Fully- and Quasi-Vertical GaN-on-Si p-i-n Diodes: High Performance and Comprehensive Comparison

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***Abstract*—We report growth and fabrication of fully- and quasi-vertical GaN-on-Si p-i-n diodes. A record high Baliga figure of merit of 304 and 152 MW/cm^2 is reported for fully- and quasi-vertical GaN-on-Si p-i-n diodes, respectively. A comprehensive comparison has been made between the two kinds of diodes in regard ON-resistance, breakdown voltage, and switching performance. An ultralow differential ON-resistance of 0.5 and 1.0 m$\Omega \cdot$ cm^2 has been demonstrated for quasi- and fully-vertical diodes with a diameter of 60 μm at 3 kA/cm^2. Current crowding effect in the n-GaN was a dominant factor of R_{ON}, especially for large size quasi-vertical diodes at high current density. A high V_{br} of 390 V has been demonstrated for the two types of device structures, regardless of device diameters. The same breakdown voltage and low off-state leakage indicated the reliability of fully-vertical device fabrication that reflects intrinsic properties of the grown epilayers. The two kinds of diodes share similar switching performance, which is much superior to a commercial fast-recovery Si diode as a reference. The device characteristics show promising potential of both fully- and quasi-vertical diodes for low-cost high-power applications.**

***Index Terms*—Baliga figure of merit (FOM), fully-vertical p-i-n diodes, GaN-on-Si, high breakdown voltage, low ON-resistance, power switching, quasi-vertical diodes.**

I. Introduction

III-N semiconductor materials have enabled various electronic devices for the next generation solid-state lighting, high frequency, and high power applications, due to their superior material properties, including wide energy bandgap, high critical electrical field, and good thermal dissipation capability [1]–[4]. In addition to the lateral structure devices, such as AlGaN/GaN HEMTs [5] and Schottky diodes [6], [7], there has been extensive research interest in the development of GaN devices with vertical structure, including vertical diodes and vertical transistors recently [3], [8]–[10]. The vertical electron devices feature high breakdown voltage with a small device size, good thermal performance, and integration flexibility [8], [9]. Among the GaN vertical devices, junction-based p-i-n diodes have been extensively studied due to their small conduction loss, low reverse leakage current, and high breakdown voltage [8], [11]–[13]. Recently, dramatic progress and excellent device performance have been demonstrated for fully-vertical p-i-n diodes on conductive n-GaN substrates through homoepitaxial growth [8], [11]. However, bulk GaN substrates with low-defect density are expensive and only available in small sizes, limiting their use for volume production.

Compared with p-i-n diodes grown on GaN substrates, GaN diodes grown on large-area Si substrates [14], [15] have been considered as a practical enabler that can greatly lower the cost using inexpensive and large-scale Si and taking advantage of the manufacturing compatibility with Si-CMOS processes. To date, both quasi-vertical diodes on original (111)Si growth substrate [14] and fully-vertical diodes after GaN thin film transfer to (100)Si [15] have been demonstrated. For quasi-vertical diodes, the anode and cathode are formed on the same side of the epilayers through metallization processes after mesa etching [12], [14], [16]. Under power operation, the nonuniformly distributed electrical field and current crowding effects tend to degrade the device performance and possibly long-term reliability [17]. To solve these issues, a fully-vertical p-i-n diode structure has been fabricated through a metal bonding and Si substrate removal process as reported in [15]. However, the device characteristics are still far away from the theoretical limit, and there is plenty of room for improvement, especially for the fully-vertical p-i-n diodes due to the more complicated process. A mature processing technology is thus

