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# Limitation of hot-carrier generated heat dissipation on the frequency of operation and reliability of novel nitride-based high-speed HFETs

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A novel fluctuation-based approach is applied to consider the unsolved problems in the realm of nitride heterostructure field effect transistors (HFETs). Fluctuations originate at a microscopic level and provide information on the processes responsible for device operation and degradation. The novel fluctuation-based approach is impelled by recent demonstration of strong correlation of microwave hot-electron fluctuations with frequency performance and degradation of nitride HFETs. The correlation has its genesis in the dissipation of the LO-mode heat accumulated by the non-equilibrium longitudinal optical phonons (hot phonons) confined in the channel that hosts the high-density hot-electron gas subjected to a high electric field. The LO-mode heat causes additional scattering of hot electrons and facilitates defect formation in a different manner than conventional heat accumulated by acoustic phonons. The heat accumulation depends on the supplied electric power and the rate of heat dissipation. We treat the problem in terms of the hot-phonon lifetime responsible for conversion of non-migrant optical phonons into migrant modes. The lifetime is measured over wide ranges of electron densities and supplied electric power. The optimal conditions for heat dissipation are determined and associated with plasmon-assisted disintegration of LO phonons. Signatures of plasmons are experimentally resolved in fluctuations, dissipation, hot-electron transport, transistor frequency performance, and device reliability. In particular, a slower degradation and a faster operation of GaN-based HFETs is demonstrated when the plasmon-assisted ultrafast dissipation of the LO-mode heat comes into play.

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## Table of Contents

## List of Figures



## List of Tables

# List of Publications

## Journal Papers

(Support from European Office Of Aerospace Research And Development
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1. A. Matulionis, J. Liberis, I. Matulionienė, M. Ramonas, E. Šermukšnis, "Ultrafast removal of LO-mode heat from a GaN-based two-dimensional channel", Special issue of *Proc. IEEE on GaN and ZnO Materials and Devices*, ed. H. Morkoç, *Proceedings of IEEE* **98** (7) 2029877, 1118–1126 (2010).
2. 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," *Applied Physics Letters* **96** (13) 133505/1-3 (2010).
3. Jacob H. Leach, Mo Wu, Xianfeng Ni, Xing Li, Ümit Özgür, Hadis Morkoç, Juozas Liberis, E. Šermukšnis, Arvydas Matulionis, H. Cheng, Ç. Kurdak, and Yong-Tae Moon. „Stress test measurements of lattice matched InAlN/AlN/GaN HFET structures" *Physica Status Solidi(A) Applications and Materials,* **207** (6) 1345-1347 (2010).
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5. A. Matulionis, J. Liberis, I. Matulionienė, M. Ramonas, E. Šermukšnis, J. H. Leach, M. Wu, X. Ni, X. Li, H. Morkoç, "Plasmon-enhanced heat dissipation in GaN-based two-dimensional chanels ", *Applied Physics Letters* **95** (19) 192102/1–3 (2009).
6. A. Matulionis, "Ultrafast decay of non-equilibrium (hot) phonons in GaN-based 2DEG channels (invited)", *Physica Status Solidi (c)* **6** (12) 2834–2839 (2009).
7. L. Ardaravičius, M. Ramonas, J. Liberis, O. Kiprijanovič, A. Matulionis, , J. Xie, M. Wu, J. H. Leach, H. Morkoç, "Electron drift velocity in lattice matched AlInN/AlN/GaN channel at high electric field", *Journal of Applied Physics* **106** (7) 073708/1–5 (2009).

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8. A. Matulionis, J. Liberis, I. Matulionienė, E. Šermukšnis, J. H. Leach, H. Morkoç, „Optimal conditions for heat dissipation in nitride HFETs: power tunable plasmon-LO-phonon resonance (invited)", Abstracts and program of Workshop on Compound Semiconductor Devices and Integrated Circuits (WOCSDICE 2010), Darmstadt/Seeheim, Germany, 191-194 (2010).
9. Arvydas Matulionis, Juozapas Liberis, and Hadis Morkoç, „Plasmon-assisted dissipation of LO-mode heat in nitride 2DEG channels", *Proceedings of SPIE* **7602,** 76020H/1-6, (2010). (SPIE – The International Society for Optical Engineering).

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10. A. Matulionis, J. Liberis, I. Matulionienė, E. Šermukšnis, J. H. Leach, H. Morkoç, „Optimal conditions for heat dissipation in nitride HFETs: power tunable plasmon-LO-phonon resonance (invited)“, Abstracts and program of Workshop on Compound Semiconductor Devices and Integrated Circuits (WOCSDICE 2010), May 17-19, 2010 Darmstadt/Seeheim, Germany.
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13. Arvydas Matulionis, Juozapas Liberis, and Hadis Morkoç, „Plasmon-assisted dissipation of LO-mode heat in nitride 2DEG channels“, SPIE Photonic West- PW09O, GaN Material and Devices V, 23-28 January 2010 San Francisco, CA. (SPIE – The International Society for Optical Engineering).
14. Jacob H. Leach, Mo Wu, Xianfeng Ni, Xing Li, Ümit Özgür, Hadis Morkoç, Juozas Liberis, E. Šermukšnis, Arvydas Matulionis, H. Cheng, Ç. Kurdak, and Yong-Tae Moon. „Stress test measurements of lattice matched InAlN/AlN/GaN HFET structures“8th Int. Conference on Nitride Semiconductors, ICNS-8, Jeju Island, Korea, October 18-23, 2009.
15. Jacob H. Leach, X. Ni, Ü. Özgür, A. Matulionis, and Hadis Morkoç,„New twists in LEDs and HFETs based on III-V nitride semiconductors (invited )" 2009 Fall EMRS meeting (European Materials Research Conference), September 14-18, 2009 Warsaw, Poland.
16. A. Matulionis, "Ultrafast decay of non-equilibrium (hot) phonons in GaN-based 2DEG channels (invited)“, SIMC-15 (Semiconducting and Insulating Materials Conference), June 13-16, 2009, Vilnius, Lithuania.

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17. Jacob H. Leach, X. Ni, Ü. Özgür, A. Matulionis, and Hadis Morkoç „New twists in LEDs and HFETs based on III-V nitride semiconductors (feature article)" *Physica Status Solidi(A) Applications and Materials,* **207** (5) 1091-1100 (2010).
18. X. Ni, X. Li, J. Lee, S. Liu, V. Avrutin, Ü. Özgür, H. Morkoç, A. Matulionis, T. Paskova, G. Mulholland, and K.R. Evans, „The effect of ballistic and quasi-ballistic electrons on the efficiency droop of InGaN light emitting diodes“, *Physica Status Solidi (A) Applications and Materials , Rapid Research Letters* **4** (8-9) 194-196 (2010)

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22. X. Ni, X. Li, J. Lee, S. Liu, V. Avrutin, Ü. Özgür, H. Morkoç, A. Matulionis, T. Paskova, G. Mulholland, and K.R. Evans, „InGaN staircase electron injector for reduced electron overflow in InGaN light emitting diodes", *Appl. Phys. Letts*, in press

23. X. Ni, X. Li, J. Lee, S. Liu, V. Avrutin, Ü. Özgür, and H. Morkoç, and A. Matulionis, „The effect of hot electron and its energy relaxation on the efficiency of InGaN light emitting diodes", *J. Appl. Phys*, in press (JR10-3186)

24. X. Ni, X. Li, J. Lee, S. Liu, V. Avrutin, A. Matulionis, Ü. Özgür, and H. Morkoç, „On the efficiency in high-brightness InGaN light emitting diodes: Role of hot electrons" *Superlattices and Microstructures*, in press

25. A. Matulionis, J. Liberis, I. Matulionienė, E. Šermukšnis, J. H. Leach, M. Wu, and H. Morkoç, „Novel fluctuation-based approach to optimization frequency performance and degradation of nitride heterostructure field effect transistors (invited)", *Physica Status Solidi(A) Applications and Materials*, submitted June 28, 2010, Pssa 201026361, pending

26. Ü. Özgür, X. Ni, X. Li, J. Lee, S. Liu, S. Okur, V. Avrutin, A. Matulionis, and H. Morkoç, „Ballistic transport in InGaN based LEDs: impact on efficiency", Submitted to the Topical issue in honor of the Nobel Laureate Zh. I. Alferov, *Semiconductor Science and Technology*, Ed. Dieter Bimberg, submitted June10,2010, pending

Summary

A novel fluctuation-based approach is applied to consider the unsolved problems in the realm of nitride heterostructure field effect transistors (HFETs). Fluctuations originate at a microscopic level and provide information on the processes responsible for device operation and degradation. The novel fluctuation-based approach is impelled by recent demonstration of strong correlation of *microwave* hot-electron fluctuations with frequency performance and degradation of nitride HFETs. The correlation has its genesis in the dissipation of the ***LO-mode heat*** accumulated by the non-equilibrium longitudinal optical phonons (hot phonons) confined in the channel that hosts the high-density hot-electron gas subjected to a high electric field. The LO-mode heat causes additional scattering of hot electrons and facilitates defect formation in a different manner than conventional heat accumulated by acoustic phonons. The heat accumulation depends on the supplied electric power and the rate of heat dissipation. We treat the problem in terms of the *hot-phonon lifetime* responsible for conversion of non-migrant optical phonons into migrant modes. The lifetime is measured over wide ranges of electron densities and supplied electric power. The optimal conditions for heat dissipation are determined and associated with plasmon-assisted disintegration of LO phonons. Signatures of plasmons are experimentally resolved in fluctuations, dissipation, hot-electron transport, transistor frequency performance, and device reliability. In particular, a slower degradation and a faster operation of GaN-based HFETs is demonstrated when the plasmon-assisted ultrafast dissipation of the LO-mode heat comes into play.

