Negative Differential Resistance Observation and a New Fitting Model for Electron Drift Velocity in GaN-Based Heterostructures

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***Abstract*— The aim of this paper is an investigation of electric field-dependent drift velocity characteristics for $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostructures without and with *in situ* Si_3N_4 passivation. The nanosecond-pulsed current–voltage (*I–V*) measurements were performed using a 20-ns applied pulse. Electron drift velocity depending on the electric field was obtained from the *I–V* measurements. These measurements show that a reduction in peak electron velocity from 2.01 × 10^7 to 1.39 × 10^7 cm/s after *in situ* Si_3N_4 passivation. Also, negative differential resistance regime was observed which begins at lower fields with the implementation of *in situ* Si_3N_4 passivation. In our samples, the electric field dependence of drift velocity was measured over 400 kV/cm due to smaller sample lengths. Then, a well-known fitting model was fitted to our experimental results. This fitting model was improved in order to provide an adequate description of the field dependence of drift velocity. It gives reasonable agreement with the experimental drift velocity data up to 475 kV/cm of the electric field and could be used in the device simulators.**

***Index Terms*— 2-dimensional electron gas (2DEG), AlGaN, drift velocity, gallium nitride (GaN), negative differential resistivity (NDR), SiN passivation.**

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I. Introduction

GALLIUM nitride (GaN)-based HEMTs are highly used devices in many applications such as radar communication, amplifiers, and satellite communication [1]–[3]. Because GaN has material properties such as wide direct bandgap, high breakdown field, high electron drift velocity, and high thermal conductivity that are important for such these high-power and high-frequency demanding device applications [4]–[6]. In AlGaN/GaN heterostructures, the spontaneous and piezoelectric polarization between AlGaN and GaN leads to significant sheet carrier density up to a few 10^{13} cm^{-2} at the interface [7]. To increase of sheet carrier density and output current of a device, Si_3N_4 surface passivation has been used in various studies [8]–[10]. Besides this purpose, it provides larger breakdown voltage due to its dielectric properties [11], [12]. Therefore, Si_3N_4 surface passivation can be used to provide the experimental data of drift velocity for higher electric fields in comparison samples without passivation [12].

Electron drift velocity υ_d is one of the important material parameters to evaluate the suitability of a semiconductor at high-voltage operation. Also, the cutoff frequency, which is the most widely used parameter as a figure of merit, depends on the electron drift velocity [13], [14]. Therefore, the determination of the electron velocity is important in the description of maximum frequency operation for a transistor structure. Experimental and theoretical studies of high-field electron drift velocity in bulk GaN and AlGaN/GaN heterostructures were reported in many papers [12], [15]–[23]. For wurtzite bulk GaN, Wraback *et al.* [15] reported experimental results of drift velocity–electric field characteristics up to 350 kV/cm of electric field. Then, the experimental results of drift velocity–electric field (υ_d–E) characteristics for an AlGaN/GaN heterostructure have been obtained up to 140 kV/cm of the electric field by Ardaravičius *et al.* [16]. They found a peak drift velocity υ_{peak} value of 2×10^7 cm/s at 140 kV/cm. In 2005, Barker *et al.* [12] reported experimental measurements up to 150 kV/cm for two different contact structures in the same sample. Also, these experimental results compared with Monte Carlo simulations reported by Yu and Brennan [17] and they found a good agreement. In another a paper, the reached applied electric field for an $Al_{0.33}Ga_{0.67}N$/AlN/GaN heterostructure was reported as 200 kV/cm [20]. In spite of Monte Carlo simulations assert a negative differential resistance (NDR) phenomenon for v_d–E characteristics in this field range, it has been not observed exactly in the previous experimental studies [21].