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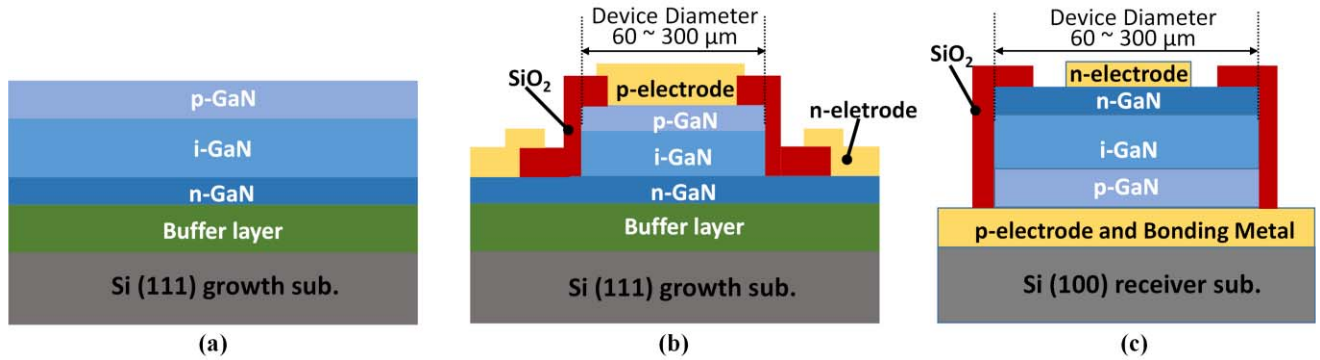

Fig. 1. Schematic of (a) epitaxial structure of p-i-n diodes grown on (111)Si, (b) quasi-vertical p-i-n diodes on original substrate (with no vertical overlap of two electrodes), and (c) fully-vertical p-i-n diodes with GaN thin film transferred onto a (100)Si receiver (with vertical overlap of two electrodes).

needed and a comprehensive understanding of both fully- and quasi-vertical configurations is highly desired, yet lacking.

In this paper, we report growth and fabrication of fully- and quasi-vertical GaN-on-Si p-i-n diodes. Both types of diodes demonstrate low differential specific ON-resistance (R_{ON}) and similar high-breakdown voltages (V_{br}). A record high Baliga figure-of-merit (FOM) of 0.3 GW/cm^2 has been achieved for GaN-on-Si fully-vertical diodes. A detailed comparison has also been made between these two kinds of devices starting from the same epitaxial wafer, regarding forward and reverse I–V characteristics, thermal behaviors, and switching performance.

II. Device Structure and Fabrication Process

The GaN p-i-n diode epilayers shown in Fig. 1(a) were grown by metal organic vapor phase expitaxy on a 6-in Si substrate. The p-i-n structure on Si started from a 1.5-μm-thick graded AlGaN buffer, followed by a 500-nm-thick Si-doped n-GaN layer ($\sim n = 1 \times 10^{19}$ cm^{-3}), a 2-μm-thick undoped i-GaN layer, and a 500-nm-thick Mg-doped p-type GaN ($\sim p = 2 \times 10^{17}$ cm^{-3}).

For fabrication of quasi-vertical diodes with anode and cathode contacts on the same front side of the GaN film [Fig. 1(b)], mesa etching was first performed to expose the n-GaN using inductively coupled plasma dry etching. After sidewall treatment in 75 °C tetramethylammonium hydroxide (TMAH) to remove etching damage, sidewall passivation [18] was carried out by SiO_2 using plasma enhanced chemical vapor deposition. Subsequently, ohmic contact to p-GaN was performed by depositing 30-/10-nm NiAu stack and annealing. The quasi-vertical devices were completed by depositing Cr/Al/Ti/Au stack as electrodes.

Fabrication of the fully-vertical diodes started from dry etching of the epilayers for device isolation, also followed by sidewall treatment in 75 °C TMAH and sidewall passivation by SiO_2. After ohmic contact formation, the wafer was flip-chip bonded onto a (100)Si receiver through Cu–Sn–Cu metal bonding. The (111)Si growth substrate was then removed by lapping and dry etching. Afterward, the buffer layer was removed by dry etching and Cr/Al/Ti/Au stack was deposited on the exposed n-GaN layer as n-electrode [Fig. 1(c)].

