p-GaN field plate for low leakage current in lateral GaN Schottky Barrier Diodes

Luca Nela^{1,a}, Catherine Erine¹, and Elisa Matioli^{1,a}

AFFILIATIONS

¹ Institute of Electrical Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, 1015, Switzerland

^a Authors to whom correspondence should be addressed: luca.nela@epfl.ch and elisa.matioli@epfl.ch

ABSTRACT

High-voltage Gallium Nitride Schottky Barrier Diodes (SBDs) suffer from large off-state leakage current, which further degrades during operation at high temperatures and limits the device blocking capabilities. The key to achieving low off-state leakage is to protect the Schottky barrier from the high electric field, which is challenging by employing conventional field plate structures due to their large pinch-off voltage. In this work, we propose a simple AlGaIn/GaN SBD architecture based on a *p*-GaIn cap layer to achieve excellent off-state performance with a very low leakage current. By properly designing the AlGaIn barrier and *p*-GaIn cap, the pinch off-voltage of the *p*-GaIn field plate is carefully controlled and the voltage drop over the Schottky junction is effectively reduced. In addition, a large carrier concentration in the access region is achieved, leading to a reduced sheet resistance. This results in good on-state performance along with a very low leakage current of ~ 1 nA/mm at 400V, which is maintained well below 100 nA/mm up to elevated temperatures of 150 °C. Besides, the proposed architecture shares the well-established fabrication process of commercial *p*-GaIn HEMTs and thus represents a promising and viable solution for future GaIn diodes.

GaN-on-Si power devices have demonstrated great potential for power conversion applications^{1–3}. GaIn High-Electron-Mobility Transistors (HEMTs) have been commercially available for several years and are gaining a considerable market share. Yet, GaIn SBDs have encountered a more difficult development and, at the moment, SiC diodes represent the main commercial solution. Achieving high-performance GaIn SBDs is, however, of great importance for GaIn power technology. Indeed, lateral GaIn SBDs would provide a competitive alternative to SiC diodes in terms of performance and cost, and would allow the integration of multiple GaIn devices on the same chip to realize power ICs^{4–8}.

The main challenge for GaIn SBDs is the difficult management of the off-state electric field at the fragile Schottky barrier, which, if not properly managed, results in a large leakage current that severely limits the device's breakdown voltage. Besides, the blocking performance of GaIn SBDs further degrades at elevated temperatures, which is, however, the typical operation condition of wide band-gap power devices. The key to decreasing the high off-state leakage is to reduce the maximum voltage drop on the Schottky barrier by engineering field plate (FP) structures with a pinch-off voltage (V_P) close to 0 V aimed at protecting the junction^{9,10}. This approach enables depleting the channel region below the FP when a reverse voltage larger than V_P is applied to the device terminals, thus limiting the voltage drop on the Schottky barrier. This is, however, challenging as conventional field plate structures with no oxide already present a rather large negative $V_P \sim - (4-5)$ V, which results in high off-state leakage for the SBD. Alternative strategies proposed in the literature include the use of a Tri-anode architecture^{5,11–13} or the partial recess of the AlGaIn barrier^{10,14} to achieve FPs with $V_P \sim -1$ V.

Nevertheless, while these approaches have been demonstrated to be effective in reducing the off-state leakage, they require complex processing that is not widely available, and increases the cost and complexity of the device fabrication. In particular, Tri-anode devices need lithographic resolutions of about 100 nm^{5,11–13} and SBDs with a partially recessed barrier require extremely precise control of the etching depth, which can be reproducibly achieved only by complex methods such as atomic layer etching^{10,14}.

Here, we propose a simple AlGaIn/GaN SBD architecture based on a *p*-GaIn cap layer to achieve excellent off-state performance with a very low off-state leakage current. While approaches based on a *p*-GaIn edge termination have been investigated, previous works were aimed at very different architectures, such as SBDs with multiple channels^{15,16} or with a Reduced Surface Field¹⁷ (RESURF) layer¹⁸. The role of the *p*-GaIn field plate in these structures was not to reduce the off-state leakage but rather to improve the electric field distribution in the drift region, similarly to conventional field plates. For these reasons, the design and physical mechanisms behind the operation of the *p*-GaIn field plate differed significantly from the one here presented, which is instead specifically aimed at reducing the off-state leakage. In addition, the design and operation of the proposed *p*-GaIn field plate are different also compared to conventional enhancement-mode (e-mode) *p*-GaIn HEMTs for which the pinch-off voltage should be as positive as possible. In particular, to achieve a low leakage current, the *p*-GaIn field plate should be designed to present a slightly negative V_P . Indeed, a too negative V_P would result in similar behavior as for conventional FPs¹⁵, which are not effective in properly protecting the Schottky junction and result in a large off-state leakage. On the contrary, a positive pinch-off voltage