## 1. Introduction

Gallium nitride and related compounds offer attractive solutions for semiconductor electronics and optoelectronics in the frequency range from microwaves to ultraviolet [1,2]. In particular, nitride heterostructure field effect transistors (HFETs) are among the most promising devices for microwave power applications. The main advantage originates from a high electric field strength and a high-density two-dimensional electron gas (2DEG) located in an undoped semiconductor (GaN) at a heterojunction with a wide band gap semiconductor (AlN and/or its alloys). The main drawbacks are low reliability and rapid drop of the power at millimeter-wave frequencies.

It would be natural to expect a higher microwave power if a higher 2DEG density were confined in a HFET channel [3]. Simultaneously, charging of capacitances would take less time. As a result, a higher power would be combined with a faster operation of HFETs. However, the experimental data do not show the expected behaviour. Figure 1 presents the unity gain cut-off frequency measured for HFETs based on nitride heterostructures that contain different 2DEG density [3–5]. At a given gate length, no increase in the cut-off frequency of the investigated HFETs is observed when the 2DEG density is increased. Experimental study of microwave hot-electron fluctuations suggests a non-traditional explanation of the behaviour in question [6,7].

Fluctuations originate at the microscopic level and provide with information on the processes responsible for device operation, reliability, and failure. The novel fluctuation-based approach is impelled by recent demonstration of strong correlation of microwave hot-electron fluctuations with RF performance and degradation of nitride HFETs [6–8]. The correlation has its genesis in the dissipation of the so-called longitudinal-optical (LO)-mode heat accumulated by the non-equilibrium LO phonons imprisoned in the channel that hosts the high-density hot-electron gas subjected to a high electric field (Fig. 2).

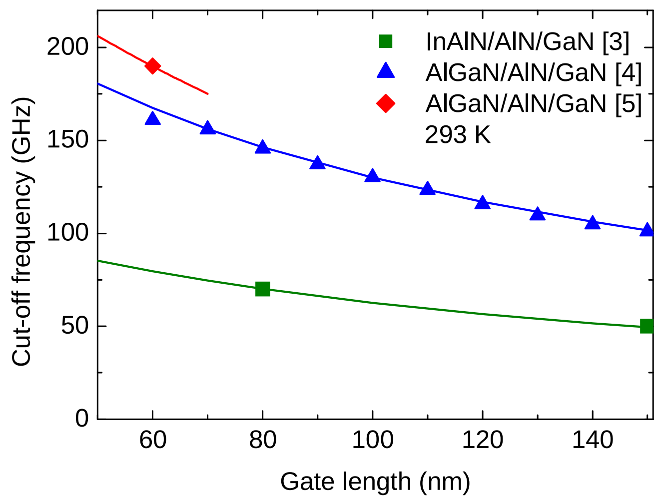


**Figure 1** Dependence of cut-off frequency on gate length for GaN HFETs with different 2DEG density in channels: $2.5x10^{13}$ $cm^{-2}$ (squares [3]), $2.07x10^{13}$ $cm^{-2}$ (triangles [4]), $1.4x10^{13}$ $cm^{-2}$ (diamond [5]). At a fixed gate length, cut-off frequency decreases as 2DEG density increases. Curves guide the eye.

At high fields present in a GaN channel, the electrons are displaced from equilibrium and become hot. Because electron–LO-phonon coupling is strong in highly ionic materials, such as GaN, the electrons tend to lose their heat mainly through emission of LO phonons (Fig. 2). The emitted LO phonons remain localized in the channel because their group velocity is very low. As a result, the LO-mode heat is accumulated; it cannot be dissipated or removed from the channel unless the non-equilibrium LO phonons are converted to some other phonon modes with higher group velocities,

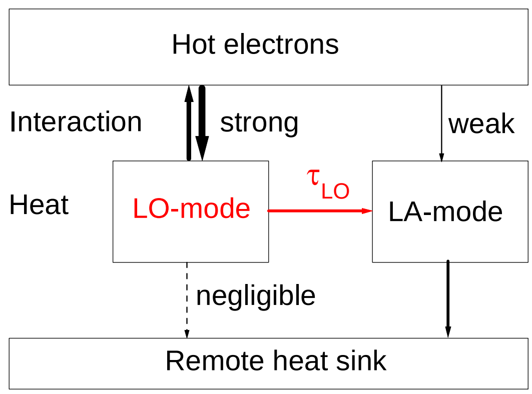


**Figure 2** Schematic routes for heat dissipation in a GaN channel. Hot electrons primarily lose their energy through emission of LO phonons. These in turn decay into LA modes before the heat is removed from the channel [10].

for example, longitudinal acoustic (LA) phonons. The conversion of the LO-mode heat into the LA-mode heat can be treated in terms of LO-phonon lifetime, associated with the decay of the LO phonons into other modes, for example, transverse optical (TO) and (mobile) LA modes through the route LO→TO+LA proposed for GaN some time ago [9]. In nitride 2DEG channels, the exact route of LO-phonon decay is not clearly understood but there is compelling experimental [6,10-12] and theoretical [13] evidence that plasmon-assisted process tends to dominate.

Hot-phonon effect is a short term used when accumulation and dissipation of LO-mode heat come into play. Figure 3 illustrates that, at a given applied electric field, the hot-phonon temperature is higher if the 2DEG density is higher [6,14,15]. Since hot phonons cause additional scattering of electrons [16], accumulation of LO-mode heat has an effect on hot-electron drift velocity and frequency performance of a HFET [7,17]. Data in Figures 1 and 3 are in strong correlation: the frequency performance of the HFETs is worse if the hot-phonon temperature is higher. Mitigating hot-phonon temperature with technological means is an important goal of HFET engineering.

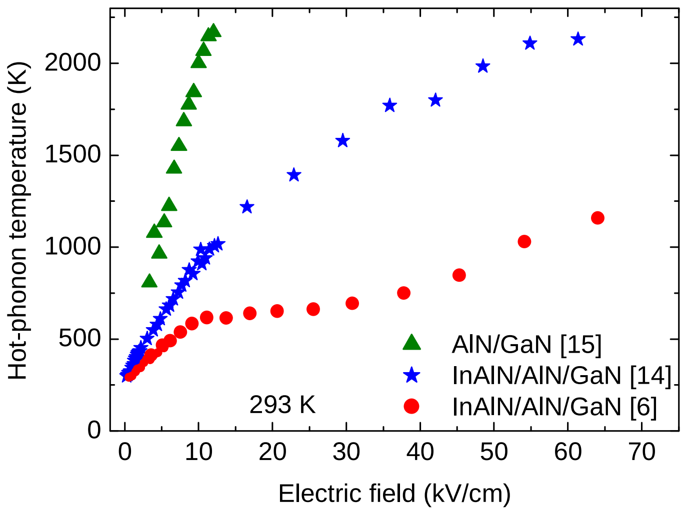


**Figure 3** Experimental dependence of hot-phonon temperature on electric field for GaN 2DEG channels with different 2DEG density: 8x$10^{12}$ $cm^{-2}$ (bullets [6]), 1.2x$10^{13}$ $cm^{-2}$ (stars [14]), 2.5x$10^{13}$ $cm^{-2}$ (triangles [15]). At a fixed electric field, hot-phonon temperature increases with 2DEG density.