NDR phenomenon was first observed in III–V semiconductors by Gunn [24]. When applied electric field exceeds a critical value, the current or drift velocity of bulk or heterostructure material is tend to decrease. This is called as NDR, and it is thought originated that electrons with high kinetic energy can transit from low energy band to upper band, which has larger electron effective mass, after the critical field in several studies [25], [26]. Direct evidence of NDR in bulk GaN was first reported by Huang *et al.* [26]. To our knowledge, it is not observed in drift velocity–electric field characteristics of GaN-based HEMT structures until now [20]–[23]. However, there are some papers reported that GaN-based diode structures exhibit NDR in I–V curves [24], [25], [27]. Exactly obtaining of the NDR effect is important to better understand device physics at high fields and in the improvement of NDR device implementations [25]. To reveal v_d–E characteristics and observe NDR at higher fields, the applied electric field in these heterostructures must be higher than 150 kV/cm according to the Monte Carlo simulations that predict the NDR effect [17]–[20]. To reach higher fields, sample sizes can be reduced and Si_3N_4 passivation can be used [12]. To our knowledge, in this paper, it is first time reported the experimental observation of NDR in v_d–E characteristics of GaN-based HEMT structures.

In this paper, we presented the experimental electric field dependence of the drift velocity of AlGaN/AlN/GaN heterostructures with and without *in situ* Si_3N_4 passivation layer in the wide range of electric field up to 475 kV/cm. The electric field dependences of these heterostructures were measured by the nanosecond-pulsed current–voltage (I–V) measurements. These experimental results revealed NDR phenomenon and behavior of drift velocity in high fields for an AlGaN/AlN/GaN heterostructure. Then, the experimental v_d–E characteristics were fitted to a well-known fitting model proposed by Farahmand *et al.* [19] and obtained fitting parameters were discussed.

II. Experiment

In this paper, the measurement results of the drift velocity at high electric fields in AlGaN/AlN/GaN heterostructures with and without Si_3N_4 surface passivation layer are presented. The drift velocity as a function of the electric field was determined using nanosecond-pulsed voltage technique. It is a widely used technique to obtain v_d–E characteristics [12], [20]–[23]. In 2002, nanosecond-pulsed voltage technique was first time used to measure drift velocity–electric field in steady state AlGaN/GaN HEMT structure by Balkan *et al.* [28]. In this technique, the electric field dependence of electron drift velocity is extracted from the dependence of current density on electric field measured using the nanosecond-pulsed I–V measurements. In these measurements, high-voltage signal generator is used and the low pulsewidth or low pulse duration is required to avoid Joule heating [14], [22]. With nanosecond-pulsed voltage technique, the current density of investigated sample measured by applying a potential to the sample. The drift velocity can be calculated from measured the current that flows through the sample

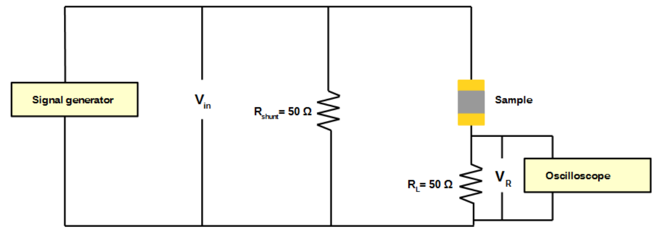

Fig. 1. Electron drift velocity measurement setup.

$$v_d = \frac{I}{\text{nqwt}} \tag{1}$$

where I is the current through the sample, and w and t are width and thickness of the sample, respectively. n is the carrier density of 2-dimensional electron gas (2DEG) and q is electron charge.

We fabricated two samples that 951N and 951Y are AlGaN/AlN/GaN heterostructures without and with *in situ* Si_3N_4 passivation layer, respectively. The $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostructures were grown in a Riber 32 molecular beam epitaxy (MBE) system. The heterostructures consisted of 25-nm $Al_{0.3}Ga_{0.7}N$ barrier layer with covered 2-nm GaN cap layer, 1-nm AlN interlayer, 1.5-μm GaN buffer, 100-nm AlN (1 nm)/GaN (1 nm) superlattice layer, and 250-nm AlN nucleation layer on a (001)-oriented 400-μm-thick sapphire substrate. For a 951Y sample, the Si_3N_4 dielectric film was deposited at 850 °C immediately following the GaN cap layer growth in the same MBE chamber. The ohmic contacts, Ti/Al/Ni/Au (15/40/40/70 nm) were deposited by e-beam evaporation and annealed in nitrogen for 30 s at 850 °C. Higher electric fields can be induced as the length of the sample is reduced. Owing to these small sample sizes, it is expected to obtain higher electric fields in comparison that of [12].