FIG. 1. (a) Schematics and (b) top SEM view of the proposed AlGaIn/GaN SBD with p -GaN cap field plate in the anode region.

in the p -GaN region, as in p -GaN e-mode HEMTs would lead to a degradation of the SBD turn-on voltage.

In this work, we show that by properly tuning the AlGaIn barrier and p -GaN cap, a p -GaN field plate with V_P close to 0 V is achieved, which effectively limits the voltage drop over the Schottky junction. Besides, tuning the AlGaIn barrier also enables to increase the carrier density in the access region compared to usual p -GaN based devices, thus leading to a low sheet resistance. This results in good on-state performance combined with a very low leakage current ~ 1 nA/mm at 400 V, which is maintained well below 100 nA/mm up to elevated temperatures of 150 °C. In addition, this architecture shares the well-established fabrication process of commercial p -GaN HEMTs and can benefit from the extensive research on these devices, which could significantly accelerate its development.

The devices were fabricated on a GaN-on-Si heterostructure comprising a 5.2 μm of buffer, 420 nm of unintentionally doped GaN (u-GaN) channel, 0.7 nm of AlN spacer, 20 nm of $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ barrier, and 75 nm of p -GaN cap-layer with a Mg concentration of $3 \times 10^{19} \text{ cm}^{-3}$. The device fabrication started with the removal of the p -GaN cap layer from the access and contact region by a low-damage, slow-etch-rate Cl_2/Ar -based inductively coupled plasma (ICP) etching. The device mesa was defined by ICP etching to a depth of 250 nm. The cathode was formed by a stack of Ti (20 nm)/Al (120 nm)/Ti (40 nm)/Ni (60 nm)/Au (50 nm) and annealed at 780 °C for 30 s, followed by the deposition of a 25 nm-thick SiO_2 layer by atomic layer deposition (ALD). The oxide was patterned by wet etching and a Ni/Au (50 nm / 120 nm) metal stack was evaporated to serve as anode contact.

Figure 1 shows the cross-sectional schematic and the scanning electron microscope (SEM) top-view of the proposed device. The device anode-to-cathode distance (L_{AC}) is 14 μm , measured from the cathode edge to the end of the p -GaN FP (Fig. 1(b)), while the device width is 60 μm . All quantities reported in the manuscript have been normalized by the total device width (60 μm). No significant variation of the device performance is expected for scaled-up devices, as verified in Refs.^{4,5,19}. Reference devices with fully removed p -GaN cap layer and Tri-anode structures were co-fabricated on the same chip.

To reduce the voltage drop on the Schottky barrier during the off-state, the heterostructure should be properly designed. To this end, the V_P of the p -GaN field plate (FP1) that protects the Schottky junction (Fig. 1 (a)) should be adjusted to be just slightly negative. Indeed, the value of $V_{P,FP1}$ represents the diode

FIG. 2. (a) Simulated V_P of a heterostructure with a 75 nm-thick p -GaN layer as a function of the AlGaIn barrier thickness and Al composition. (b) Simulated N_s in the access region (with no p -GaN) and V_P under the p -GaN cap for a 20 nm-thick AlGaIn barrier as a function of its Al composition. (c) I-V curves for the proposed p -GaN SBD in logarithmic (c) and linear (d) scale at different temperatures. V_{AC} represents the anode-to-cathode voltage.

