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MICROWAVE NOISE TECHNIQUE FOR MEASUREMENT OF HOT-ELECTRON ENERGY RELAXATION TIME AND HOT-PHONON LIFETIME *

E. Šermukšnis, J. Liberis, and A. Matulionis

Semiconductor Physics Institute, A. Goštauto 11, LT-01108 Vilnius, Lithuania
E-mail: sermuksnis@pfi.lt

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Gated modulation-type radiometric technique for microwave noise measurement is upgraded for convenient investigation of hot-electron energy relaxation and hot-phonon dynamics in a channel with a high-density electron gas. The technique is applied to a GaN-based structure held at 80 and 293 K channel temperature. The results are discussed in terms of hot-phonon effect on hot-electron energy relaxation. The hot-phonon lifetime, estimated from the noise analysis, is compared with the values obtained by more traditional techniques.

Keywords: GaN-based channels, hot electrons, hot phonons, microwave noise

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1. Introduction

Progress in semiconductor electronics is mainly associated with rapid shrinking of device dimensions. In order to achieve high currents needed for high power performance, the active region of a device usually contains a high electron density and operates at a strong electric field. This implies specific conditions for hot-electron energy relaxation. The accelerated electrons dissipate their excess energy on longitudinal optical (LO) phonons, and the latter tend to accumulate in the active region [1]. The accumulation causes additional scattering for the drifting electrons; the effect depends on the rate of disintegration of the non-equilibrium phonons into acoustic and other vibration modes [1]. The non-equilibrium LO phonons are called hot phonons [2]; the associated effects are often treated in terms of hot-phonon lifetime.

Subpicosecond pump-probe Raman scattering is the most direct technique for measurement of hot-phonon lifetime in a semiconductor [3]. The lifetime is determined from the decay of intensity of anti-Stokes line after the pump pulse. The problems arise when the channel dimensions shrink: thus, the technique has never been applied for the lifetime measurement in a single two-dimensional electron gas (2DEG) channel of importance for high-speed field-effect transistors [1]. Unlike this, the current fluctuations are generated exactly where the current flows. As a result, the noise technique for the lifetime measurement [4] is applicable to 2DEG and 3DEG channels. Supposing that the electron density per unit volume is the same, the noise technique yields the lifetime in GaN-based 2DEG channels [1, 4] comparable with the values obtained by the Raman technique for bulk GaN [3].

In this work, the main attention is paid to advancement of microwave noise technique for experimental investigation of electron scattering by hot phonons. The text is structured as follows. A block diagram of the gated-radiometric set-up is presented and principles of operation are explained. The main characteristics of the upgraded system are given together with explanations of stochastic signal measurements. Equations illustrate how one can extract the equivalent noise temperature of hot electrons from the measured noise power and the complementary data. A GaN-based channel is used as an example for illustration of the technique in action. The range of electric field and temperature is selected where the electron-LO-phonon scattering is the dominant energy dissipation mechanism. In this range, the noise temperature almost equals the hot-electron temperature, the power dissipation is activated by the hot-

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electron temperature, the activation energy equals to the LO-phonon energy. The non-equilibrium LO phonons are taken into account in order to interpret the experiment data in terms of hot-phonon lifetime.

2. Microwave noise technique

Noise temperature Tn of a resistor is obtained from the measured noise power. The noise power, dissipated by the resistor into a matched load, is called the available noise power P_n:

$$P_\mathrm{n} = k_\mathrm{B} T_\mathrm{n} \Delta f \,, \tag{1}$$

where k_B is the Boltzmann constant and Δf is the bandwidth at which the noise power is measured. The available noise power differs from the measured noise power if the impedances of the sample and the load do not match. The mismatch is taken into account in different ways [5].

At equilibrium, the noise temperature is the same as the sample temperature. When the electrons are displaced from equilibrium by the applied electric field, the electron temperature exceeds that of the lattice [5]. As a rule, the longitudinal noise temperature of hot electrons exceeds the electron temperature since additional sources of noise act in the bias direction; noise due to electron temperature fluctuations, inter-subband noise, real-space transfer noise, shot noise are several examples [5–7]. On the other hand, the transverse noise temperature approximately equals the electron temperature. The transverse hot-electron noise can be measured on four terminal samples but these measurements are complicated [8].