The project deals with hot-phonon effects in nitride 2DEG channels and HFETs. The unsolved problem of heat dissipation is treated in terms of the hot-phonon lifetime responsible for conversion of the LO-mode heat into other modes. Section 2 of the report presents the novel fluctuation–dissipation technique for measurement of hot-phonon lifetime and its approval through comparison of the results with those available from other techniques. The experimental evidence that plasmons assist dissipation of the LO-mode heat is given in section 3. The fluctuation–dissipation technique is demonstrated to be the most powerful way for resolving signatures of plasmon–LO-phonon resonance in 2DEG channels through measuring dependence of the hot-phonon lifetime on the 2DEG density. Section 4 illustrates that the plasmon–LO-phonon resonance can be tuned in, at a fixed 2DEG density, with supplied electric power. Tuning of the resonance with gate voltage is illustrated in section 5 together with signatures of the resonance resolved in HFET frequency performance and HFET reliability.

## 2. Methods, Assumptions, and Procedures

Our measurements of hot-phonon lifetime are based on hot-electron fluctuations. Fluctuation-based technique [16] was developed and implemented after careful analysis of different sources of hot-electron fluctuations in voltage-biased 2DEG channels at microwave frequencies [18,19]. The results on hot-phonon lifetime are available for nitride-based 2DEG channels [6,11,16,20–23], arsenide-based 2DEG channels [24], $SiO_2/Si/SiO_2$ channels [25], and SiC [26]. For recent reviews see [10–12,27–29].

The measurements are carried out on gateless channels supplied with ohmic electrodes. The technique works best at electric fields and ambient temperatures where the electron–LO-phonon scattering is the dominant electron energy dissipation mechanism. The associated hot-electron fluctuations cause emission of microwave radiation (noise power) detected by a sensitive radiometer. The equivalent noise temperature, or simply noise temperature, is determined from the measured noise power. The measurements can be made before, during, and after the voltage pulse used to heat the electrons; short pulses of voltage allow one to control thermal walkout [14,18,21,27,28].

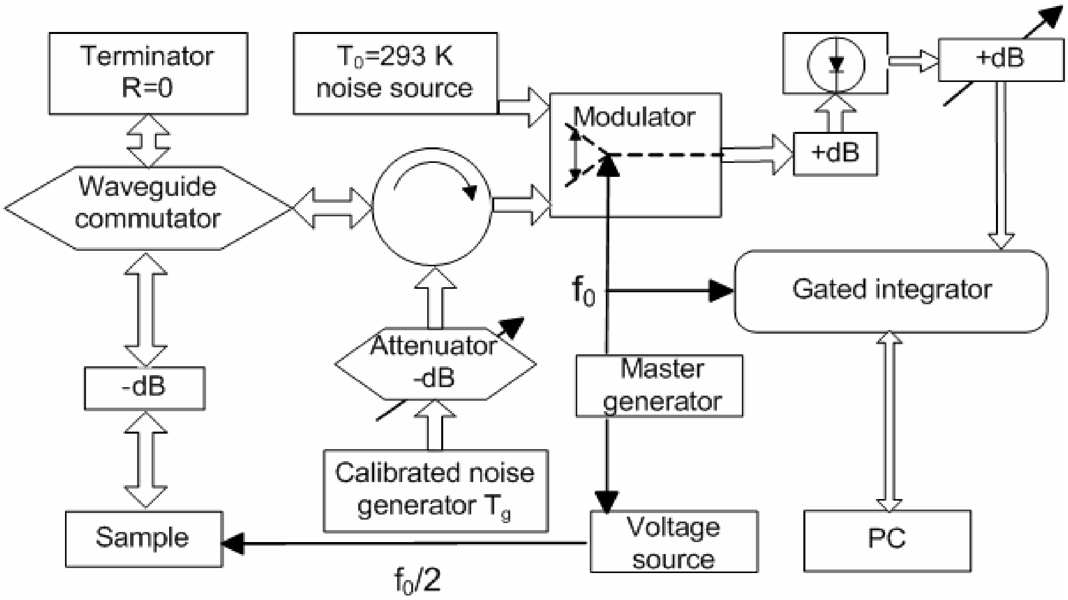


**Figure 4** X-band waveguide-type radiometric set-up for pulsed hot-electron noise temperature measurement [14].

A schematic circuit of the gated radiometric set-up is illustrated in Fig. 4 [14]. The sample is mounted into the waveguide, and the noise temperature is measured in the bias direction at 10 GHz before, during, and after the voltage pulse applied to the sample. The set-up includes JCA812 microwave low noise amplifiers and Stanford Research Systems modules (gated integrator and boxcar averager module SR250, Quad fast amplifier SR240A, and computer interface module SR245). Cascaded wideband (DC–350 MHz) SR240A amplifiers amplify the signal after the microwave detector before the gating. The module SR250 contains an exponential moving averager used for integration of the averaged noise power. The integrator is open for time interval from 10 ns to 10 μs for the integration of the noise power and comparison with the power of the known source of noise. Every second value is inverted before the averager, and the noise power difference is obtained. The averaged noise values are digitized in the computer module SR245 and loaded through RS232 interface to the PC for further averaging. Hand-written Labview software controls the measurements and the data processing. Sample mismatch is taken into account. The measurements include four steps used to obtain the noise temperature together with the sample reflection coefficient and the set-up parameters that include power amplification and additional noise generated by non-ideal waveguide components. The measurements before, during, and after the voltage pulse help to control the thermal walkout.

The hot-electron noise temperature $T_n(f)$ is determined from the available noise power $\Delta P_n(f)$ emitted by the hot electrons into a matched load (input of the measurement circuit):

$$T_n(f) = \frac{1}{k_B}\frac{\Delta P_n(f)}{\Delta f} \qquad (1)$$

where $k_B$ is the Boltzmann constant and $\Delta f$ is the frequency bandwidth around the frequency $f$.

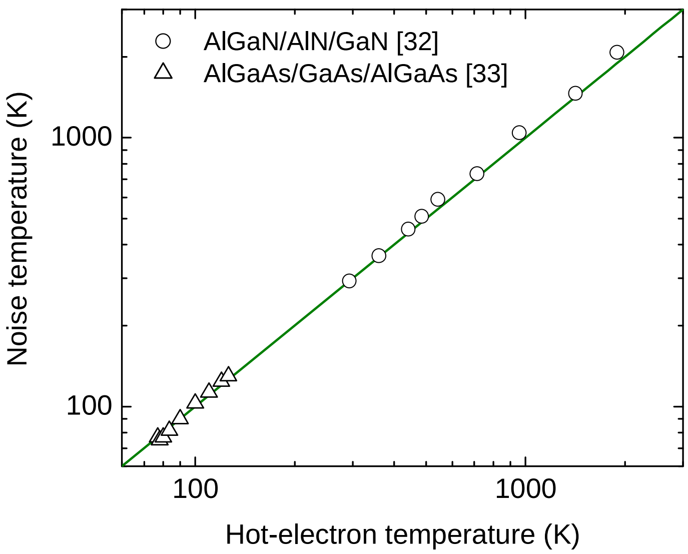


**Figure 5** Calculated dependence of noise temperature on hot-electron temperature for 2DEG channels located in AlGaN/AlN/GaN at 300K (circles [32]) and AlGaAs/GaAs/AlGaAs at 77K (open triangles [33]). Line is the hot-electron temperature.

Because of intense electron–LO-phonon interaction in GaN and high density of electrons in a 2DEG channel, the electron temperature can be introduced [30,31]. According to Monte Carlo simulation, the noise temperature $T_n$ is close to the hot-electron temperature $T_e$ [11,32] (Fig. 5, circles and line). A similar conclusion has been earlier reported for AlGaAs/GaAs/AlGaAs 2DEG channels [33] (open triangles). The hot-electron temperature approximation simplifies the theoretic treatment of the hot-phonon problem.

Originally, the hot-phonon lifetime $\tau_{LO}$ was estimated according to the Arrhenius-type expression for the dissipated power $P_d$ [16]:

$$P_d = \frac{\hbar\omega_{LO}}{\tau_{LO}} \exp(-\frac{\hbar\omega_{LO}}{k_B T_e}) \tag{2}$$

where $\hbar\omega_{LO}$ was the LO-phonon energy. Expression (2) fitted the experimental data in the range of not too high electron temperatures [16]. The activation energy equaled the LO-phonon energy; this fitting confirmed that acoustic phonons played a negligible role in the electron energy dissipation. Thus, the electron–LO-phonon interaction was the dominant electron energy dissipation mechanism (Fig. 2). Under steady-state conditions, the dissipated power equaled the supplied power: $P_d = P_s$. In a voltage-biased channel, the supplied electric power per electron was:

$$P_s = \frac{UI}{N_{el}} \tag{3}$$

where $U$ is the applied voltage, $I$ is the current, and $N_{el}$ is the number of electrons in the channel.

