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Study of the Leakage Current Transport Mechanisms in Pseudo-Vertical GaN-on-Silicon Schottky Diode Grown by Localized Epitaxy

Mohammed El amrani[1,2], Julien Buckley[1], Thomas Kaltsounis[1], David Plaza Arguello[1], Hala El Rammouz[1], Daniel Alquier [2], Matthew Charles [1]

[1] CEA, Leti, University Grenoble Alpes, 38000 Grenoble, France
[2] GREMAN UMR 7347, Université de Tours, CNRS, INSA Centre Val de Loire, 37071 Tours, France
* Correspondence: mohammed.elamrani@cea.fr

Abstract: In this work, a GaN-on-Si quasi-vertical Schottky diode was demonstrated by growing locally the n-GaN drift layer. The diode achieves a high current density of 2.5 kA/cm², a specific on-resistance $R_{ON,sp}$ of 1.9 mΩ.cm² despite the crowding effect in quasi-vertical device and on/off current ratio (I_{on}/I_{off}) of 10^{10}. Temperature-dependent current-voltage characteristics have been measured in the range of 300-433 K to investigate the mechanisms of leakage conduction. At near zero bias, thermionic emission was found to dominate. At voltage range from -1 to -10 V, electrons gain enough energy to excite into trap states, leading to the dominance of Frenkel-Poole emission (FPE). For a relatively higher voltage range (-10V to -40V), the increased electric field promotes electrons hopping along the threading dislocations in the "bulk" GaN layers, and thus, Variable Range Hopping becomes the main mechanism for the whole temperature range. This work provides an in-depth insight into the leakage conduction mechanism on vertical GaN-on-Si SBDs grown by localised epitaxy, and also provides a useful design guide for the edge termination of vertical power devices.

Keywords: Gallium nitride; pseudo-vertical p-n-diodes; localized epitaxy; Leakage Mechanism.

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1. Introduction

Gallium Nitride (GaN) has become increasingly popular in the world of power devices due to its remarkable properties such as wide bandgap, high electron mobility, and a strong breakdown field strength. These factors collectively enable GaN-based devices to offer low on-resistance (Ron) and the ability to operate at high frequencies in high-voltage applications [1].

Vertical and quasi-vertical GaN devices have undergone extensive research in the past decade and show substantial promise for entry into the power electronics market [2-3]. The use of free-standing GaN substrates holds the potential for strain-free GaN epitaxy and the development of fully vertical device geometries [4]. However, challenges such as high production costs, variable quality, and limited availability hinder their widespread adoption. Consequently, there has been a heightened focus on fabricating vertical power

devices on foreign substrates in recent years such as silicon, sapphire and QST™ [5-6]. Silicon substrates, highly favored from a commercial point of view, encounter a significant challenge during GaN growth due to the onset of plastic substrate deformation, which restricts the maximum drift layer thickness to ~ 6μm [7]. In order to overcome this limitation and increase the maximum achievable Breakdown Voltage (BV), Selective-Area Growth (SAG) is a promising approach. It has been shown that during SAG of GaN micropillars, stress is effectively reduced by the formation of hexagonal facets, and thus the maximum epitaxial layer thickness can be increased [8-9].

In this work we demonstrate quasi-vertical GaN Schottky barrier diodes (SBDs) grown on Si substrate using localized Epitaxy [9], as well as investigate their electrical performance in forward and reverse bias. The leakage current transport of the GaN quasi-vertical SBDs on Si is much different with lateral GaN SBDs than SBDs on freestanding GaN substrates, due to the different current conduction, the large dislocation density caused by the mismatch of lattice constant and thermal expansion between GaN and Si. Therefore, it is necessary to understand the leakage current transport mechanism of GaN quasi-vertical SBDs on Si. Many researchers have reported that variable range hopping (VRH) by dislocation is the main off-state leakage mechanism in vertical GaN diodes on all Si, sapphire and GaN substrates [10–11]. Others have found that the dominated leakage mechanisms in GaN-on-Si SBDs are different at different reverse biases, and subjective to the presence of Edge termination [12-13]. The objective of this work was to provide deeper insight into the physics and to determine the leakage mechanisms in the case of GaN obtained by selective growth area (SAG).