Our measurements of the longitudinal noise temperature follow the procedure described in detail in Ref. [6]. The noise temperature of hot electrons is measured at 10 GHz in the direction of bias, the bandwidth ($\Delta f = 1$ GHz) is mainly determined by the microwave amplifier. Figure 1 shows the schematic block circuit of the advanced gated radiometric set-up. A sample under test is mounted inside the waveguide and subjected to voltage pulses. The hot electron noise is generated during the voltage pulse. The pulse duration is short in order to avoid channel self-heating. The noise power emitted by the hot electrons is directed to the modulator through the waveguide commutator and the circulator, is amplified by the microwave low-noise amplifier, and detected by the microwave detector. The detector signal is also amplified and forwarded to the gated radiometer where the signal (proportional to the microwave noise power) is measured at appropriate time moments. The radiometer gate is opened twice during the voltage pulse repetition period $2/f_0$ in order to compare the noise power due to the hot electrons with that of the standard noise source kept at a known temperature ($T_0 = 293$ K). The both signals are subtracted later in the radiometer.

Only a part of the hot electron noise power is emitted because of reflection if the impedances of the sample and the waveguide do not match. The reflection coefficient ρ depends on the differential resistance of the sample, while the resistance itself depends on the applied electric field and the temperature. The mismatch effect is taken into account as follows. Supposing that the sample is under bias and the calibrated noise generator is on, the noise power x_ng detected by the radiometric set-up after the subtraction can be written as [6]

$$x_\mathrm{ng} = \lambda \big[T_\mathrm{n}(1-\rho) + T_\mathrm{g}\rho - T_0 \big] \,, \tag{2}$$

where T_g is the known noise temperature of the calibrated noise generator, T_n is the sample noise temperature, and T_0 is the room temperature; λ is the transfer function which takes into account the amplification and the other linear operations processed in the radiometer.

In order to obtain ρ, the noise generator is switched off and the additional measurement is made for the biased sample:

$$x_\mathrm{n} = \lambda \big[T_\mathrm{n}(1-\rho) + T_0\rho - T_0 \big] \,, \tag{3}$$

where $T_0\rho$ is the contribution due to the attenuator.

Equations (2) and (3) can be used to find ρ and T_n. In order to obtain λ, the waveguide commutator replaces the sample with the terminator (short-circuit element). In this case, the detected power x_g is

$$x_\mathrm{g} = \lambda \big[T_\mathrm{g} - T_0 \big] \,. \tag{4}$$

If some additional noise sources or attenuators exist in the waveguide line, they generate additional noise. Their contribution should be taken into account in Eqs. (2)–(4).

Stanford Research Systems NIM modules are used: gated integrator and boxcar averager module SR250, Quad fast amplifier SR240A, and computer interface module SR245. The gate width of SR250 can be adjusted from 2 ns to 15 μs for integration of the noise power while the gate is open. Cascaded wideband (DC-350 MHz) SR240A amplifiers amplify the signal after the microwave detector before the gating in order to achieve the optimal signal needed for the radiometer. Each integrated noise value is averaged by the exponential moving averager contained in SR250. Every second value can be inverted before the averager. The

