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Hot phonons in Si-doped GaN

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Microwave noise and electron transport are studied in silicon-doped GaN channels grown by molecular beam epitaxy and subjected to a high electric field. The drift velocity of 2.8×10^7 cm/s is reached at 290 kV/cm for $n \sim 1 \times 10^{18}$ cm^{-3} channel. No negative differential resistance is observed. The noise temperature exceeds ~5000 K at ~110 kV/cm for $n \sim 3 \times 10^{17}$ cm^{-3} channel. The hot-phonon effect on power dissipation in GaN:Si is 3–4 times weaker as compared with the effect in an undoped AlGaN/GaN two-dimensional channel. Monte Carlo simulation shows a weak effect of hot phonons on hot-electron energy distribution. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2388866]

Accumulation of longitudinal optical (LO) phonons introduces an additional friction for drifting electrons. The accumulated nonequilibrium LO phonons are termed hot phonons. In particular, they are of importance for high-power operation of biased nitride two-dimensional electron gas (2DEG) channels designed for microwave transistors.[1] Under a steady state, LO-phonon emission by high-energy electrons is balanced with LO-phonon reabsorption and conversion into other vibrations. The conversion is often treated in terms of hot-phonon lifetime. Calculations show[2] that the undesired additional friction diminishes in channels with a lower electron density if the lifetime is independent of doping. However, the lifetime is not constant: it is short at a high electron density (~0.35 ps in AlGaN/GaN channels[3,4]) and long (~3 ps in GaN) at a low density.[5] According to recent Raman data for GaN,[6] the lifetime gradually increases from 0.35 ps at the highest electron-hole plasma density up to 2.5 ps at 10^{16} cm^{-3}. The additional friction due to hot phonons is not found in transport experiments on GaN.[7]

On the other hand, the hot-phonon effect on electron energy dissipation can be easily resolved.[8] This idea has been used in most experiments on hot phonons in nitride 2DEG channels subjected to high electric fields.[1] In AlGaN/GaN channels, hot phonons reduce (~30 times) the energy dissipation rate.[3] Our goal is to resolve the hot-phonon effect on power dissipation in Si-doped GaN at high electric fields.

Silicon-doped GaN layers were grown in a Vecco Gen 930 molecular beam epitaxy system at a substrate temperature ~700 °C.[9] Solid sources of Ga and Si were used; two different Si fluxes were set for wafers A and B. Active nitrogen was purified by Aeronex filter and supplied through a Vecco unibulb rf plasma generator. The GaN growth rate of ~210 nm/h was set under Ga-rich conditions. The resulting surfaces were smooth, and atomic steps were observed in hexagonal patterns around dislocations.

The layer surface was cleaned with HCl to remove Ga droplets, and Ohmic Ti/Al/Ni/Au contacts (100×100 μm^2 electrodes separated by 2–6, 8, and 10 μm gaps) were formed in a standard way. Simultaneously, eight-contact bars were formed for Hall-effect measurement. The low-field Hall mobilities at room temperature were 352 and 434 cm^2/V s for wafers A and B, respectively. The Ohmic low-field mobilities, $\mu_O^A = 196$ cm^2/V s and $\mu_O^B = 241$ cm^2/V s, were estimated from the Hall mobility divided by the calculated Hall factor ($r_H = 1.8$). The electron sheet densities were 9.4×10^{12} cm^{-2}, and 2.9×10^{12} cm^{-2}, and the electron densities (per unit volume) were $\sim 1 \times 10^{18}$ and $\sim 3 \times 10^{17}$ cm^{-3} for A and B wafers, respectively.

The dependence of current I on pulsed voltage U was measured on samples supplied with two coplanar Ohmic electrodes for three pulse durations: 500, 100, and 4 ns. The average electric field is estimated as follows: $E = (U - IR_c)/L$ where L is the channel length and R_c is the contact resistance. The latter is estimated from the dependence of the sample resistance on the channel length. The electrical circuit for 4 ns pulses included a mercury-wetted relay and a 0–5 GHz bandwidth sampling oscilloscope. Some samples survived 4 ns pulses of electric field exceeding 300 kV/cm. A soft damage of the survived samples was estimated according to the change of the zero-field resistance measured before and after the high-field experiments. This letter presents the results for the samples damaged less than 5% at fields below 290 kV/cm (sample A) and less than 3% at fields below 200 kV/cm (sample B). No sample damage was observed at fields below 40 kV/cm for 500 ns pulses and below 90 kV/cm for 100 ns pulses.

The dependence of the hot-electron noise temperature T_n on the applied electric field was measured near 10 GHz frequency with the renovated waveguide modulation-type gated radiometric setup (the technique was described elsewhere[10]). The voltage pulse durations were 100 and 500 ns depending on the range of the electric field. Typical results are presented for 4-μm-long channels.

