ELECTRON TRANSPORT IN A COUPLED GaN/AlN/GaN CHANNEL OF NITRIDE HFET

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Longitudinal hot-electron transport is investigated for the alloy-free AlGaN/AlN/{GaN/AlN/GaN} heterostructure at electric fields up to 380 kV/cm. The structure featured a coupled channel with a camelback electron density profile. The hot-electron drift velocity in the coupled channel is estimated as ~1.5×10^7 cm/s and is ~50% higher as compared with the standard AlN-spacer GaN 2DEG channel. The HFET with the pristine 2DEG density of 1.75×10^{13} cm^{-2} confined in the coupled channel demonstrates the optimal frequency performance in terms of electron velocity at a relatively low gate bias of V_{GS} = –1.75 V. These results are consistent with the ultra-fast decay of hot phonons.

Keywords: nitride heterostructure, HFET, electron drift velocity, hot phonons, high electric fields

PACS: 72.10.Di, 72.20.Ht, 72.20.Fr, 72.30.+q, 85.30.Tv

1. Introduction

Gallium nitride heterostructure field-effect transistors (HFETs) are very promising for high-speed high-power applications [1]. Recently, HFETs with current unity gain cut-off frequency of 400 GHz were reported [2]. The cut-off frequency is related to the average carrier velocity in a two-dimensional electron gas (2DEG) channel. The experimental reports show that the room temperature electron velocity values in GaN-based 2DEG channels lie between (1–3)×10^7 cm/s [3–9]. While the low-field electron mobility tends to decrease as the density of 2DEG increases, the high-field drift velocity is not a monotonous function of the density [10]. The highest value is reached at ~(1.0±0.1)×10^{13} cm^{-2} electron density in agreement with the resonance decay of hot phonons (non-equilibrium longitudinal optical (LO) phonons): the resonance takes place in the vicinity of the crossover of dispersion curves for initially non-interacting LO phonons and plasmons. The plasmon-assisted decay of LO phonons has been confirmed experimentally [11–13]. For GaN-based 2DEG channels the hot LO phonon lifetime is the shortest near

7×10^{12} cm^{-2} at low electric fields, in reasonable agreement with the resonance condition. Also, as expected, the resonance 2DEG density increases with the applied electric field [10, 14] because the plasma frequency decreases when the bulk density of the electron gas decreases under heating.

The optimal 2DEG density for frequency performance is a compromise. Experimental results illustrate that the cut-off frequency for standard GaN-based HFETs is f_T = 205 GHz for n_{2D} = 2.4×10^{13} cm^{-2} [15] and f_T = 300 GHz for n_{2D} = 1.65×10^{13} cm^{-2} [16]. Because the optimal frequency performance takes place at a negative gate bias, the 2DEG density in the channel under the biased gate electrode is lower than the pristine 2DEG density in the as-grown heterostructures. The estimated effective density under the gate (namely, (1.0±0.1)×10^{13} cm^{-2} in the standard GaN 2DEG channel at the optimum bias for the cut-off frequency) is consistent with the condition for ultrafast decay of hot phonons [17].

The signature of the LO-phonon–plasmon crossover manifests itself in experiments on electron drift velocity [10], transistor cut-off frequency [18], and transistor degradation: the electron drift velocity is the highest,

the transistor operation is the fastest, the phase noise level is the lowest, and the device degradation is the slowest inside the electron density window where the hot-phonon lifetime acquires the shortest values [17, 19].

It should be noted that the LO-phonon–plasmon interaction and the associated hot LO phonon decay are determined by the profile of vertical electron distribution rather than the total number of electrons in the channel (proportional to the 2D density). Hence, a faster decay of hot phonons can be achieved at a higher 2D density – even if it exceeds the resonance value at low electric fields – when the vertical distribution of electrons is spread out. For example, application of a high field can reduce 3D density and make the profile closer to the resonance one. Calculations reveal the reduced 3D peak density at elevated hot-electron temperature [20], which in turn has an impact on the associated LO-phonon–plasmon resonance. However, it might not be practical to heat the electrons sufficiently in order to reduce their peak density to the resonance one without damaging the sample. An alternative solution which does not require electric field to spread the electron distribution is to diminish the 3D density in composite channel structures with a camelback electron density profile [21–26].