A more sophisticated way for estimating the hot-phonon lifetime is based on estimation of equivalent hot-phonon temperature [20,23,28]. When the electron–LO-phonon interaction is the dominant electron energy dissipation mechanism, the hot-electron energy dissipation rate, or the dissipated power, is determined by the temperatures of hot electrons and hot phonons, $T_e$ and $T_{LO}$. The electron energy dissipation includes spontaneous and stimulated emission of LO phonons by high-energy electrons and re-absorption of LO phonons by all electrons. Let us introduce equivalent occupancy of the hot-phonon modes $N_{LO}$ and express the power dissipated by an average electron as follows [34]:

$$P_d = \frac{\hbar\omega_{LO}}{\tau_{sp}}(1+N_{LO})p^- - \frac{\hbar\omega_{LO}}{\tau_{abs}} N_{LO} p^+ \tag{4}$$

where $\tau_{sp}$ is the mean time for spontaneous emission of an LO-phonon by a high-energy electron, $\tau_{abs}$ is the mean time for LO-phonon absorption by any of the electrons (the time "constants" $\tau_{sp}$ and $\tau_{abs}$ demonstrate weak variation with the electron energy), and the probabilities $p^{\pm}$ to find an electron ready either to emit (–) or absorb (+) an LO phonon are:

$$p^{\pm} = \int D(\varepsilon) f(\varepsilon)[1 - f(\varepsilon \pm \hbar\omega_{LO})] d\varepsilon / n_{2D} \tag{5}$$

where $\varepsilon$ is the electron energy, $D$ is the density-of-states function, $f(\varepsilon)$ is the electron-temperature-dependent Fermi–Dirac distribution function, and $n_{2D}$ is the 2DEG density (the sheet electron density in the 2DEG channel).

The occupancy $N_{LO}$ is obtained from Eq. (4) and the balance $P_d = P_s$; the equivalent hot-phonon temperature $T_{LO}$ is estimated according to Bose–Einstein function. Squares and bullets in Fig. 6 illustrate that, for a GaN 2DEG channel, the equivalent hot-phonon temperature is close to the hot-electron temperature (line); this behaviour is typical for an almost isolated hot electron–LO-phonon subsystem [16]. Moreover, because of the strong coupling inside the hot subsystem, the temperatures of the hot electrons and the hot-phonons relax together. In other words, the corresponding relaxation time constants acquire comparable values [20]:

$$\tau_{LO} \approx \tau_\varepsilon \tag{6}$$

where $\tau_\varepsilon$ is the hot-electron energy (temperature) relaxation time. Consequently, the hot-phonon lifetime can be estimated after Eq. (6) if the hot-electron energy relaxation time is measured. The hot-electron energy relaxation time, $\tau_\varepsilon$ , can be determined from the noise experiment [18–20]:

$$\tau_\varepsilon = k_B \frac{dT_e}{dP_s} \tag{7}$$

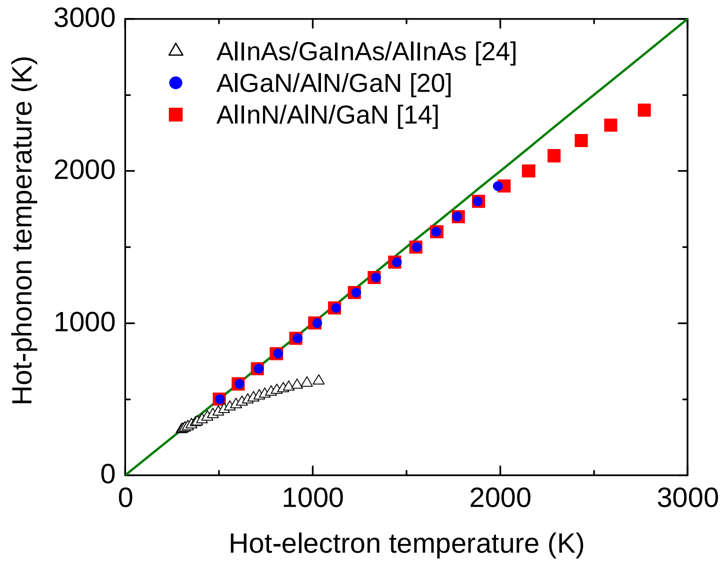


**Figure 6** Experimental dependence of equivalent hot-phonon temperature at room temperature for 2DEG channels located in AlInAs/GaInAs/AlInAs (triangles [24]), AlInN/AlN/GaN (squares \cite [14]), and AlGaN/AlN/GaN (bullets [20]). Line is the hot-electron temperature.

For illustration, consider experimental data on AlInAs/GaInAs/AlInAs structure with the 2DEG channel confined in the InGaAs layer [24]. This structure demonstrates a weaker coupling inside the hot electron–LO-phonon subsystem, as compared with the GaN structures, and the estimated hot-phonon temperature was up to 30% lower than the hot-electron temperature (Fig. 6, triangles, line). Anyway, the time constants of hot-phonon and hot-electron relaxation acquired different but comparable values [24].

Another way for estimating the hot-phonon lifetime follows from the dependence of the hot-phonon mode occupancy $N_{LO}$ on the supplied electric power $P_s$ (symbols in Figure 7). The dependence can be obtained from the experimental dependence of the hot-phonon temperature on the supplied power for GaN 2DEG channels [11,20]. The effective dynamic hot-phonon lifetime is introduced as follows [11]:

$$\tau_{LO} = \hbar\omega_{LO} \frac{dN_{LO}}{dP_s} \qquad (8)$$

The power-independent hot-phonon lifetime can be introduced at a low occupancy of hot-phonon states: $N_{LO} < 0.4$ (solid lines). The fitting of the experimental data is reasonably good. Blue line stands for the value $\tau_{LO}$ = 300 fs; this value is less than 25% lower than the hot-electron energy relaxation time estimated according to Eq. (8) for the same AlGaN/AlN/GaN structure [20]. The definition of the dynamic hot-phonon lifetime, Eq. (6) becomes of special importance when the lifetime depends on supplied power. The corresponding experimental data [6,10,11,23,28] for GaN 2DEG channels will be discussed later.

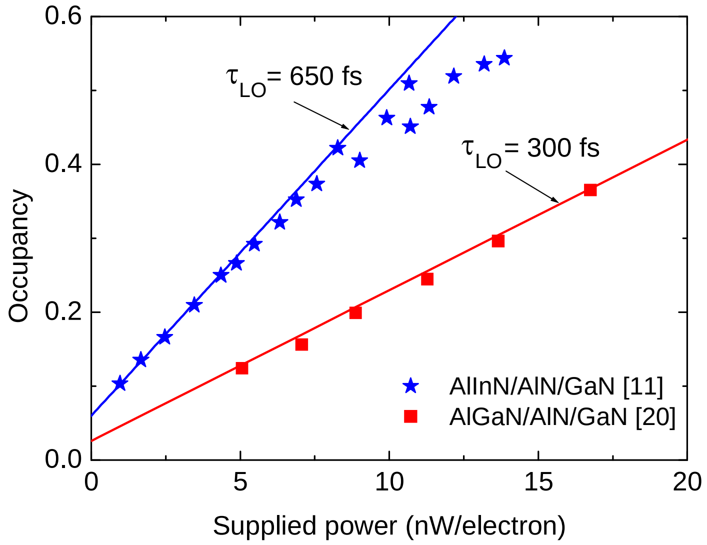


**Figure 7** Dependence of hot-phonon mode occupancy on supplied electric power for 2DEG channels: AlGaN/AlN/GaN (squares, after [20]) and InAlN/AlN/GaN (stars [11]). Fitted lines stand for $\tau_{LO}$= 300 fs (blue) and $\tau_{LO}$ = 650 fs (red).

The hot-phonon lifetime, estimated from the hot-electron fluctuations for AlGaN/GaN 2DEG channel (Fig. 8, red bullet [16]), is in good agreement with the value obtained from the independent time resolved pump–probe phonon-assisted inter-subband absorption experiment carried on a similar structure (star [35]). Thus, the fluctuation technique has received a solid approval.

