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Abstract:

The reverse recovery characteristics of vertical bulk GaN-based Schottky rectifiers which were fabricated on the free-standing GaN substrates, were systematically investigated. The reverse recovery time was obtained to be about 18.8 ns, 46.4 ns and 86.6 ns for 1 mm, 2 mm, and 3 mm diameter Schottky diodes, respectively. The dominant factor that affect the reverse recovery time of bulk GaN-based Schottky rectifier was found to be the *RC* time constant, which was the product of the circuit resistance and capacitance. Besides that, the reverse recovery characteristics of the bulk GaN-based Schottky rectifiers at different temperature were also measured and analyzed. It was found that the reverse recovery time of the bulk GaN-based Schottky diodes was less influenced by temperature, since the intrinsic exitation in the wide bandgap semiconductor of GaN was almost not influenced by temperature.

Keywords: Schottky rectifier, Vertical, Bulk GaN, Free-standing substrate, HVPE

Gallium nitride (GaN) is a promising material for power electronic applications because of its inherent material advantages like larger energy bandgap, higher critical electric field for breakdown, higher saturation electron drift velocity and so on.[1-6] However, the performance of GaN-based electronic device is significantly limited by the material quality. Most of previous GaN-based devices are laterally fabricated on heteroepitaxially grown GaN wafers such as silicon, sapphire, and SiC by MBE or MOCVD, which have a high density of dislocations (10^8–10^{10} cm^{-2}) originating from the high lattice-misfit or strained.[7] Such dislocations are electrically active and make serious effects as carrier scattering centers, and leakage current paths.[8] Meanwhile, it is also difficult to fabricate vertical devices in which current flows towards threading dislocations on such foreign substrates.[9] However, the recent research of free-standing GaN substrates with low defect density (on the order of 10^6 cm^{-2} or less) has achieved great progress[6, 10-12] and attracted a renewed interest in the development of the homo-epitaxially growth of the vertical-type electronic device, such as the bulk GaN-based Schottky diode which can be employed in power rectifier applications.[13-16] Compared to the p–n junction diode, the Schottky diode does not exhibit the minority carrier storage effect due to its unipolar nature, and thus shows a negligible reverse transient current and faster switching time. Up to now, there are only few reports about the reverse recovery characteristics of the bulk GaN-based Schottky diode.[9, 16-18] Johnson *el at.*[19] reported that the 75 μm diameter bulk GaN-based Schottky diode had nanosecond switching time, producing an approximate high-injection level hole lifetime of ~ 15 ns. Zhou *el at*.[20] fabricated different diameter (50 μm, 150 μm and 300 μm) vertical Schottky rectifiers on free-standing n-GaN substrate and found that they had almost the same reverse recovery time. However, such studies play more attention to the switching time of GaN-based Schottky rectifier, and the main factors that influence its reverse recovery characteristics have not been fully investigated.

In this paper, we fabricated the vertical bulk GaN-based Schottky diode on free-standing GaN substrate and then systematically studied the dominant factor affecting its reverse recovery time. The reverse recovery characteristics of bulk GaN-based Schottky rectifier at different temperature were also analyzed. Our results may serve as a reference for further improving the performance of GaN-based device.

The free-standing GaN substrate was produced by hydride vapor phase epitaxy (HVPE). All HVPE process was used to synthesize n^- epilayer on n^+ bulk GaN wafer. The thickness of Si-doped n^+ GaN layer was about 100 μm, followed by a homoepitaxy growth of a 400 μm thick nominally undoped n^- GaN layer. The dislocation density of the free-standing GaN substrate was evaluated with cathodoluminescence (CL) mapping. Figure 1 (a) shows a typical CL image of the homoepitaxial GaN layer, in which individual dislocations are represented by small dark spots resulting from the local non-radiative recombination. The CL measurements were performed at more than 10 regions, and the dislocation density of the bulk GaN substrate was measured to be 3×10^6 cm^{-2} in average.

All vertical Schottky rectifiers were fabricated on the same bulk GaN substrate. Figure 1 (b) shows the cross-section of the device structure. Full backside Ti (50 nm) /Al (100 nm) /Ti (50 nm) /Au (100 nm) ohmic contacts were formed on the back surface (N Face) of GaN wafer by DC magnetron sputtering. Ni (50nm) /Au (200nm) Schottky contacts were formed on the front surface (Ga Face) by electron beam evaporation. The Schottky contacts with three different diameters (1, 2, and 3 mm) were defined by photolithography and formed by conventional lift-off technique.