For easy comparison of different channels, the current I_O in the Ohmic range is expressed as $I_O = C\mu_O E$, and the normalized variable I/C is plotted in Fig. 1 (symbols) together with $\mu_O E$ data (solid lines). A comparison of up triangles with left and down triangles illustrate a negligible self-heating effect at fields below 40 kV/cm for 500 ns pulses and below 90 kV/cm for 100 ns pulses. Open and closed stars stand for two channels cut from the same wafer B and

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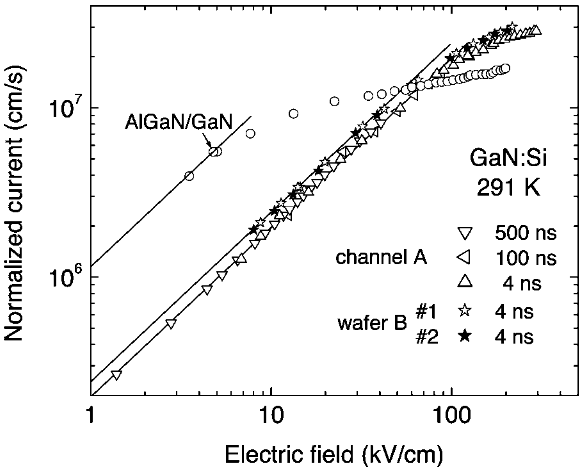

FIG. 1. Dependence of normalized current on electric field for Si-doped GaN channels A (triangles) and B (stars). Circles stand for drift velocity data (Ref. 11). Lines are $\mu_O E$.

illustrate a good uniformity of the wafer. Ohm's law approximately holds at fields below 70 kV/cm.

When the sheet electron density is independent of the electric field, the normalized current equals the electron drift velocity. At high electric fields ($E < 70$ kV/cm), the electron drift velocity for the investigated Si-doped GaN (stars and triangles) exceeds the velocity (circles[11]) reported for the 2DEG channel located in AlGaN/GaN. The lower velocity in the 2DEG is possibly caused by hot phonons and alloy scattering.[1] When alloy scattering is avoided, the drift velocity increases by 20%.[1,12]

The experimental results on noise temperature are illustrated in Fig. 2. The temperature increases with the applied electric field [except for channel A in the field range of 2–6 kV/cm where the noise temperature is below the ambient temperature (triangles)]. The electron cooling has been associated with a fast emission of a LO phonon followed by a slow acceleration of the electron at low energies where impurity scattering is intense.[13] At higher electric fields, the results for samples cut from different wafers tend to merge (triangles and stars), but a systematically higher noise temperature is observed for channel B (stars) at fields above 50 kV/cm.

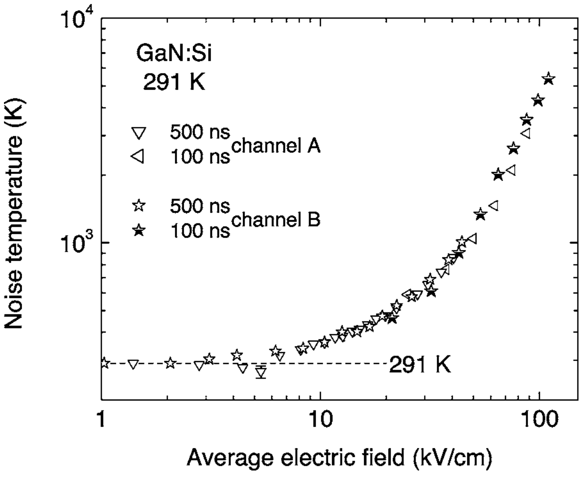

FIG. 2. Dependence of noise temperature at 10 GHz on applied electric field for Si-doped GaN channels.

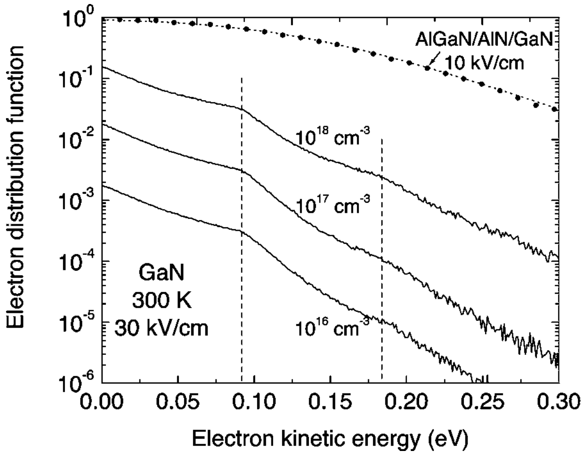

FIG. 3. Hot-electron energy distribution function (Monte Carlo simulation): GaN (solid lines) and 2DEG channel (bullets) (Ref. 14). Dotted line is the fitted Fermi-Dirac function.