The time-resolved pump–probe Raman experiment is the most reliable way for measuring the hot-phonon lifetime [36]. Photons of the probe beam are scattered by the LO phonons injected earlier by the pump pulse of a laser. The intensity of scattered light depends on the time delay of the probe pulse since the LO-phonon number decreases as the non-equilibrium LO phonons convert into other modes. The hot-phonon lifetime is obtained from relaxation of intensity of the anti Stokes line.

The fluctuation-based result for AlInAs/GaInAs/AlInAs 2DEG (Fig. 8, closed triangle [24]) is in a reasonable agreement with the extrapolated dependence on the carrier density (dashed curve) measured for GaAs by the Raman pump–probe technique (open triangles [36]). According to the Raman data for bulk for GaAs [36] and GaN [37], the hot-phonon lifetime monotonously decreases as the electron–hole density increases (open symbols). The results for bulk GaN (open circles [37]) are close to those (star, diamond [16,31]) for the AlGaN/GaN 2DEG channels when the electron density per unit volume is estimated as the sheet 2DEG density divided by the quantum well width at the Fermi energy.

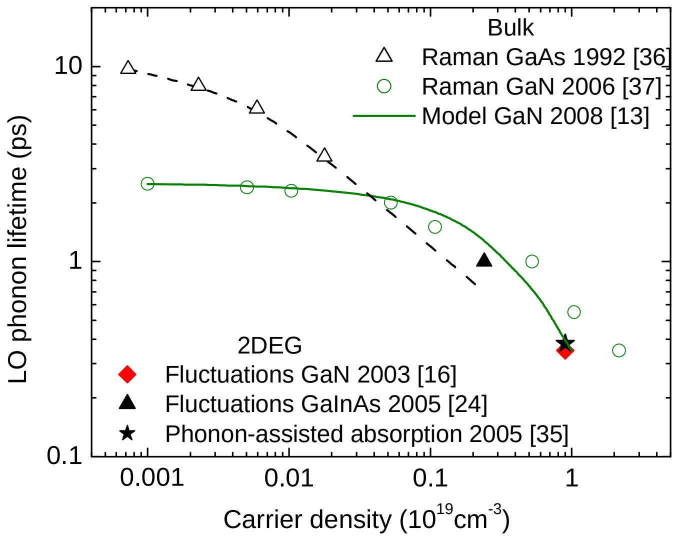


**Figure 8** Monotonous decrease of hot-phonon lifetime when carrier density increases. Raman data (open symbols): GaAs (open triangles [36]) and GaN (circles [37]). Fluctuations and inter-subband absorption (closed symbols): AlGaN/GaN (red diamond [16], star [35]) and AlInAs/GaInAs/AlInAs (triangle [24]). Solid curve is plasmon model for GaN [13]. Dashed curve guides the eye.

However, no lifetime datum is available from Raman experiments for the voltage-biased 2DEG channels that contain a high density of electrons at equilibrium and are used for HFET fabrication. Therefore, the fluctuation–dissipation technique is chosen for experimental investigation during the project. We measure dependence of hot-phonon lifetime on electron density and supplied electric power [6,10-12] beyond the ranges investigated by other techniques. Nominally undoped InAlN/AlN/GaN gateless structures and HFETs for this project were grown on c-plane semi-insulating GaN:Fe substrates (with a bulk resistivity of ~$10^9\Omega$-cm) in a low-pressure custom-designed organo-metallic vapor phase epitaxy (OMVPE) system at Virginia Commonwealth University (Richmond, VA) [6–8,23]. The growth was initiated with a 250 nm AlN nucleation layer, and followed with a 2–4 μm thick undoped GaN layer, a 1-nm-thick undoped AlN spacer layer, and a 18-nm-thick undoped InAlN barrier layer, and finally a ~2-nm-thick GaN cap layer. The 2DEG channel was located in the GaN layer. Coplanar ohmic Ti/Al/Ni/Au electrodes were annealed at 1120 K. For HFETs, a standard liftoff procedure was used to define source and drain contacts, to etch mesas for isolation, and to deposite Pt/Au gate contacts. The devices were not passivated. Schottky diodes, incorporated into the HFET masks, were fabricated alongside the HFET devices in order to determine the 2DEG electron density in the regions directly adjacent to the devices under test. X-ray diffraction was used to confirm the barrier layer thickness and composition.

## 3. Plasmon-assisted Decay of Hot Phonons

The monotonous decrease of the lifetime with the increase in the 2DEG density (Fig. 8, circles [37]) can be explained within the plasmon–LO-phonon model developed for GaN (solid curve [13]). According to the model, the hot-phonon lifetime decreases when the plasmon frequency increases and approaches the LO-phonon frequency at densities near $10^{19}$ $cm^{-3}$ in GaN [28]. A strong argument in favour of plasmon-assisted decay of hot phonons can be obtained from the experimental data on the lifetime at electron densities above the plasmon–LO-phonon resonance. As mentioned, the fluctuation technique is suitable for measuring the lifetime in the range of electron densities in question (Table 1).

Figure 9 illustrates the experimental data obtained from hot-electron fluctuations for different nitride heterostructures with 2DEG channels located in undoped GaN layer [6].

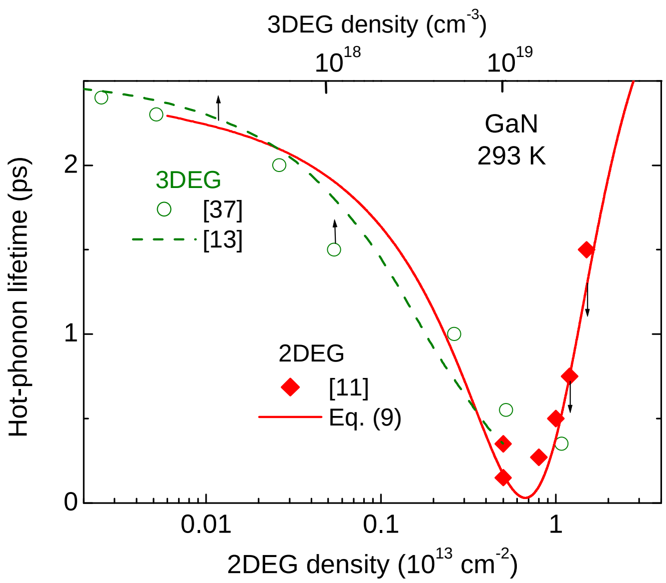


**Figure 9** Non-monotonous dependence of hot-phonon lifetime on carrier density in GaN and GaN-based 2DEG channels: Raman data (open circles [37]), fluctuations (closed diamonds, for references see Table 1). Solid curve is Eq. (9) Dashed curve is plasmon model for GaN [13].

**Table 1** Nitride heterostructures with 2DEG channels located in GaN [11]

| Barrier mole ratio, % | | | Spacer | 2DEG density $10^{13}$cm$^{-2}$ | Hot-phonon lifetime, fs | Reference |
|---|---|---|---|---|---|---|
| Al | In | Ga | | | | |
| 15 | -- | 85 | none | 0.5 | 350 | [16] |
| 22 | -- | 78 | GaN/AlN | 0.5 | 150 | [40] |
| 33 | -- | 67 | AlN | 1.0 | 500 | [20] |
| 82 | 18 | -- | AlN | 0.8 | 270 | [6] |
| 82 | 18 | -- | AlN | 1.2 | 750 | [28] |
| 82 | 18 | -- | AlN | 1.5 | 1500 | [11] |

The experimental results of Fig. 9 can be approximated with a simple resonance curve [12,38,39]:

$$\tau = a\left[1+\frac{b}{\left(\sqrt{n}-\sqrt{n_{res}}\right)^2+c}\right]^{-1} \qquad (9)$$

where $n_{res}$ is the fitting parameter—the resonance 2DEG density for the fastest decay of hot phonons. The resonance curve (solid) fits the experimental data on bulk GaN as well (open circles). Solid curve (Fig. 9) is drawn for $n_{res}$ = 6.7x10$^{12}$ cm$^{-2}$. When the average electron density per unit volume is estimated as the sheet 2DEG density divided by the quantum well width at the Fermi energy, the result is 1.3x10$^{19}$ cm$^{-3}$; this value is comparable with the electron density where the plasmon–LO-phonon resonance takes place in bulk GaN [28].

