Multi-channel AlGaN/GaN Lateral Schottky Barrier Diodes on Low Resistivity Silicon for Sub-THz Integrated Circuits Applications

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Abstract—This work presents novel multi-channel RF lateral Schottky-barrier diodes (SBDs) based on AlGaN/GaN on Low Resistivity (LR) (σ = 0.02 Ω.cm) silicon substrates. The developed technology offers a reduction of 37 % in onset voltage, V_{ON} (from 1.34 to 0.84 V), and 36 % in ON-resistance, R_{ON} (1.52 to 0.97 to Ω.mm) as a result of lowering the Schottky barrier height, φ, when compared to conventional lateral SBDs. No compromise in reverse-breakdown voltage and reverse-bias leakage current performance was observed as both multi-channel and conventional technologies exhibited V_{BR} of (V_{BR} > 30 V) and I_{R} of (I_{R} < 38 μA/mm), respectively. Furthermore, a precise small-signal equivalent circuit model was developed and verified for frequencies up to 110 GHz. The fabricated devices exhibited cutoff frequencies of up to 0.6 THz, demonstrating the potential use of lateral AlGaN/GaN SBDs on LR silicon for high-efficiency high-frequency Integrated Circuits applications.

Index Terms—GaN, RF diodes, lateral Schottky barrier diode, sub-THz applications, fin-FET, GaN on silicon.

I. INTRODUCTION

Due to the superior electrical properties of III nitride semiconductors, lateral AlGaN/GaN Schottky-barrier diodes (SBDs) grown on LR silicon substrates are emerging as a promising device technology for fast switching speed, high-power, low-cost and compact-size communications and radar applications, such as mixers, frequency multipliers, detectors and tunable filters operating at millimeter wave frequencies [1] [2]. GaN-based SBDs with low onset voltage (V_{ON}), high reverse-breakdown (V_{BR}) voltage, and low reverse-current leakage (I_{R}), high-switching speed (R_{ON}) and high cutoff frequency (f_{c}) are essentially required to compete with current III-V technologies [3]. Conventional GaN-based SBD DC and RF performance is still limited to their large V_{ON}, switching loss and RF leakage when utilizing LR Si substrates. Several researchers have recently proposed low V_{ON} along with low I_{R} and high V_{BR} technologies, including recessed anode, dual-filed plates, regrowth cathodes, and dual- channel field-effect rectifier (LFER) [4] [5] [6]. However, these approaches require accurate control of anode etching to the 2DEG and a complicated fabrication process, which incorporates reliability issues and extra processing cost. Nevertheless, a 3-D SBDs integrated with a tri-gate MOS structure has shown outstanding DC characteristics at the expense of RF performance owing to the inherently large junction capacitance (Cj) and series resistance (Rj) [7]. Therefore, these techniques are only limited to low-frequency applications. To date, most of the research effort into GaN-based SBDs on silicon is predominantly focused on power electronics, with limited literature targeting RF operation. However, achieving high f_{c} while maintaining low I_{R} and superior V_{BR} remains a challenge [1].

In this letter, an optimized multi-channel RF AlGaN/GaN SBDs on LR Si structure is demonstrated using a cost-effective (GaN on LR Si) which is fully compatible with III-V THz monolithic integrated circuit (THz-MIC) technology. In contrast to conventional SBDs, the newly developed devices significantly enhanced the turn-on characteristics, switching loss, ideality factor (η_{R}) and f_{c}, where a V_{ON} = 0.84 V, R_{ON} = 0.97 Ω.mm, V_{BR} > 30 V, η_{R} = 1.69 and f_{c} = 0.6 THz were achieved. This attributes to the direct contact of Schottky anode to 2DEG at the sidewalls of the multi-mesa trenches along with proper design geometries to suppress substrate coupling effects.

II. DEVICE DESIGN AND FABRICATION

Fig. 1 indicates a cross-section of the fabricated AlGaN/GaN SBDs on LR Si using a multi-channel structure, which was simultaneously fabricated with conventional SBDs on the same substrate to allow precise comparison. A combination of multi-mesa and T-shaped structures was adopted to form the anode to reduce Schottky barrier height and anode resistivity, respectively. The height (H_{F}), width (W_{F}), spacing (S_{F}) and length (L_{F}) of the nanowires were ~ 50, 41, 89 nm and 2 μm, respectively. The Anode length (L_{A}) and anode head length (L_{AH}) were 0.550 μm and 1.1 μm, respectively, whereas the junction length (L_{j}) was 4.28 μm. The total physical anode
width was \(2 \times 10 \mu m\), while the effective anode width for the fin-like anode structure was \(2 \times 5.829 \mu m\).