The current–voltage (*I-V*) measurements were performed using a Keithley 4200 semiconductor characterization system, and the capacitance-voltage (*C-V*) measurements were carried out at 1MHz using an Agilent E4980A precision LCR meter. In order to study the reverse recovery characteristics of the bulk GaN-based Schottky rectifiers, a pulse generator was applied to supply a periodic square-wave voltage signal from + 10 V to - 10 V to the device under test, and the transient current variations were detected by a high speed current probe connecting to the Tektronix MDO 4104-3 oscilloscope to derive the reverse recovery wave form of the bulk GaN-based Schottky rectifiers.

The performances of the bulk GaN-based Schottky rectifiers were firstly tested by *I-V* and *C-V* measurements. Figure 2 shows the typical forward and reverse (inset) *I-V* characteristics of the Schottky rectifiers. Performing the linear fitting, these devices show a turn-on voltage from 0.76 to 0.82 V, which present a low values in the reported studies of the vertical GaN SBDs.[21, 22] And the forward *I-V* characteristics of a Schottky barrier diode obeying the thermionic emission model are given by[23]

$$I = AA^{*}T^{2}\exp\left(-\frac{q\phi_m}{kT}\right)\left\{\exp\left[\frac{q(V-IR_s)}{nkT}\right]-1\right\}, \tag{1}$$

where A is the effective area of the device, A^* is the Richardson constant, ϕ_m is the Schottky barrier height, n is the ideality factor and R_s is the series resistance. For $V - IR_s > 3kT/q$, equation (1) becomes

$$I = AA^{*}T^{2}\exp\left(-\frac{q\phi_m}{kT}\right)\exp\left[\frac{q(V-IR_s)}{nkT}\right], \tag{2}$$

This method purposed by Cheung is adopted to deduce the ideality factor, the Schottky barrier height and the series resistance from a single *I-V* curve. All obtained fitting results for the three different diameters Schottky rectifiers are listed in Table I. The *I-V* curves and fitting results indicate that the bulk GaN-based Schottky diodes have good rectification characteristics. Meanwhile, the ideality factor n is calculated between 1 and 2, which is resulted from the combined effect of compound current and diffusion current. And it is also observed that the ideality factor n increases with the increase of diameter. It is believed the compound current strongly depends on the number of dislocations. Thus, when the diameter is increasing, the compound current is also increasing with the dislocation, which is finally resulted to the increasing of ideality factor.

Table I. Obtained fitting parameters: series resistance (R_s), ideality factor (n) and Schottky barrier height (ϕ_m).

Device diameter (mm)	R_s (Ω)	n	ϕ_m (eV)
1	35.5	1.31	0.99
2	34.6	1.35	0.96
3	30.6	1.54	0.94

Figure 3(a) shows the *C-V* curves of the 1, 2, and 3mm diameter Schottky rectifiers, and the device capacitance increases with the increase of electrode size, where the *G/ω-V* curves were presented in the inset. Meanwhile, the capacitance of a Schottky barrier diode is given by[24]

$$C = A\sqrt{\frac{q\varepsilon_r\varepsilon_0 N_D}{2(V_{bi} - V - kT/q)}}, \quad (3)$$

where ε_r is the relative dielectric constant (9.5), ε_0 is the vacuum permittivity, N_D is the dopant concentration, A is the effective area of the device, and V_{bi} is the built-in potential. Thus, the dopant concentration in the n$^-$ GaN layer determined from the slope of $1/C^2$ vs V curve is approximately 3 × 10^{16} cm^{-3}, and the N_D versus junction depth profile for a typical 2 mm diameter Schottky diode is shown in Fig. 3(b).

Figure 4 shows the reverse recovery characteristics of the three different diameter Schottky rectifiers. As the traps mainly work on extending the reverse recovery time, which is hardly observed in the form of ringing, here, the oscillation current before steady state is due to the parasitic inductance.[25] If the first recovery is considered and the reverse recovery time τ_{rr} is defined as the reverse current decreases from maximum to 1/e of its value, the τ_{rr} is obtained to be about 18.8, 46.4 and 86.6 ns for 1, 2, and 3 mm diameter Schottky rectifiers, respectively. It was considered that a parasitic inductance from measurement system will play a certain role in the reverse recovery process. Here, such contribution of parasitic components was deducted based on an extraction method introduced in Ref.[26], and the corrected τ_{rr} are 13.4, 41.0, 81.2 ns, respectively, for the above SBD with Φ = 1, 2, and 3 mm. Meanwhile, the circuit RC time constant, which is the product of the circuit resistance R and the Schottky rectifier capacitance C, was also measured. Based on the measured forward current at the voltage of + 10V, which was about 113, 116 and 121 mA for the three different diameter rectifiers, the total resistance R in the circuit was calculated to be 88.9, 86.2 and 82.6 Ω for 1, 2, and 3 mm diameter Schottky rectifiers. The capacitance C of the Schottky rectifiers at – 10 V was obtained from the C-V curves in Fig. 3(a). For the convenience of analysis, all obtained results are listed in Table II.