An additional argument in favour of the plasmon-assisted decay has been obtained through comparison of the results for nitride and arsenide 2DEG channels [11]. Supposing that this interpretation were correct, the resonance would take place at a lower 2DEG density in the arsenide channels where the electron effective mass and the LO-phonon energy are lower as compared with those in GaN. The hot-phonon lifetime was estimated for the GaInAs 2DEG channel at sheet density of 2.3x10$^{12}$ cm$^{-2}$ [24] (Fig. 8, closed triangle), but no other result is known

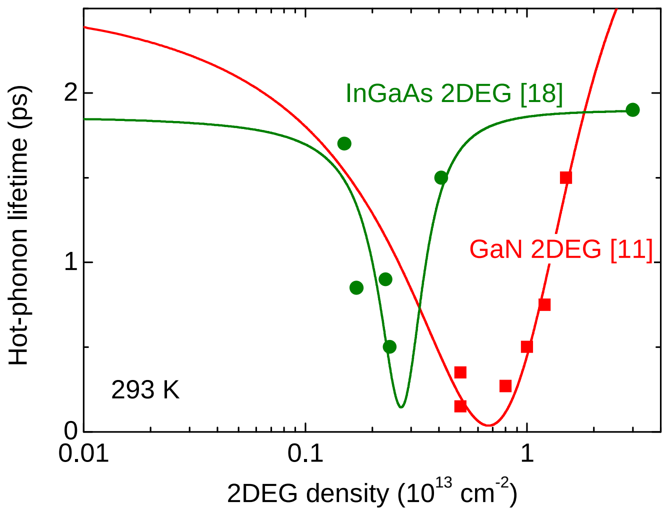


**Figure 10** Resonance-type dependence of hot-phonon lifetime on 2DEG density for channels confined in GaN (red squares [11]) and InGaAs (green bullets [18]). For references see Tables 1 and 2. Solid curves illustrate Eq. (9).

for us. However, after Eq. (6), the hot-phonon decay is the bottleneck for the hot-electron energy relaxation time [24], and the plasmon effect can be illustrated by the available data on the energy relaxation at different 2DEG density [18] (Fig. 10, green bullets). As expected, the resonance is resolved (green line) at the 2DEG density that is lower in the GaInAs 2DEG channels as compared with that for the GaN-based structures (red line). The green curve in Fig. 10 is Eq. (9), where $n_{res}$ = 2.7x10$^{12}$ cm$^{-2}$.

**Table 2** Arsenide heterostructures with 2DEG channels located in $Ga_{1-x}In_xAs$

| $x$ | Composition | 2DEG density $10^{13}cm^{-2}$ | Reference |
|---|---|---|---|
| 67 | $InP/Ga_{1-x}In_xAs/ InP$ | 0.17 | [18] |
| 80-53 | $Al_{0.48}In_{0.52}As/Ga_{1-x}In_xAs/ Al_{0.48}In_{0.52}As/InP$ | 0.15 | [18] |
| 70/53 | $Al_{0.48}In_{0.52}As/Ga_{1-x}In_xAs/ Al_{0.48}In_{0.52}As/InP$ | 0.23 | [18] |
| 53 | $Al_{0.48}In_{0.52}As/Ga_{1-x}In_xAs/ Al_{0.48}In_{0.52}As/InP$ | 0.24 | [18] |
| 70 | $Al_{0.48}In_{0.52}As/Ga_{1-x}In_xAs/ Al_{0.48}In_{0.52}As/InP$ | 0.41 | [18] |
| 53 | $Al_{0.48}In_{0.52}As/Ga_{1-x}In_xAs/ Al_{0.48}In_{0.52}As/InP$ | 3.0 | [41] |

As predicted, the resonance 2DEG density is lower in the investigated arsenide 2DEG channels (Fig. 10, green curve and bullets) as compared with their nitride counterparts (red curve and squares). Since LA phonons are thought to take part in dissipation of the LO-mode heat (Fig. 2), the resonance 2DEG density differs from (but is close to) the 2DEG density where the plasmon–LO-phonon resonance takes place.

## 4. Power-tuned Resonance Decay of Hot Phonons

Schrödinger–Poisson calculations show that the electron density profile depends on the hot-electron temperature in the 2DEG channel [10]. Because of electron gas expansion under heating, the peak value of the three-dimensional density decreases as the hot-electron temperature increases (Fig. 11). In accord with data of Fig. 11, the plasma frequency decreases when the electron gas is heated up at a fixed 2DEG density (Fig. 11).

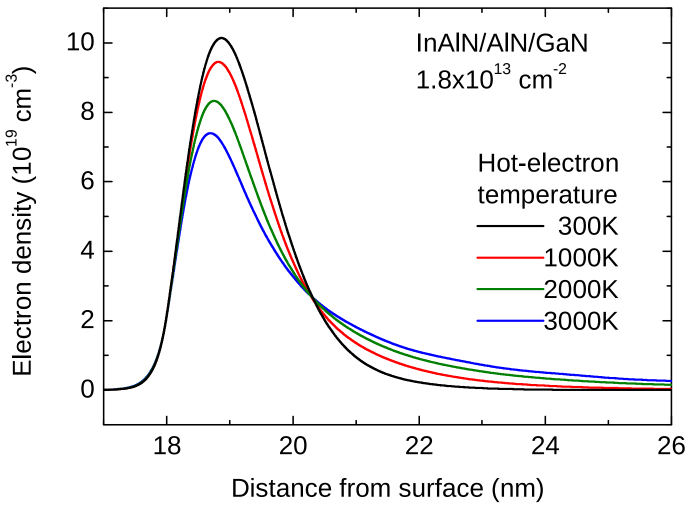


**Figure 11** Calculated electron density profile in an InAlN/AlN/GaN structure at different hot-electron temperatures: 300 K (black curve), 1000 K (red curve), 2000 K (green curve), and 3000 K (blue curve) [10].

As discussed in Section 3, plasmons assist conversion of LO phonons into LA phonons, and the fastest decay of hot phonons takes place in the vicinity the plasmon–LO-phonon resonance. Since the plasma frequency depends on the hot-electron temperature, this, in turn, changes the position of the plasmon–LO-phonon resonance on the 2DEG density scale [6]. When the 2DEG density is increased at a slope of $2.7 \times 10^{9}$ $cm^{-2}K^{-1}$ [39] (Fig. 12, green line and open circles), the calculated peak value remains independent of the electron temperature.

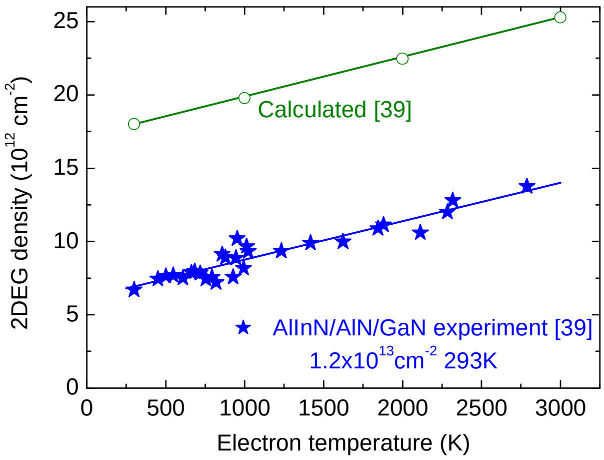


**Figure 12** Dependence on hot-electron temperature of the resonance 2DEG density (stars), and the 2DEG density required to keep the peak electron density unchanged under thermal expansion of 2DEG gas (circles ) [39].

The shift of the resonance 2DEG density with the supplied power can be estimated from the power-dependent hot-phonon lifetime. In experiment, the lifetime is obtained according to Eq. (8) from power-dependent occupancy of hot-phonon modes. At a low supplied power, the lifetime is almost independent of the power, but essential changes develop at high supplied powers [6,11]. The results for an AlInN/AlN/GaN heterostructure are shown in Fig. 13: the lifetime decreases

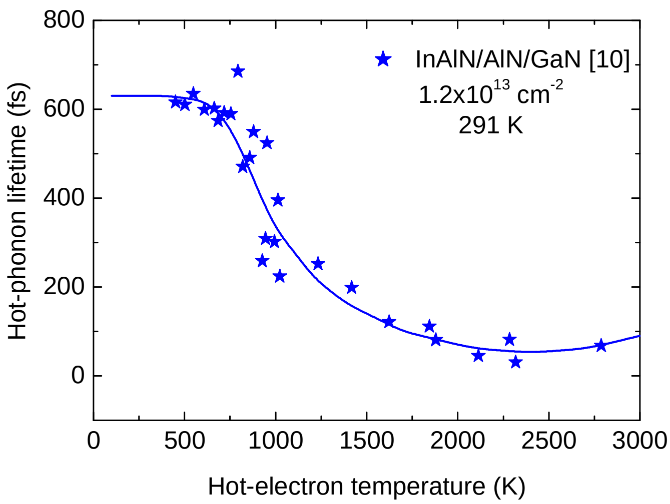


**Figure 13** Experimental dependence of hot-phonon lifetime on hot-electron temperature for AlInN/AlN/GaN structure with 2DEG channel subjected to electric field (stars [10]). The 2DEG density is $1.2 \times 10^{13} cm^{-2}$. Curve guides the eye.

from the low-power value of above 600 fs and reaches 60 fs at the hot-electron temperatures above 2000 K [10].

