Lithuanian Journal of Physics, Vol. **54**, No. 4, pp. 227–232 (2014)

SCHOTTKY DIODES AND HIGH ELECTRON MOBILITY TRANSISTORS OF 2DEG AlGaN/GaN STRUCTURES ON SAPPHIRE SUBSTRATE

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Received 21 May 2014; revised 13 October 2014; accepted 10 December 2014

We report Schottky diodes (SDs) and High Electron Mobility Transistors (HEMTs) fabricated of 2DEG AlGaN/GaN structures grown by Metalorganic Chemical Vapour Phase Epitaxy (MOVPE) on sapphire substrate. The SDs and HEMTs were designed intentionally without surface passivation and were successfully fabricated at the Center for Physical Sciences and Technology (CPST), using standard UV photolithography procedures. The performance of Ohmic contacts formed of quaternary Ti/Al/Ni/Au stack was optimized varying the temperature of rapid thermal annealing process. Deposited on the semiconductor metal Ni/Au stack was used to form 0.75 eV height Schottky barriers. The fabricated SDs demonstrated low reverse current and high electric current switching ratio while the HEMTs showed high transconductance and drain saturation currents performance with good transistor channel closing. This work paves a way to develop advanced AlGaN/GaN based HEMT structures as well as new electronic components for operation at high powers and high frequencies.

Keywords: AlGaN, GaN, Schottky diode, High Electron Mobility Transistor, HEMT

PACS: 72.80.Ey, 71.55.Eq, 72.20.-i, 73.30.+y

1. Introduction

Wide band gap, high electron mobility and saturation velocity as well as thermal stability made gallium nitride (GaN) a promising material for high power and high frequency electronic devices. Growth of high-electron-mobility-transistor (HEMT) structures of graded aluminum gallium nitride–gallium nitride (AlGaN/GaN) resulted in high power density RF amplifiers and components [1]. Usually GaN-based electronic devices are fabricated on foreign substrates such as sapphire, Si, and SiC with the preference for the last one due to better performances achieved [2]. However, AlGaN/GaN HEMT structures on high quality ammonothermal GaN substrate became recently available [3] allowing development of low leakage current electronic devices [4].

In 1993 a great interest was triggered after publication of a theoretical work by Dyakonov and Shur who proposed a new mechanism of plasma waves generation by DC current in the field effect transistor (FET) channel [5]. Since then different groups are expecting to develop an efficient plasmonic FET terahertz (THz) emitter. However, only recently room temperature THz emission below 2 μW has been achieved from AlGaN/GaN HEMT with a periodic Ohmic contacts design [6]. And substantially weaker radiation power was generated by submicron gate size HEMT demonstrating, for the first time, the emission peak tunability by the gate voltage between frequencies 0.75 and 2.1 THz [7–8].

The main aim of the TERAGAN project is development of the AlGaN/GaN HEMT plasmonic THz sources which should emit power more than 5 μW at room temperature. In this work, Schottky diodes and HEMTs based on AlGaN/GaN 2DEG structures were developed for the project needs at the Center for Physical Sciences and Technology (CPST), Vilnius, Lithuania. Here we proposed only a two-step photolithography GaN HEMT processing procedure in order to reduce the fabrication complexity and price. We processed and tested more electronic devices in parallel in order to optimize the performance of Ohmic and Schottky contacts required for development of efficient plasmonic THz sources.

Usually GaN device fabrication is completed with a deposition of dielectric passivation layers which suppress current collapse effects and reduce gate leakage current [9–10]. The effects are critical for achieving high power and high frequency performance, especially in smaller nano-scale devices. However, in our case, we put forward simplified GaN HEMT processing technology considering micrometer dimensions of the plasmonic THz emitters [6]. This effort was also inspired by the work where good performance for unpassivated as well as passivated micrometer-gate-length GaN HEMTs has been reported [11]. The paper has exposed unsolved problems selecting surface passivants which might lead to up to three orders of magnitude higher gate leakage currents for passivated GaN HEMTs in comparison to unpassivated ones due to the occurrence of surface related traps.