Table II. The Obtained results: total circuit resistance (R), capacitance (C) of the Schottky rectifiers at a fixed voltage of – 10 V obtained from the C-V curves in Fig. 3(a), RC time constant, reverse recovery time (τ_{rr}) of the Schottky rectifiers.

Device diameter (mm)	R (Ω)	C (nF)	RC (ns)	τ_{rr} (ns)
1	88.9	0.11	9.92	13.4
2	86.2	0.43	36.7	41.0
3	82.6	0.98	81.3	81.2

From Table II, it can be seen that both the reverse recovery time τ_{rr} and the RC time constant increase with the increase of the device diameter, and the smaller one has a faster reverse recovery time. Through comparison, it is found that there is a very good dependency between the reverse recovery time τ_{rr} and the RC time constant. The small difference between the two times may come from the inaccuracy of capacitance C. In this special case, the accurate capacitance of the device should be the overall equivalent capacitance at 20 V_{pp} voltage swing from + 10 V to - 10 V, which is difficult to determine since the capacitance varies with voltage before steady state, instead of the capacitance at the fixed voltage of – 10 V obtained from the C-V curves in Fig. 3(a). If the accurate capacitance is used, the RC time constant will be closer to the reverse recovery time τ_{rr}. Therefore, it can be inferred that the RC time constant is the dominant factor that affecting the reverse recovery time of vertical bulk GaN-based Schottky rectifiers.

In fact, for high power application, special attention is also focused on the temperature stability of GaN Schottky rectifiers due to their great impact on the performance, as the working temperatures generally range from 300 to 500 K. In order to investigate the influence of temperature on the characteristics of bulk GaN-based Schottky rectifiers, the temperature-dependent C-V and G/ω-V characteristics of the 2 mm diameter GaN Schottky diode were measured at 300, 375 and 475 K, respectively, using a homemade temperature control probe station as shown in Fig. 5(a) and (b). It can be seen that the C-V and G/ω-V curves show little change at different temperature. It is believed that in the wide bandgap semiconductor (as the GaN~3.4 eV discussed here), the intrinsic exitation is less influenced by temperature, hence the carrier concentration is also less changed as the temperature rises. Consequently, the capacitance of the GaN Schottky rectifiers remain almost the same according to equation (3), the measured capacitances increased from 0.453 to 0.471 nF at the voltage of -10V as shown in shown in Fig. 5(a).

From 300 to 475 K, the total circuit resistances R increase from 84.6 to 87.7 Ω, which could be extracted from the measured currents at the voltage of + 10V as shown in Fig.5(c). From our early research, the mobility μ is about 900 cm^2/(V s) at 300 K, [6] and it should change to 451 cm^2/(V s) at 475 K according to its $T^{-3/2}$ dependence due to acoustic phonons scattering. The thickness d of GaN in the investigated SBD devices is 500*10^{-4} cm. The carrier concentration N_D is 2.43×10^{16} and 2.52×10^{16} cm^{-3} at 300 and 475K, respectively, which is calculated from C-V curves. Using the formula of $\rho = \frac{1}{N_D q \mu} = R_s d$, the material resistance from bulk GaN is obtained to be 5.7 and 11.4 Ω at 300 and 475 K, respectively. This resistance increase of 5.7 Ω is close to the value of 3.1 Ω, that is a circuit resistance increase obtained from the 84.6 and 87.7 Ω of circuit resistance under 300 and 475 K, respectively. The significant difference between the material resistance from GaN and the total circuit resistance implies that the total circuit resistance should include other resistances. The input impedance in our pulse test system is checked to be 50 Ω. The left 28.9 Ω in our total circuit resistance at 300 K should be from the contact resistance. The sum of 28.9 Ω of contact resistance and 5.7 Ω of material resistance is 34.6 Ω, which should be the series resistance of SBD device at 300 K. This obtained series resistance from the pulse measurement is consistent with the value extracted from the forward I-V measurement. Input impedance of 50 Ω is independent on temperature. The contact resistance will decrease with increase temperature due to the reduction of barrier height. From the above difference between the calculated material resistance increase of 5.7 Ω and total circuit resistance increase of 3.1Ω, we can extract a contact resistance decrease of 2.6 Ω for temperature increase from 300 to 475 K.[27] Based on above analysis, it is found that from 300 to 475 K the RC time constant would increase by 7.55%, which is also thought to be the dominant factor that affecting the reverse recovery time.