III. Results and Discussion

Fig. 2 shows representative forward I–V characteristics of the fully- and quasi-vertical diodes with mesa diameters ranging from 60 to 300 μm. Fig. 2(a)–(c) show that for device with diameters equal to or smaller than 150 μm, the fully-vertical diodes present a larger R_{ON} than the quasi-vertical ones for current densities <500 A/cm^2, while a smaller R_{ON} for densities > 500 A/cm^2. For smaller diodes ($\leq$150 μm) at relatively low current regime (<500 A/cm^2), current can spread well over the entire junction area for both types. The difference in this regime can be attributed to a difference in dry etching damage. Quasi-vertical structures suffered less as only 2.7-μm-deep mesa etching was needed to expose n-GaN, while the whole GaN epilayer ($\sim$4.5 μm) of the fully-vertical diodes has to be etched through for individual GaN p-i-n diode isolation. Moreover, after the isolation and flip-chip bonding to the receiver, the buffer layer needed to be etched away for n-GaN exposure. As a result, fully-vertical diodes suffered more etching damage, leading to a higher R_{ON} at this current range (< 500 A/cm^2). With increasing current density, current crowding at the edge of the n-electrode became obvious in the quasi-vertical structure that a higher R_{ON} was observed. In contrast, more uniform current spreading as expected occurred in the fully-vertical diodes, particularly for large size diodes and at high current density, resulting from the vertical electrodes with a short interelectrode current path. Data show that for diodes with diameters no smaller than 200 μm, the fully-vertical ones showed consistently smaller R_{ON} than its quasi-vertical counterpart even at relatively small current density [Fig. 2(d) and (e)]. Fig. 2(f) shows the ideality factor, n, extracted in the linear region of the I–V curves, to be 2.7 and 3.4 for quasi- and fully-vertical diodes, respectively, comparable to our previous work [19]. The slightly higher ideality factor in the fully-vertical diodes was associated with additional dry etch steps, causing more damage and enhanced recombination process under forward bias in the diode.

Fig. 3 shows the forward I–V characteristics of the vertical diodes at 25 °C and an elevated temperature of 160 °C. For both types of diodes, the turn-ON voltage decreases slightly with rising temperature due to increased thermally induced carrier concentration. However, after the diode was turned ON, the slope of I–V curve decreased at 160 °C, indicating an