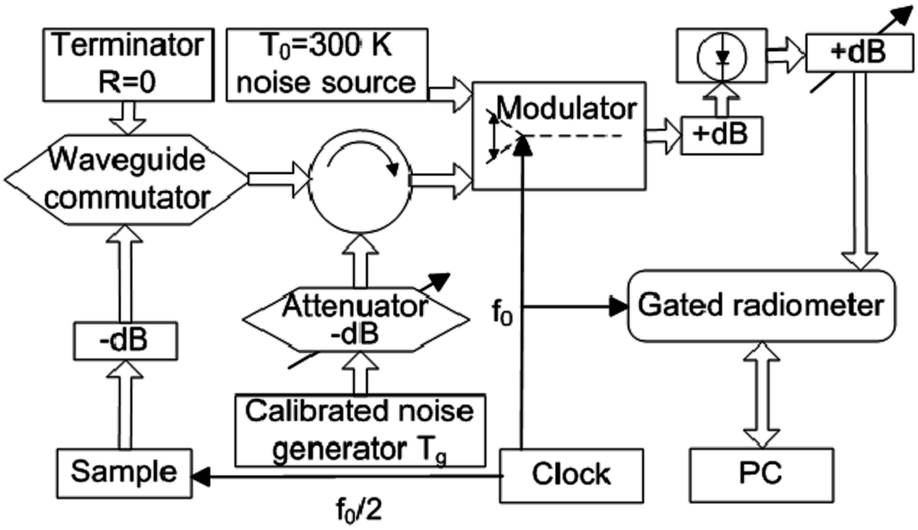

Fig. 1. Gated radiometric set-up for hot-electron noise measurements at X band microwave frequency (for details see text).

inversion together with the averaging serves as subtraction. The computer module SR245 is connected with PC by RS232 interface. The averaged noise values are digitized in the computer module and loaded to the PC for further averaging. Our original Labview program is used to control the computer module and process the loaded noise values. The moving averaging in the radiometer and averaging in the PC are needed in order to increase the accuracy when the integration time is short. Standard deviation of the mean value is inversely proportional to square root of the averaging time, thus, after N averages taken in PC, the total averaging time increases N times. The voltage repetition frequency ($f_0 < 100$ Hz) is relatively low in order to avoid sample self-heating. Because of long time needed to obtain a desired accuracy, the slow drift of the system is taken into account by calculating the power spectra of many averaged values.

3. Sample

The investigated sample is GaN / AlGaN / GaN / AlN / GaN heterostructure with a 2DEG channel designed, grown, and processed at University of California at Santa Barbara for a microwave high-power field-effect transistor [9]. The heterostructure is grown by metal-organic chemical vapour deposition onto sapphire substrate (Fig. 2). The 2DEG channel forms due to piezoelectric and polarization fields in the undoped GaN buffer layer near the AlN layer. The plane of donors (Si delta doping) supplies extra electrons for the 2DEG channel. The thin AlN layer together with the GaN spacer helps to reduce the alloy scattering and the real-space transfer noise [10]. The electron sheet density $n_{2DEG} = 4.92 \cdot 10^{12}$ cm^{-2} and the electron mobility $\mu = 1468$ cm$^2/(\mathrm{V \cdot s})$ are estimated from Hall effect measurements. For noise measurements,