Moreover, the reverse recovery time of the 2 mm diameter Schottky diode were also measured at 300, 375 and 475 K, respectively. As shown in Fig. 5 (c), no obvious variation of the reverse recovery time was observed for the 2 mm diameter Schottky diode, which is in good agreement with our above analysis. It is reported the reverse recovery time of Si-diode (bandgap ~1.12 eV) would increase by 336% as the temperature rises from 300 K to 450 K,[28] due to the intrinsic excitation and carrier concentration are much more influenced by temperature in the narrow bandgap semiconductor. Therefore, the temperature variation of bulk GaN-based Schottky rectifiers for the reverse recovery characteristics is much better than those of traditional diodes, which can be concluded that GaN is a very suitable material for making high power devices and the devices needing to work steadily over a wide range of temperature.

In conclusion, the vertical bulk GaN-based Schottky rectifiers were fabricated on the free-standing GaN substrates, and their reverse recovery characteristics were systematically studied. It was found that the reverse recovery time of the GaN Schottky rectifiers increases with the increase of the device size, and the *RC* time constant is the dominant factor that affecting the reverse recovery time. In addition, it was found that the reverse recovery time of the bulk GaN-based Schottky diodes was less influenced by temperature, which could be a suitable material for fabricating high power devices working in a wide range of temperature.

Acknowledgments

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FIG. 1. (a) CL image of the free-standing GaN substrate showing individual dislocations; (b) Structure of the vertical bulk GaN-based Schottky rectifier.

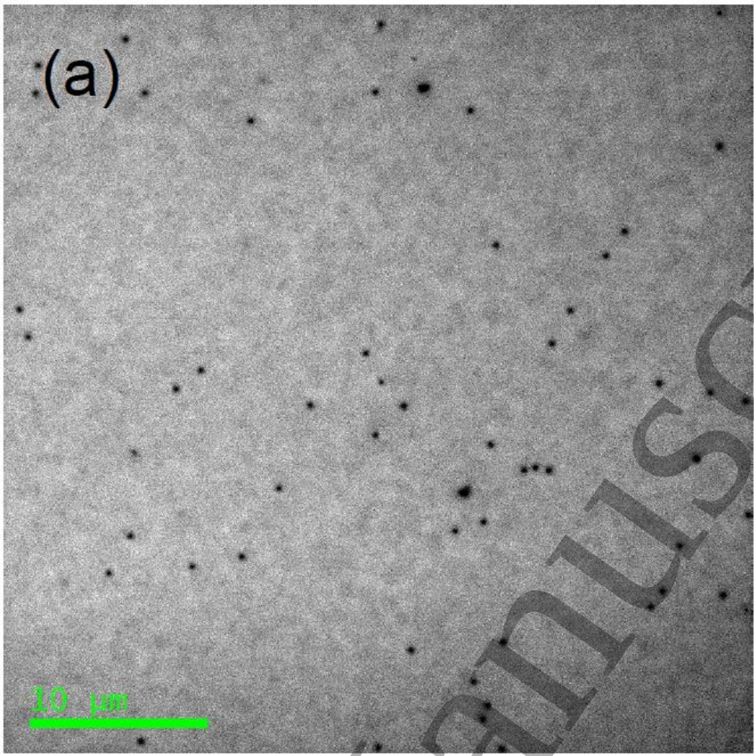
FIG. 2. Forward and reverse (inset) *I-V* characteristics of the bulk GaN-based Schottky rectifiers with different diameters.

FIG. 3. (a) *C-V* and *G/ω-V* (inset) characteristics of the bulk GaN-based Schottky rectifiers with different diameters; (b) The dopant concentration N_D as a function of junction depth for a typical 2mm diameter Schottky diode.

FIG. 4. Reverse recovery characteristics of the 1, 2 and 3mm diameter Schottky rectifiers.

FIG. 5. (a) *C-V* with $1/C^2$-V (inset) characteristics (b) *G/ω-V* characteristics and (c) Reverse recovery characteristics of the 2 mm diameter Schottky rectifier measured at 300, 375 and 475K, respectively.