2. Materials and Methods

In this study, as presented in Figure 1a, samples were carried out on a single-wafer AIXTRON Crius-R200 metal-organic vapour phase epitaxy (MOVPE) tool, on 200 mm-diameter Si(111) wafers. The sutructure from the bottom to the top, consist of a buffer layers of AlN and AlGaN, an undoped 300 nm-thick GaN layer and three 350 nm thick n+-GaN layers for current spreading layer (5×10^{18} cm^{-3}, 5×10^{17} cm^{-3} and 5×10^{16} cm^{-3} from top to bottom). A 50 nm-thick Al_2O_3 mask was deposited on these layers by atomic layer deposition at 300 °C, and was then patterned with lithography and etching. Localized epitaxial growth of drift layer was subsequently performed on the openings of this mask, demonstrating a doping concentration of N_D-N_A~ 1.5×10^{16} cm^{-3} as showed in Figure 1b. After that, Ti/Al/Ni/Au (95 nm/200 nm/20 nm/165 nm) stacked metal layers were deposited on the n+GaN to form the ohmic contacts followed by rapid thermal annealing (RTA) at 750 °C. Finally, circular Ni/Au (50 nm/150 nm) Schottky contacts were formed on the n−GaN by the liftoff process followed by 5 min of thermal annealing of 400 °C. The circular anode has a diameter of 60μm.

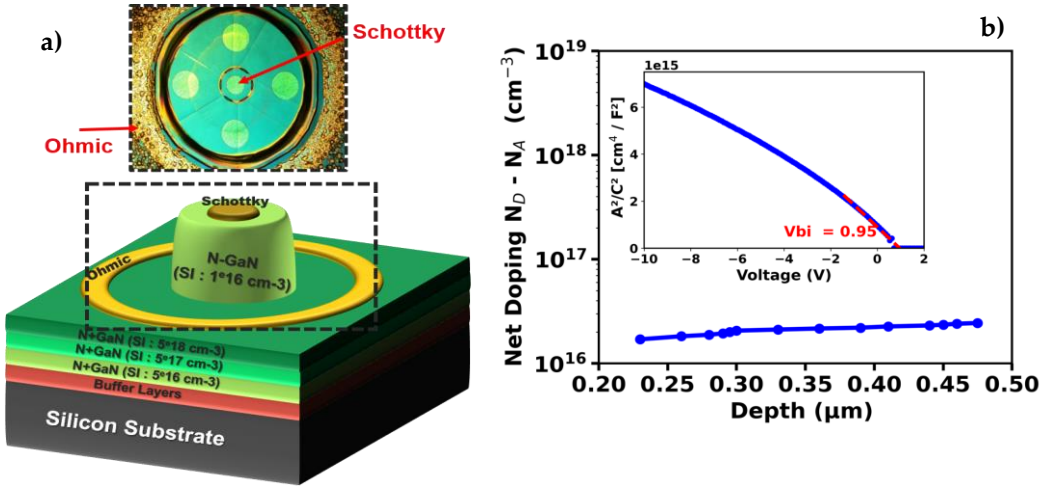

Figure 1. (a) Schematic cross-section of quasi-vertical Schottky diode using localized epitaxy; (b) net doping concentration (N_D - N_A) in the n—GaN drift layer from the C-V curve at 1MHz. Inset: (A^2/C^2) versus the reverse voltage.

3. Results

3.1. Forward Bias

The electrical characteristics of device were performed using a 4156C Precision semiconductor parameter analyzer and Keithley K2657 Tesla GPIB 24 parameter analyzer.

