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Design Space and Origin of Off-State Leakage in GaN Vertical Power Diodes

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Abstract

Variable-range-hopping through dislocations was identified as the main off-state leakage mechanism for GaN vertical diodes on different substrates. The behavior of leakage current for vertical devices as a function of dislocation density and electric field was derived by TCAD simulations, after careful calibration with experiments and literature data. Designed GaN vertical diodes demonstrate 2-4 orders of magnitude lower leakage current while supporting 3-5 times higher electric field, compared to GaN lateral, Si and SiC devices.

Introduction

GaN-based transistors and diodes are excellent candidates for high-power electronics. Currently, both lateral and vertical GaN devices are being considered. Specifically, vertical devices have attracted increased attention, due to several potential advantages over lateral devices: 1) higher breakdown voltage (BV) without enlarging chip size; 2) superior reliability and 3) enhanced thermal performance [1]. Recently, high-performance GaN vertical devices have been demonstrated on GaN [2], sapphire and Si [3] substrates with over 3.7 kV BV, 3-3.5MV/cm peak electric field (E field) and a lower leakage than GaN lateral devices [1][3].

Off-state leakage current is a key factor determining the device BV, power circuit loss and, potentially, device and circuit reliability. However, the physical mechanisms and the design space of the leakage current in GaN vertical devices are still unknown.

In this work, we fabricated GaN vertical diodes on different substrates, and then unveiled the leakage mechanism of GaN vertical devices by analytical analysis and TCAD simulation. Finally, the design space of leakage current in GaN vertical devices was derived and benchmarked with GaN lateral, Si and SiC devices.

Device Fabrication and Material Characterization

GaN vertical p-n diodes were fabricated on GaN, sapphire and Si substrates with similar doping levels in p-GaN and n-GaN drift layers (Fig.1). Details of diode fabrication and edge termination were described in [1] and [3]. The total dislocation density of GaN-on-GaN, GaN-on-sapphire and GaN-on-Si structures are ~10^7, ~10^9 and ~10^9 cm^{-2}, measured by commercial wafer providers. The total screw dislocation densities of the three structures are ~8×10^6, ~10^8 and ~5×10^8 cm^{-2}, estimated from X-ray rocking curves (Table I). The pure screw dislocation density, which is directly related to bulk leakage in GaN, is typically 3%~5% of the total dislocation density and 5%~20% of the total screw dislocation density for GaN epitaxial layers by MOCVD [4].

Analytical Study of the Origin of Leakage Current

The previously proposed leakage current mechanisms for GaN devices included: Poole Frenkel (PF), Variable Range Hoping (VRH), Surface Leakage and Space-charge Limited [5], each one with different current dependence on E field and temperature (Table II). In our work, the surface leakage was excluded for the GaN-on-Si and GaN-on-sapphire diodes with a pseudo-vertical structure, by showing no linear dependence of leakage current density on diode periphery (Fig. 2).

To identify the bulk leakage mechanism, correlation between leakage current I and E field were studied. The average E field in the drift layer, E_{av}, was estimated by the equation $E_{av}=(V_{bi}-V_r)/W_d$, where V_{bi} is the built-in voltage of GaN diodes (~3.4 V) and W_d is the drift layer thickness [5]. A linear relationship of $\ln(I)\propto E_{av}$ was found valid for all the GaN vertical diodes, independently of the substrate, that we fabricated and also the ones