Figure1


(a)
10 μm

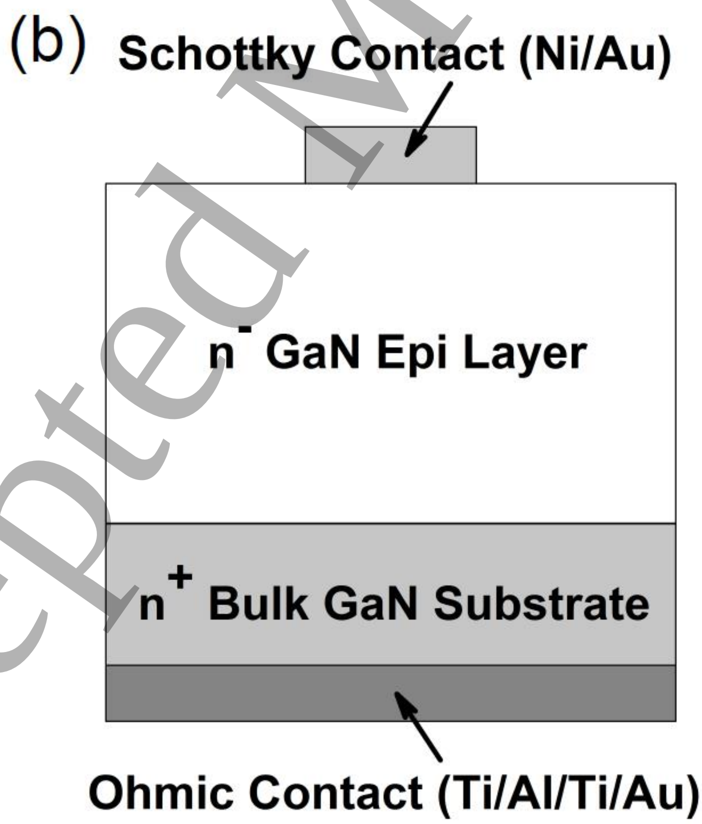

(b)
Schottky Contact (Ni/Au)
n- GaN Epi Layer
n+ Bulk GaN Substrate
Ohmic Contact (Ti/Al/Ti/Au)

Figure 2

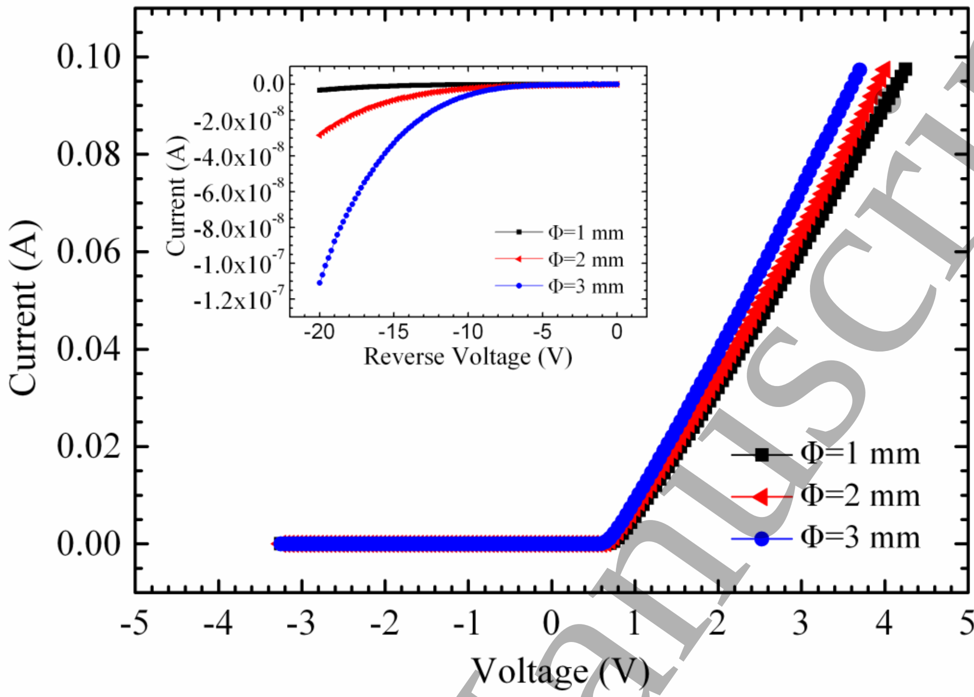

Current (A)
0.10
0.08
0.06
0.04
0.02
0.00
-5
-4
-3
-2
-1
0
1
2
3
4
5
Voltage (V)
Φ=1 mm
Φ=2 mm
Φ=3 mm
Current (A)
0.0
-2.0x10^-8
-4.0x10^-8
-6.0x10^-8
-8.0x10^-8
-1.0x10^-7
-1.2x10^-7
-20
-15
-10
-5
0
Reverse Voltage (V)