2. Device fabrication

High quality AlGaN/GaN HEMT structures were grown on two-inch diameter sapphire by the metal organic vapor phase epitaxy (MOVPE) technique at the Institute of High Pressure Physics (UNIPRESS), Warsaw, Poland. Used structures are schematically shown in Fig. 1(a). An undoped $Al_XGa_{1-X}N$ layer with an AlN spacer were grown on the top of unintentionally doped (UID) GaN on the top of high resistivity (HR) and low-temperature (LT) GaN buffer layers on the 330 μm thick Al_2O_3 substrate. Analysis of Al content in a heterostructure layer was measured by 2theta-omega x-ray diffraction scan. The thickness of about 25 nm and $Al_XGa_{1-X}N$ composition with X = 20.4% of Al were found, as the experimental curve was reproduced by the simulation data based on the dynamical x-rays diffraction theory.

Test electronic devices, Schottky diodes, and HEMTs were fabricated of 2DEG AlGaN/GaN structures at the CPST employing the electron-beam thin film deposition system and standard UV photolithography procedures. Ohmic contacts were formed of the metal stack of Ti/Al/Ni/Au annealed for 30 s in N_2 gas atmosphere. Rapid thermal annealing (RTA) temperature was experimentally optimized to achieve the lowest contact resistance. As for the Schottky contact, the Ni/Au metal stack was deposited on the semiconductor. Only two photo lithography procedures were used in total and the surface of the devices was intentionally left unpassivated in order to put forward a low cost GaN HEMT processing technology. The fabricated electronic devices, namely the Schottky diode and the transistor, are shown in Figs. 1(b) and 1(c), respectively.

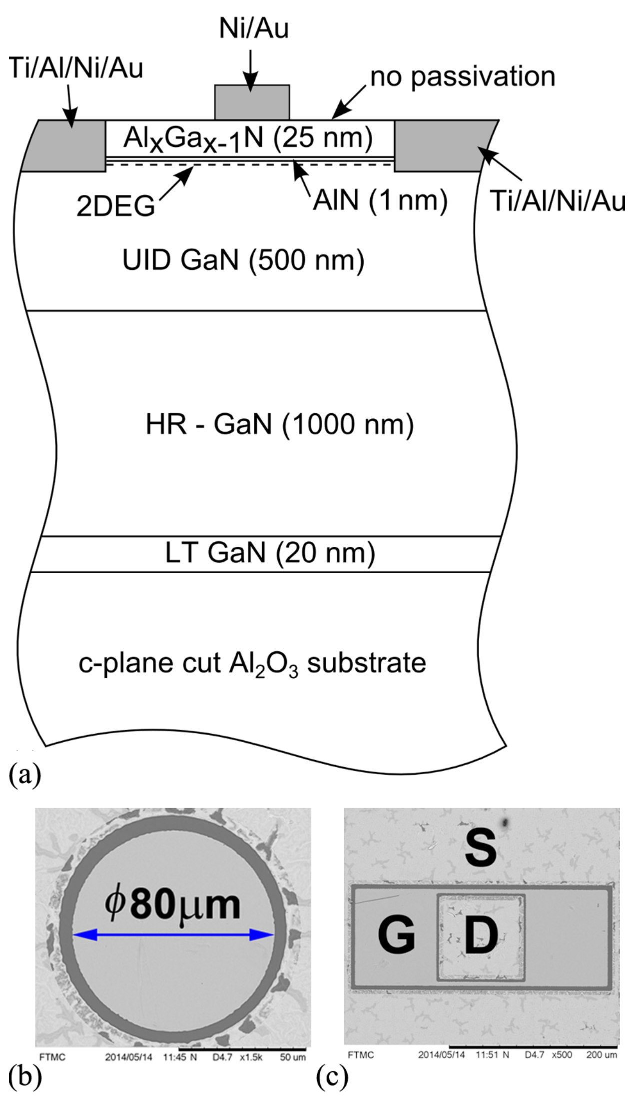

Fig. 1. (a) Schematic view of employed 2DEG AlGaN/GaN structures. Picture of the (b) Schottky diode and (c) High Electron Mobility Transistor (HEMT) fabricated by two-step technology process.