To determine the high-field transport properties, the nanosecond-pulsed I–V measurements have been performed using simple-bar-shaped samples of $l = 4$ μm and $w = 1$ μm at 77 K. The voltage pulses of 20 ns duration with a duty cycle of 0.005% were applied along the length of the sample up to a maximum electric field of $E = 475$ kV/cm with Avtech AVIR-3-B high-voltage pulse generator in a homemade LN_2-cooled sample holder. Applied voltage and current across the 50-Ω load resistor R_L connected in series with the sample were measured using a 50-Ω input impedance high-speed digital oscilloscope. Measurement setup is shown in Fig. 1. From the pulsed I–V measurements, electron drift velocity as a function of the electric field was obtained with the assumption that the 2DEG electron density within the heterostructure

TABLE I
HALL EFFECT MEASUREMENTS RESULTS OF THE SAMPLES [30]

Sample	Passivation	Sheet carrier density at 77 K (cm^{-2})	2DEG mobility at 77 K (cm^2/Vs)
951N	No	$1.21x10^{13}$	2385
951Y	Yes	$1.31x10^{13}$	2244

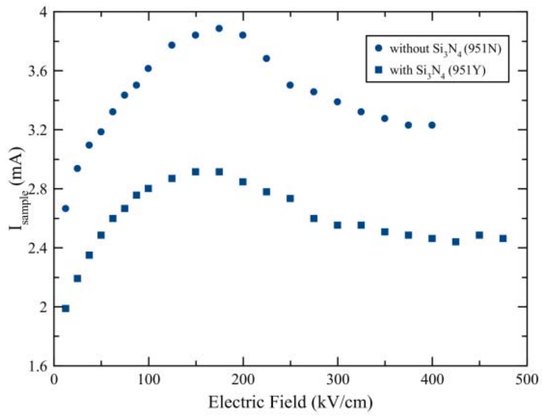

Fig. 2. Sample current versus electric field in AlGaN/AlN/GaN heterostructures with (951Y) and without (951N) Si_3N_4 passivation layer.

remains constant within the applied electric field ranges [29]. The results of the Hall effect measurements of the samples are given in Table I. The measured sheet carrier densities of heterostructures without and with *in situ* Si_3N_4 passivation layer are 1.21×10^{13} and $1.31 \times 10^{13} cm^{-2}$, respectively [30].

III. RESULTS AND DISCUSSION

Sample current–electric field curves of the AlGaN/AlN/GaN heterostructures with and without Si_3N_4 passivation layer shown in Fig. 2. In both of heterostructures, the curve at low electric fields gives a linear relation obeying ohm's law [31]. Then, around 150 kV/cm, the sample current has a peak point. With further increasing the electric field, the sample current is decreased. This behavior obeys with NDR phenomenon [25], [26]. In our case, NDR effect in AlGaN/GaN heterostructures is observed owing to smaller sample dimensions. On the other hand, the nanosecond pulses in the range of 1–200 ns were used to minimize self-heating effect in many studies [12], [16], [20]–[23]. In this paper, our signal generator Avtech AVIR-3-B can produce in the range of 10–200 ns pulse and we observed square voltage pulse shape in 20 ns as a minimum point. At high electric fields, the self-heating effect could imply considerable effects on current–electric field characteristics even a few nanosecond pulsewidths was used [16]. According to these studies, a reduction in current values due to self-heating can be expected in our case. However, Ardaravičius *et al.* [16] stated that channel self-heating causes the current to saturate if pulses longer than 20 ns were applied. In our case, no saturation in the current was observed. In addition to this, observed negative slope in the current–electric field characteristics is not mainly caused by the self-heating effect at high electric fields [32]. Moreover, to consider