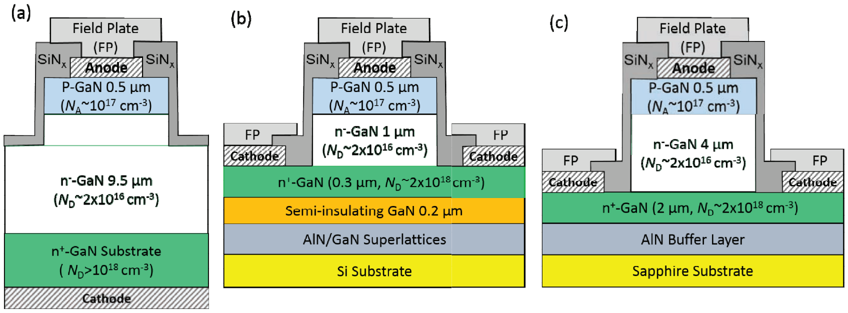

Fig. 1. Schematic of GaN vertical p-n diodes on (a) GaN, (b) Si and (c) Sapphire substrates. GaN-on-GaN vertical diodes have a fully-vertical structure, while GaN-on-Si and GaN-sapphire diodes have a pseudo-vertical structure due to insulating buffer/transistion layers.

Table I. Total screw dislocation density of GaN on different substrates, estimated from the full-width at half-maximum (FWHM) intensity of X-ray diffraction (XRD) rocking curve.

Substrate	FWHM of rocking curve (deg)		Screw Dislocation Density (cm^{-2})
	(0002)	(0004)	
GaN	0.01784	0.01814	~8×10^6
Sapphire	0.07126	0.05334	~1×10^8
Si	0.14473	0.14105	~5×10^8

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Table II. Summary of conduction mechanisms in insulators under high electric field (E) field that can impact the off-state leakage in GaN vertical devices. [5]

Mechanism	Expression	E-field Dependence	Differential Slope
Poole Frenkel (PF)	$I = I_0 \exp\left(\frac{\beta_{PF} E^{0.5}}{k_B T}\right)$	$\ln(I) \propto E^{0.5}$	$\frac{dlog(\ln(I))}{dlog(E)} \propto 0.5$
Variable-range hopping (VRH)	$I = I_0 \exp\left(\frac{CE}{2k_B T}\left(\frac{T_0}{T}\right)^{\frac{1}{4}}\right)$	$\ln(I) \propto E$	$\frac{dlog(\ln(I))}{dlog(E)} \propto 1$
Surface Leakage	$I \propto E/\rho$	$I \propto E$	$\frac{dlog(I)}{dlog(E)} \propto 1$
Space-charge limited	$I = \frac{9\varepsilon\mu E^n}{8W_d^3}$	$I \propto E^n \ (n \geq 2)$	$\frac{dlog(I)}{dlog(E)} \propto n$

T: temperature; k_B: Boltzmann constant; ρ resistivity; C: constant.

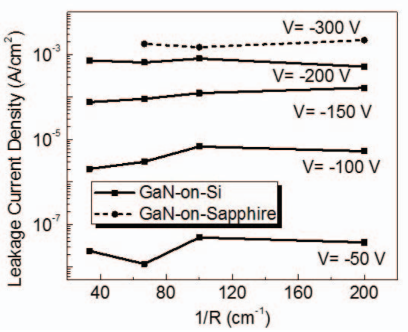

Fig. 2.Leakage current density of GaN-on-Si and GaN-on-sapphire vertical diodes with different anode radius *R*. Non-linear dependence of current density on 1/*R* indicates that the bulk component rather than the surface leakage is the main contribution to device lekage current.

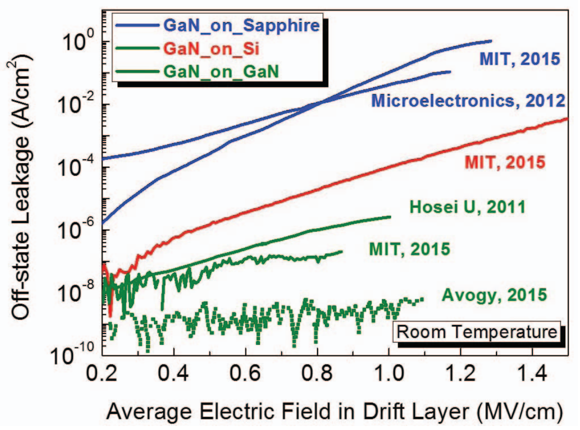

Fig. 3. The $\ln(I)$ *vs* E characteristics for the GaN-on-GaN, GaN-on-sapphire and GaN-on-Si vertical diodes fabricated at MIT and reported in the literature: by Avogy [2], Hosei Univ. [8] and Microelectronics [9]. The reported Avogy's GaN-on-GaN wafer has a 2-3 orders of magnituede lower dislocation density and leakage current probably due to different wafer growth technology.