3. Results and discussion

The performance of the Ohmic contacts was optimized by the transmission line method (TLM) [12]. The circular TLM structure consists of eight 80 μm diameter central contact pads surrounded by the Ohmic contact area. The fabricated circular TLM structure is shown in the inset of Fig. 2(a). Both circular inner and outer contacts were separated by a distance varying from 5 μm to 40 μm. Contact resistances were found from the *I–V* data of the measured resistance versus gap spacing by the TLM. The results are shown in Fig. 2(a). The lowest specific contact resistance of 6.7×10^{-5} Ω cm^2 was achieved at RTA temperature of 830 °C (see Fig. 2(b)).

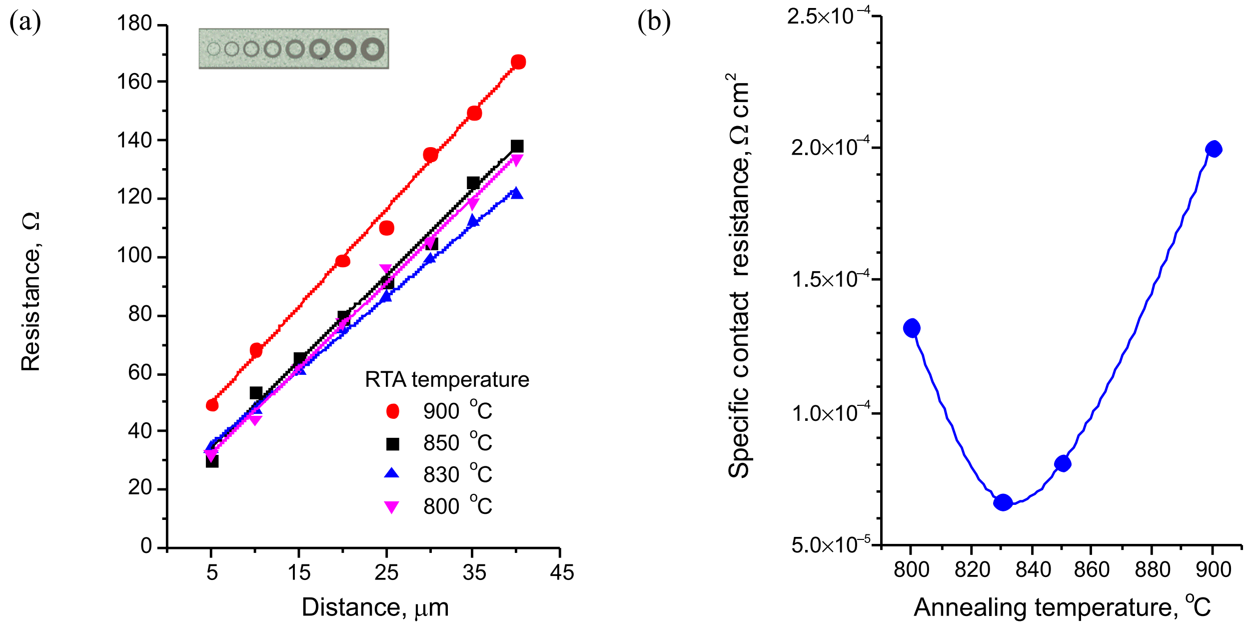

Fig. 2. (a) Linear regression of Ti/Al/Ni/Au contacts on HEMT structures annealed for 30 s at various RTA temperatures. Inset: picture of the circular TLM structures. (b) Obtained specific contact resistance dependence on RTA temperature (points are experiment, line is for eye guide).