The epitaxy material used in this work was grown on LR Si (111) \((\sigma = 0.02 \Omega \text{ cm})\) provided by Nexperia. The epilayer consists of \(4.65 \mu m\) buffer, \(20 \text{ nm Al}_{0.8}\text{Ga}_{0.2}N\) barrier and \(3 \text{ nm GaN}\) cap layer. A sheet carrier density of \(5.9 \times 10^{12} \mu m^{-2}\) and electron mobility of \(1713 cm^{-2} V^{-1} s^{-1}\) were provided by Nexperia. The epilayer and substrate parasitics \(S_{\text{sub}}\) and \(R_{\text{sub}}\) are incorporated into the standard SBD circuit model when considering lossy Si substrates, substrate parasitics \(S_{\text{sub}}\) and \(R_{\text{sub}}\) are incorporated into the standard SBD circuit model when considering lossy Si substrates, substrate parasitics \(S_{\text{sub}}\) and \(R_{\text{sub}}\) are incorporated into the standard SBD circuit model when considering lossy Si substrates.
as a substrate. Furthermore, $C_p$ and $L_p$ represents pad parasitics. However, the external parasitic elements have a significant influence on the model at frequencies beyond 20 GHz.

Table I shows the extracted circuit element values of conventional and multi-channel structures at 0 V bias. In contrast to conventional SBDs, an increase in $R_S$ by 15.6% (44.9 to 51.9 Ω) and a slight reduction in $C_j$ by 5.5% (form 49.1 to 46.4 fF) were observed for the newly developed fin-type technology. This attributes to the additional anode length in the multi-mesa trenches and reduction in $\Phi_m$, respectively. In addition, the low value of $C_{sub}$ and high value of $R_{sub}$ indicates that substrate coupling effect could be neglected in both design structures. This was a result of the proper design geometries where the anode-to-cathode separation (2.415 μm) is less than the buffer thickness (4.65 μm) [10].

The extracted values of $C_j$ as a function of the applied voltage of the fabricated devices are shown in Fig. 4a. It can be seen that $C_j$ was inversely proportional to the applied reverse voltage, where a sharp drop in $C_j$ was obtained when changing the voltage form 0 to -2 V. Furthermore, owing to the direct anode contact to 2DEG for multi-channel SBDs, $C_j$ was significantly reduced at reverse biases beyond -2 V, as compared to conventional SBDs. This reflected a dramatic enhancement in $f_c$ which can be calculated from $R_S$ and $C_j$ [1]. Therefore, $f_c$ was improved by 32.7% (from 0.457 to 0.607 THz), as shown in Fig. 4b. However, the achieved $f_c$ of the fabricated lateral SBDs on LR Si is still limited to their larger $R_S$, which mainly depends on material growth quality and cathode contact resistivity, as compared to SBDs realized on GaN-on-Si-SiC substrates [1].

![Fig. 3: (a) Schematic of the proposed small-signal equivalent circuit model and (b) measured versus modelled S-parameters of the fabricated multi-channel AlGaN/GaN SBDs on LR Si at 0 V bias.](image)

![Fig. 4: Junction capacitance ($C_j$) versus voltage, and (b) Cut-off frequency ($f_c$) versus voltage of the fabricated conventional and multi-channel SBDs.](image)

### IV. CONCLUSION

A newly developed multi-channel RF lateral AlGaN/GaN SBD on LR Si technology has been realized in this work. A $V_{ON}$ of 0.84 V along with $R_{ON}$ of 0.97 Ω.mm and $\eta_{on}$ of 1.69 were achieved as a result of the direct Schottky anode contact to the 2DEG resulting in a $\Phi_m$ of 0.64 eV. The fabricated devices exhibited $V_{BV}$ of greater than 30 V along with $I_P$ of less than 38 μA/mm. In addition, a newly proposed small-signal circuit model was introduced up to 110 GHz. An $f_c$ of 0.6 THz at a reverse bias of -10 V was achieved as a result of the optimized SBD design structure and geometries. These findings enable an effective pathway for the realization of high-performance sub-THz-MIC topologies.

### REFERENCES