The procedure to obtain the shift (Fig. 12, stars) from the experiment (Fig. 13, stars) is as follows. Each value of the lifetime (Fig. 13) is fitted with the resonance-type expression given by Eq. (9) where the coefficients ***a***, ***b***, and ***c*** are assumed independent of the hot-electron temperature. The fitting yields the dependence of the resonance 2DEG density on the hot-electron temperature shown in Fig. 12 (stars). The blue line in Fig. 12 is drawn for 2.6x10$^{9}$ cm$^{-2}$K$^{-1}$. The slope of the shift of the resonance 2DEG density (Fig. 13, blue line, stars) is close to the shift estimated from the Schrödinger–Poisson calculations (green line, circles). According to the blue line of Fig. 12, the shortest hot phonon lifetime is reached at ~2400 K if the 2DEG density is 1.2x10$^{13}$cm$^{-2}$.

Figures 12 and 13 suggest that the resonance can be tuned in, at a given 2DEG density, with the hot-electron temperature that depends on the supplied power. For example, at the 2DEG density of 1.2x10$^{13}$ cm$^{-2}$, the lifetime possibly reaches the minimum value at the resonance temperature of 2500 K (Fig. 13, curve).

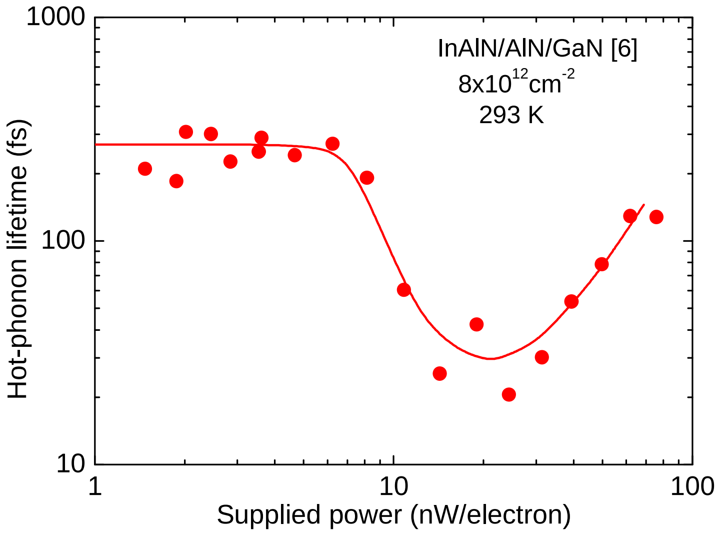


**Figure 14** Experimental dependence of hot-phonon lifetime on supplied power for AlInN/AlN/GaN structure (bullets [6]). The 2DEG density is 8x10$^{12}$cm$^{-2}$. Line guides the eye.

The resonance hot-electron temperature is considerably lower if the 2DEG density is closer to the resonance 2DEG density of 6.7x10$^{12}$ cm$^{-2}$ estimated at a low supplied power (Fig. 9, red curve). The blue line in Fig. 12 helps to estimate the resonance temperature as ~700 K when the 2DEG density is 8x10$^{12}$ cm$^{-2}$. This possibility is demonstrated in Fig. 14 where the minimum value for the lifetime of ~30 fs is reached at the resonance power of ~20 nW/electron [6]. To reiterate, the fluctuation technique is the way for observing the plasmon–LO-phonon resonance that is tuned in with the electric power supplied to a 2DEG channel. The tuning with the supplied power is a new way for achieving the ultrafast dissipation of the LO-mode heat [11].

## 4. Signatures of the Resonance in HFET Performance

The study of microwave fluctuations puts a solid background for considering the ultrafast processes responsible for dissipation of the LO-mode heat. Figures 9, 12, and 14 summarize the main results on the observed non-monotonous dependence of the hot-phonon lifetime on the 2DEG density and the supplied power. The plasmon-assisted resonant behavior of the lifetime is demonstrated through the experiments carried out on gateless 2DEG channels.

A longer hot-phonon lifetime introduces a stronger scattering of electrons and causes a lower drift velocity (Fig. 15) [16]. In particular, the LO-phonon emission rate by an electron increases in proportion with $1+N_{LO}$, and the LO-phonon absorption rate increases proportional to $N_{LO}$ where $N_{LO}$ is the non-equilibrium occupancy of the involved hot-phonon modes. When an event of emission of an LO phonon is followed with an absorption event of another LO phonon, the resultant change in the electron energy is negligible, but the direction of motion changes considerably; as a result, the electron drift velocity reduces. A shorter hot-phonon lifetime leads to a lower occupancy $N_{LO}$, and in fact a higher drift velocity of electrons has been obtained through Monte Carlo simulation (Fig. 15) [16]. The effect is stronger at higher electric fields. Our next goal is resolve similar signatures of the resonance in HFET performance and reliability.

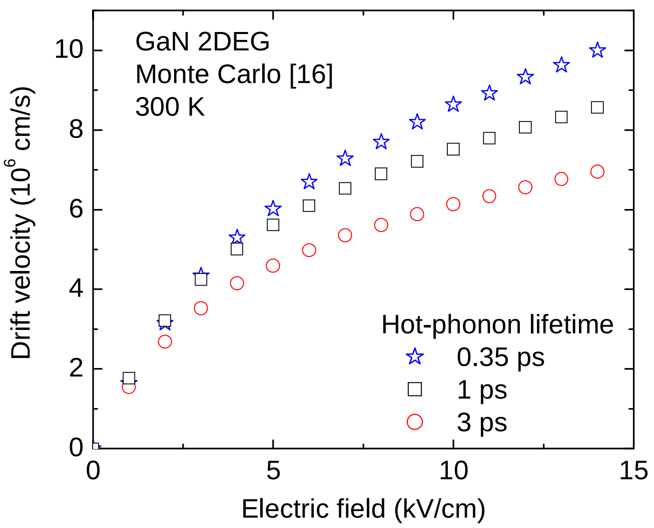


**Figure 15** Simulated dependence of hot-electron drift velocity on applied electric field for AlGaN/GaN 2DEG channel [16]. Symbols stand for different hot-phonon lifetime: 3 ps (circles), 1 ps (squares), and 0.35 ps (stars).

Since the hot-phonon lifetime demonstrates the resonance-like dependence on the 2DEG density (Fig. 9), the electron drift velocity and the associated frequency performance of a HFET should contain a similar signature of the resonance. Figure 16 illustrates the statement with the data on the drift velocity extracted from the transit time obtained from unity gain cut-off frequency measured for an InAlN/AlN/GaN HFET [7]. On-wafer microwave measurements from 2 to 20GHz were carried out with an HP8510B vector network analyzer, which was calibrated to the probe tips with an impedance standard substrate and the simple short, open, load, through (SOLT) calibration method. The S-parameters were collected under many DC bias conditions and subsequently were used to compute the small signal current gain, $H_{21}$. By collecting small signal current gain cutoff frequencies at various bias conditions, we were able to perform Moll's transit time analysis [42]. The 2DEG density under the gate electrode was controlled with the gate voltage. The results show the signature of the resonance at the 2DEG density of $n_{res}$ = 9.5x10$^{12}$ cm$^{-2}$ as evidenced through fitting the results with inverted Eq. (9) (Fig. 16, curve). The fitted resonance 2DEG density (Fig. 16, curve) together with the results of Fig. 12 (blue line, stars) allows one to estimate the hot-electron temperature in the channel under the gate. The hot-electron temperature is slightly above 1200 K.

Figure 16 demonstrates non-monotonically varying electron drift velocity in InAlN/AlN/GaN HFET structures (determined from an examination of the current gain cut off frequency under a fixed source–drain bias). This behavior is associated with the non-monotonic change in hot-phonon lifetime obtained in an independent experiment on a gateless 2DEG channel. Since the effect of hot phonons is deleterious for device performance, we propose that optimal performance can only be expected when the device is operating under the optimal bias conditions in which the 2DEG density associated with the given bias condition is congruent with the value associated with the shortest hot-phonon lifetime.