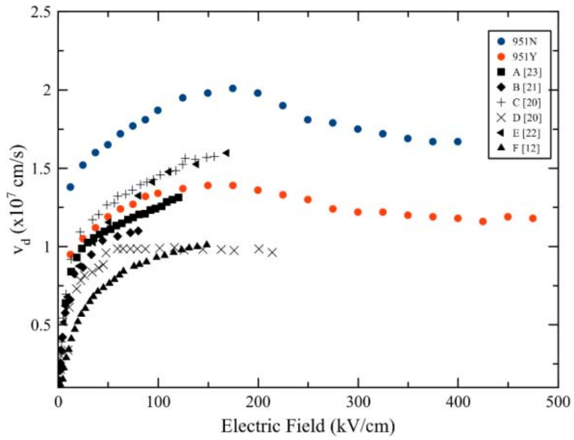

Fig. 3. Experimental results of electron drift velocity as a function of electric field for $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostructures without (951N) and with (951Y) *in situ* Si_3N_4 passivation and AlGaN/GaN heterostructures reported in [12] and [20]–[23]. A summary of all these heterostructures is given in Table II.

whether self-heating has an influence on current–electric field characteristics at high electric fields, we tried to calculate the hot-phonon lifetime in our samples. Because, the hot-phonon effects are weaker when the lifetime is shorter and Liberis *et al.* [33] and Barker *et al.* [34] have shown that hot-phonon effects may not be very serious and the suggested hot phonon lifetime is less than 0.3 ps. In our samples, it is estimated that the hot-phonon lifetime in our samples changes between 0.01 and 0.13 ps at high fields using a simple expression suggested by several studies to calculate hot phonon lifetime [35], [36]. Further studies including detailed investigations using Monte Carlo simulations on these results are needed to investigate possibility of the self-heating effect and reveal high-field transport properties.

Fig. 3 shows an electric field dependence of drift velocity of AlGaN/AlN/GaN heterostructures without and with *in situ* Si_3N_4 passivation layer. These measurements of this dependence are taken up to 400 and 475 kV/cm field owing to smaller lengths of samples and protection maintained by the Si_3N_4 surface passivation layer. The dependence of the drift velocity on the electric field is almost linear at low fields. However, after drift velocity reached its peak value, it is decreased as electric field increases. This behavior is clear evidence of NDR in v_d–E characteristics [37]. In this case, 2DEG electrons in the lowest Γ minimum point accelerate under high fields and gain enough energy to transfer to L valley minima which is 0.90 eV above conduction band minimum [38]–[42]. Therefore, when they reached peak velocity, it begins the transfer from Γ valley to L satellite valley. In the L satellite valley, drift velocity decreases because of 2DEG electrons have higher effective mass [14], [18]. This is called as the transferred-electron effect in GaN and it is experimentally confirmed for bulk GaN [26].

From Fig. 3, it is found that the maximum peak velocity is 2.01×10^7 cm/s and the peak electric field where peak electron velocity is 174 kV/cm for unpassivated heterostructure. For the passivated heterostructure, while the v_{peak} is 1.39×10^7 cm/s, the peak electric field is around 149 kV/cm. The value of v_{peak}

is decreased from 2.01×10^7 to 1.39×10^7 cm/s after passivation. Similarly, the electric field where υ_{peak} is decreased from 174 to 149 kV/cm after passivation. In GaN-based heterostructures, the υ_{peak} occurs in very large fields which resulted in a higher effective mass and higher density of states when compared with GaAs [18]. After passivation, this decrement in the value of υ_{peak} can be explained with the increment in the sheet carrier density because of electron velocity depends on sheet carrier density. The origin of high 2DEG density in an AlGaN/GaN heterostructure is polarization, and therefore, polarization-induced charges scatter carriers and limit their mobility [43]. Sheet carrier density in the studied sample is increased from 1.21×10^{13} to 1.31×10^{13} cm^{-2} after passivation. However, this increment in sheet carrier density is limited. Moreover, it may not cause a significant change in the peak electric field. On the other hand, it is well known that Si_3N_4 passivation layer alters the density of states and the trap density at the surface of heterostructures [9], [42], [44]. Actually, NDR effect depends on the density of states and trap density at the surface [45]–[47]. Therefore, the decrement in the peak electric field is observed after the passivation may be caused by a reduction in free surface states and surface trap density.