Figure 3

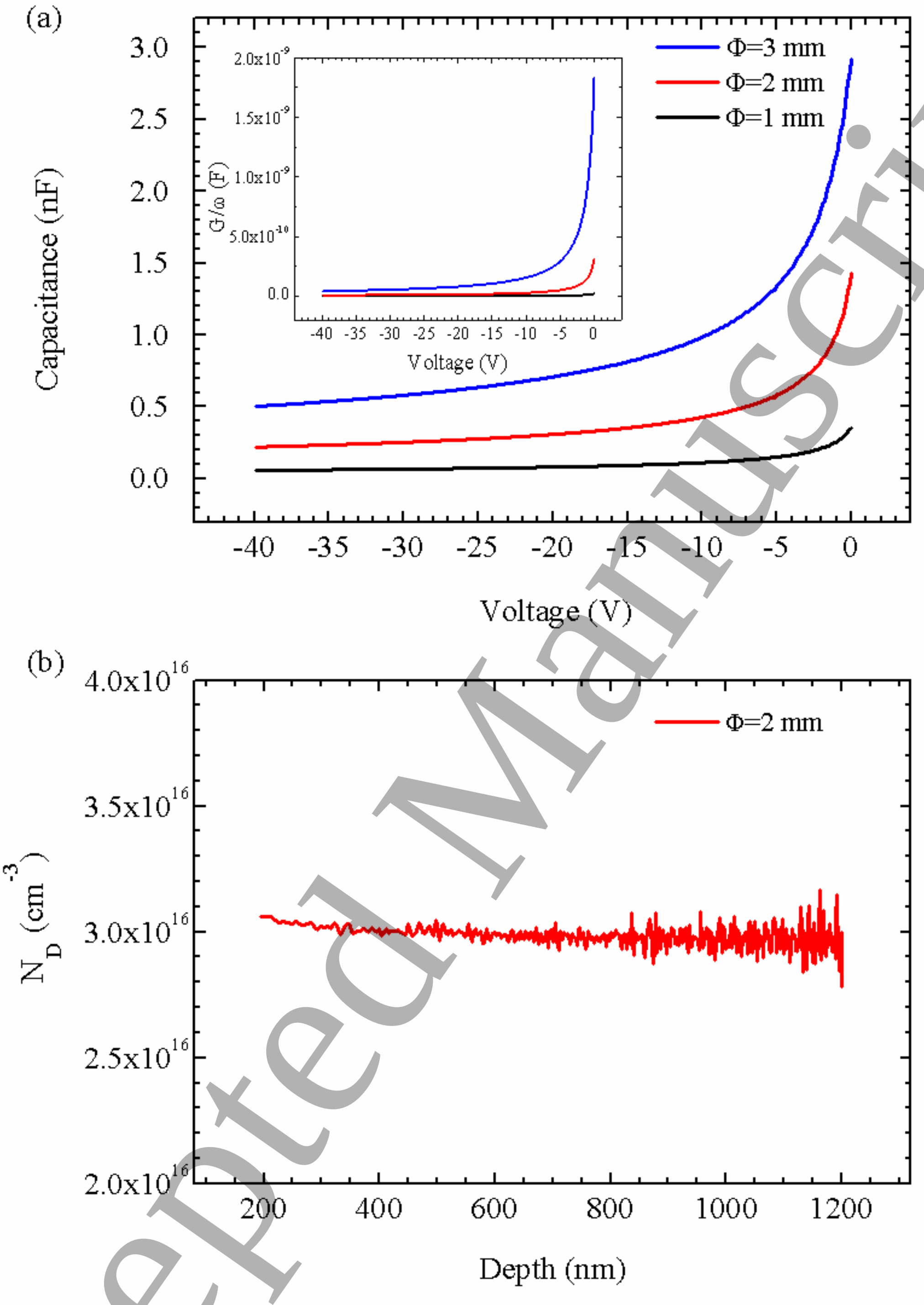

(a)
Capacitance (nF)
Voltage (V)
Φ=3 mm
Φ=2 mm
Φ=1 mm
G/ω (F)
Voltage (V)
(b)
N_D (cm^{-3})
Depth (nm)
Φ=2 mm