In this work the current–voltage dependence was measured by the nanosecond-pulsed voltage technique in alloy-free coupled channel AlGaN/AlN/{GaN/AlN/GaN} heterostructures with a camelback electron density profile. The estimated drift velocity and the performance of a coupled channel nitride HFET is discussed in terms of plausible plasmon-assisted hot-phonon decay.

2. Samples

The investigated heterostructures were grown on c-sapphire substrates in a low-pressure custom-designed Organo-Metallic Vapour Phase Epitaxy (OMVPE) system at Virginia Commonwealth University (USA). The sample growth and processing procedure is described in Ref. [23]. The schematic diagram resulting in an alloy-free coupled channel heterostructure is shown in Fig. 1. Figure 2 presents the 3D electron density n_{3D} (cm^{-3}) profile versus the distance (nm) estimated from capacitance–voltage (CV) measurements at a frequency of 1 MHz for the AlGaN/AlN/{GaN/AlN/GaN} heterostructure at room temperature (blue solid line). The profile was calculated from the CV measurements by using the expression given in Ref. [18]: $n_{3D} = -2\{\epsilon eA^2 \mathrm{d}(1/C^2)/\mathrm{d}V\}$, where ϵ is the dielectric constant, e is the elementary charge, and A is the area of the diode. It is clearly seen that the alloy-free struc-

ture exhibits a camelback density profile (coupled channel) at the equilibrium (zero electric field).

#3584

GaN – 2 nm
AlGaN: 20 nm 28.5 % Al
AlN – 1 nm
GaN: 4 nm
AlN – 1 nm
GaN – 3.5 µm
AlN – 350 nm
Sapphire

Fig. 1. A schematic view of an alloy-free coupled channel AlGaN/AlN/{GaN/AlN/GaN} heterostructure.

3. Experimental results and discussion

3.1. Low-field electron mobility, current–voltage dependence

Electron transport measurements were carried out on two-electrode samples taken from TLM (Transmission Line Model) structures of width $\omega = 240$ µm. The contact resistance R_c was estimated at low electric fields from the dependence of the sample resistance R on the channel length L. The low-field mobility μ_M was deduced from magneto-resistance data, and the 2DEG electron density n_{2DM} was estimated as $n_{2DM} = L/Re\mu_M\omega$, where e is the elementary
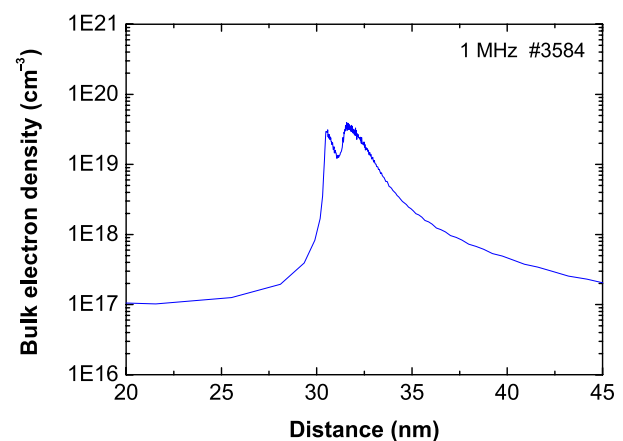
Fig. 2. 3D electron density (cm^{-3}) profile versus distance (nm) estimated from CV measurements for the sample (blue solid line online) with a coupled channel.

Table 1. 2DEG density from CV, magneto-resistance, Hall measurements and magneto-resistive, Hall mobility for a coupled {AlN/GaN/AlN} channel and single AlN-spacer GaN-based channel [4] at room temperature.

Structure	n_{2DCV} $\times 10^{13}$ cm^{-2}	n_{2DM} $\times 10^{13}$ cm^{-2}	n_{2DHall} $\times 10^{13}$ cm^{-2}	μ_M cm^2/Vs	μ_{Hall} cm^2/Vs
This work	0.72	0.6	1.3–1.75	1750	1410
[4]	–	–	1.0	–	1152

charge. The sheet electron density was also estimated as n_{2DCV} = 0.72×10^{13} cm^{-2} through the integration of the density profile from CV measurements (Fig. 2) for the alloy-free coupled channel. It is worth noting that the magneto-resistive mobility was estimated on the same TLM pattern where the high-field transport was studied, which is critically important. Hall mobility was measured before TLM processing. Hall mobility values were lower than that obtained from magneto-resistance measurements (Table 1). The discrepancy may arise because of the wafer non-uniformity. The Hall and TLM sample may not correspond to the same radial position. The channel magneto-resistive mobility μ_M was thought to be the best choice to evaluate the 2DEG density which was taken to estimate the electron drift velocity. If no μ_M data was available, Hall mobility values were used.