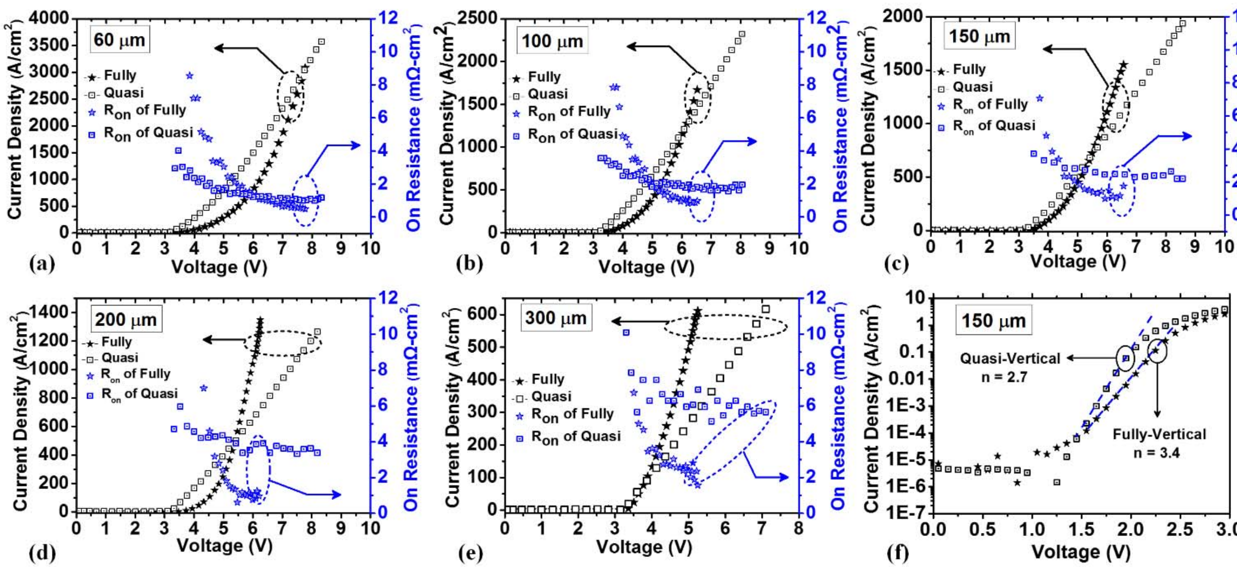

Fig. 2. (a)–(e) Forward bias I–V characteristics of fully- and quasi-vertical diodes with diode mesa diameter ranging from 60 to 300 μm (black symbols); the corresponding specific ON-resistance for all the current level is also plotted (blue symbols). Very low specific $R_{ON} < 1\ m\Omega \cdot cm^2$ could be readily observed for fully-vertical diodes at high current injection. (f) Ideality factor for two kinds of diodes with a diameter of 150 μm.

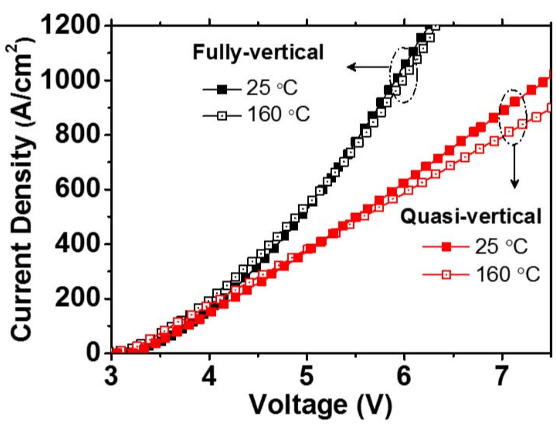

Fig. 3. Comparison of forward bias I–V characteristics of two kinds of diodes (150 μm) at 25 °C and an elevated 160 °C.

increase of series resistance due to carrier mobility reduction in the n-type drift region at high temperatures [20]. The mobility reduction effect is more prominent in the quasi-vertical diodes because of the longer distance (dozens of micrometer) between the anode and the cathode. So for the quasi-vertical diodes, the I–V curves at 25 °C and 160 °C diverge more significantly at high current compared with the fully-vertical ones.

Table I summarized the differential specific R_{ON} measured at various current densities of the two types of diodes with different device sizes.

TABLE I

SUMMARY OF SPECIFIC R_{ON} FOR THE FULLY- AND QUASI-VERTICAL DIODES WITH VARIOUS DIAMETERS AT DIFFERENT INJECTION CURRENT LEVELS. THE LETTERS F AND Q DENOTE THE FULLY-VERTICAL AND QUASI-VERTICAL STRUCTURES

DIAMETER (μm)		60	100	150	200	300
V_{ON} (V) @ 1 A/cm²	F	*2.4*	*2.5*	*2.5*	*2.6*	*3.2*
	Q	*2.4*	*2.4*	*2.6*	*2.9*	*3.4*
R_{ON} (mΩ·cm²) @300A/cm²	F	*2.4*	*2.5*	*2.3*	*1.9*	*2.2*
	Q	*2.3*	*2.6*	*3.2*	*3.8*	*6.4*
R_{ON} (mΩ·cm²) @1.0kA/cm²	F	*1.0*	*0.9*	*1.0*	*0.8*	-
	Q	*1.3*	*1.8*	*2.4*	*3.4*	-
R_{ON} (mΩ·cm²) @ HIGHER DENSITY	F	*0.5* @ *3.0* kA/cm²	*0.8* @ *1.5* kA/cm²	*0.7* @ *1.2* kA/cm²	*0.8* @ *1.0* kA/cm²	*1.8* @ *0.5* kA/cm²
	Q	*1.0* @ *3.0* kA/cm²	*1.7* @ *1.5* kA/cm²	*2.4* @ *1.2* kA/cm²	*3.4* @ *1.0* kA/cm²	*5.3* @ *0.5* kA/cm²

