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# Vertical Current Temperature Analysis of GaN-on-Si Epitaxy through Analytical Modelling

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## Abstract

The current temperature dependence of a 3.9  $\mu\text{m}$  GaN-on-Silicon epitaxy at temperatures ranging from 25  $^{\circ}\text{C}$  to 200  $^{\circ}\text{C}$  and for voltages beneath the plateau limited by the carrier generation in the p-doped substrate is analyzed. Based upon a fit with analytical transport models, the vertical current is reported for the first time to be the superposition of three different transport mechanisms: Recombination limited at low and middle voltages for low temperatures, Ohmic at low and middle voltages for high temperatures and Nearest Neighbor Hopping (NNH) at high voltages. Thanks to their temperature dependences and therefore to their energy, the transports can be related to either point defects clustered around threading dislocations or to interstitial nitrogen.

## 1. Introduction

For about ten years, tremendous efforts have been made to tackle with thermal and lattice mismatch of GaN-on-Si epitaxy to produce high quality GaN active layers [1] for power diodes and transistors in the 100 V to 1000 V range.

Many transport mechanisms were identified as governing the vertical leakage that may contribute to the device leakage. Near the breakdown, the study of Borga [2] reveals that the current depends on the nucleation layer/Substrate interface with a plateau in the I-V characteristics limited by the thermal carrier generation preceding an avalanche at the AlN/Si interface. At lower voltage, several mechanisms such as Space Charge Limited Current or Poole Frenkel were identified by means of TCAD [3], or analytical fit [4]. However, no analytical fitting was done for a wide range of temperature and for voltage below the plateau limited by thermal carrier generation to identify the possible origin of the leakage.

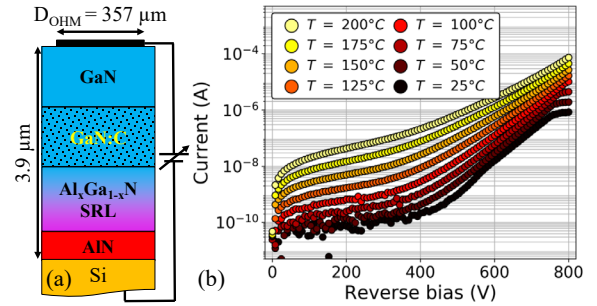


Fig. 1. (a) Schematic of the vertical epitaxy (b) Experimental vertical current characteristics at temperature ranging from 25  $^{\circ}\text{C}$  to 200  $^{\circ}\text{C}$

## 2. Experiments and models

The 3.9  $\mu\text{m}$  AlGaIn/GaN-on-Si epitaxy analyzed in this study was grown on a 1 mm thick p-doped 200 mm (111)-oriented silicon substrate with a resistivity between 3 and 20  $\Omega\cdot\text{cm}$ . It consists of four main parts as illustrated in Fig. 1(a) deposited by Metal Organic Chemical Vapor Deposition (MOCVD). There is an AlN nucleation layer followed by an  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  Strain Relief Layer (SRL), and a 1.3  $\mu\text{m}$  thick GaN:C with carbon concentration of roughly  $5 \times 10^{18} \text{ cm}^{-3}$ . The last hundred nanometers are composed of GaN layers. The top contact is a Ti/Al bilayer circular Ohmic contact with a diameter of 357  $\mu\text{m}$ .

The measurements were done between 0 V and 800 V with a sweep rate of 20 V/s to prevent trapping from occurring and an integration over two Power Line Cycles (PLC). White light illumination was used to have a wider voltage range without being limited by the generation of electrons in the substrate. This phenomenon can still be identified in the temperature curves of the vertical current in Fig. 1(b) above 750 V. Verification was made to enhance that this illumination does not affect the leakage level studied here.

TABLE I : TRANSPORT MECHANISMS

Transport model	Analytical model
Ohmic conduction	$I \propto A_1 \times V$
Recombination-limited model	$I = q \times A_2 \times G \times \sqrt{\mu_n \times \tau_n} \times \sqrt{V}$ (hyp. : $\mu_n \gg \mu_p$ )
Nearest Neighbor Hopping (NNH)	$I = A_3 \times C_1 \times q \times K_B \times T \times a \times e^{\frac{q \times a \times E}{K_B \times T} - \frac{\Phi_t}{K_B \times T}} \times 2 \times \frac{a}{\alpha}$ (hyp. : $q \times a \times E \approx 10 \times K_B \times T$ )

$I$  = Current,  $A_1$  = Effective surface,  $V$  = Voltage,  $q$  = Elementary charge,  $G$  = Generation rate,  $\mu_n$  = Electron mobility,  $\tau_n$  = Electron lifetime,  $C_1$  = Arbitrary constant,  $\Phi_t$  = trap level,  $E$  = Electric field,  $K_B$  = Boltzmann constant,  $T$  = Temperature,  $a$  = Mean hopping distance,  $\alpha$  = Decay length

### 3. Results and discussion

A clear temperature and bias dependence is visible in Fig. 1(b) and is analyzed with 1D analytical models reported in TABLE I assuming a temperature independent effective surface. Transport models such as Variable Range Hopping have not been used because either their temperature or bias dependence could not fit the data. Noting that the uncertainty levels that are reported were determined by visual graphic method when fitting data.