Figure 2a shows the typical forward J-V characteristics in semi-log scale for pseudo-vertical Schottky diode, showing a low turn-on voltage ~ 0.6 V and a good ON/OFF current ratio of 10^{10}. As shown in Figure 2b, the device achieves a high current density of ~ 2.5 kA/cm² and low differential specific on-resistance $R_{ON,sp}$ of 1.9 mΩ.cm² at 5V despite the current crowding effect on the edges. The extracted ideality factor n and the Schottky barrier height $\emptyset_b$ from the expressed equation (1) [14], at RT were close to 1.03 and 0.95 eV, respectively, indicating that the dominant current is thermionic emission and a good quality of metal-GaN interface.

$$I_{TE} = AA^{*}T^{2}\exp\left(-\frac{q\emptyset_b}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \quad (1)$$

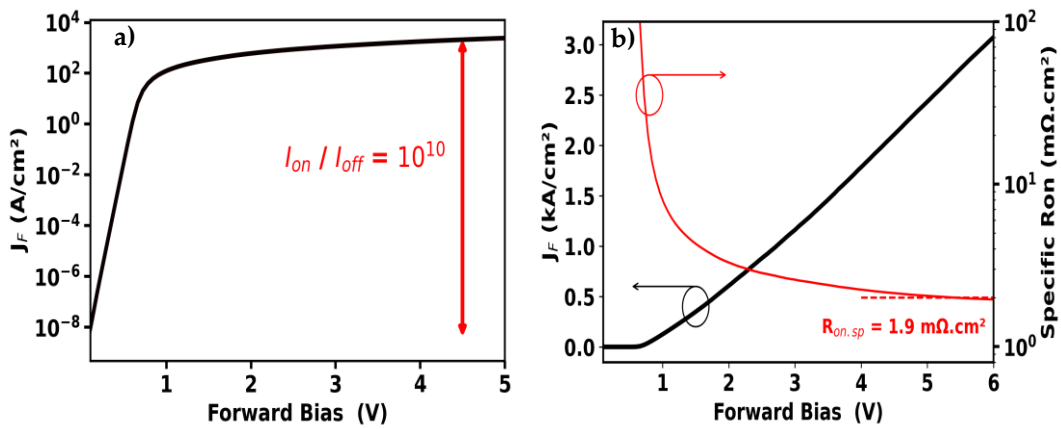

Figure 2. Forward J-V curves of SBD diode with (a) semi-log, (b) Linear scale.

Figure 3a and Figure 3b show the temperature-dependent forward characteristics of the SBD. As shown in the inset of Figure 3a, as the temperature increases, the differential Ron,sp increases from 1.9 mΩ.cm² at 25 °C to 2.5 mΩ.cm² at 160 °C, probably due to the reduced electron mobility, mainly due to thermally enhanced phonon scattering [26]. In Figure 3c the ideality factors n increases from 1 to ~ 1.7 at higher temperature which may indicate the impact of the surface traps on device performance [14]. This is also confirmed by the change in barrier height with temperature at the range from 375 to 425K. These results suggest thermal instability of the Schottky contact of the SBD at high temperatures. Figure 3d, illustrates the experimental Richardson's constant of 4.59 A cm^{-2} K^{-2}. The discrepancy from the theoretical value of 26.64 A K^{-2} cm^{-2}, could be ascribed to the properties of the epitaxial layers and the inhomogeneous barrier [15].