anode-to-cathode voltage (V_{AC}) for which the region under the field plate 1 is depleted, limiting the voltage drop over the Schottky barrier. Too positive $V_{P,FP1}$ would result in a degraded diode turn-on voltage while too negative values would lead to a large leakage current, as shown in the following sections. While varying the thickness and doping of the p -GaN layer does not impact significantly the V_P of the p -GaN field plate, tuning the AlGaIn barrier is an effective approach to set the $V_{P,FP1}$. Figure 2 (a) illustrates the simulated V_P of a heterostructure with a 75 nm-thick p -GaN cap layer as a function of the AlGaIn barrier thickness and composition. The simulation was performed by Atlas Silvaco software. The 20 nm-thick $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ barrier employed in this work results in a $V_{P,FP1} \sim -0.4$ V, which satisfies the requirements aforementioned. Besides, the use of a 20 nm $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ barrier, which is thicker and with higher Al composition than for usual p -GaN based devices, leads to a large two-dimensional electron gas (2DEG) concentration (N_s) in the access region (where the p -GaN cap is removed) (Fig. 2 (b)). This results in a low sheet resistance (R_{sh}) in the drift region, which reduces the device on-resistance. Finally, while the proposed structure differs from the typical p -GaN heterostructures used for e-mode transistors, it was shown that e-mode devices can be realized on this platform by employing a Tri-gate architecture²⁰, hence enabling the integration of e-mode HEMTs and SBDs on the same chip.

Figure 2 (c-d) presents the I-V curve for the proposed devices. The SBD shows a turn-on voltage (V_{ON}) of 0.7 V at 1 mA/mm (Fig. 2 (c)), which is a typical value for Ni/Au anode contact^{12,21} and confirms no degradation in the diode turn-on due to the p -GaN layer. Besides, thanks to the effective p -GaN field plate, an excellent I_{ON}/I_{OFF} above 10^9 at room temperature (RT) is obtained, whose value is maintained above 10^7 even at 150 °C. The large N_s in the access region also results in a low R_{ON} of 12

FIG. 3. (a) $V_{P,FP1}$ as a function of the nanowire width for p -GaN and MOS devices. The bottom-left inset shows the schematics of the reference Tri-Anode devices. (b) Output capacitance for p -GaN and MOS SBDs Tri-anode devices having different nanowire width (c) SBD leakage current (extracted at 20 V) as a function of the $V_{P,FP1}$. The inset shows the potential distribution close to the anode electrode for p -GaN and reference MOS SBDs for V_{AC} of -10 V. V_{sc} is the voltage drop on the Schottky barrier (d) Off-state current as a function of the p -GaN FP lengths (L_{p-GaN}).

Ω -mm for a L_{AC} of 14 μ m (Fig. 2 (d)), which increases to 19 Ω -mm at 150 $^{\circ}$ C, showing the device's potential to operate at high temperatures. It should be noted that the majority of the on-state current goes through the AlGaIn/anode metal interface (Fig. 1 (a)) rather than through the p -GaN layer, which was verified both by TCAD simulations and experimentally. Indeed, the presence of an anode region in direct contact with the AlGaIn barrier is fundamental to ensure low V_{ON} and R_{ON} , which would otherwise be degraded by the conduction through the p -GaN layer.

To investigate the role of the p -GaN field plate in reducing the SBD off-state leakage, reference MOS Tri-anode devices (inset in Fig. 3 (a)), like the ones presented in Ref. ^{5,11-13}, were considered. While the proposed p -GaN SBDs are based on a conventional planar architecture (see Fig. 1), the use of a Tri-anode enables a gradual tuning of the field plate 1 pinch-off voltage ($V_{P,FP1}$, Fig. 1 (b)). This provides a more complete understanding of the physical mechanisms involved and enables deriving a relation between $V_{P,FP1}$ and the leakage current. However, while employing a Tri-anode architecture is a convenient method to gradually shift $V_{P,FP1}$, the conclusions of the proposed analysis are general. Indeed, they also apply to other techniques such as the use of a p -GaN cap layer (as here presented) or the partial recess of the barrier^{10,14}. In addition, while the device L_{AC} influences the breakdown voltage, the value of the off-state current up to a few hundred Volts is mainly determined by the leakage through the Schottky barrier. Thus the presented analysis is general and can be applied to SBDs with different lengths. Figure 3 (a) shows that a planar

FIG. 4. (a) Off-state leakage current for a p -GaN SBD at different temperatures. Inset: I_{leak} as a function of temperature at a reverse voltage of 400 V for a planar p -GaN and MOS SBD (b) I_{leak} at RT and 150 $^{\circ}$ C for state-of-the-art SBDs present in the literature ^{5,10,28-32,12-14,21,24-27}. The corresponding diode V_{ON} is shown in brackets. The off-state voltage is 400 V unless differently specified (c) Breakdown curve for a planar p -GaN and MOS SBD with L_{AC} of 14 μ m and grounded substrate. (d) $R_{ON,sp}$ vs V_{BR} benchmark for the proposed p -GaN SBD compared to state-of-the-art GaN-on-Si lateral SBDs present in the literature ^{5,12,13,21,24,26,29-32}. The breakdown has been defined at an off-state current of 1 μ A/mm and a 3 μ m transfer length, adding up to L_{AC} , has been considered to evaluate $R_{ON,sp}$.