Figure 4

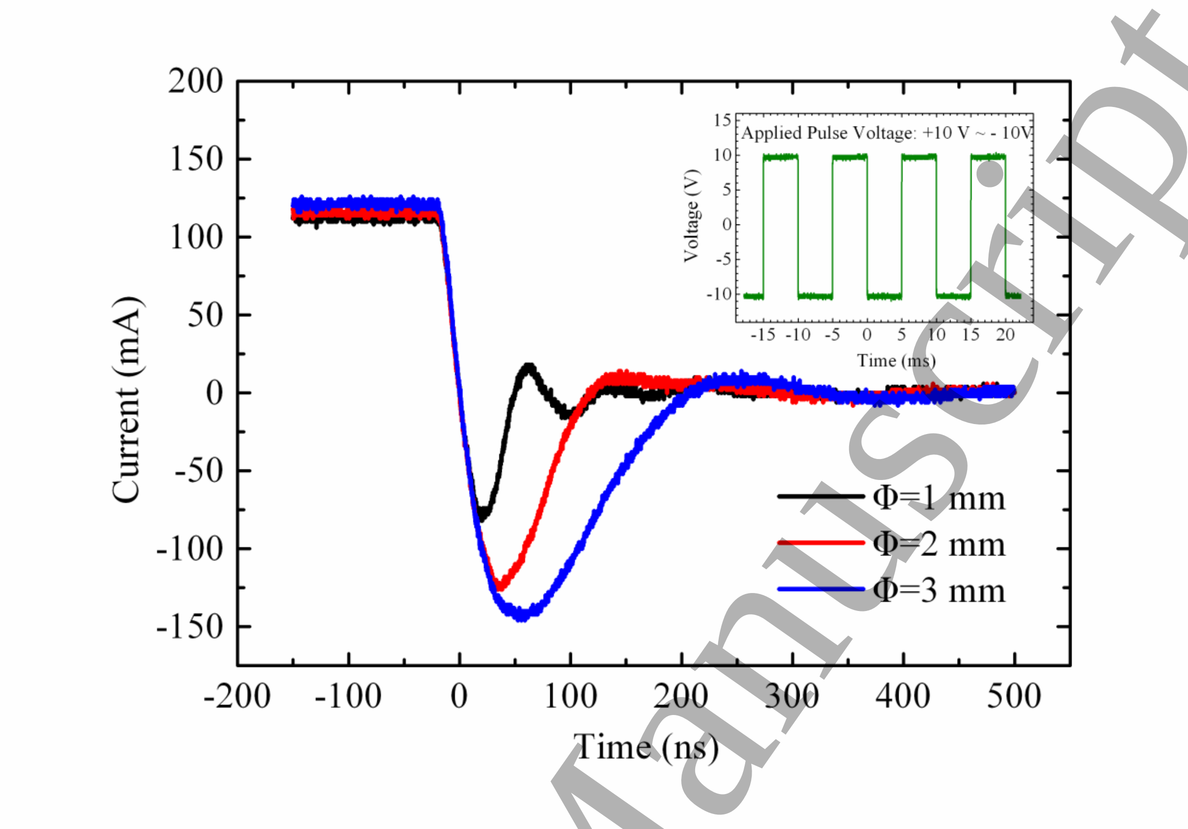
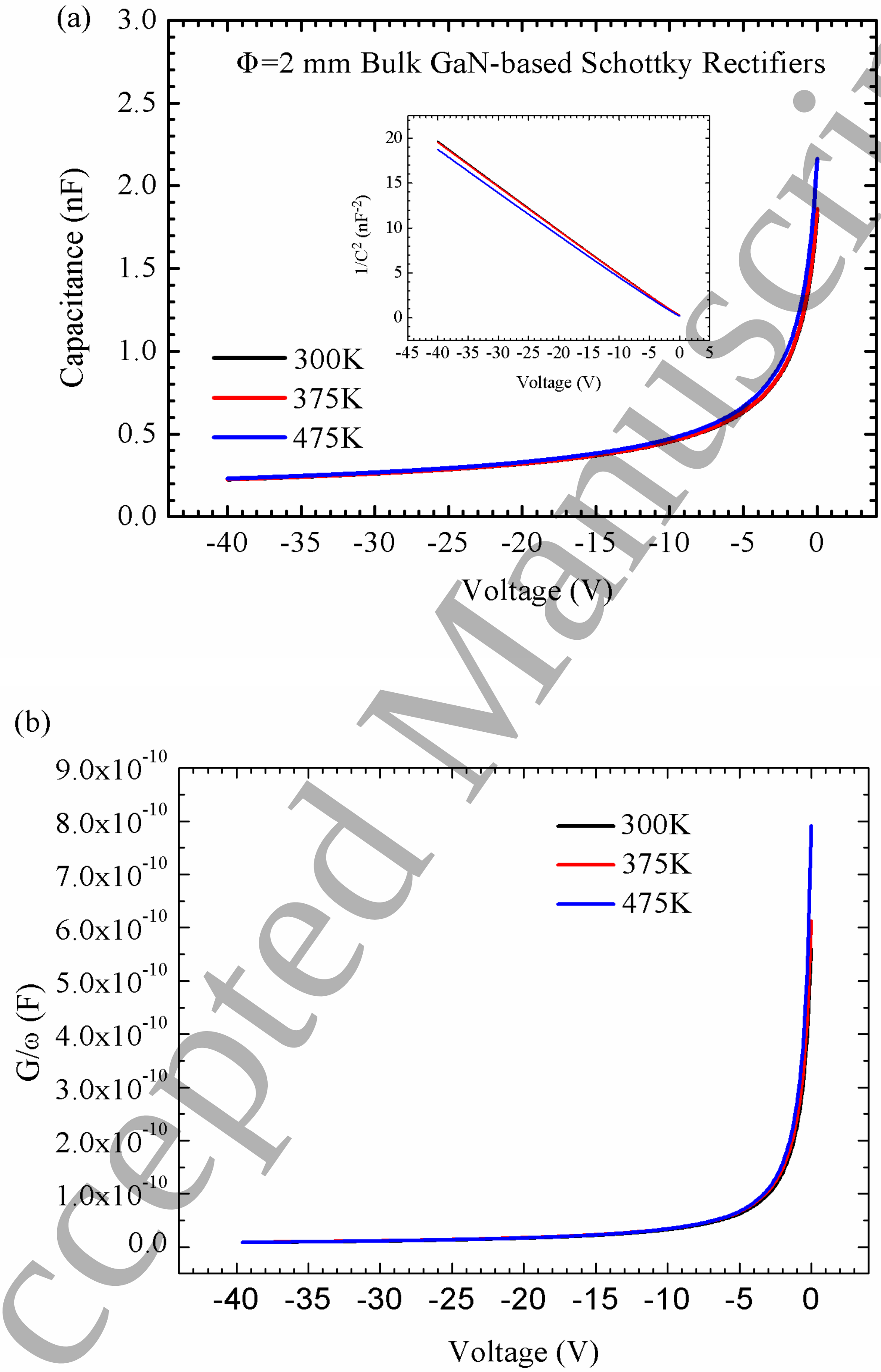
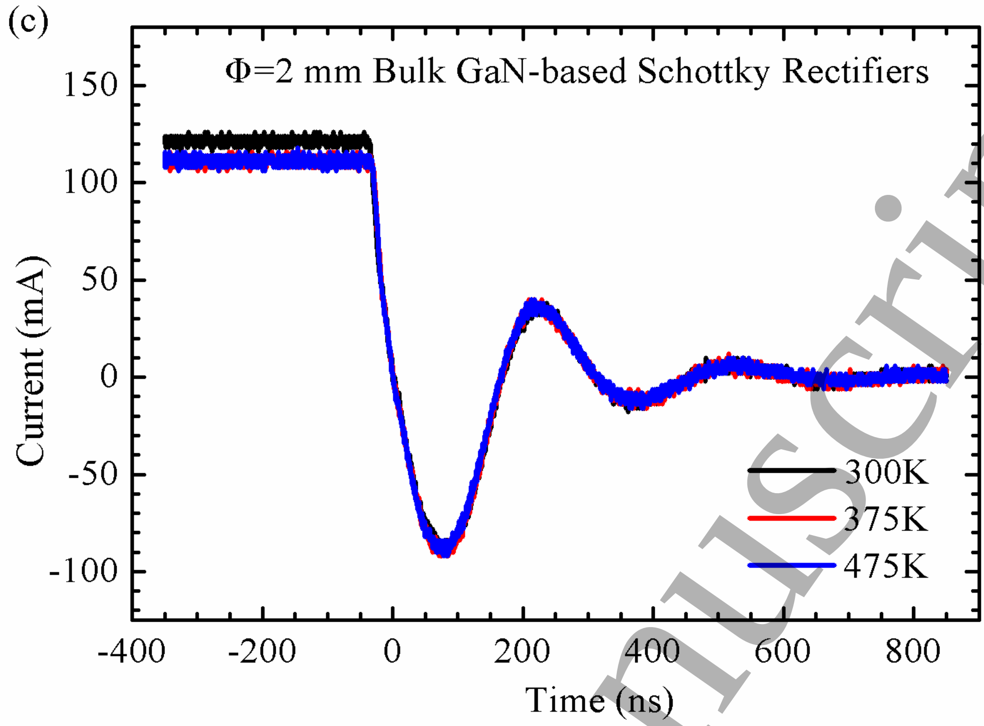

Current (mA)
Time (ns)
Φ=1 mm
Φ=2 mm
Φ=3 mm
Applied Pulse Voltage: +10 V ~ - 10V
Voltage (V)
Time (ms)

Figure 5


(a)
Φ=2 mm Bulk GaN-based Schottky Rectifiers
Capacitance (nF)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-40 -35 -30 -25 -20 -15 -10 -5 0
Voltage (V)
300K
375K
475K
1/C² (nF⁻²)
20
15
10
5
0
-45 -40 -35 -30 -25 -20 -15 -10 -5 0 5
Voltage (V)
(b)
G/ω (F)
9.0x10⁻¹⁰
8.0x10⁻¹⁰
7.0x10⁻¹⁰
6.0x10⁻¹⁰
5.0x10⁻¹⁰
4.0x10⁻¹⁰
3.0x10⁻¹⁰
2.0x10⁻¹⁰
1.0x10⁻¹⁰
0.0
-40 -35 -30 -25 -20 -15 -10 -5 0
Voltage (V)
300K
375K
475K


(c)
Φ=2 mm Bulk GaN-based Schottky Rectifiers
Current (mA)
150
100
50
0
-50
-100
-400
-200
0
200
400
600
800
Time (ns)
300K
375K
475K