reported in the literature (Fig. 3). The $\ln(I) \propto E_{av}$ linear relationship is valid at various temperatures for the fabricated and reported devices (Fig. 4). Referring to Table II, this $\ln(I) \propto E_{av}$linearity indicates that the VRH is the dominant leakage mechanisms for GaN vertical diodes [5]. This was further confirmed by having $dlog(\ln(I))/dlog(E) \sim 1$ in our fabricated GaN-on-Si and GaN-on-sapphire vertical diode, as shown in Fig. 5. (GaN-on-GaN *I-V* was too noisy for this derivation, as the leakage is as low as our measurements limits.)

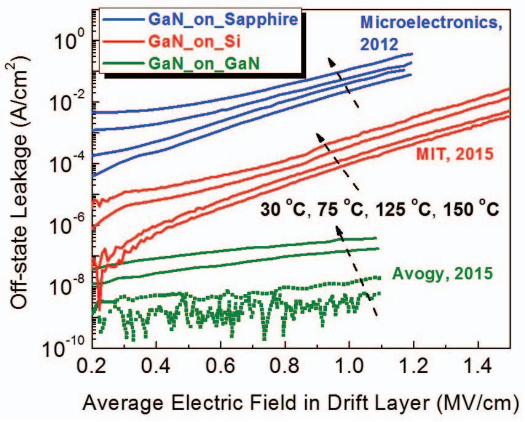

Fig. 4. The $\ln(I)$ *vs* E characteristics at different temperatures for the GaN-on-GaN, GaN-on-sapphire and GaN-on-Si vertical diodes fabricated at MIT or reported in the literature.

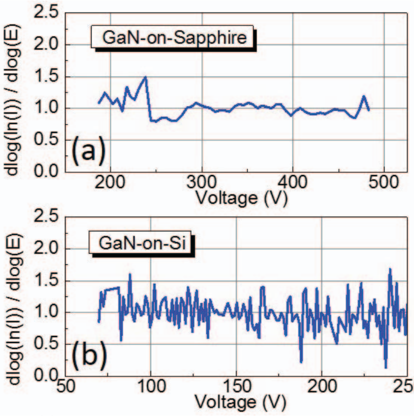

Fig. 5. $dlog(\ln(I))/dlog(E)$ *vs Voltage* calculated from *I-V* charateristics of fabricated GaN-on-Si and GaN-on-sapphire vertical diodes. $dlog(\ln(I))/dlog(E) \sim 1$ indicates VRH is the dominant leakage mechanism.

TCAD Simulation of Leakage Currents

TCAD simulations [6] incorporating various leakage mechanisms, namely VRH [7] through threading dislocation (TD) (Fig. 6), PF transport and Trap-Assisted Band-to-Band Tunneling (TA-BTBT) (Fig. 7), were conducted to compare with experimental results. A cylindrical coordinate system was used (therefore the simulation is essentially 3D) to match the forward current of GaN-on-Si vertical diodes (Fig. 8). TD is modeled as a cylindrical line. It is assumed that conduction along the TD is due to carrier hopping between dislocation traps in the "dislocation mini-band" under the VRH framework and is modeled using a Gaussian disorder model drift mobility [7] with $\mu = \nu_0 b/(2F)\exp(-(\sigma/kT)^2)[\exp(qbF/kT)-1]$, where ν_0 (hopping frequency) = 10^{11}/s, b (average trap to trap