The R_{ON} of a typical 300-μm quasi-vertical diode at 300 A/cm² was extracted to be 6.4 m$\Omega \cdot$ cm², which is much better than that reported in the literature [14] and our previous device [15], as a result of optimizing active layer structure and electrode design. For a 300-μm fully-vertical diode, R_{ON} at 300 A/cm² was extracted to be 2.2 m$\Omega \cdot$ cm², which is only 34% of that extracted from the quasi-vertical diodes using the same epitaxial layers. Moreover, this number is also 33% smaller than our prior work on fully-vertical diodes [15]. The corresponding forward voltage was also significantly reduced to 4.5 V from previously reported 8.3 V [15]. The significant improvement was attributed to three main reasons. First, the p-GaN metallization was optimized to be 30-/10-nm NiAu bilayer from the previous 5-/5-nm NiAu, improving the durability of the p-GaN ohmic contact after the flip-chip bonding and other thermal processes. Second, the n-GaN doping concentration was increased to 1×10^{19} cm^{-3}, which can provide a better ON-resistance and smaller voltage drop across the n-GaN layer. Third, the n-electrode was changed from previously a cross-shaped electrode to almost full coverage of the n-GaN layer for better current spreading. As the current density was increased, even lower R_{ON} could be observed. In addition to the 300-μm devices, devices with smaller dimensions showed even lower R_{ON} due to better current spreading in a smaller area. For example, a 60-μm

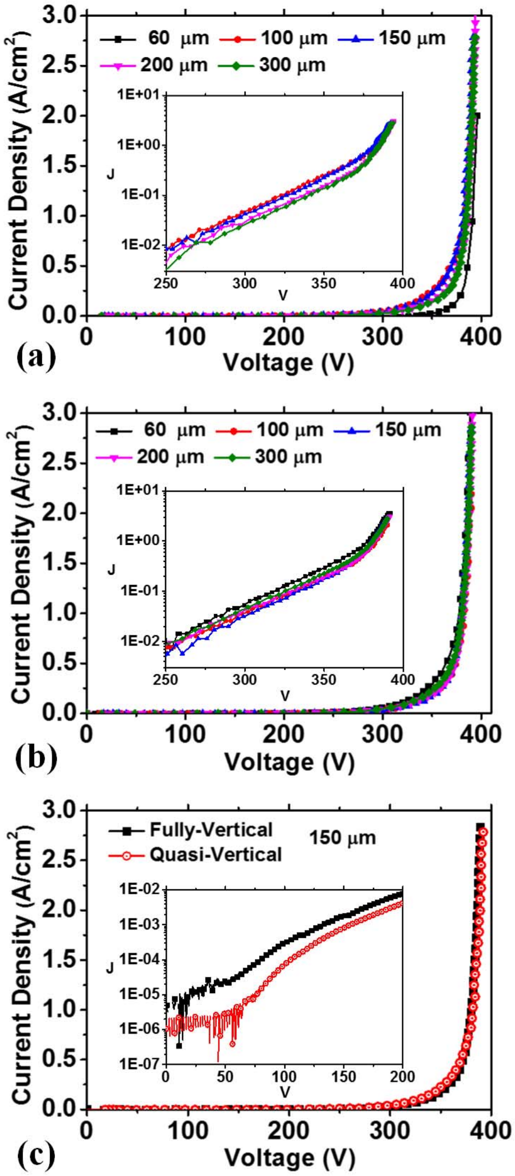

Fig. 4. Reverse bias I–V characteristics of (a) quasi-vertical p-i-n diodes and (b) fully-vertical p-i-n diodes with various diode dimensions. (c) Comparison of two kinds of diodes with a mesa diameter of 150 μm. Insets: current density (J, A/cm^2) versus voltage (V) characteristics.

diode at 3 kA/cm^2, the extracted $R_{\rm ON}$ was as small as 0.5 and 1 m$\Omega \cdot$ cm^2 for fully- and quasi-vertical diodes, respectively, as a result of conductivity modulation.