The nanosecond pulsed technique [27] was applied to study high-field transport at room temperature. The electric field was estimated as $E = (V - IR_c)/L$ where V is the voltage, I is the current, and R_c is the total contact resistance. The data for evaluating the current and the voltage drop along the channel were obtained from the oscilloscope amplitudes when either a gauge resistor or the sample under test was present in the circuit.
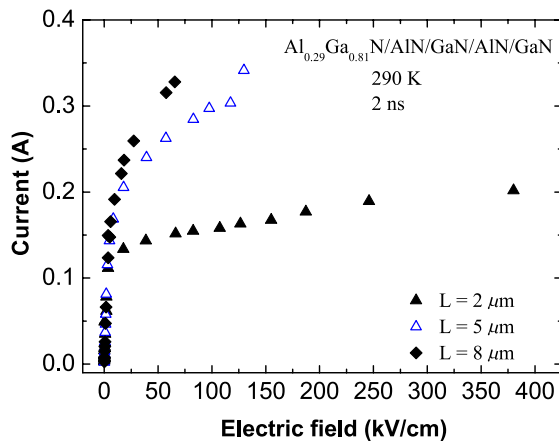
The pulsed current–field characteristics measured for the alloy-free AlGaN/AlN/{GaN/AlN/GaN} structures are shown in Fig. 3. The use of short nanosecond pulses of voltage (2 ns) and short channels (2 μm) enabled us to reach 380 kV/cm electric field (Fig. 3, full triangles). The maximum current attained was 0.35 A for the L = 5 μm sample (Fig. 3, empty triangles).

3.2. *Drift velocity, optimal conditions for HFET frequency performance*

The hot-electron drift velocity is determined according to the simple relation under assumptions of uniform electric field and no change in the electron density due to the applied field: $v_{dr} = I/(en_{2DM}\omega)$. Figure 4 shows that the drift velocity in the 2 μm coupled channel at the highest field (380 kV/cm) is relatively low (0.8×10^7 cm/s, stars) and is comparable with a single GaN channel with an electron density of 9.5×10^{12} cm^{-2} [9]. The 5 μm long {GaN/AlN/GaN} coupled channel reaches a drift velocity of 1.5×10^7 cm/s at 130 kV cm/s (triangles). The maximum velocity attained in the alloy-free coupled channel is approximately the same as in the alloy-containing dual channel made from {Al$_{0.1}$Ga$_{0.9}$N/GaN} [22]. This is a strong argument that alloy
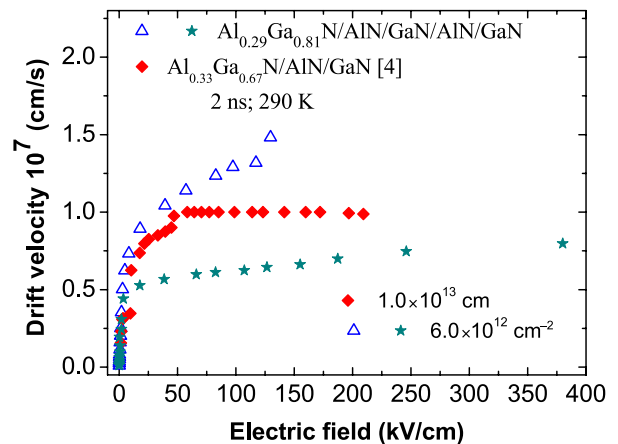

Fig. 3. The current–field dependences for an alloy-free coupled channel AlGaN/AlN/{GaN/AlN/GaN} heterostructure. Diamonds stand for L = 8 μm, empty triangles for L = 5 μm and full triangles for L = 2 μm. Voltage pulse duration is 2 ns.

Fig. 4. Room temperature dependence of the drift velocity on the electric field for the alloy-free coupled {GaN/AlN/GaN} channels (L = 5 μm, blue triangles; L = 2 μm, stars) and single AlN-spacer GaN-based 2DEG channel (L = 5 μm, diamonds [4]). Voltage pulse duration is 2 ns.

scattering does not play a significant role in camel-back channels. Also, the maximum attained drift velocity in the alloy-free coupled channel exceeds that in a standard AlN-spacer single GaN-based 2DEG channel by 50% [4]. Despite the fact that the velocity in the coupled channel is twice lower than the maximum drift velocity measured in the single GaN 2DEG channel [7], for similar electron densities (6×10^{12} cm^{-2}) the velocity in the coupled channel is 50% higher than in the single GaN 2DEG channel [9].