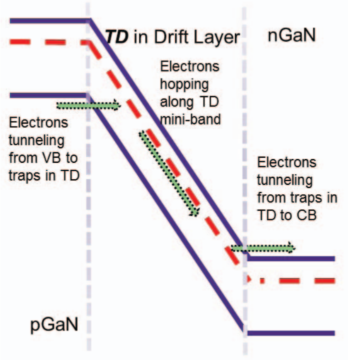

Fig. 6. Diagram illustrating the concept of VRH and how it is implemented in TCAD simulation.

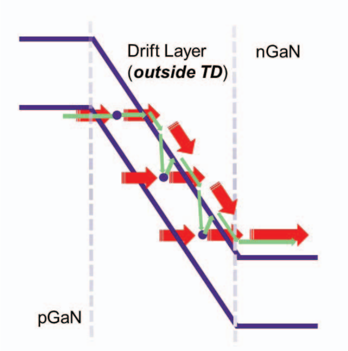

Fig. 7. Diagram illustrating the concepts of PF transport (Green thin arrows) and TA-BTBT (Red thick arrows). Both mechanisms are mediated by deep level traps in the band gap.
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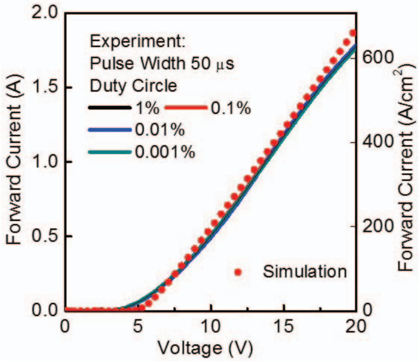

Fig. 8. The comparison between simulations and experiments shows that the simulation is well-calibrated by experimental on-state forward current (w/ different pulsed modes) for GaN-on-Si vertical diodes.

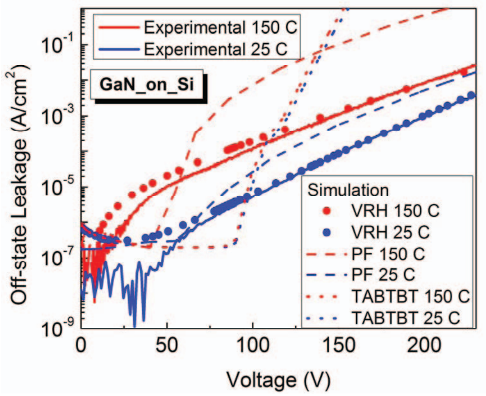

Fig. 9. Experimental and simulated off-state leakage current of GaN-on-Si vertical diodes, at different temperatures. VRH model gives the best agreement with experiment among variuos leakage models.

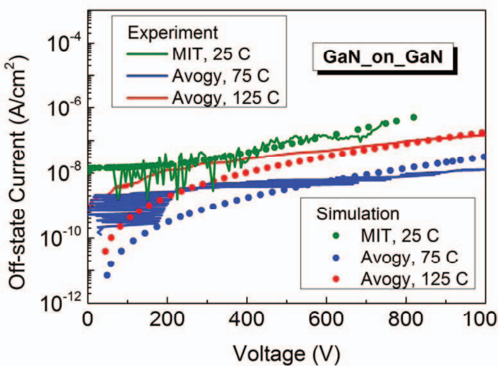

Fig. 10. Experimental and simulated leakage current of GaN-on-GaN vertical diodes fabricated at MIT or reported by Avogy, at different temperatures. The slight mismatch between simulation and Avogy's data is probably due to the incomplete information of Avogy's wafer properties and device structure.

distance) =1.1 nm, σ (energy sigma)=80 meV and F is the electric field. The "dislocation mini-band" is assumed to be coupled perfectly to p-GaN VB and n-GaN CB through