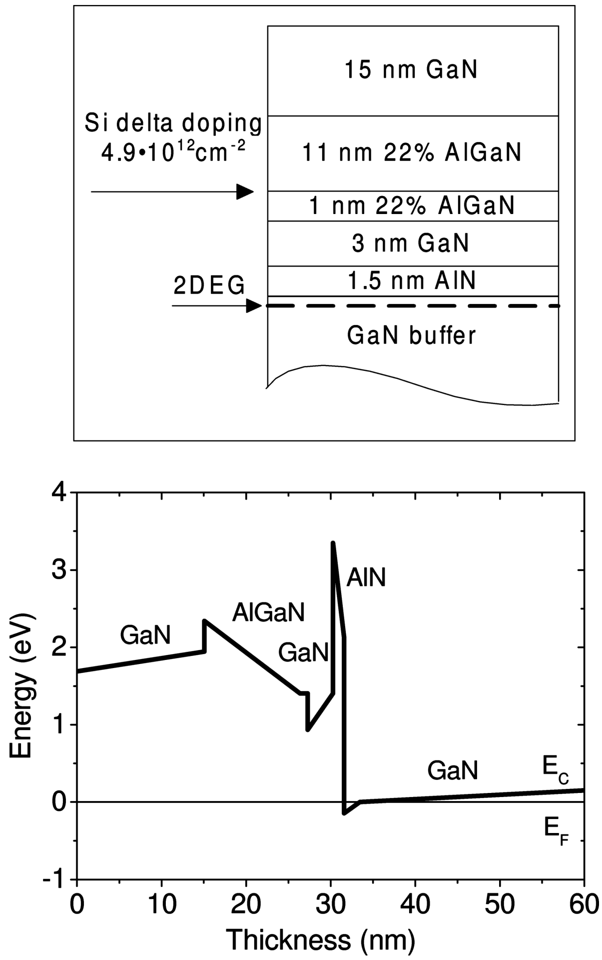

Fig. 2. Schematic illustration of composition and band diagram of GaN / AlGaN / GaN / AlN / GaN heterostructure.

the channel is supplied with two coplanar ohmic electrodes. The channel length is 10 μm, the electrode area is 100×100 μm^2. The estimated electron number in the channel is $N_\mathrm{e} = 4.9\cdot10^7$. The electron volume density is around $n \sim 10^{19}$ cm^{-3}: the effective quantum well width is not known, and the value d = 4.8 nm is assumed (this value is available from calculations for a similar 2DEG channel [11]). The contact resistance is taken into account when the applied electric field and the noise temperature are estimated.

4. Results

Measurements are carried out in the range of electric fields and temperatures where intervalley and intersubband sources of noise play a negligible role. In this range, the longitudinal noise temperature can be expressed as [5]

$$T_\mathrm{n} = T_\mathrm{e} + cT_\mathrm{e}\,, \tag{5}$$

where T_e is the hot-electron temperature; c takes into account the hot-electron temperature fluctuations. When hot phonons are ignored, the factor c can be written through tensor components of conductance as

$$c = \frac{T_\mathrm{e}}{4(T_\mathrm{e}-T_0)}\left(\frac{\sigma_\parallel}{\sigma_\perp}-1\right)^2\frac{\sigma_\perp}{\sigma_\parallel}\,. \tag{6}$$

Here $\sigma_\parallel = \mathrm{d}I/\mathrm{d}U$ and $\sigma_\perp = I/U$, I is the bias current, and U is the voltage applied along the channel (voltage drop on contacts is subtracted). It is evident, that the factor c is zero if Ohm's law holds. After Eqs. (5) and (6), the factor c is small enough at electric fields below 10 kV/cm in our case. Hot phonons reduce the factor c considerably [12, 13]. Consequently, $T_\mathrm{n} \approx T_\mathrm{e}$ is an acceptable approximation in the investigated range of electric fields.

As mentioned, the voltage pulse should be short enough to avoid the channel self-heating effect on the noise temperature. The time-resolved noise measurements help to check whether the self-heating is important [14]. Noise temperature relaxation is measured after the voltage pulse. Since the electrons reach equilibrium with the lattice immediately (in several picoseconds), the noise temperature follows that of the lattice when the electric field is off. By measuring the lattice temperature at different time moments, an exponential decrease is obtained (the time constant of about 400 ns). Back-extrapolation of the exponential dependence gives the lattice temperature under bias.

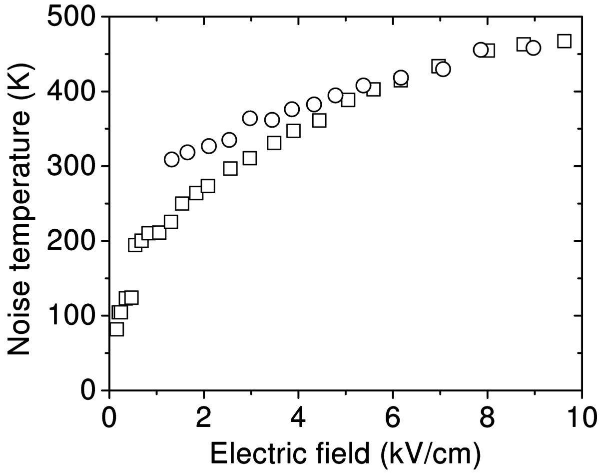

Fig. 3. Dependence of noise temperature on electric field at ambient temperatures T_0 = 293 K (circles), T_0 = 80 K (squares).