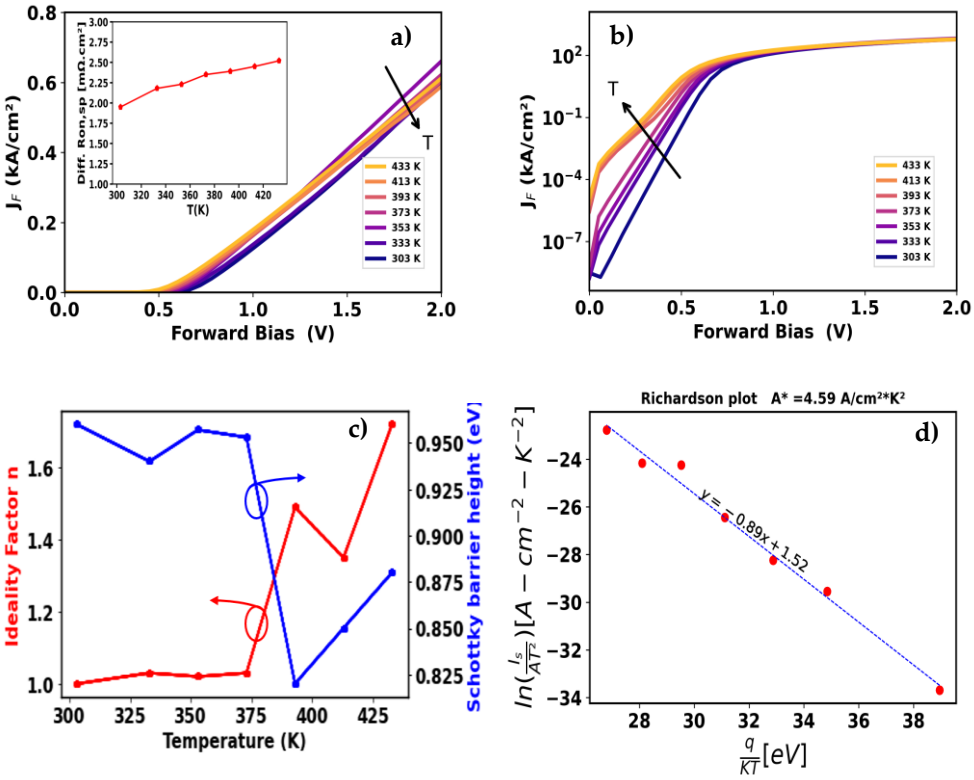

Figure 3. (a) Temperature-dependent forward J-V characteristics on the linear scale. Inset: differential specific on-resistance $Ron_{,sp}$ as a function of temperature T. (b) Temperature-dependent forward J-V characteristics on a semi-log scale.(c) Extracted ideality factor n and Schottky barrier height as a function of temperature for the Metal/n-GaN Schottky contacts and (d) the exprerimental Richardson's plot.

3.2. Reverse Bias

Figure 4a shows the reverse J-V characteristics of the GaN pseudo-vertical SBD. The destructive BV of the SBD is ~ 80 V probably due to the absence of edge termination [12-13]. Figure 4b shows the reverse bias J-V characteristics in semi-logarithmic scale for Ni/Au SBD in the temperature ranging from 300–433 K up to – 40 V. The characteristics can be divided into three different voltage regions. Region "A"is near zero bias, while region "B" is from -1 to -10 V and region "C" is -10 to -40 V. For schottky devices under a reverse regime, the depletion region can be considered as an insulation layer with a strong

electric filed which should be managed by edge termination. It's worth noting that leakage current in vertical devices is typically caused by defects and dislocations in the active layers [16]. Table I summarizes the possible current transport mechanisms and their electric field and temperature dependencies of SBDs.

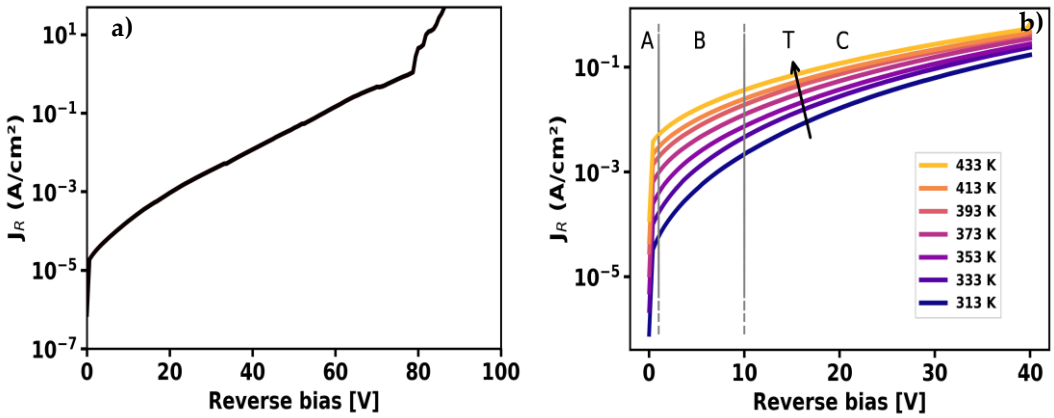

Figure 4. (a) Breakdown characteristic of the fabricated pseudo-vertical GaN and (b) Temperature-dependent reverse J–V characteristics on the log scale.