The Schottky diodes were designed and fabricated in a similar way as the circular TLM structures except for the center contact which was fabricated of Ni/Au stack forming a Schottky barrier with a height below 1 eV [13]. The measured current-voltage (I–V) characteristics of the Schottky diodes with different spacing between the contacts are shown in Fig. 3. The performance of the diodes is summarized in the Table 1. The average value of the ideality factor and the barrier height was found equal to $n = 1.7 \pm 0.2$ and $\Phi_B = 0.74 \pm 0.02$ eV, respectively.

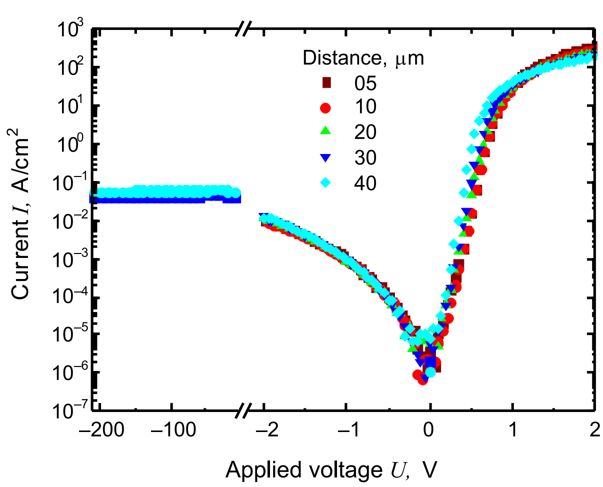

Fig. 3. I–V characteristics of the Schottky diodes with different distance between the Ohmic and Schottky contact pads. Results are shown on a semi-log scale.

Table 1. Performance of the diodes with the central Schottky contact pad of the diameter d = 80 μm (the area $S = 5.0265 \cdot 10^{-5}$ cm²) and the distance L_{SO} between the Schottky and Ohmic contact pads.

Diode	Spacing L_{SO}, μm	Saturation current I_0/S, A/cm²	Ideality factor n	Barrier height Φ_B, eV
D5	5	$1.4 \cdot 10^{-6}$	1.9	0.72
D10	10	$4.4 \cdot 10^{-7}$	1.7	0.75
D15	15	$7.4 \cdot 10^{-7}$	1.7	0.74
D20	20	$7.8 \cdot 10^{-7}$	1.9	0.74
D25	25	$5.7 \cdot 10^{-6}$	1.8	0.68
D30	30	$5.3 \cdot 10^{-7}$	1.6	0.75
D35	35	$1.9 \cdot 10^{-7}$	1.4	0.77
D40	40	$4.7 \cdot 10^{-7}$	1.3	0.75

I–V characteristics of the Schottky diodes were obtained at the applied bias voltage from –210 V to +2 V. Even though the spacing between the electrodes of the Schottky diode differs up to 8 times, the mean value of the leakage current was obtained of 33 ± 17 mA/cm² at the reverse bias larger than –50 V. The data demonstrates quite good quality of the AlGaN/GaN HEMT structures used. As for the forward bias, the maximum current was reached at 360 A/cm² for the diodes having contacts with the 5 μm separation distance while the maximum current for the diode with the largest 40 μm spacing was only 180 A/cm^2, showing a decrease of approximately 2 times due to the presence of Ohmic losses.

We found that the leakage current starts to increase at a relatively low –0.2 V reverse bias and saturates below 0.1 A/cm^2 for the applied voltage from –3 V up to –210 V. The fabricated Schottky diodes demonstrated high up to 70 dB electric current switching ratio, which exceeds 30 dB within the entire studied region (from –210 V to +2 V).