A comparison between our results and experimental results of drift velocity as a function of the electric field measured in various previous studies at 300 K for AlGaN/GaN heterostructures is also shown in Fig. 3. In Fig. 3, A, B, C, D, E, and F implies that υ_d–E characteristics of various AlGaN/GaN heterostructures extracted using nanosecond-pulsed I–V measurements at 300 K in [12] and [20]–[23]. Characteristics of sample A with sample dimensions of 20×20 μm was measured by Guo *et al.* [23] using an 80-ns pulsewidth and saturation velocity is 1.30×10^7 cm/s at 120 kV/cm. Danilchenko *et al.* [21] reported that measured saturation velocity of an AlGaN/GaN heterostructure (sample B) with 100×10 μm using 30-ns pulsewidth is 1.1×10^7 cm/s at 80 kV/cm. Characteristics of sample C, sample D, and sample E were measured by Ardaravičius *et al.* [20], [22] in different studies. Measured saturation or peak drift velocities of these samples are 1.50×10^7 cm/s at 156 kV/cm, 1×10^7 cm/s at 210 kV/cm, and 1.34×10^7 cm/s at 162 kV/cm, respectively. Barker *et al.* [12] measured υ_d–E characteristics of an $Al_{0.25}Ga_{0.75}N$/GaN heterostructure with 10×3 μm sample dimensions using a 200-ns pulsewidth. Saturation velocity of sample F is around 1×10^7 cm/s at 150 kV/cm. According to Fig. 3, the electric field dependence of drift velocity of specially 951Y is agreement with the experimental data previously obtained by [20]–[23] for low fields. A summary of all these heterostructures is given in Table II.

Table II compares the applied maximum electric field, the peak electric field, and the υ_{sat} or υ_{peak} values obtained using the nanosecond-pulsed I–V measurements in AlGaN/GaN heterostructures for various sample dimensions. In Table II, the applied maximum electric field is increased by reducing the sample dimensions. Especially in this paper, for the $l = 4$ μm, it is reached up to 400 and 475 kV/cm obtaining larger electric fields with smaller voltages. To obtain the applied maximum electric field of 150 kV/cm for a sample with $l = 10$ μm, the applied voltage to sample should be 150 V. In the 4 μm case, the applied voltage of 150 V is corresponding to 375 kV/cm. So, this Table II and the findings in this paper present that the drift velocity measurement investigations of GaN-based heterostructures with smaller sample lengths is important to reveal the NDR effect and drift velocity characteristics in high fields.

TABLE II

APPLIED MAXIMUM ELECTRIC FIELD (F_{MAX}), AND THE v_{SAT} OR v_{PEAK} VALUES OBTAINED USING THE NANOSECOND-PULSED I–V MEASUREMENTS IN AlGaN/GaN HETEROSTRUCTURES FOR VARIOUS SAMPLE DIMENSIONS [12], [20]–[23]

Sample	Sample type	wxl (μm)	Si_3N_4	F_{max} (kV/cm)	v_{sat} or v_{peak} (x10^7 cm/s)
A [23]	$Al_{0.24}Ga_{0.76}N$/GaN	20x20	Yes	120	1.30
B [21]	$Al_{0.33}Ga_{0.67}N$/GaN	100x10	Yes	80	1.10
C [20]	$Al_{0.15}Ga_{0.85}N$/GaN	120x7	Yes	156	1.50
D [20]	$Al_{0.33}Ga_{0.67}N$/AlN/GaN	100x5	Yes	210	1.00
E [22]	$Al_{0.33}Ga_{0.67}N$/AlN/$Al_{0.1}Ga_{0.9}N$/GaN	260x4	Yes	162	1.34
F [12]	$Al_{0.25}Ga_{0.75}N$/AlN/GaN	10x3	Yes	150	1.00
951N	$Al_{0.3}Ga_{0.7}N$/AlN/GaN	1x4	No	400	2.01
951Y	$Al_{0.3}Ga_{0.7}N$/AlN/GaN	1x4	Yes	475	1.39