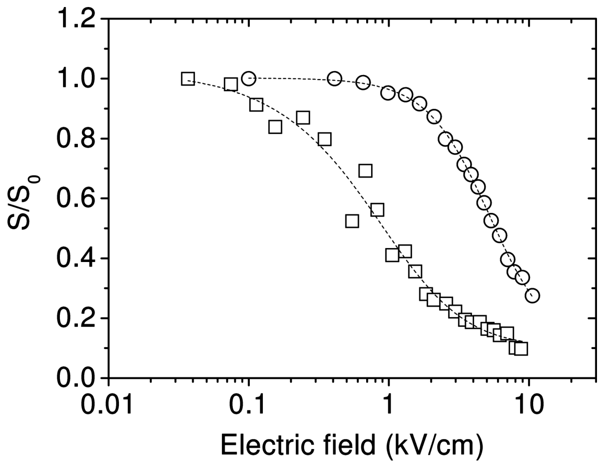

Fig. 4. Dependence of normalized spectral density of current fluctuations on electric field at ambient temperatures T_0 = 293 K (circles), T_0 = 80 K (squares).

The spectral density of current fluctuations can be obtained from the response and noise temperature data:

$$\frac{S_I(E)}{S_{I0}} = \frac{4k_\mathrm{B}T_\mathrm{n}(E)\,\sigma(E)\,\Delta f}{4k_\mathrm{B}T_0\,\sigma_0\,\Delta f} = \frac{T_\mathrm{n}(E)\,\sigma(E)}{T_0\,\sigma_0} = \frac{T_\mathrm{n}(E)\,\mu_\mathrm{d}(E)}{T_0\,\mu_0}\,, \tag{7}$$

where E is the electric field, σ and μ_d are the hot-electron differential conductance and the differential mobility, σ_0 and μ_0 are the conductance and the mobility at $E=0$. The spectral density of current fluctuations provides complementary data. For example, data of Fig. 3 show that the ambient temperature is not important for the noise temperature at high electric fields, but the same statement is not applicable to the spectral density of current fluctuations (Fig. 4).

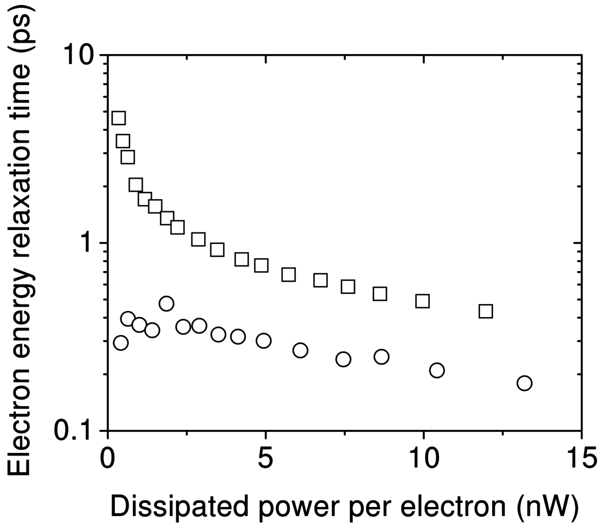

Fig. 5. Dependence of electron energy relaxation time on dissipated power per electron at ambient temperatures $T_0 = 293$ K (circles), $T_0 = 80$ K (squares).