Table 1 Summary of the possible leakage mechanisms for SBDs [10], where J is current density, E is the electric field, E_c the characteristic field, n is the ideality factor, T is absolute temperature, k is Boltzmann's constant, $\emptyset_t$ is barrier height for the electron emission from the trap state associated with FP emission, ε_s is the relative dielectric constant of GaN, C is a constant of the order of unity, a is the localization radius of the electron wave function, T0 is characteristic temperature, and W_D is the depletion width. The electric field can be obtained from the following expression:

$$E = \sqrt{\frac{2q(ND - NA)}{\varepsilon_s}\left(V + V_{bi} - \frac{kT}{q}\right)}, \quad (2)$$

Where V_{bi} and $N_D - N_A$ were extracted from CV measurements as above mentioned.

Mechanism	Expression	E-field dependence	Temperature dependence
Thermionic emission [14]	$J_{TE} = J_s\left[\exp\left(\frac{qV}{nkT}\right) - 1\right]$	$\ln(J_{TE}/T^2) \propto \sqrt{E}$	Yes
Frenkel–Poole [17]	$J_{FPE} = CE\exp\left(-\frac{q(\emptyset_t - \sqrt{qE}/\pi\varepsilon_s)}{kT}\right)$	$\ln(J_{FPE}/E) \propto \sqrt{E}$	$\ln(J_{FPE}) \propto 1/T$
Variable-range-hopping [18]	$J_{VRH} = J(0)\exp\left(C\frac{qEa}{2kT}\left(\frac{T_0}{T}\right)^{-0.25}\right)$	$\ln(J_{VRH}) \propto E$	$\ln(J_{VRH}) \propto (1/T)^{0.25}$
Phonon-assisted tunneling [19]	$J_{PaT} = \exp\left(\frac{E^2}{E_c{}^2}\right)$	$\ln(J_{PAT}) \propto E$	Insensitive

Region A: Figure 5a shows the reverse ln (J) versus V obtained at different temperatures, a strong linear relationship with higher thermal activation as shown in Figure 5b, indicating that the TE is the main conduction mechanism at low voltage.

Region B: by increasing the reverse bias, it is obvious that the leakage current increases with temperature. This can be caused by the Frenkel–Poole emission (FPE), specifically; thermal excitation of electrons can cause emission from traps into the conduction band of the drift layer. When considering an electron in a trapping center, the coulomb potential energy of the electron can be decreased by an applied electric field across the depletion layer. According to the FPE's equation, the ln (J/E) exhibited a linear relationship with the

square root of electric field as shown in Figure 6a, which indicates that the Frenkel-Poole emission (FPE) is the dominated leakage process in region B. Furthermore, the $\emptyset_t = 0.25$ eV and $\varepsilon_s = 5.86$ extracted from the linear fitting as shown in Figure 6b and Figure 6c, are consistent with already reported values, and they confirm the domination of FPE at voltage range -0.5 to -10 V [20], [21].

