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Plasmon-enhanced heat dissipation in GaN-based two-dimensional channels

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Decay of nonequilibrium longitudinal optical (LO) phonons is investigated at room temperature in two-dimensional electron gas channels confined in nearly lattice-matched InAlN/AlN/GaN structures. A *nonmonotonous* dependence of the LO-phonon lifetime on the supplied electric power is reported for the first time and explained in terms of plasmon–LO-phonon resonance tuned by applied bias at a fixed sheet density ($8\times10^{12}\ \mathrm{cm}^{-2}$). The shortest lifetime of 30 ± 15 fs is found at the power of 20 ± 10 nW/electron. © *2009 American Institute of Physics*. [doi:10.1063/1.3261748]

Heat dissipation is important for most applications of GaN-based heterostructure field-effect transistors.[1] When electric power is supplied to a two-dimensional electron gas (2DEG) channel, a nonequilibrium population of longitudinal optical (LO) phonons builds up.[2–7] Because of low group velocity of LO phonons, the associated heat is stored in the channel unless the involved LO phonons (hot phonons) decay into other modes. The decay is often quantified in terms of hot-phonon lifetime.[8,9] Experiments on AlN, GaN, and InN show that the lifetime depends on ambient temperature and electron density.[10–14] The dependence on temperature suggests that a hot phonon splits into a transverse optical phonon and an acoustic phonon.[8,9] However, this mechanism fails to explain the observed decrease of the lifetime when the carrier density increases (Fig. 1, open circles[13]) unless plasmon–LO-phonon coupling is taken into account (dashed curve[15]). The results for AlGaN/GaN 2DEG channels (diamond[2] and bullet[16]) are close to the dashed curve when the electron density per unit volume in the 2DEG channel is estimated as the sheet density divided by the quantum well width (~5 nm).[17]

In 2DEG channels, the lifetime is shortest when the frequencies of plasma and LO phonons approach each other.[17] The estimated resonant density is $\sim6.5\times10^{12}\ \mathrm{cm}^{-2}$ for GaN 2DEG channels (Fig. 1, black curve and black symbols[2,5,16,18–21]). The plasmon–LO-phonon resonance takes place at a lower 2DEG density in InGaAs 2DEG channels.[22]

At a fixed 2DEG density, the lifetime decreases as the supplied power increases.[19] The decrease ensures high values of electron drift velocity measured for the same sample.[23] This has been explained by a shift of the resonant 2DEG density when electron temperature increases.[22] The shift is illustrated by blue and red curves in Fig. 1 and supported by the experimental data (red symbols[21]).

The most nontrivial hot-phonon behavior takes place at a fixed 2DEG density if the density is slightly above the resonant value at zero power: the lifetime is expected to decrease first, pass through a minimum, and increase again with the supplied power. Unfortunately, the supplied power that the samples could withstand was not high enough in the previous experiment for observing the increase of the lifetime with the supplied power.[19]

Our goal is to measure the expected nonmonotonous dependence of the lifetime on the supplied power in order to present the experimental evidence for the power-controlled tuning in and out of the plasmon–LO-phonon resonance at a fixed 2DEG density.

The hot-electron fluctuation technique[2] is the most suitable for measuring the dependence of the hot-phonon lifetime on the supplied electric power.[19] In this method, short pulses of voltage are applied to a gateless 2DEG channel, and a gated X-band radiometer is used for measuring the noise temperature of hot electrons.[18,19]

The nominally undoped InAlN/AlN/GaN structure was grown on (0001) sapphire substrate in the organometallic