The capacitance–voltage (*C–V*) characteristics of the Schottky diodes were measured in a bias range of –10 to 0 V. The results are shown in Fig. 4(a). Charge distribution from the surface towards the substrate

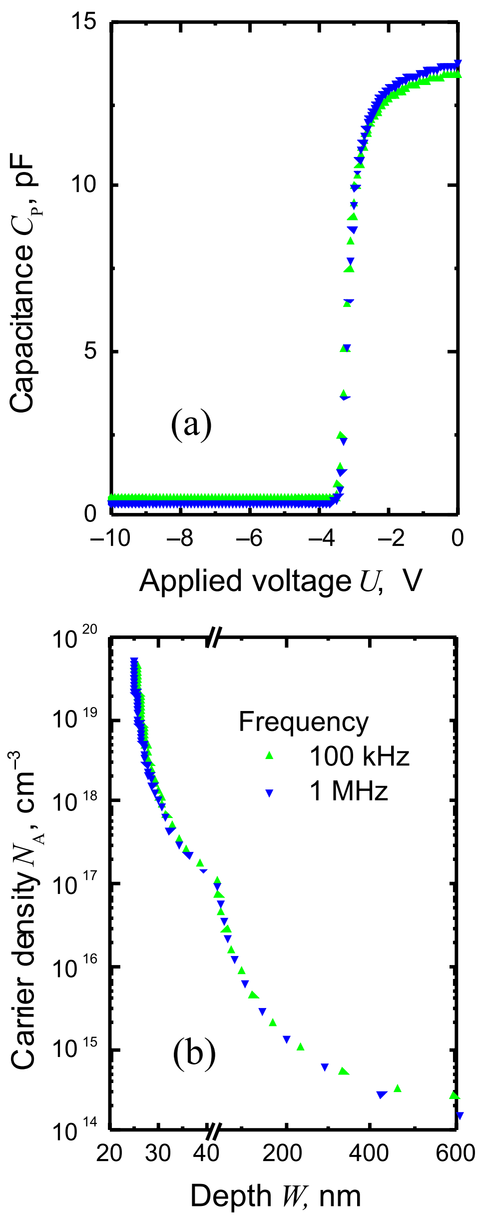

Fig. 4. (a) *C–V* characteristic of the D35 diode with Schottky contacts area of $S = 5.03 \times 10^{-5}$ cm^2 measured at modulation frequency of 100 kHz and 1 MHz. (b) Carrier density against depth in the AlGaN/GaN HEMT structures.

was found by differentiating the *C–V* characteristic in accordance to the method described in Chapter 2.2 of Ref. 12. The results are shown in Fig. 4(b). The position of 2DEG was found at around 26 nm from the surface in agreement with the fabrication protocol of the AlGaN/GaN HEMT structures (see Fig. 1(a)). The *C–V* data was used to estimate the 2DEG density: $n^{CV}{}_{2DEG} = (4.97 \pm 0.12) \times 10^{12}$ cm^{-2}. In addition, the Hall experiment with Van der Pauw structures was performed and the 2DEG density of $n^{VP}{}_{2DEG} = 9.15 \times 10^{12}$ cm^{-2} and the mobility of $\mu = 1337$ cm^2/V s and $\mu = 4170$ cm^2/V s at 300 K and 77 K temperatures, respectively, were obtained. Note that the carrier freeze-out was not observed at liquid nitrogen temperature indicating good 2DEG localization by the AlN spacer.

Inspection of the Schottky diodes fabricated at slightly different technologic procedures showed that dislocations were responsible for shunting paths for the leakage current rather than the unpassivated device surface. And indeed, the leakage current independence of spacing between Schottky diode electrodes proves a reasonably good surface quality (see Fig. 3).

Finally, planar rectangular HEMTs with a ring shape gate were developed. The planar view of the processed HEMT is shown in Fig. 1(c). The dimensions of the gate (G) electrode of 5.5 μm × 100 μm, the distance between the source (S) and drain (D) of 13 μm, and the GS length of $L_{GS} = 2.5$ μm were chosen considering the accuracy of our photolithography procedures being not better than 2 microns and micrometer dimensions of the plasmonic THz emitters.