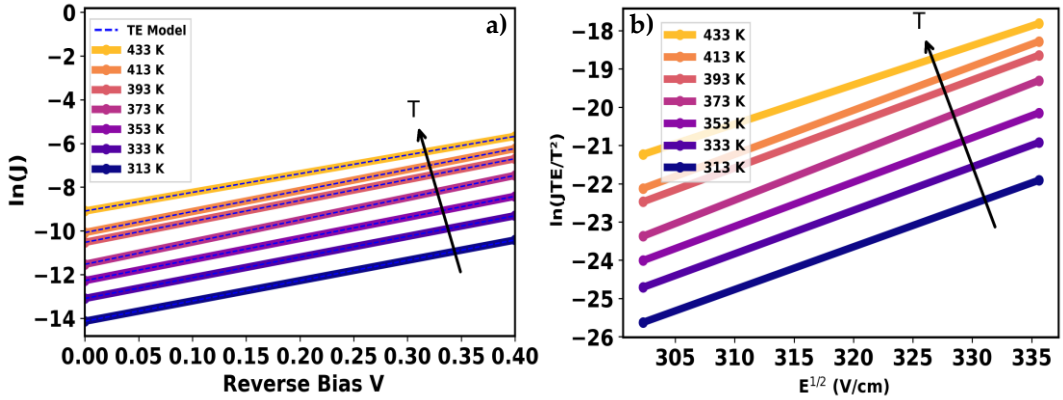

Figure 5. (a) Reverse ln (J) versus V with the fitting model and (b) ln (JTE/T²) versus E½ at the voltage range of 0 to -0.4 V

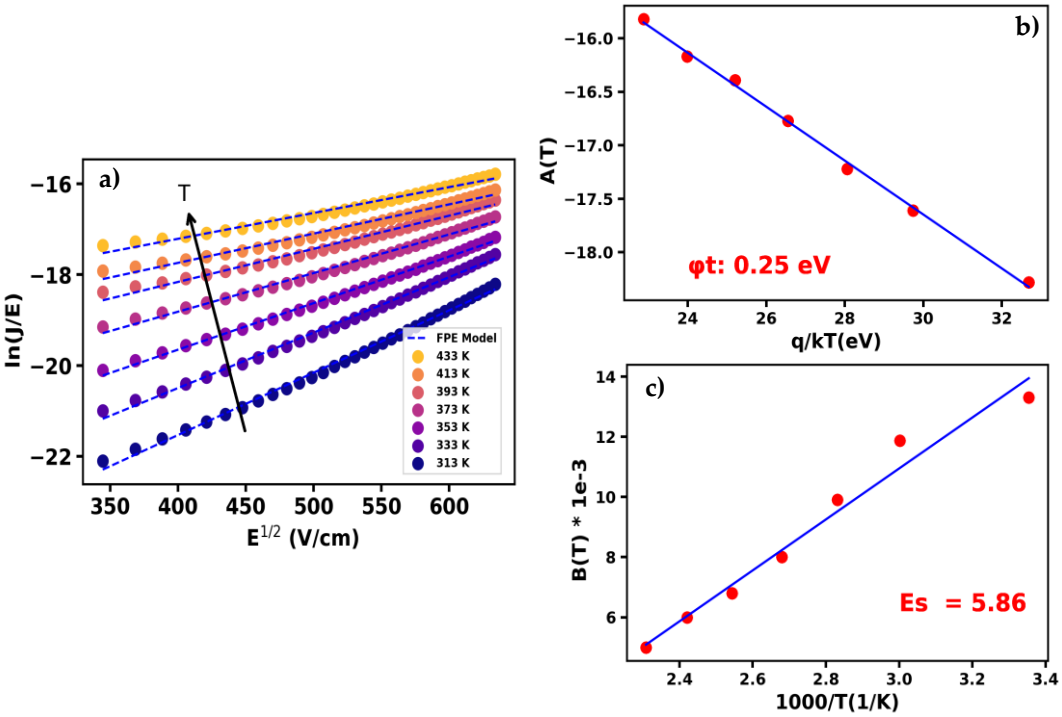

Figure 6. (a) ln (J/E) versus $E^{1/2}$ fitted with FPE model. (b) A (T) as a function of $\frac{q}{kT}$. (c) B(T) as a function of 1000/T.