Analytical models describing υ_d–E characteristics have been widely used in device simulators [37], [48], [49]. With the relation between mobility and drift velocity, $\upsilon_d = \mu E$, the analytical models are compatible with the experimental measurements of drift velocity play important role in development of mobility models used in device simulations [17], [19], [37]. Therefore, improvement of analytical models describing υ_d–E characteristics is essential to make more reliable device design for device simulators. Mobility model developed by Caughey and Thomas [50] is a widely used empirical expression. The field dependence of drift velocity expression derived from the mobility model is not suited for modeling the drift velocity at high fields where NDR effect may be observed [37]. So, field-dependent mobility models due to the absence of experimental data in high fields were developed relying on Monte Carlo simulations. Farahmand *et al.* [19] first reported a field-dependent mobility model of bulk GaN and then, Yu and Brennan [17] reported the same mobility model for an AlGaN/GaN heterostructure. While AlGaN/GaN heterostructures in the previous experimental studies reached to 150 kV/cm as can be seen in Fig. 3, our samples reached over 400 kV/cm. Therefore, this mobility model should compare with electric field dependence of drift velocity of our samples in the wide range of electric field up to 475 kV/cm. Drift velocity–electric field expression extracted from this mobility model in [17] and [19] is given in the following:

$$\upsilon(E) = \frac{\mu_0 E + \upsilon_{sat}(E/E_C)^{n_1}}{1 + n_2(E/E_C)^{n_3} + (E/E_C)^{n_1}} \tag{2}$$

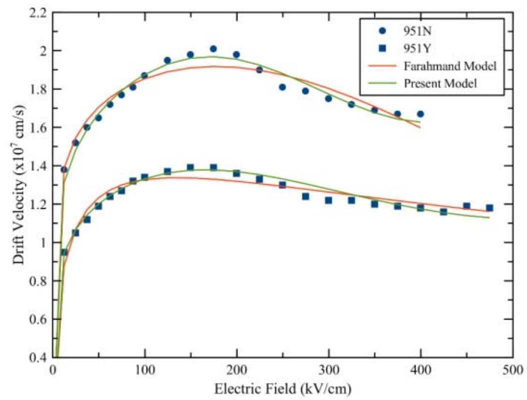

Fig. 4. Experimental results of electron drift velocity as a function of electric field in $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostructures without (951N) and with (951Y) *in situ* Si_3N_4 passivation and a comparison to mobility models. Red line represents the Farahmand model given in (2), and green line represents the derived expression given in (5).

TABLE III
VALUES OF FITTING PARAMETERS EXTRACTED FROM THE EXPERIMENTAL DATA OF AN $Al_{0.3}Ga_{0.7}N$/AlN/GaN HETEROSTRUCTURE WITHOUT *in situ* Si_3N_4 PASSIVATION (951N)

Parameters	*Farahmand Model*	*Present Model (Eq.5)*
v_{sat} (v_{peak}) (cm/s)	4.01x10^7	2.06x10^7
E_C (kV/cm)	180.20	180.20
n_1	0.24	0.17
n_2	0.13	-0.93
n_3	2.22	-
n_4	-	4.04
b	-	0.06

TABLE IV
VALUES OF FITTING PARAMETERS EXTRACTED FROM THE EXPERIMENTAL DATA OF AN $Al_{0.3}Ga_{0.7}N$/ALN/GAN HETEROSTRUCTURE WITH *in situ* Si_3N_4 PASSIVATION (951Y)