Let us use the plasmon-assisted hot-phonon decay concept to discuss the observed electron velocity. As mentioned earlier, the hot-phonon lifetime reaches the minimum value and the associated resonance takes place at the electron sheet density near 7×10^{12} cm^{-2} at low electric fields in GaN 2DEG channels [20]. The drift velocity in the coupled channel can be high because it has a similar electron density (6–7×10^{12} cm^{-2}) and the hot-phonon lifetime estimated from microwave noise measurements is short (15 fs at 50 kV/cm). It is known from the Monte Carlo simulation [4] that the shorter the lifetime is, the faster hot-phonon decay and the higher the electron velocity are. For the standard AlN-spacer single GaN-based 2DEG channel the phonon lifetime is longer (1 ps, [4]) even at high electric fields as compared to that in the coupled channel, and this causes the reduction in drift velocity (Fig. 4, diamonds).

Let us consider the frequency performance of HFETs processed from the heterostructures with different pristine (initial) 2DEG density measured before transistor processing. In agreement with the concept of an optimum electron density window, a higher negative gate voltage must be applied if the initial 2DEG density is higher. Thus, the optimal frequency performance calls for a reduced effective sheet density under the biased gate in the channel, namely, 1.0×10^{13} cm^{-2} [19].

The alloy-free coupled {GaN/AlN/GaN} channel is promising for its improved low-field transport properties. When the pristine electron density exceeds the resonance value, the resonance can be tuned in with a variable negative bias applied to the gate of a nitride HFET [17]. The HFET with a pristine 2DEG density of 1.75×10^{13} cm^{-2} in the alloy-free coupled GaN/AlN/GaN channel demonstrates the optimal frequency performance in terms of electron velocity (f_T = 8.6 GHz for L_g = 1 μm; V_{DS} = 15 V, where L_g is gate length, and V_{DS} is drain-source voltage) at a relatively low gate bias of V_{GS} = –1.75 V, while single-channel HFETs typically require a higher gate bias (–2.9 V at 1.75×10^{13} cm^{-2} [28]). Among other advantages, the ability to tune into the resonance with a lower gate bias is potentially useful for reducing gate leakage currents.

4. Conclusions

Longitudinal hot-electron transport is studied in a coupled {GaN/AlN/GaN} channel with a vertically dispersed quasi two-dimensional electron gas. In this alloy-free coupled channel, the highest velocity reaches ~1.5×10^7 cm/s at 130 kV/cm and exceeds the corresponding values in a standard single AlN-spacer GaN-channel heterostructure by 50%. The high-field drift velocity observed for a particular electron density (~6–7×10^{12} cm^{-2}) is consistent with the ultra-fast decay of hot phonons. No negative differential resistance is observed within the investigated electric field range (<400 kV/cm). A coupled channel nitride HFET demonstrates the optimal frequency performance at a relatively low gate bias.

Acknowledgements

References

[1] H. Morkoç, *Nitride Semiconductor Devices: Fundamentals and Applications* (Wiley-VCH, Weinheim, 2013).

[2] Y. Yue, Z. Hu, J. Guo, B.S. Rodriguez, G. Li, R. Wang, F. Faria, B. Song, X. Gao, S. Guo, T. Kosel, G. Snider, P. Fay, D. Jena, and H.G. Xing, Ultrascaled InAlN/GaN high electron mobility transistors with cutoff frequency of 400 GHz, Jpn. J. Appl. Phys. **52**, 08JN14 (2013).

[3] C.H. Oxley and M.J. Uren, Measurements of unity gain cutoff frequency and saturation velocity of a GaN HEMT transistor, IEEE Trans. Electron Dev. **52**, 165–169 (2005).

[4] L. Ardaravičius, M. Ramonas, O. Kiprijanovič, J. Liberis, A. Matulionis, L.F. Eastman, J.R. Shealy, X. Chen, and Y.J. Sun, Comparative analysis of hot electron transport in AlGaN/GaN and AlGaN/AlN/GaN 2DEG channels, Phys. Status Solidi A **202**, 808–811 (2005).