Fig. 4 shows the reverse biased I–V and breakdown characteristics of both quasi- and fully-vertical diodes. With a 2-μm-thick i-GaN drift layer, the quasi-vertical p-i-n rectifiers demonstrated a uniform $V_{\rm br}$ of 390 V regardless of diode diameters. More importantly, the same $V_{\rm br}$ was measured for the fully-vertical diodes with various mesa dimensions from 60 to 300 μm. The reverse leakage can be explained by variable-range hopping [21], [22] when the reverse voltage is smaller than 300 V while the trap-assisted space-charge-limited current [14], [15], [23] was thought to be the dominant mechanism when the voltage is over 300 V [19]. The same breakdown and low level of leakage current (5~7 $\times 10^{-3}$ A/cm^2 at 200 V) for both configurations of diodes

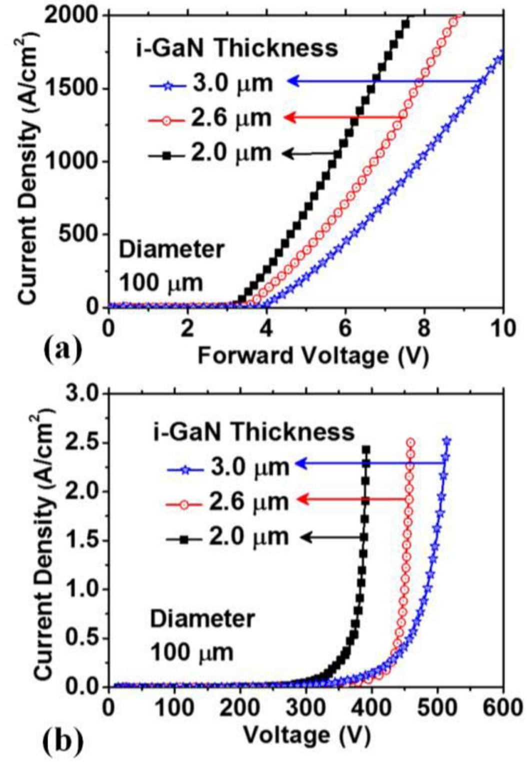

Fig. 5. (a) Forward bias I–V characteristics and (b) reverse bias I–V characteristics of quasi-vertical diodes with i-drift layer thickness from 2 to 3 μm. (c) Summary of specific $R_{\rm ON}$ and breakdown voltages for quasi-vertical diodes with increasing i-drift layer thickness.

TABLE II

THE THREE EPI-LAYERS SHARE THE SAME DOPING CONCENTRATION, I.E., MG-DOPED P-GAN (~ P = 2×10^{17} CM^{-3}), UNDOPED I-GAN LAYER (CARRIER CONCENTRATION IN THE ORDER OF 10^{16} CM^{-3}), SI-DOPED N-GAN (~ N= 1×10^{19} CM^{-3}), WHILE THE ONLY DIFFERENCE IS THE I-GAN THICKNESS

i-GaN Thickness (μm)	$V_{\rm ON}$ (V) @1 A/cm^2	$R_{\rm ON}$ (mΩ·cm^2) @ 300 A/cm^2	$R_{\rm ON}$ (mΩ·cm^2) @1.0 kA/cm^2	$V_{\rm br}$ (V)
2.0	***2.4***	***2.6***	***1.8***	***390***
2.6	***2.5***	***4.0***	***3.3***	***460***
3.0	***2.4***	***4.7***	***3.6***	***515***

indicate that these are the intrinsic properties of the grown epilayers, independent of the fabrication processes and diode configuration. With a consistently high $V_{\rm br}$, a resultant record high Baliga FOM ($V_{\rm br}^2/R_{\rm ON}$) of 304 and 152 MW/cm^2 could be achieved for the 60-μm fully-vertical and quasi-vertical GaN-on-Si diodes at 3 kA/cm^2, respectively.

