical trench MOSFET, channel doping, ON-state performance.**

I. Introduction

ALGAN/GAN based lateral GaN power transistors have demonstrated great promise for low and medium voltage ($\leq$ 650 V) power switching applications over the past decade [1]–[5]. To enhance the voltage rating and current handling capability of GaN transistors, device structures with vertical current conduction path have attracted extensive research interest [6]–[20]. Current aperture vertical electron transistors (CAVETs) [14], [16], [17], vertical fin MOSFETs [19], [20], and inversion channel vertical trench MOSFETs [6], [7] with a high breakdown voltage over 1 kV have been achieved. On the other hand, low ON-resistance (R_{ON}) to minimize the power loss, high output current (I_{ON}) to maximize the driving capability, and large threshold voltage (V_{th}) (>3 V) to avoid false turn-on are always highly desired device metrics in these devices.

However, among the above mentioned three types of vertical GaN transistors, the CAVETs and vertical FinFETs were mainly operated in accumulation-mode, usually resulting in a small V_{th} (typically ~1-2 V). Their fabrication processes were also relatively complicated (channel regrowth or precise dry etch required), which may slow down their pace for wide adoption in manufacturing. As for the vertical GaN trench MOSFETs, despite the remarkable progress made in recent years [6]–[12], the ON-state performance including the R_{ON} and $I_{D,max}$ are not on par with the CAVET [12]–[17] and their vertical fin MOSFET [18]–[20] counterparts, mainly because of the large channel resistance of the inversion channel layer in the trench MOSFETs. To take advantage of the simple device fabrication process and resulting large V_{th} of GaN trench MOSFETs, lowering the channel resistance-dominated R_{ON} is essential to minimize the total power loss of the device. Although the ON-state performance of vertical trench MOSFETs was improved by optimizing the gate trench formation process [11], [21]–[23], the impact of material parameters, especially the body doping, of the device epilayers, has seldom been reported.

In this work, we investigated the effects of p-GaN body doping concentration on the ON-state performance of vertical GaN trench MOSFETs. We found that decreased p-GaN body doping concentration results in enhanced $I_{D,max}$, reduced $R_{ON,sp}$, but a lower V_{th}. Resulting from the fine tuning of the Mg doping concentration in the channel layer, a high ON-performance quasi-vertical GaN trench MOSFET is demonstrated, exhibiting not only a large V_{th} of 4.8 V, but also an ultralow specific on-resistance ($R_{ON,sp}$) of 0.87 mΩ·cm^2 in conjunction with a high $I_{D,max}$ of 2.8 kA/cm^2.

II. Device Design and Fabrication

The n^+-p-n^--n^+-GaN structures for the quasi-vertical trench MOSFETs were grown on sapphire substrates by MOCVD (Fig. 1). The epilayers, from bottom to top, consist of a 1-μm i-GaN buffer, a 1-μm n^+-GaN [Si: 5×10^{18} cm^{-3}], a 2.5-μm n^--GaN drift layer [Si: 5×10^{16} cm^{-3}], a 400-nm p-GaN body (Mg-doped), and a 200-nm n^+-GaN layer [Si: 5×10^{18} cm^{-3}]. Five samples (denoted as sample A, B, C, D, and E) were grown with the same structure and growth conditions except for the Mg doping concentration in the p-GaN body. The Mg concentration was varied from 3.0 to 1.2 $\times10^{19}$ cm^{-3}, as confirmed by secondary-ion mass spectrometry (SIMS) depth-profiling measurements (Fig. 1(b)).