[5] J.M. Barker, D.K. Ferry, S.M. Goodnick, D.D. Koleske, A. Allerman, and R.J. Shul, High field

transport in GaN/AlGaN heterostructures, J. Vac. Sci. Technol. B **22**, 2045–2050 (2004).

[6] B.A. Danilchenko, S.E. Zelensky, E. Drok, S.A. Vitusevich, S.V. Danylyuk, N. Klein, H. Lüth, A.E. Belyaev, and V.A. Kochelap, Hot-electron transport in AlGaN/GaN two-dimensional conducting channels, Appl. Phys. Lett. **85**, 5421–5423 (2004).

[7] J.M. Barker, D.K. Ferry, D.D. Koleske, and R.J. Shul, Bulk GaN and AlGaN/GaN heterostructure drift velocity measurements and comparison to theoretical models, J. Appl. Phys. **97**, 063705 (2005).

[8] L. Ardaravičius, M. Ramonas, J. Liberis, O. Kiprijanovič, A. Matulionis, J. Xie, M. Wu, J.H. Leach, and H. Morkoç, Electron drift velocity in lattice-matched AlInN/AlN/GaN channel at high electric fields, J. Appl. Phys. **106**, 073708 (2009).

[9] S. Bajaj, O.F. Shoron, P.S. Park, S. Krishnamoorthy, F. Akyol, T.-H. Hung, S. Reza, E.M. Chumbes, J. Khurgin, and S. Rajan, Density-dependent electron transport and precise modeling of GaN high electron mobility transistors, Appl. Phys. Lett. **107**, 153504 (2015).

[10] L. Ardaravičius, J. Liberis, O. Kiprijanovič, A. Matulionis, M. Wu, and H. Morkoç, Hot-electron drift velocity and hot-phonon decay in AlInN/AlN/GaN, Phys. Status Solidi RRL **5**, 65–67 (2011).

[11] A. Matulionis, Hot phonons in GaN channels for HEMTs, Phys. Status Solidi A **203**, 2313–2325 (2006).

[12] K.T. Tsen, J.G. Kiang, D.K. Ferry, and H. Morkoç, Subpicosecond time-resolved Raman studies of LO phonons in GaN: dependence on injected carrier density, Appl. Phys. Lett. **89**, 112111 (2006).

[13] A. Matulionis, J. Liberis, I. Matulionienė, M. Ramonas, E. Šermukšnis, J.H. Leach, M. Wu, X. Ni, X. Li, and H. Morkoç, Plasmon-enhanced heat dissipation in GaN-based two-dimensional channels, Appl. Phys. Lett. **95**, 192102 (2009).

[14] A. Matulionis, J. Liberis, I. Matulionienė, E. Šermukšnis, J.H. Leach, M. Wu, and H. Morkoç, Novel fluctuation-based approach to optimization of frequency performance and degradation of nitride heterostructure field effect transistors, Phys. Status Solidi A **208**, 30–36 (2011).

[15] H. Sun, A.R. Alt, H. Benedickter, E. Feltin, J.-F. Carlin, M. Gonschorek, N. Grandjean, and C.R. Bolognesi, 205-GHz (Al,In)N/GaN HEMTs, IEEE Electron Device Lett. **31**, 957–959 (2010).

[16] D.S. Lee, X. Gao, S. Guo, and T. Palacios, InAlN/GaN HEMTs with AlGaN back barriers, IEEE Electron Device Lett. **32**, 617–619 (2011).

[17] A. Matulionis, J. Liberis, E. Šermukšnis, L. Ardaravičius, A. Šimukovič, C. Kayis, C.Y. Zhu, R.A. Ferreyra, V. Avrutin, Ü. Özgür, and H. Morkoç, Window for better reliability of nitride heterostructure field effect transistors, Microelectron. Reliabil. **52**, 2149–2152 (2012).

[18] J.H. Leach, C.Y. Zhu, M. Wu, X. Ni, X. Li, J. Xie, Ü. Özgür, H. Morkoç, J. Liberis, E. Šermukšnis, A. Matulionis, T. Paskova, E. Preble, and K.R. Evans, Effect of hot phonon lifetime on electron velocity in InAlN/AlN/GaN heterostructure field effect transistors on bulk GaN substrates, Appl. Phys. Lett. **96**, 133505 (2010).

[19] A. Matulionis, Electron density window for best frequency performance, lowest phase noise and slowest degradation of GaN heterostructure field-effect transistors, Semicond. Sci. Technol. **28**, 074007 (2013).