Further epistructure studies were also carried out to investigate parameters for device performance improvement. Fig. 5 shows the I–V characteristics of quasi-vertical diodes with three different i-GaN drift layer thicknesses from 2.0 to 2.6 μm and 3.0 μm. For quasi-vertical diodes with a diameter of 100 μm, higher breakdown voltage can be achieved by growing a thicker i-GaN drift layer. Slightly higher $R_{\rm ON}$ was measured at low current density but can still remain low at relatively higher current injection level as a result of conductivity modulation. Table II presents a corresponding quantitative summary of $V_{\rm ON}$, $R_{\rm ON}$, and$V_{\rm br}$ with increasing

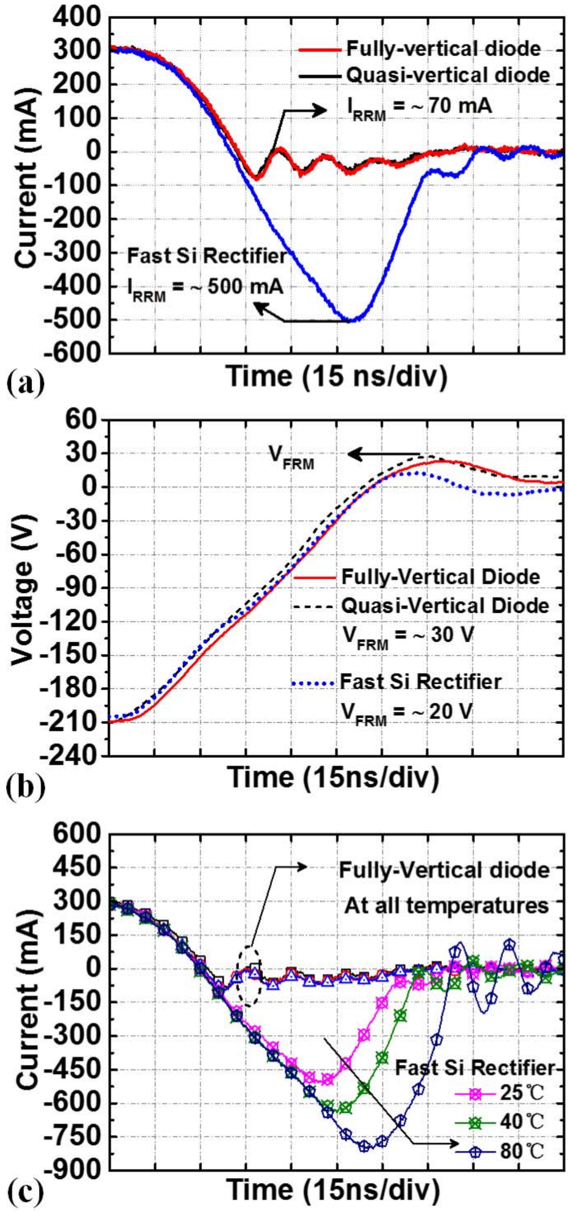

Fig. 6. (a) Current waveforms during reverse recovery and (b) voltage waveforms during forward recovery of the fully-, quasi-vertical p-i-n GaN diode, and commercial fast Si rectifier (Fairchild, UF4004), respectively. (c) Current waveforms during reverse recovery of fully-vertical p-i-n GaN diode and Si rectifier at different temperatures.

i-layer thickness in a stepwise way. It is worth mentioning that the 515 V is the highest value for breakdown voltage reported for GaN p-i-n diodes grown on Si substrates, which shows great potential of our devices for low-cost high-voltage applications.