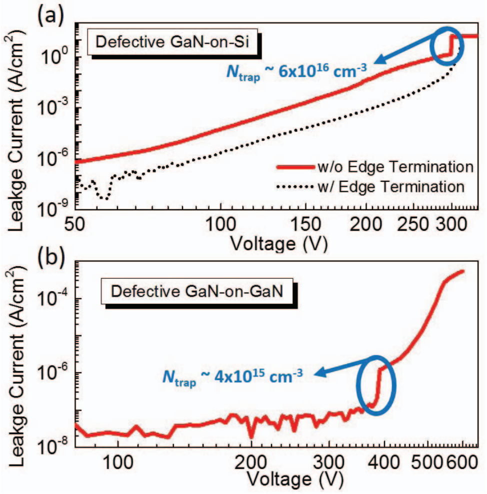

Fig. 11. Reverse characteristics of (a) GaN-on-Si and (b) GaN-on-GaN vertical diodes in the samples with unsuccessful growth or non-optimized process, where the leakage is dominant by trap-assisted space-charge-limited conduction. Average trap density is estimated from the trap-filled-limited voltage (i.e. the voltage with a current hump). (a) The traps in GaN-on-Si diodes are located at the etching sidewall due to high-power etching, and can be eliminated by advanced edge termination [1].

tunneling but decoupled from VB and CB in the drift layer. Fig. 9 shows that by assuming the leakage being dominated by VRH along TD and a pure screw dislocation density ~3×10^{7} cm^{-2}, the simulation results match experimental results well for GaN-on-Si vertical diodes. It also shows that the field and temperature dependencies are much stronger with TA-BTBT and PF, respectively, than the experimental results.

The VRH model also works well when simulating the performance of the GaN-on-GaN vertical diodes fabricated at MIT or reported by Avogy [2]. Good agreement (Fig. 10) is found over a wide range of temperatures, for a pure screw dislocation density of 6×10^{4} cm^{-2} for Avogy's device and 2×10^{6} cm^{-2} for MIT's device.

Origin of Leakage in Defective Structures

Optimized material growth and fabrication process

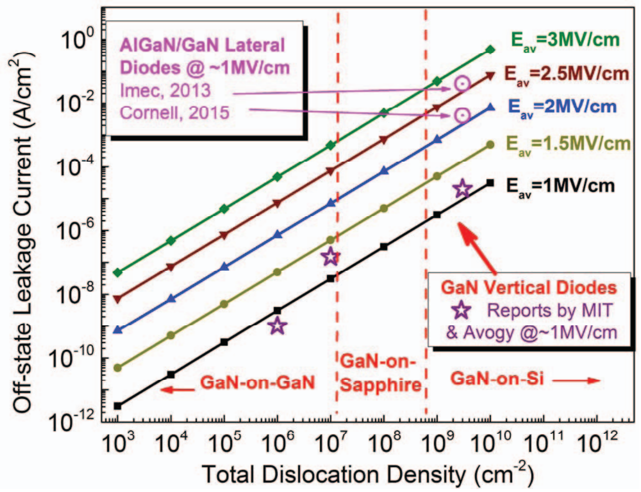

Fig. 12. Design space of the off-state leakage current of GaN vertical diodes as a function of the total dislocation density level in the structure, and the average electric field in the drift layer (E_{av}=1~3 MV/cm).The different dislocation density represents GaN vertical diodes fabricated on different substrates, and we assumed 3% of the total dislocation density corresponds to pure screw dislocations. The leakage of state-of-the-art GaN lateral diodes reported by Cornell [10] and Imec [11] is 2~3 orders of magnitude higher than the leakage of GaN vertical diodes with similar E_{av} and dislocation density.