The measured DC *I–V* output and transfer characteristics of the AlGaN/GaN HEMT are shown in Figs. 5(a) and 5(b), respectively. It shows almost saturated drain currents reaching more than 320 mA/mm at $U_{GS} = 2$ V when normalized to the transistor gate width of 2 × 100 μm. A tiny decline seen in the output characteristics at higher gate voltages is caused by the heating effects which disappears in pulsed *I–V* characteristics [14]. The pinch-off voltage was measured at around –3.2 V and that was the similar value found from the *C–V* characteristics of the Schottky diodes (see also Fig. 4(a)). The leakage currents dependence on drain voltage was expected after the discussion about the performance of Schottky diodes (see the text above). The HEMT transconductance was found to be more than $g_m = 100$ mS/mm at used bias of $U_{GS} = 0$ V and $U_{DS} = 6.0$ V. The performance of the fabricated 2.5 μm gate length HEMTs was still up to three times worse in comparison to the HEMTs fabricated using more advanced submicron photolithography or nanolithography procedures [10, 14–15].

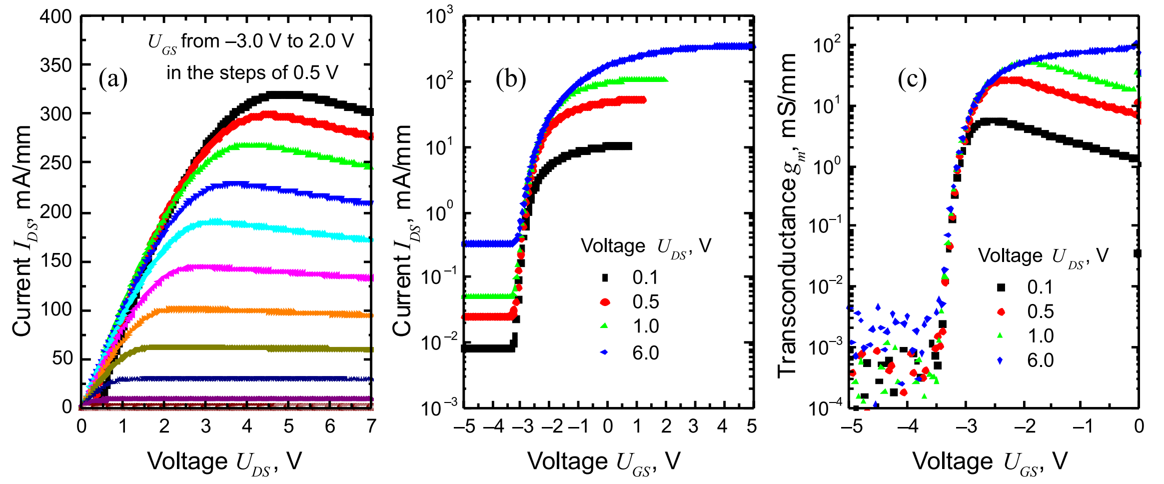

Fig. 5. Measured DC characteristics of the processed AlGaN/GaN HEMT: (a) output characteristic at the gate voltage from –3 V to +2 V in steps of 0.5 V, (b) transfer and (c) transconductance characteristics at the selected drain voltage values.

5. Conclusions

The Schottky diodes and the High Electron Mobility Transistors have been successfully developed of the 2DEG AlGaN/GaN on sapphire at the Center for Physical Sciences and Technology. We proposed two-step photo-lithography GaN HEMT processing without surface passivation in order to maintain electronic devices low cost fabrication technology taking a close look at the performance achieved.

The processed Schottky diodes demonstrated high up to 70 dB electric current switching ratio and small below 0.1 A/cm^2 leakage current which was independent from the distance between the contacts (reduced up to 5 μm) at the reverse bias voltage up to –210 V. The average value of the ideality factor and the barrier height of the Schottky diodes was of n = 1.7 ± 0.2 and Φ_B = 0.74 ± 0.02 eV, respectively.