Let us discuss the results in terms of electron energy dissipation. At high electric fields, the main contribution comes for electron–LO-phonon interaction (e-LO interaction) as confirmed through the Monte Carlo simulation for the GaN model that takes into account inelastic acoustic phonon scattering (deformation and piezoelectric potentials and equilibrium phonon distribution) and LO-phonon scattering (screened polar potential and hot-phonon distribution). Figure 3 illustrates the simulated electron distribution function (solid lines). It differs from a Maxwell function: kinks appear at energies $\varepsilon = m\hbar\omega$, where $m = 0, 1, 2$ ($\hbar\omega = 92$ meV). Hot phonons are known to smooth the distribution function:[14] as a result, no kink is observed (bullets) for the 2DEG channel where the hot-phonon effect is strong enough to establish a Fermi-Dirac distribution (dotted line). Unlike this, no electron temperature can be introduced for GaN (solid lines). A weak hot-phonon effect is found only at $\varepsilon > \hbar\omega$ at an electron density of 10^{18} cm^{-3} (solid line).

In order to resolve the hot-phonon effect in the experiment, let us combine the data on transport (Fig. 1) and noise (Fig. 2) into the dependence of logarithm of the supplied power per electron against the inverse noise temperature in the range of electric fields where the noise temperature stands for the mean kinetic energy of electrons. The supplied power per electron is estimated according to $P_s = evE$, where v is the drift velocity available from Fig. 1. The results are shown in Fig. 4 (stars and triangles). Data below 6 kV/cm are omitted because of the mentioned electron cooling observed in the field range of 2–6 kV/cm (Fig. 2, channel A).

Under steady state conditions, the supplied power equals the dissipated power. The solid line in Fig. 4 illustrates the semiempiric expression for the dissipated power controlled by the e-LO interaction,[15]

$$P_d = A\left\{\left[\exp\frac{\hbar\omega}{k_B T_n} - 1\right]^{-1} - \left[\exp\frac{\hbar\omega}{k_B T_0} - 1\right]^{-1}\right\}. \qquad (1)$$

The coefficient A in Eq. (1) is selected to fit the experimental data (Fig. 4, triangles, stars, solid line); a reasonably good fitting is obtained. This confirms that the e-LO interaction dominates over a wide range of electric fields (6–70 kV/cm) and temperatures (320–2000 K). At $E < 70$ kV/cm, the noise temperature (stars, triangles) exceeds the values (solid line) obtained from Eq. (1). This might

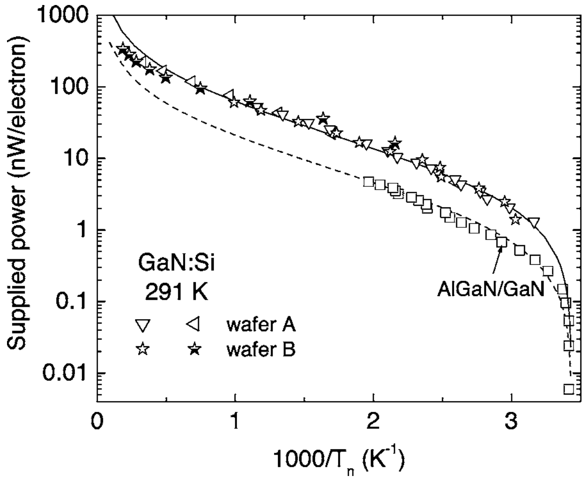

FIG. 4. Arrhenius-type plot of supplied power. Experimental data for Si-doped GaN (triangles and stars) and AlGaN/GaN 2DEG channels (squares) (Ref. 3). Solid and dashed lines stand for the dissipated power after Eq. (1).

indicate an onset of intervalley transfer noise of hot electrons. The non-Ohmic behavior develops in the same range of electric fields (Fig. 1, stars and triangles).

The experimental data for the 2DEG channel (Fig. 4, squares) are presented for comparison. Again, the e-LO interaction dominates until the real-space-transfer noise onsets at ~500 K.[3] The dashed line is the dissipated power obtained after Eq. (1) for a three times lower value of the coefficient A than the solid line. Consequently, at a chosen mean kinetic energy of hot electrons, the dissipated power per electron is three to four times lower in the 2DEG channel (squares) than in GaN (stars and triangles). As mentioned, the hot phonons are known to reduce (~30 times) the dissipated power in AlGaN/GaN channels.[3]

The observed weak hot-phonon effect (Fig. 4, stars and triangles) and the associated high drift velocity at high electric fields (Fig. 1) should favor the fast transit of hot electrons through the high-field region controlled by the gate in a field-effect transistor with a doped GaN channel. On the other hand, because of low electron mobility at $E < 70$ kV/cm (Fig. 1, stars and triangles) the gate charging time should increase as compared to the 2DEG case (Fig. 1, circles).

A hot-phonon lifetime is known[5] to increase under cooling at a low electron density (10^{16} cm^{-3}), but a negligible temperature dependence is reported[16] for 2DEG channels (10^{19} cm^{-3}) at ambient temperatures ranging from 80 to 373 K. Thus, at intermediate electron densities (10^{18} cm^{-3}), a relatively weak temperature dependence is expected.

In conclusion, the experimental data show that the hot-phonon effect on dissipated power is three to four times weaker while the drift velocity at high electric fields is 1.5–2 times higher in the investigated Si-doped GaN channels as compared with the corresponding values for the AlGaN/GaN 2DEG channel.

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