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) (\(\sigma = 0.02 \Omega . \text{cm}\)) silicon substrates. The developed technology offers a reduction of 37\% in onset voltage, \(V_{\text{ON}}\) (from 1.34 to 0.84 V), and 36\% in ON-resistance, \(R_{\text{ON}}\) (1.52 to 0.97 to \(\Omega . \text{mm}\)) as a result of lowering the Schottky barrier height, \(\phi_b\), 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 \(V_{\text{BV}}\) of \((V_{\text{BV}} > 30 \text{ V})\) and \(I_{\text{e}}\) of \((I_{\text{e}} < 38 \mu A/\text{mm})\), 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 \((V_{\text{ON}})\), high reverse-breakdown \((V_{\text{BV}})\) voltage, and low reverse-current leakage \((I_{\text{e}})\), high-switching speed \((R_{\text{ON}})\) and high cutoff frequency \((f_{\text{c}})\) 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 \(V_{\text{ON}}\) switching loss and RF leakage when utilizing LR Si substrates. Several researchers have recently proposed low \(V_{\text{ON}}\) along with low \(I_{\text{e}}\) and high \(V_{\text{BV}}\) 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 \((C_j)\) and series resistance \((R_s)\) [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 \(f_{\text{c}}\) while maintaining low \(I_{\text{e}}\) and superior \(V_{\text{BV}}\) 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 \((\eta_e)\) and \(f_{\text{c}}\), where a \(V_{\text{ON}} = 0.84 \text{ V}\), \(R_{\text{ON}} = 0.97 \Omega . \text{mm}\), \(V_{\text{BV}} > 30 \text{ V}\), \(\eta_e = 1.69\) and \(f_{\text{c}} = 0.6 \text{ THz}\) 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 \(\approx 50, 41, 89 \text{ nm and } 2 \mu m\), respectively. The Anode length \((L_{\text{an}})\) and anode head length \((L_{\text{ah}})\) were \(0.550 \mu m\) and \(1.1 \mu m\), respectively, whereas the junction length \((L_j)\) was \(4.28 \mu m\). The total physical anode...
The system was calibrated with an off-standard substrate parasitics, using a Short-Open-Load-Thru (SOLT) calibration technique.

Fig. 3a shows the extracted small-signal circuit model of the fabricated devices, which was validated by the good agreement between modelled and measured S-parameters up to 110 GHz, as shown in Fig. 3b. This allows the extraction of SBD intrinsic elements: junction resistance \( R_s \), capacitance \( C_j \) and \( R_s \), which used to determine \( f_c \) of the fabricated devices. As indicated in Fig. 3a, unlike SI-substrates, substrate parasitics \( (S_{sub} \) and \( R_{sub} \) are incorporated into the standard SBD circuit model when considering lossy Si
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 $\Omega$) 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 $\Phi_a$, 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 mm) is less than the buffer thickness (4.65 $\mu$m) [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].

### References