All the samples shared the same fabrication procedures. The device process started with Cl_2/BCl_3-based dry etching of the gate trench (~900 nm-deep) with a Ni hard mask, followed by hot tetramethylammonium hydroxide (TMAH) wet etching to remove the dry etching induced damage in the gate trenches [21], [24]. The gate trench sidewalls were aligned to the *m*-plane for better ON-state performance [11], [22]. Process continued with the mesa formation and exposure of bottom n^+-GaN layer for drain Ohmic contacts. After the

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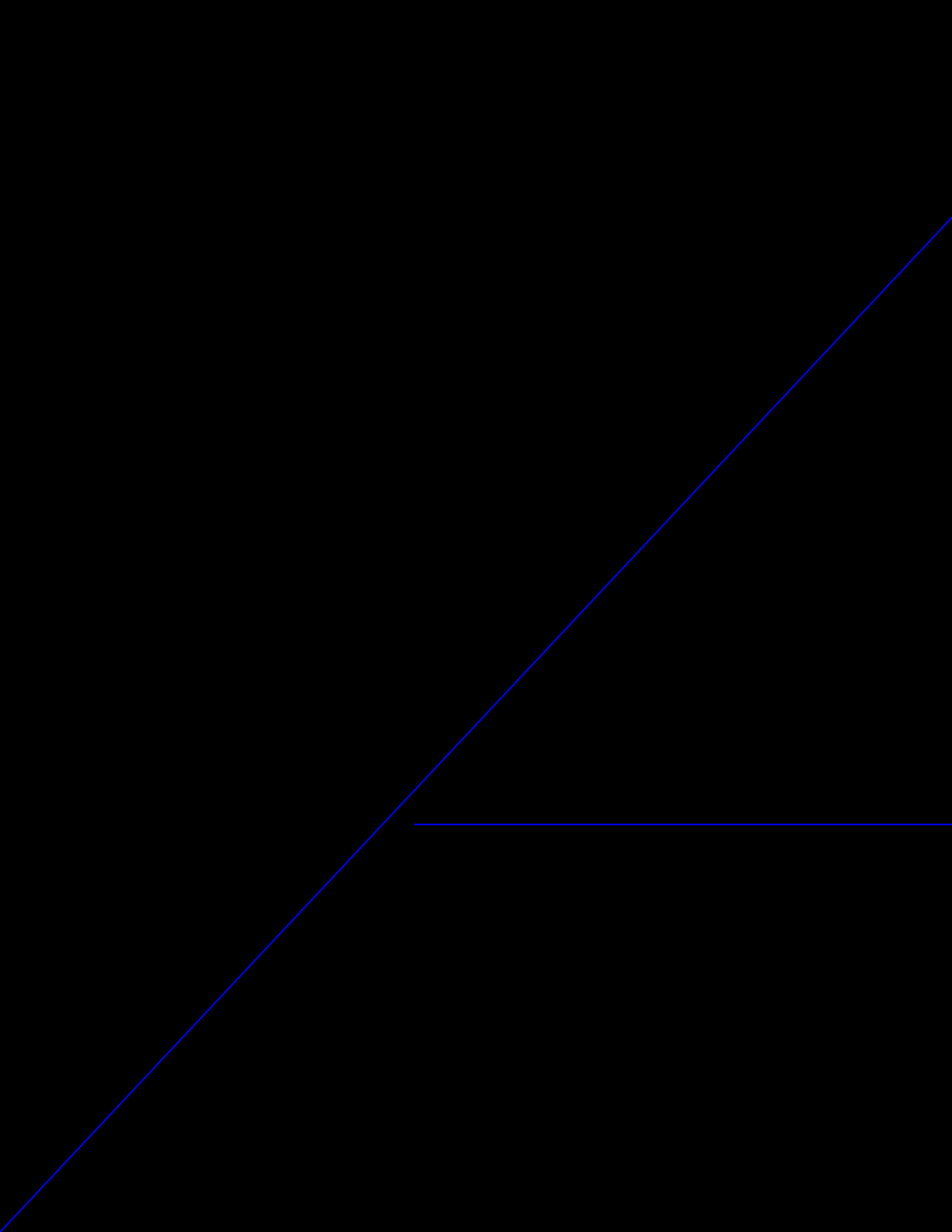

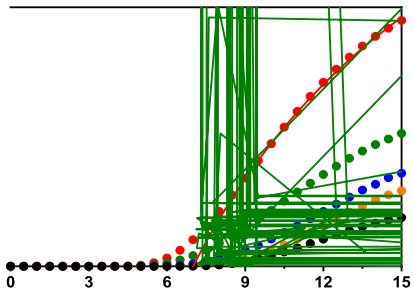
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