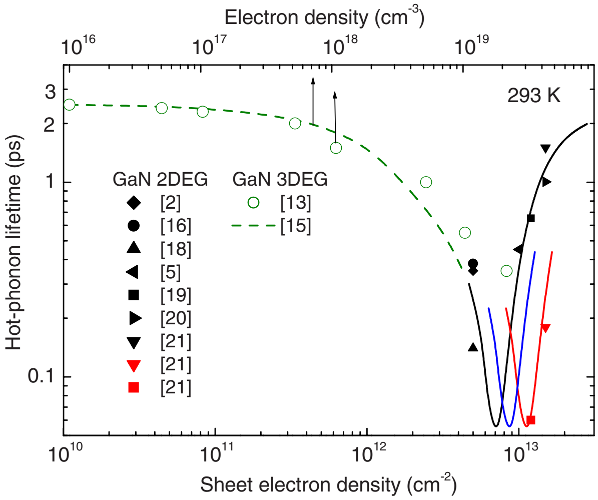

FIG. 1. (Color online) Dependence of hot-phonon lifetime on electron density for GaN 2DEG channels (closed symbols, bottom scale) and for GaN at zero electric field (open circles, top scale). Green dashed curve is plasmon–LO-phonon model for GaN (top scale). Black symbols and black curve stand for low supplied power, red symbols, and red curve stand for high power, and blue curve corresponds to moderate power (solid curves guide the eye).

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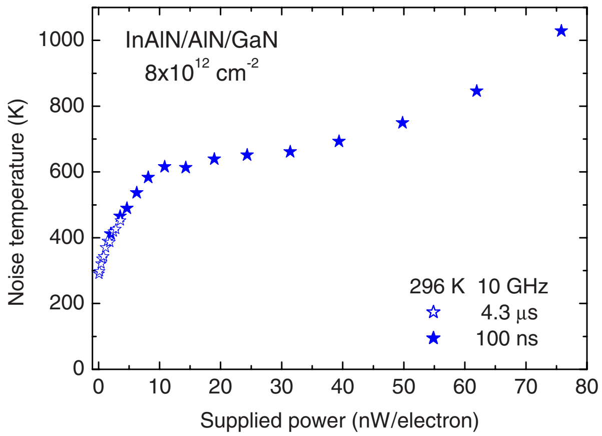

FIG. 2. (Color online) Dependence of hot-electron noise temperature on supplied electric power at room temperature for $In_{0.2}Al_{0.8}N/AlN/GaN$. Voltage pulse duration: 4.3 μs (open stars, present paper) and 100 ns (closed stars, present paper).

vapor phase epitaxy process.[24] The growth was initiated with a 250 nm AlN nucleation layer, and followed with a 4 μm thick undoped GaN layer, a 1-nm-thick undoped AlN spacer, and a 19-nm-thick undoped $In_{0.2}Al_{0.8}N$ barrier layer. The channel is located in the GaN layer and contains 2DEG density of 8×10^{12} cm^{-2}. The low-field mobility is 1330 cm^2/V s at room temperature.

The noise temperature increases with the supplied power (Fig. 2). When the thermal walkout due to channel heating becomes noticeable at above 3 nW/electron for 4 μs voltage pulses, short pulses of 100 ns are used in the range from 2 to 75 nW/electron (solid stars). In the considered range of the supplied power, the electron–LO-phonon scattering dominates. Thus, the noise temperature T_n yields the electron temperature T_e, and the error constitutes a couple percent[25–27] if other sources of noise are weak. In particular, the real space transfer noise of hot electrons does not show up when an AlN spacer is used.[26]

Hot electrons and hot phonons strongly interact and form an almost isolated hot subsystem in GaN 2DEG channels.[2] In particular, the hot-phonon temperature T_{ph} is only several percent lower than the hot-electron temperature T_e.[5] The experimental study of GaN-based transistors leads to a similar conclusion.[7] Thus, the equivalent occupancy N_{ph} of the hot-phonon modes can be estimated as

$$N_{ph}=\left[\exp\frac{\hbar\omega_{ph}}{k_BT_n}-1\right]^{-1}, \tag{1}$$

where $\hbar\omega_{ph}$ is the LO-phonon energy and k_B is the Boltzmann constant.

After Eq. (1), the results of Fig. 2 yield the dependence of the equivalent occupancy on the supplied power (Fig. 3, stars). Solid line assumes a constant lifetime of 270 fs. Beyond the fitting range, the slope of the dependence decreases first and increases again as the supplied power increases (stars). No increase of the slope has been reported for the other InAlN/AlN/GaN structure in the selected range below 80 nW/electron (Fig. 3, squares) and in the entire investigated range up to 200 nW/electron.[27]

Let us treat the results of Fig. 3 in terms of the hot-phonon lifetime. The power-dependent dynamic hot-phonon lifetime can be estimated from the derivative[25,27]