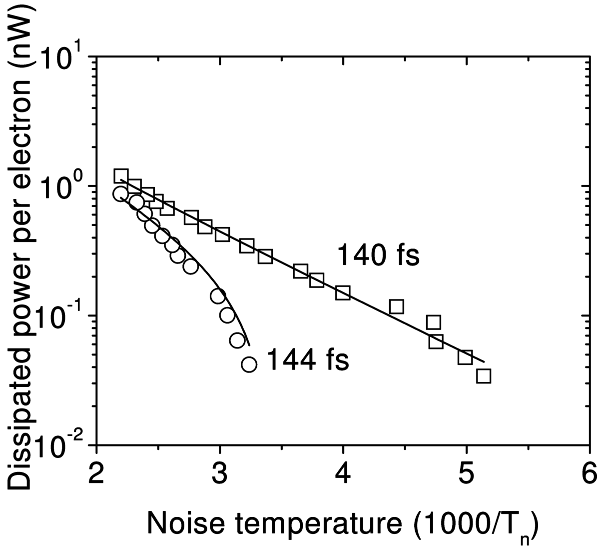

Fig. 6. Dependence of dissipated power per electron on inverse noise temperature at ambient temperatures $T_0 = 293$ K (circles), $T_0 = 80$ K (squares). Solid lines: Eq. (9) and Eq. (12) where $T_n \approx T_e \approx T_{ph}$ is assumed.

In a resistor under steady-state non-equilibrium conditions, the power supplied to the electrons by the electric field $P_s = UI$ is the same as the power dissipated by the hot electrons P_d. The dissipated power can be expressed through the effective electron energy relaxation time τ_e and the excess temperature $T_e - T_0$:

$$\frac{P_d}{N_e} = \frac{UI}{N_e} = \frac{k_B(T_e - T_0)}{\tau_e}, \quad (8)$$

where N_e is the number of electrons in the channel. Since UI/N_e is known, the energy relaxation time τ_e can be obtained from the noise temperature T_n data (Fig. 3) in the range of electric fields where Eq. (5) holds and $c \ll 1$. The data on energy relaxation (Fig. 5) illustrate the transition from the acoustic-phonon controlled energy dissipation to that dominated by LO phonons. At a low temperature, the dissipation through acoustic phonons is important. Optical phonons dominate at high electron temperatures.

When the ambient temperature is low and the dissipation through LO phonons dominates, the supplied-dissipated power obeys Arrhenius-like dependence on the hot-electron noise temperature [4]:

$$\frac{UI}{N_e} = \frac{\Delta\varepsilon}{\tau_{ph}} \exp\left(-\frac{\Delta\varepsilon}{k_B T_n}\right), \quad (9)$$

where $\Delta\varepsilon$ is the activation energy and τ_{ph} is the time constant.

The experimental data at 80 K (Fig. 6, squares) can be fitted with Eq. (9) if $\Delta\varepsilon = \hbar\omega$, where $\hbar\omega$ is the LO phonon energy ($\hbar\omega = 0.092$ eV) (Fig. 6, solid line). The activation energy equals the LO-phonon energy in GaN; this confirms that (i) the LO phonons are responsible for the dissipation and (ii) the noise temperature approximately equals the hot-electron temperature. The other fitting parameter is $\tau_{ph} = 140$ fs. This time constant ($\sim$140 fs) exceeds many times the spontaneous LO-phonon emission time, $\tau_{sp} = 10$ fs [15].

Equation (9) can be modified to include, in addition to the spontaneous emission of LO phonons, the stimulated emission of LO phonons, and the LO phonon reabsorption [4]:

$$\frac{UI}{N_e} = (1 + f_{ph})\frac{\hbar\omega}{\tau_{sp}} \exp\left(-\frac{\hbar\omega}{k_B T_e}\right) - f_{ph}\frac{\hbar\omega}{\tau_{sp}}, \quad (10)$$

where $f_{ph}(T_e)$ is the non-equilibrium occupancy of the hot-phonon states. The term "hot phonons" stands for non-equilibrium LO phonons [2]. The estimated LO phonon occupancy exceeds many times the equilibrium one when the hot-electron temperature is high enough. Expression (10) and the experimental data of Fig. 6 can be used to find the non-equilibrium occupancy f_{ph} and estimate the equivalent hot-phonon temperature T_{ph} [4]:

$$f_{ph} = \left[\exp\left(\frac{\hbar\omega}{k_B T_{ph}}\right) - 1\right]^{-1}. \quad (11)$$