The first analytical model that was used for this study is the ohmic model as described in TABLE I with an Arrhenius temperature dependence as in [5]. Indeed, a linear dependence in the log-log plot is visible as already exposed in the literature [6], [7]. An activation energy of  $0.76 \pm 0.03$  eV was obtained for this transport mechanism.

Nevertheless, at lower temperature, the log-log slope is smaller. This is due to the recombination-limited transport contribution that vanishes with temperature. In fact, its square root dependence with voltage, as shown in TABLE I, leads to a slope of one-half in the log-log plot and allows fitting the experimental at lower temperatures but still below 400 V. The Arrhenius temperature dependence gives an activation energy of  $0.27 \pm 0.02$  eV.

The third analytical model that has been used to fit the experimental curves especially between 575 V and 750 V is the Nearest Neighbor Hopping (NNH) with its equation given in TABLE I. Thanks to the  $\ln(I)$  vs.  $E$  graph in Fig. 2, plotted by assuming that the electric field was uniformed in the III-V buffer, the trap energy level is  $0.75 \pm 0.01$  eV.

To be complete, the authors proved that the Poole Frenkel (PF) model could not explain the experimental data because the relative permittivity extracted with the formula in [4] from the fit of 1.59 is inconsistent with the expected value of 8.9. The addition of all of these three different models in parallel as illustrated in Fig. 3(a) with the parameters exposed before gives the fitting plotted in Fig. 3(b).

Having identified three different energies related to all the contributions of the vertical leakages with two that are similar, their possible origins will be discussed now.

The energy range:  $0.27 \pm 0.02$  eV related to the recombination-limited model embeds energy levels that were reported in the bulk GaN or AlGaIn Deep Level Trap Spectroscopy (DLTS) literature but there is no consensus concerning its precise origin. The common signature of these energy levels is the logarithmic capture kinetics [8]–[10], revealing an extended defect such as a dislocation. Furthermore, this is more likely to be related to a cluster of punctual defects around the dislocation indiscriminately of its kind (screw, edge or mixed) rather than a dislocation alone

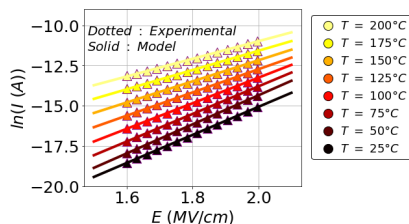


Fig. 2. Fitting between 575 V and 750 V with the nearest neighbor hopping model (fitting parameters:  $\Phi_T = 0.75$  eV &  $a = 2.42$  nm &  $\alpha = 0.24$  nm) with respect to the experimental values

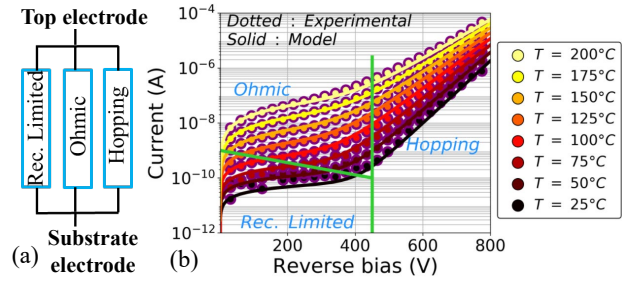


Fig. 3. (a) The different contributions modeling for the vertical current (b) Final fitting with the experimental data

according to Soh et al. [8]. According to the authors, the most relevant hypothesis for the cluster is the gallium vacancies  $V_{Ga}$  or a  $V_N-V_{Ga}$  pairs as presented by Fang [11]. In fact, ab-initio simulations that in an N-rich environment (the case of the MOCVD deposition used in this study), the formation of  $V_{Ga}$  near the dislocation has quite a low formation energy and even lower than the  $V_N$  [12]. The Ohmic and hopping models revealed energies of  $0.76 \pm 0.03$  eV and  $0.75 \pm 0.01$  eV respectively. This can be related to interstitial nitrogen as reported in the paper of Asghar [13] on MOCVD grown vertical p-n diodes. This hypothesis is consistent since the GaN epitaxy studied here was grown in an N-rich environment.

### 3. Conclusions

The vertical current temperature dependence of a GaN-on-Si epitaxy has been studied from 25 °C to 200 °C for voltages below 800 V where the current is limited by carrier thermal generation. Under 400 V, at low temperature, the current is expected to be limited by the recombination of carriers through edge, screw or mixed dislocations clustered with Gallium vacancies or Nitrogen vacancies or both in pair because of its activation energy of  $0.27 \pm 0.02$  eV. At higher temperature and still below 400 V, the main current contribution is ohmic. The activation energy of the mechanism is equal to  $0.76 \pm 0.03$  eV that could be due to the present of nitrogen in interstitial sites. Above 400 V and whatever the temperature, the transport is enhanced with a NNH mechanism possibly related to interstitial nitrogen because its energy is equal to  $0.75 \pm 0.01$  eV. This is consistent with the N-rich environment during growth.

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