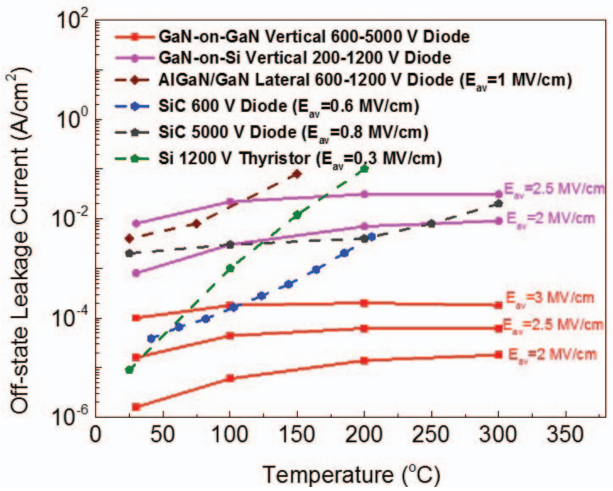

Fig. 13. Off-state leakage current versus temperature of the designed GaN-on-GaN vertical diodes (assuming a target E_{av} of 2~3 MV/cm for 600-5000 V application) and GaN-on-Si vertical diodes (assuming a target E_{av} of 2~2.5 MV/cm for 200-1200 V application), and the reported lateral GaN diodes [11], SiC 600 V [12] and 5000 V [13] diodes and Si 1200 V thyristors [14]. A dislocation density of 2×10^6 cm^{-2} and 10^9 cm^{-2} was used to simulate the GaN-on-GaN and GaN-on-Si vertical diodes. It should be noted that the lower dislocation density of GaN-on-GaN is available by using ammonothermal GaN substrates, which would further increase the outperformance of GaN-on-GaN vertical diodes.

are essential to enable the VRH leakage in GaN vertical devices. In contrast, high-power etching process or unsuccessful growth may introduce large amount of defects in device structures [1]. The leakage mechanism in the devices with non-optimized fabrication processes or growth conditions was also studied and compared to that of optimized devices. In these defective structures, trap-assisted space-charge-limited-current rather than VRH is the dominant leakage mechanism (Fig. 11), where a higher leakage current with a hump at trap-filled-limited voltage is observed.

Design Space and Benchmark

With the VRH simulation model calibrated by experiments, the off-state leakage current density I was simulated as a function of the total dislocation density N_d in GaN epi-layers at different E_{av} levels (Fig. 12). An empirical formula can then be derived for an estimation of the leakage current in GaN vertical power diodes at 30 °C:

$$\ln[I(A/cm^2)] = \ln[N_d(cm^{-2})] + 4.86E_{av}(MV/cm) - 38.0$$

The leakage of GaN vertical diodes was first benchmarked with AlGaN/GaN lateral diodes (Fig. 12). At least 2~3 orders of magnitude lower leakage is seen in GaN vertical diodes compared to lateral diodes with similar average internal E field and dislocation density.

Off-state leakage current versus temperature was then simulated for 600-5000 V GaN-on-GaN vertical diodes (assume N_d~2×10^6 cm^{-2}, with even lower N_d experimentally reported) and 200-1200 V GaN-on-Si vertical diodes (assume N_d~10^9 cm^{-2}), and was benchmarked with reported lateral GaN diodes, SiC 600 V and 5000 V diodes and Si 1200 V thyristors (Fig. 13). Low-cost GaN-on-Si vertical diodes can achieve compatible leakage than commercial Si and SiC devices while sustaining 3-5 times higher E field. GaN-on-GaN vertical diodes can achieve 2-4 orders of magnitude lower leakage while sustaining 5-10 times higher E field.

Conclusion

In this work, we identified VRH through TD as the main off-state leakage mechanism for GaN vertical diodes on different substrates. With a well-calibrated TCAD simulation, we demonstrated that the designed GaN vertical diodes can offer 2-4 orders of magnitude lower leakage while supporting 3-5 times higher E field than GaN lateral, Si and SiC devices. This demonstrates great potential of GaN vertical devices for high-voltage applications.

Acknowledgement

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