The estimated hot-phonon temperature is below the electron temperature by several percent [1,4]. The hot phonons accumulate because their lifetime is much longer than the time constant for spontaneous emission. As a result, the hot electrons and the hot phonons form an almost isolated quasi-equilibrium hot subsystem and have approximately the same temperature [4]. The subsystem dissipates power when the LO phonons disintegrate. Thus, the dissipated power can be expressed in terms of the hot-phonon lifetime [4, 7]:

$$\frac{UI}{N_\mathrm{e}} = \frac{\hbar\omega}{\tau_\mathrm{ph}}[f_\mathrm{ph} - f_\mathrm{eq}] = \frac{\hbar\omega}{\tau_\mathrm{ph}} \times \left(\frac{1}{\exp\left(\frac{\hbar\omega}{k_\mathrm{B}T_\mathrm{ph}}\right) - 1} - \frac{1}{\exp\left(\frac{\hbar\omega}{k_\mathrm{B}T_0}\right) - 1} \right), \quad (12)$$

where f_eq is the equilibrium LO-phonon occupancy at the ambient temperature.

Under a realistic assumption of $T_\mathrm{e} \approx T_\mathrm{n} \approx T_\mathrm{ph}$ [4, 7], equation (12) fits the experimental results of Fig. 6 (circles and solid line), and the fitting yields τ_ph. The fitting values for the hot-phonon lifetime range from 140 to 150 fs. These values are shorter than those reported for AlGaN / GaN and AlGaN / AlN / GaN channels [1, 4].

5. Discussion

The investigated microwave noise and the hot-electron energy relaxation illustrate the transition from the power dissipation controlled by acoustic phonons to that dominated by LO phonons. The transition temperature is in a reasonably good agreement with the earlier experimental data: the LO phonons dominate at $T_\mathrm{e} > 70$ K when $T_0 = 1.5$ K [15], at $T_\mathrm{e} > 160$ K when $T_0 = 80$ K [16], and at $T_\mathrm{e} > 300$ K when $T_0 = 293$ K [6]. The Arrhenius-like dependence of the dissipated power on the inverse noise temperature (9) is valid at 80 K, while the modified expression (12) holds at room temperature. The activation energy equals the LO-phonon energy in GaN. The experimental data support the following statements:

- the LO phonons are responsible for the power dissipation,
- the noise temperature approximately equals the hot-electron temperature, and
- the hot-electron temperature approximately equals the hot-phonon temperature.

These statements allow one to estimate the hot-phonon lifetime. The estimated lifetime (∼140 fs) is comparable with the hot-electron energy relaxation time measured at the highest electric field. At a high electric field, the measured energy relaxation time (Fig. 5) exceeds the value obtained through Monte Carlo simulation when hot phonons are not taken into account [17].

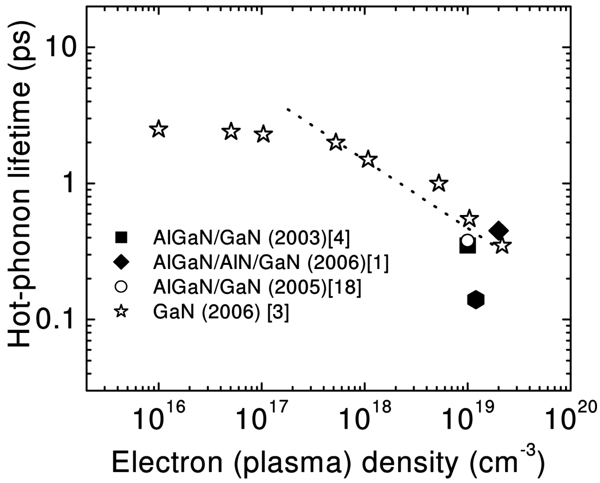

Fig. 7. Dependence of hot-phonon lifetime on electron density for GaN bulk and 2DEG channels. Open symbols correspond to time-resolved laser experiments: Raman scattering for bulk GaN (stars) [3] and intersubband absorbtion for AlGaN / GaN (circle) [18]. Closed symbols are for microwave noise measurements of 2DEG channels: AlGaN / GaN (square) [4], AlGaN / AlN / GaN (diamond) [1], and GaN / AlGaN / GaN / AlN / GaN (hexagon, present paper).