To explore the potential of the diodes for switching applications, switching performance was carried out to determine the clearing time of the minority carriers injected into the drift region. Similar reverse recovery time and maximum current (~70 mA) were measured for the fully- and quasi-vertical diodes, while a much longer reverse recovery time and larger maximum current (~500 mA) were observed for a commercial Si rectifier [Fig. 6(a)]. As a result, the turning-OFF energy of the fully- and quasi-vertical diodes during one recovery event

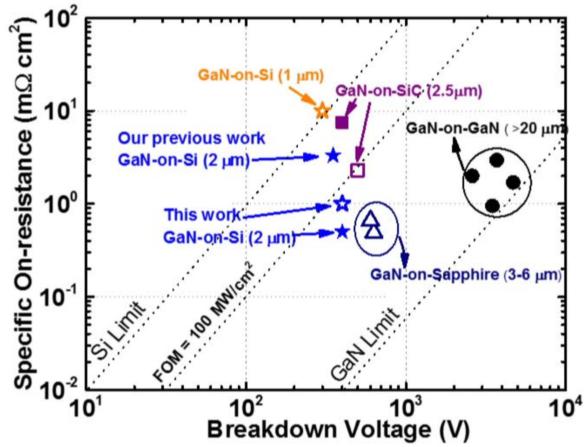

Fig. 7. Baliga FOM benchmarking of reported GaN p-i-n diodes on various substrates, including GaN, SiC, sapphire, and Si.

can be calculated to be around 0.21 μJ, which was 87% lower than that of the Si rectifier. This can be attributed to the very short carrier lifetime in GaN, at an order of 10 ns. In addition, only a small amount of carriers have to be removed in both vertical structures [24] due to the small device area and a thin drift layer (2 μm) in the structure compared with the Si diode. fully- and quasi-vertical diodes also share similar forward recovery performance [Fig. 6(b)], and the forward recovery voltage was extracted as ~30 and ~20 V for GaN p-i-n diodes and fast Si rectifier, respectively. In addition, it was observed that an elevated temperature of 80 °C has little influence on the reverse recovery performance [Fig. 6(c)], which is thought to be beneficial to the wide energy bandgap of GaN.

Fig. 7 benchmarks the performance of fully- and quasi-vertical GaN-on-Si p-i-n diodes in an FOM plot [8], [12], [14]–[16], [24]–[28]. In this paper, extremely low differential ON-resistance of 0.5 and 1 m$\Omega \cdot$ cm^2 for 60-μm fully- and quasi-vertical diodes (2-μm-thick i-GaN drift layer) at 3 kA/cm^2 has been demonstrated, respectively. Compared with our previous work [15], the significant improvement resulted from optimized growth structure and p-type metal scheme. The differential ON-resistance of 0.5 m$\Omega \cdot$ cm^2 at 3 kA/cm^2 is the lowest reported value for p-i-n diodes grown on foreign substrates. Meanwhile, the same breakdown voltage and low off-state leakage indicated the reliability of the fully-vertical device fabrication. Correspondingly, Baliga FOM can be calculated as 304 and 152 MW/cm^2 for fully- and quasi-vertical GaN-on-Si diodes, respectively.

IV. Conclusion

Record performance and a detailed comparison of the fully- and quasi-vertical GaN-on-Si p-i-n diodes are reported. A low R_{ON} of 0.5 and 1 m$\Omega \cdot$ cm^2 was extracted for fully- and quasi-vertical diodes, respectively. It was found that current crowding effect is a dominant factor of R_{ON}, especially for large-size quasi-vertical diodes at high current density. With a 2.0-μm-thick drift layer, similarly high V_{br} of 390 V has been demonstrated for the two kinds of device structures, regardless of device diameters. The statically similar leakage current level and breakdown voltage of the two device configurations demonstrated the reliability of the fabrication processes, particularly the effectiveness of the sidewall treatment and passivation. A longer drift region (3.0 μm) can improve the breakdown voltage to over 500 V, which is the highest number reported for p-i-n diodes based on GaN-on-Si epilayers. The fully- and quasi-vertical diodes shared nearly identical but superior recovery performance compared with a commercial Si rectifier. The device characteristics indicate that both kinds of diodes are promising low-cost options for high-power applications.

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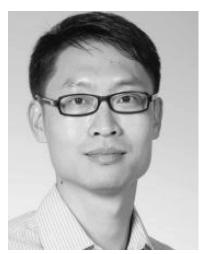

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