Here $A(T)$ and $B(T)$ are the intercept and slope of the ln (J / E) versus $E^{1/2}$ plot and are defined as:

$$A(T) = -\frac{q\emptyset_t}{kT} + \ln C, \tag{3}$$

$$B(T) = \frac{q}{kT}\sqrt{\frac{qE}{\pi\varepsilon_s\varepsilon_r}}, \tag{4}$$

Region C: When the reverse bias increases up to 40 V with a corresponding calculated E up to 1.1 MV/cm, the linear relationship between ln(J) and E is demonstrated, as shown in Figure. 7a. This indicates that the reverse leakage is mainly dominated by variable range hopping (VRH) process, which the increased electric field promotes electrons hopping along the threading dislocations in the "bulk" GaN layers [5], [22]. Figure. 7b shows the reverse current at serval voltage versus the invers of the temperature so-called Arrhenius plot. It is clear that at high field, the current has a lower temperature dependency and follows the Mott's law [ln(J) $\propto (1/T)^{1/4}$]. The extracted characteristics temperature T_0 is 2.17 x 10^7 K, which is falling within the typical range 10^6- 10^9 K and is consistent with the reported value (4.92 x 10^7 for N_D ~ 3 x 10^{16} cm^{-3}) [23-24].

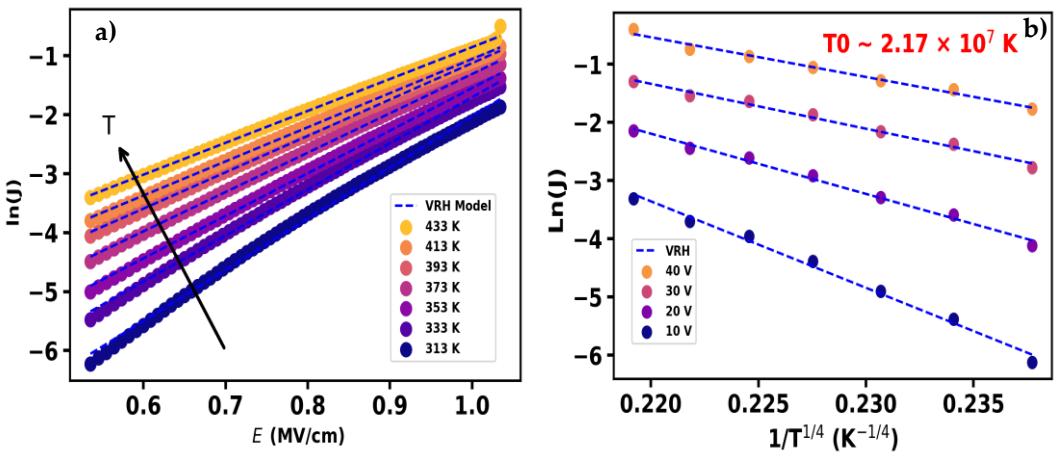

Figure. 7(a) ln (J) as a function of applied electric field E. (b) ln (J) versus $(1/T)^{1/2}$ at reverse voltage of −10, −20, -30 and −40 V.

5. Conclusions

In this work, a GaN-on-Si quasi-vertical SBD was fabricated with localized epitaxy (or Selective Area Growth). The SBD achieved good forward performance, with a high current density of 2.5 kA/cm² , a low turn-on voltage of 0.6 V and a $R_{ON,sp}$ of 1.9 mΩ.cm². A limited breakdown voltage of ~ 80 V was found probably due to the absence of edge termination. Temperature-dependent reverse bias I–V characteristics in a range of 300–433 K were performed and the leakage current transport mechanisms were investigated. At near zero bias (Region A : 0V to -0.5V), the current density (J) follows a linear relationship with 1/T and the characteristics corresponds to the TE leakage process [25]. By increasing reverse voltage up to -10 V (Region B), Frenkel-Poole emission (FPE) with an emission barrier $\emptyset_t$ of 0.25 eV becomes dominant. At high voltage (Region C: -10V to -40V), the leakage current becomes insensitive to the temperature which suggest that the VRH mechanism dominates. This work gives an in-depth insight for the leakage mechanisms and provides a useful guidance to improve GaN vertical power devices on silicon substrates.

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Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Conflicts of Interest: The authors declare no conflict of interest.

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