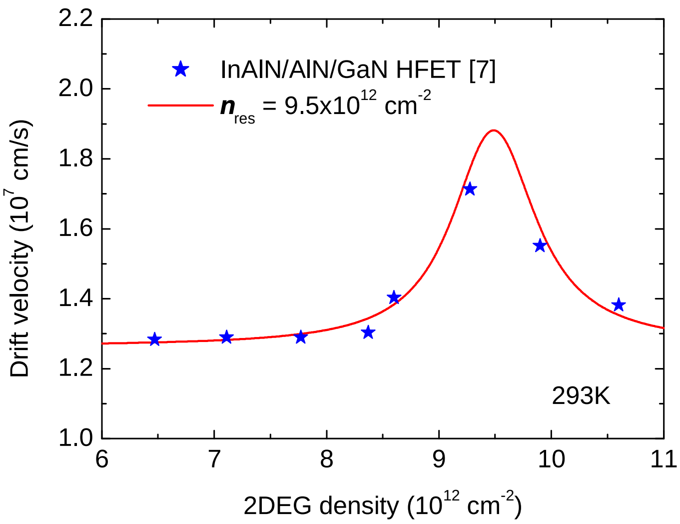


**Figure 16** Dependence of electron drift velocity on 2DEG density for InAlN/AlN/GaN HFET (stars [7]). Solid curve is inverted Eq. (2) for $n_{res}$ = 9.5x10$^{12}$ cm$^{-2}$ .

In a similar way, the signature of the resonance has been resolved in an independent experiment on device reliability [8]. The degradation of InAlN/AlN/GaN HFETs caused by a fixed amount of charge transported along the channel at a fixed drain voltage (Fig. 17, stars) correlates with Eq. (9) (curve). High electric field stress measurements were carried out at room temperature on a set of InAlN/AlN/GaN HFETs. The degradation rate as a function of the average electron density in the GaN channel (as determined by gated Hall bar measurements for the particular gate biases used), has a minimum for electron densities around 1 x 10$^{13}$ cm$^{-2}$, and tends to follow the hot-phonon lifetime dependence on electron density (Fig. 17, curve). The observations are consistent with the buildup of hot phonons and their ultrafast decay at about the same electron density in the gateless

2DEG channel when the shift of the resonance with the hot-electron temperature is taken into account in the discussed way (see Figs. 11–14). Again, after Fig. 12, the hot-electron temperature in the channel under the gate is estimated to be ~1400 K under the optimal (resonance) conditions, but the temperatures of the hot electrons and the hot phonons are essentially higher away from the resonance where the hot-phonon lifetime is may times longer (Fig. 17, solid curve). Because the hot phonons have negligible group velocity, we believe that the hot phonons build up and cause accumulation of the LO-mode heat, unless the heat is rapidly converted into longitudinal acoustic phonons. The observed strong correlation of HFET degradation and hot-phonon lifetime (Fig. 17) likely causes defect generation (aggravated by the existing defects). These findings call for modified approaches in modeling device degradation.

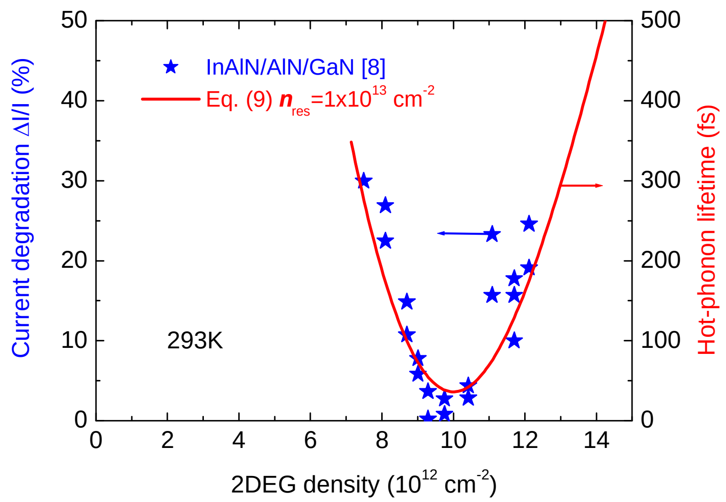


**Figure 17** Drain current degradation of InAlN/AlN/GaN HFETs (stars [8]) correlates with hot-phonon lifetime (curve). Curve is Eq. (9) when $n_{res}$ = 1x10$^{13}$ cm$^{-2}$.

The signatures of the resonance demonstrate that the optimal HFET frequency performance (Fig. 16) and the optimal HFET reliability (Fig. 17) are closely associated with the hot-phonon decay. In agreement with the resonance concept, the cut-off frequency increases as the 2DEG density approaches the resonance value from both sides: from the low 2DEG density side and from the high 2DEG density side. Apparently, the results of Fig. 1 deal with the high-density wing above the resonance where the electron drift velocity and the cut off frequency of a HFET decrease as the 2DEG density increases. This correlation suggests that ultrafast dissipation of the LO-mode heat is a prerequisite for the fastest operation and the slowest degradation of nitride HFETs.

## 5. Main Conclusions

The experimental investigation of fluctuations is a source of information on fast and ultrafast processes responsible for HFET performance. A novel fluctuation-based approach, based on hot-electron velocity fluctuations measured at a microwave frequency, is used for prediction of nitride HFET operation and failure. The following statements summarize the main results:

1. Resonance-type dependence of hot-phonon lifetime on 2DEG density is resolved from fluctuations.
2. The optimal density for ultrafast dissipation of LO-mode heat is estimated for 2DEG channels located in GaN and InGaAs.
3. The optimal 2DEG density depends on the supplied power.
4. HFET degradation is slower and operation is faster when LO-mode heat is dissipated faster.
5. Signatures of plasmons are found in fluctuations, hot-phonon lifetime, electron drift velocity, HFET cutoff frequency, and HFET reliability.

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# List of Symbols, Abbreviations, and Acronyms

HFET – hetereostructure field effect transistor
2DEG – two-dimensional electron gas
2DEG density – electron sheet density
3DEG – three-dimensional electron gas
3DEG density – electron density per unit volume
RF – radio frequency
X-band – microwave frequency band near 10 GHz
cut-off frequency – unity gain frequency
millimeter-wave frequencies – above30 GHz, below 300 GHz
X-ray diffraction – diffraction of Roentgen rays
JCA812 – microwave low noise amplifier
SR250 – gated integrator and boxcar averager module (Stanford Research Systems)
SR240A – quad fast amplifier (Stanford Research Systems)
SR245 – computer interface module (Stanford Research Systems)
RS232 – interface module
Labview – computer software
PC – personal computer
OMVPE – organo-metallic vapor phase epitaxy
heterojunction – monocrystallic interface of two semiconductors with different bandgap
heterostructure – monocrystallic structure that contains one or more heterojunctions
LA phonons – longitudinal acoustic phonons
LO phonons – longitudinal optical phonons
TO phonons – transverse optical phonons
LO-mode heat – heat accumulated by non-equilibrium LO phonons
hot electrons – non-equilibrium high energy electrons
hot phonons – LO phonons launched by hot electrons
hot-phonon lifetime – time constant for conversion of hot phonons into migrant modes
plasmons – quanta of collective vibrations of electrons
plasmon–LO-phonon resonance – plasmon energy equals LO-phonon energy
thermal walkout – time-dependent variation of measurables caused by device self-heating
ultrafast – in subpicosecond range
$a$, $b$, and $c$ are the coefficients in Eq. (9)
$f$ is the frequency
$f(\varepsilon)$ is the electron-temperature-dependent Fermi–Dirac distribution function
$\hbar\omega_{LO}$ is the LO-phonon energy
$I$ is the current
$k_B$ is the Boltzmann constant
$n_{2D}$ is the 2DEG density
$N_{el}$ is the number of electrons in the channel
$N_{LO}$ is the hot-phonon mode occupancy
$n_{res}$ is the resonance 2DEG density
$p^{\pm}$ are the probabilities to find a suitable electron
$\Delta P_n(f)$ is the available noise power
$P_d$ is the dissipated power per electron

$P_s$ is the supplied electric power per electron
$T_n(f)$ is the hot-electron noise temperature
$T_e$ is the hot-electron temperature
$T_{LO}$ is the hot-phonon temperature
$\tau_{LO}$ is the hot-phonon lifetime
$\tau_{sp}$ is the mean time for spontaneous emission of an LO-phonon by a hot electron
$\tau_{abs}$ is the mean time for LO-phonon absorption by any of the electrons
$\tau_{\varepsilon}$ is the hot-electron energy (temperature) relaxation time
$U$ is the applied voltage.