And the fabricated 2.5 μm gate length HEMTs showed rather promising current-voltage characteristic with good transistor channel closing. The transistors exhibited transconductance values up to g_m = 100 mS/mm, at the gate voltage +2 V, and the current drive capability as high as 320 mA/mm, at the drain voltage +6 V, both normalized to the channel width (2 × 100 μm).

Acknowledgements

This work was supported by the TERAGAN project under Contract MIP-064/2012 from the Research Council of Lithuania. The research in Warsaw was supported by the PolHEMT Project under the Applied Research Programme of the National Centre for Research and Development, Contract Number PBS1/A3/9/2012. We greatly acknowledge dr. Andrius Maneikis for SEM images and prof. Gintaras Valušis and dr. Ramūnas Aleksiejūnas for careful manuscript reading and encouragement to publish this work.

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2DEG AlGaN/GaN HETEROSTRUKTŪRŲ ANT SAFYRO PADĖKLO ŠOTKIO DIODAI IR DIDELIO ELEKTRONŲ JUDRIO TRANZISTORIAI

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Santrauka

Darbe pristatome Šotkio diodus ir didelio elektronų judrio tranzistorius (angl. HEMT), padarytus iš AlGaN/GaN struktūrų su dvimatėmis elektronų dujomis (angl. 2DEG), suformuotomis metalorganinio nusodinimo iš garų fazės būdu ant safyro padėklo. Elektronikos komponentai, sukurti be papildomo paviršiaus pasyvavimo, pagaminti Fizinių ir technologijos mokslų centre naudojant standartinę UV fotolitografiją. Ominių kontaktų, kurie suformuoti iš keturių metalų (Ti, Al, Ni ir Au) lydinio, varža buvo optimizuota parinkus greito atkaitinimo temperatūrą. Užgarinus dviejų metalų (Ni ir Au) sluoksnį, suformuoti apie 0,75 eV potencialo Šotkio barjerai. Pagaminti Šotkio diodai pasižymėjo mažomis nuotėkio srovėmis, o tranzistoriai – dideliu perdavimo charakteristikos statumu ir didelėmis santakos soties srovėmis. Įvairių Šotkio diodų, besiskiriančių nuo 5 iki 40 μm atstumu tarp kontaktų, srovės tiesiogine kryptimi kito 180–360 A/cm^2 intervale, kai įtampa +2 V, o nuotėkio srovės buvo visiems diodams vienodos ir neviršijo 0,1 A/cm^2 vertės, kuri nekito įtampų ruože nuo –3 V iki –210 V. Diodų volt-faradinės charakteristikos leido įvertinti 2DEG pasiskirstymo profilį heterostruktūroje bei nustatyti elektronų tankį $n^{CV}_{2DEG} = 5 \cdot 10^{12}$ cm^{-2}. Papildomai atlikti Holo eksperimentai su Van der Pauw formos bandiniais parodė, kad 300 K ir 77 K temperatūroje krūvininkų judris atitinkamai buvo lygus μ = 1337 cm^2/V s ir μ = 4170 cm^2/V s, o krūvininkų tankis $n^{VP}_{2DEG} = 9.15 \times 10^{12}$ cm^{-2} nepriklausė nuo temperatūros. Tai rodė gerą krūvininkų lokalizaciją dėl įterpto AlN pasluoksnio.

Pagaminti 2,5 μm ilgio planariniai HEMT tranzistoriai pasižymėjo santakos soties srovėmis iki 320 A/mm, kai užtūros įtampa +2 V, ir perdavimo charakteristikos statumu iki g_m = 100 mS/mm, kai ištakos įtampa +6 V; abu parametrai sunormuoti į kanalo plotį 2 × 100 μm.

Šie Šotkio diodų ir lauko tranzistorių rezultatai turėtų paskatinti Lietuvoje sudėtingesnių AlGaN/GaN heterodarinių tyrimus bei didelės galios ir aukšto dažnio elektronikos komponentų kūrimą bei vystymą.