MOS field-plate presents a rather negative $V_{P,FP1}$ of -2.8 V, which reduces as the Tri-anode widths (w) decreases (Fig. 3 (a), red arrow). On the contrary, the proposed p -GaN field plate enables achieving slightly negative (-0.25 V) $V_{P,FP1}$ even for a planar device (Fig. 3 (a), blue arrow), in agreement with the simulation in Fig. 2 (a-b). This behavior is confirmed by the SBD output capacitance (C_{oss}) (Fig. 3 (b)), which shows a very small $V_{P,FP1}$ for p -GaN devices, and an instead rather large $V_{P,FP1}$ for MOS devices, with a strong dependence on w . The role of $V_{P,FP1}$ is fundamental as it represents the voltage drop over the Schottky barrier (V_{sc}) (inset of Fig. 3 (c)) and directly determines the electric field at the barrier and the SBD leakage current (I_{leak})^{9,13}, as shown in Fig. 3 (c). Indeed, negative values below ~ -2 V of $V_{P,FP1}$ result in an exponential increase of the SBD leakage current due to the enhanced conduction through the Schottky barrier. On the contrary, the small $V_{P,FP1}$ of p -GaN SBDs results in a very low leakage <1 nA/mm even for planar devices, proving the effectiveness of the proposed approach. It should be noted that while a similar approach based on a p -GaN layer was proposed for field-effect rectifiers^{22,23}, this typically results in a large off-state current due to the very strong dependence of I_{leak} on the exact $V_{P,FP1}$ value. In the proposed p -GaN SBDs, the presence of a Schottky barrier allows more tolerance on $V_{P,FP1}$ (Fig. 3 (c)), enabling to achieve extremely low off-state leakage. Another important aspect to consider when designing the p -GaN FP is the $V_{P,FP1}$ dependence on its length. Indeed, for too short FP lengths (L_{p-GaN}), the field plate pinch-off voltage reduces, as shown in Ref. ²⁰, which results in

an increase of the leakage current (Fig. 3 (d)). On the contrary, $L_{p\text{-GaN}}$ values above 1.5 μm ensure $V_{P,FP1}$ close to 0 V and a considerable reduction of the off-state leakage.

Thanks to the small voltage drop on the Schottky barrier, the proposed $p\text{-GaN}$ SBDs results in very low leakage current even during high-temperature operation with $I_{\text{leak}} \sim 2$ nA/mm at 400 V and 100 °C, and well below 100 nA/mm at 150 °C (Fig. 4 (a)). This offers an important advantage over devices with no $p\text{-GaN}$ FP that instead show a large leakage increase at high temperatures (inset in Fig. 4 (a)). In particular, the presented $p\text{-GaN}$ SBDs show a largely reduced leakage current both at RT and 150 °C compared to state-of-the-art devices based on a planar field plate strategy (Fig. 4 (b)). They also show very competitive performance compared to Tri-anode and partially recessed devices, which however require a much more complex fabrication process. Finally, the $p\text{-GaN}$ SBDs present a breakdown voltage of 1 kV at 1 $\mu\text{A/mm}$ for a L_{AC} of 14 μm , showing a significant leakage current reduction compared to reference MOS devices with I_{leak} below 2 nA/mm up to V_{AC} of -850 V (Fig. 4 (c)). This results in an excellent $R_{ON,sp}$ vs V_{BR} benchmark for the proposed $p\text{-GaN}$ SBDs compared with state-of-the-art GaN-on-Si lateral SBDs in the literature (Fig. 4 (d)), which proves the great potential of the proposed devices for power conversion applications.

In conclusion, in this work, we proposed an AlGaIn/GaN SBD architecture based on a $p\text{-GaN}$ cap layer to achieve excellent off-state performance with a very low off-state leakage current. By a proper design of the heterostructure, the voltage drop over the Schottky junction was effectively reduced while a large carrier density in the access region was achieved. This led to good on-state performance combined with a very low leakage current both at RT and up to 150 °C. Finally, the proposed device is particularly appealing as it shares the well-established fabrication process of commercial $p\text{-GaN}$ HEMTs and thus represents a promising and viable solution for future GaN SBDs.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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