[20] A. Matulionis, J. Liberis, I. Matulionienė, M. Ramonas, and E. Šermukšnis, Ultrafast removal of LO-mode heat from a GaN-based two-dimensional channel, Proc. IEEE **98**, 111826 (2010).

[21] J.H. Leach, M. Wu, H. Morkoç, J. Liberis, E. Šermukšnis, M. Ramonas, and A. Matulionis, Ultrafast decay of hot phonons in an AlGaN/AlN/AlGaN/GaN camelback channel, J. Appl. Phys. **110**, 104504 (2011).

[22] L. Ardaravičius, O. Kiprijanovič, J. Liberis, A. Matulionis, X. Li, F. Zhang, M. Wu, V. Avrutin, Ü. Özgür, and H. Morkoç, Hot-electron drift velocity in AlGaN/AlN/AlGaN/GaN camelback channel, Semicond. Sci. Technol. **27**, 122001 (2012).

[23] R.A. Ferreyra, X. Li, F. Zhang, C. Zhu, N. Izyumskaya, C. Kayis, V. Avrutin, Ü. Özgür, and H. Morkoç, Microwave performance of AlGaN/AlN/GaN-based single and coupled channels HFETs, Proc. SPIE **8625**, 86252B (2013).

[24] R. Tülek, E. Arslan, A. Bayrakli, S. Turhana, S. Gökden, O. Duygulud, A.A. Kaya, T. Firat, A. Teke, and E. Özbay, The effect of GaN thickness inserted between two AlN layers on the transport properties of a lattice matched AlInN/AlN/GaN/AlN/GaN double channel heterostructure, Thin Solid Films **551**, 146–152 (2014).

[25] A. Wille, H. Yacoub, A. Debald, H. Kalisch, and A. Vescan, AlGaN/AlN-GaN-SL HEMTs with multiple 2DEG channels, J. Electron. Mater. **44**, 1263–1267 (2015).

[26] E. Arslan, S. Turan, S. Gökden, A. Teke, and E. Özbay, Current-transport mechanisms in the AlInN/AlN/GaN single-channel and AlInN/AlN/GaN/AlN/GaN double-channel heterostructures, Thin Solid Films **548**, 411–418 (2013).

[27] L. Ardaravičius, O. Kiprijanovič, J. Liberis, A. Matulionis, E. Šermukšnis, R.A. Ferreyra, V. Avrutin, Ü. Özgür, and H. Morkoç, Threshold field for soft damage and electron drift velocity in InGaN two-dimensional channels, Semicond. Sci. Technol. **30**, 105016 (2015).

[28] D.S. Lee, X. Gao, S. Guo, D. Kopp, P. Fay, and T. Palacios, 300-GHz InAlN/GaN HEMTs with InGaN back barrier, IEEE Electron Device Lett. **32**, 1525–1527 (2011).

ELEKTRONŲ PERNAŠA NITRIDINIAM LAUKO TRANZISTORIUI SKIRTAME SUSIETAME GaN/AlN/GaN KANALE

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Santrauka

Eksperimentiškai ištirti su kvazidvimatėmis elektronų dujomis {GaN/AlN/GaN} susieti kanalai. Tirtas kanalas suformuotas AlGaN/AlN/GaN/AlN/GaN įvairialyčiame darinyje, užaugintame MOCVD būdu ant safyro padėklo. Dvimatės elektronų dujos buvo veikiamos išoriniu elektriniu lauku, nukreiptu lygiagrečiai darinio plokštumai (statmenai c ašiai). Nanosekundinė VACH matavimo technika panaudota siekiant sumažinti Džaulio šilumos įtaką. Elektronų dreifo greitis įvertintas darant prielaidą, kad elektronų tankis nuo elektrinio lauko nepriklauso. Nustatyta, kad susietame {GaN/AlN/GaN} kanale didžiausias elektronų dreifo greitis yra $1,5 \times 10^7$ cm/s, kai elektrinio lauko stipris – 130 kV/cm, o tai 50 % viršija dreifo greitį standartiniame GaN dvimačių elektronų dujų kanale, nuo barjero atskirtame tarpiniu AlN sluoksniu. Parodyta, kad susieto nitridų kanalo lauko tranzistorius pasižymi geriausia dažnine charakteristika, kai sklendės įtampa gana maža. Maksimalus dreifo greitis ir optimali tranzistoriaus veika susietame kanale priklauso nuo ultraspartaus karštųjų optinių fononų suirimo.