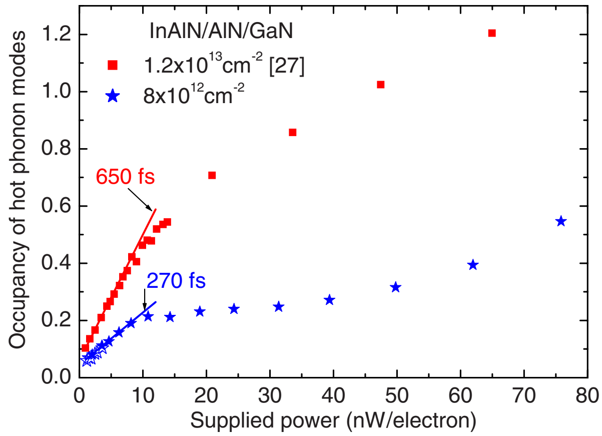

FIG. 3. (Color online) Dependence of hot-phonon mode occupancy on supplied electric power at room temperature for $In_{0.2}Al_{0.8}N/AlN/GaN$ (stars, present paper), and $In_{0.18}Al_{0.82}N/AlN/GaN$ (squares, Ref. 27). Lines illustrate power independent hot-phonon lifetime: 270 fs (blue line) and 650 fs (red line).

$$\tau_{ph}=\hbar\omega_{ph}\frac{dN_{ph}}{dP_s}, \tag{2}$$

where P_s is the power supplied to an average electron. The definition in Eq. (2) together with the data of Fig. 3 lead to power-dependent lifetime (Fig. 4, symbols).

The results of Fig. 4 correspond to channels where the electron density exceeds the resonant 2DEG value. The resonance is approached when the supplied power heats the electrons and the plasma frequency decreases. For $In_{0.2}Al_{0.8}N/AlN/GaN$ (Fig. 4, stars), the resonance is tuned in at around 20 ± 10 nW/electron where the lifetime reaches the minimum value of 30 ± 15 fs. At higher power levels, the resonance is tuned out, and the lifetime increases. The structure with the 2DEG density of 1.2×10^{13} cm^{-2} is far from the resonance at the low power (Fig. 1, black square), and the supplied power of 100 nW/electron is not high enough to reach the resonance (Fig. 4, squares).

A nonmonotonous dependence of the effective lifetime on the hot-electron temperature also follows from the migration model.[28] The group velocity of coupled plasmon–LO-phonon modes can reach 5×10^6 cm/s at the electron temperature of 2000 K where the shortest lifetime of ~200 fs is

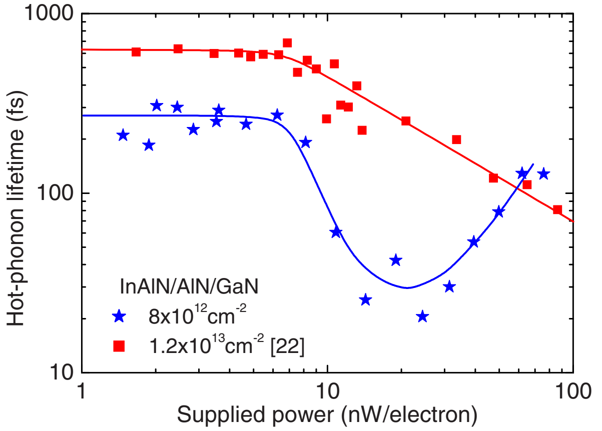

FIG. 4. (Color online) Dependence of dynamic hot-phonon lifetime on supplied power at room temperature for $In_{0.2}Al_{0.8}N/AlN/GaN$ (stars, present paper), and $In_{0.18}Al_{0.82}N/AlN/GaN$ (squares, Ref. 22). Curves guide the eye.

predicted. According to the experiment (Fig. 4, stars), the shortest lifetime of ~30 fs is observed when the hot-electron temperature is between 600 and 700 K (Fig. 2). Thus, the migration model is not supported by the experiment since the estimated contribution due to the plasmon-enhanced migration is less than 10% when the hot-electron temperature is below 1000 K.

In conclusion, the nonmonotonous dependence of the hot-phonon lifetime on the supplied power is observed for the first time. The result for the InAlN/AlN/GaN confirms that, at a fixed 2DEG density of 8×10^{12} cm^{-2}, the plasmon–LO-phonon resonance tunes in and out as the supplied power increases.

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