Parameters	*Farahmand Model*	*Present Model (Eq. 5)*
v_{peak} (cm/s)	4.01x10^7	1.44x10^7
E_C (kV/cm)	165.00	149.63
n_1	0.46	0.17
n_2	1.03	-0.93
n_3	1.04	-
n_4	-	2.95
b	-	0.04

where μ_0 is low-field mobility and $\upsilon_{\rm sat}$ is saturation velocity. μ_0 values of 951N and 951Y are used as 2385 and 2244 $cm^2/V\cdot s$ from [30], respectively. E_C, n_1, n_2, and n_3 are adjustable fitting parameters. When this expression is fitted to the experimental data as it can be seen in Fig. 4, it seems like the expression describes to υ_d–E characteristics of our samples. However, according to Tables III and IV, $\upsilon_{\rm sat}$ parameter value is 4.01×10^7 cm/s as a fitting parameter. This value has no a counterpart in the experimental results. On the other hand, $\upsilon_{\rm sat}$ found to be a misinterpreted parameter to describe the υ_d–E characteristics with an NDR behavior. The υ_d–E characteristics that included NDR effect exhibit a peak drift velocity rather than saturation velocity. Hence, a new expression which is consistent with experimental data obtained in this paper was derived from (2) as

$$\upsilon(E) = \frac{\mu_0 E + \upsilon_{\rm peak}(E/E_C)^{n_1}}{1 + n_2(E/E_C)^{n_3} + (E/E_C)^{n_4}}. \tag{3}$$

where $\upsilon_{\rm peak}$ is the electron peak velocity and E_C is the critical electric field where electron peak velocity occurs. n_4 is the additional a fitting parameter. However, we found that there is a relation between n_3 and n_4 fitting parameters, where n_3 should be bigger with very little difference than n_4. To consider it, if we assume that $n_3 = n_4 + b$, where n_3, n_4, and b are positive numbers

$$\upsilon(E) = \frac{\mu_0 E + \upsilon_{\rm peak}(E/E_C)^{n_1}}{1 + n_2(E/E_C)^{n_4+b} + (E/E_C)^{n_4}}. \tag{4}$$

Then, (3) transform into the following equation:

$$\upsilon(E) = \frac{\mu_0 E + \upsilon_{\rm peak}(E/E_C)^{n_1}}{1 + (E/E_C)^{n_4} \times \left(1 + n_2(E/E_C)^{b}\right)}. \tag{5}$$

Also, we used (5) as a fitting procedure for other materials with NDR behavior, and b parameter shows a very small deviation. Our all tryouts with different materials show that b parameter can be used as 0.05 ± 0.01. When (5) is fitted to the experimental data, the reasonable agreement between the experimental data and the model is obtained. This expression gives us that $\upsilon_{\rm peak}$ parameter values of 951N and 951Y are 2.06×10^7 and 1.44×10^7 cm/s, respectively. These values are very close to our experimental data. According to these results, the expression given in (5) can more satisfactory describe the υ_d–E characteristics with the NDR effect in GaN-based heterostructures. Another notable result in Tables III and IV is that n_1 and n_2 parameters of (5) are the same for two samples and b parameter varies between 0.04 and 0.06. It could be considered in further studies.

Therefore, a new field-dependent mobility model obtained from (5) has been developed which is given by

$$\mu = \frac{\mu_0 + \upsilon_{\rm peak}\frac{E^{n_1-1}}{E_C^{n_1}}}{1 + (E/E_C)^{n_4} \times \left(1 + n_2(E/E_C)^{b}\right)}. \tag{6}$$

IV. CONCLUSION

The nanosecond-pulsed I–V measurements for $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostructures without and with *in situ* Si_3N_4 passivation layer are performed at 77 K and up to 475-kV/cm electric field values owing to smaller lengths of the sample and the protection maintained by the Si_3N_4 surface passivation layer. These measurements revealed the electron drift velocity data as a function of electric field for the wide range. The effect of *in situ* Si_3N_4 passivation on υ_d–E characteristics in $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostructures was also investigated. After passivation, peak velocity reduction from 2.01×10^7 to 1.39×10^7 cm/s was observed. As another result of this paper, a fitting expression describing the υ_d–E characteristics for AlGaN/AlN/GaN heterostructures has been derived. It can explain the experimental v_d–E characteristics with NDR effect at large electric fields up to 475 kV/cm. This expression can be used in the device simulators to design better GaN-based semiconductor structures and to obtain more reliable results.

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