The hot-phonon effect on the electron energy dissipation manifests in the range of electric fields and temperatures where the electron scattering on LO phonons dominates.

The investigated 2DEG channel shows the lifetime values essentially below those reported for bulk GaN at a low density of electrons [3]. This difference is expected to result from the dependence of the lifetime on the electron density. Figure 7 compares the lifetime obtained for GaN / AlGaN / GaN / AlN / GaN (hexagon) with those reported earlier for GaN (stars) [3] and 2DEG channels (closed diamond, closed square, open circle) [1, 4, 18]. Different techniques lead to similar results if the electron density per unit volume is approximately the same.

6. Conclusions

Microwave noise measurements are suitable for investigation of fast and ultra-fast kinetic processes in semiconductors. The hot-electron microwave noise temperature method helps to obtain important kinetic parameters such as hot-electron energy relaxation time and hot-phonon lifetime. The lifetime in the invesigated GaN / AlGaN / GaN / AlN / GaN heterostructure with a 2DEG channel is shorter as compared with those measured for AlGaN / GaN and AlGaN / AlN / GaN structures by the noise technique and for AlGaN / GaN structure measured by the femtosecond-time-resolved optical-phonon-assisted infrared intersubband absorption technique.

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MIKROBANGŲ TRIUKŠMŲ METODIKA KARŠTŲJŲ ELEKTRONŲ ENERGIJOS RELAKSACIJOS TRUKMEI IR KARŠTŲJŲ FONONŲ PUSAMŽIUI MATUOTI

E. Šermukšnis, J. Liberis, A. Matulionis

Puslaidininkių fizikos institutas, Vilnius, Lietuva

Santrauka

Mikrobangų triukšmų metodika panaudota labai spartiems kinetiniams vyksmams puslaidininkiniuose nanometriniuose dariniuose tirti. Esant kambario bei skysto azoto temperatūrai, elektrinių laukų stiprių srityje iki 10 kV/cm ištirtos nitridų protakos su dvimatėmis elektronų dujomis. Pagal išmatuotą triukšmo temperatūrą įvertinta karštųjų elektronų temperatūra ir karštųjų elektronų energijos relaksacijos trukmė: stiprėjant elektriniam laukui trukmė mažėja nuo 5 iki 0,2 ps. Silpnuose laukuose karštųjų elektronų energijos nuostolius lemia akustiniai fononai, bet stipriuose laukuose vyrauja nuostoliai per optinius fononus. Tik įskaičius nepusiausvirąją karštųjų fononų būsenų užpildą, savaiminę ir priverstinę optinių fononų emisiją bei jų sugertį pavyksta gauti neblogą eksperimentinių duomenų ir įverčių sutapimą. Nepusiausvirieji karštieji fononai dalyvauja intensyviuose energijos mainuose su karštaisiais elektronais, kai tuo tarpu energijos mainai su likusiais (pusiausviraisiais) fononais vyksta daug lėčiau. Todėl susidaro beveik atskirta nuo pusiausvirųjų fononų karštoji elektronų ir optinių fononų posistemė, kurioje karštųjų elektronų ir karštųjų fononų temperatūros skiriasi nežymiai. Stacionariomis sąlygomis karštosios posistemės energijos nuostolius atsveria elektronų iš elektrinio lauko gaunama galia. Žinant galią ir įvertinus karštųjų fononų būsenų užpildą, įvertinta karštųjų fononų gyvavimo trukmė, lygi 140–150 fs. Ištirtoje elektrinių laukų srityje ji beveik nepriklauso nuo elektronų temperatūros. Triukšmų metodu įvertintos trukmės palyginamos su vertėmis, gautomis kitais metodais.