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Camelback channel for fast decay of LO phonons in GaN heterostructure field-effect transistor at high electron density

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Fluctuation technique is used to measure hot-phonon lifetime in dual channel GaN-based configuration proposed to support high-power operation at high frequencies. The channel is formed of a composite $Al_{0.1}Ga_{0.9}N/GaN$ structure situated in an $Al_{0.82}In_{0.18}N/AlN/Al_{0.1}Ga_{0.9}N/GaN$ heterostructure. According to capacitance–voltage measurements and simultaneous treatment of Schrödinger–Poisson equations, the mobile electrons in this dual channel configuration form a camelback density profile at elevated hot-electron temperatures. The hot-phonon lifetime was found to depend on the shape of the electron profile rather than solely on its sheet density. The camelback channel with an electron sheet density of 1.8×10^{13} cm^{-2} demonstrates ultrafast decay of hot phonons at hot-electron temperatures above 600 K: the hot-phonon lifetime is below ~60 fs in contrast to ~600 fs at an electron sheet density of 1.2×10^{13} cm^{-2} obtained in a reference $Al_{0.82}In_{0.18}N/AlN/GaN$ structure at 600 K. The results suggest a suitable method to increase the electron sheet density without the deleterious effect caused by inefficient hot-phonon decay observed in a standard design at similar electron densities. © *2011 American Institute of Physics*. [doi:10.1063/1.3615284]

Gallium nitride heterostructure field-effect transistors are promising power devices for microwave applications and switching.[1–4] Cut-off frequencies of short-gate transistors exceed 200 GHz.[5–7] It is proverbially believed that a higher microwave power levels can be attained if the transistor channel contains more electrons. In this regard, electron densities over 3×10^{13} cm^{-2} have been demonstrated in GaN-based heterostructures with a composite AlInN/AlN barrier.[8] The electrons are confined in the quantum well of nanometric thickness where the current density and power density per unit volume are extremely high at high electric fields. Unfortunately, deleterious effects due to heat accumulation, mainly due to nearly immobile longitudinal optical (LO) phonons which are not easily decayed to longitudinal acoustic (LA) phonons, come into play at high supplied power levels. The thermal conductance helps to drain out the excess LA phonons, but a different approach is needed to treat the heat accumulated by non-equilibrium LO phonons (hot phonons) emitted by hot electrons.[9]

Hot-phonon decay is often evaluated in terms of LO-phonon lifetime.[10] It has been suggested, based on experimental data,[11] that the lifetime is shorter if the three-dimensional (3D) carrier density is closer to LO-phonon–plasmon resonance.[12] The signature of the resonance has also been observed in a two-dimensional electron gas (2DEG).[9,10] In particular, a resonance-type non-monotonous dependence on the electron density is resolved in phenomena involving hot-electron transport,[13,14] transistor cut-off frequency,[13] and transistor degradation.[15] For standard GaN-based channels, the resonance 2DEG density is near 6.5×10^{12} cm^{-2} at low electric fields, but the resonance shifts towards higher 2DEG densities as the hot-electron temperature increases.[10,16] In voltage-biased channels, the hot electrons spread over a larger volume, the plasma frequency decreases, and the resonance is observed at higher 2DEG densities: 9.5×10^{12} cm^{-2},[13] 1×10^{13} cm^{-2},[15] and $(1.1–1.2) \times 10^{13}$ cm^{-2}.[14] These resonance values are lower than the achievable 3×10^{13} cm^{-2}, and no benefit from the LO-phonon–plasmon resonance is expected in the standard GaN-based channels at these highest 2DEG densities. The camelback channel has been proposed[17] in order to increase the 2DEG density without increasing the 3D electron density. In this communication, we experimentally explore the avenue of combining a high 2DEG density (preferred for power operation) and ultrafast decay of LO phonons (useful for high-frequency operation and slow degradation of transistors).

The self-consistent solution of coupled Schrödinger–Poisson equations for the reference single-channel $Al_{0.82}In_{0.18}N/AlN/GaN$ structure (Fig. 1, dashed line) is compared with the profiles obtained for the composite-channel $Al_{0.82}In_{0.18}N/AlN/Al_{0.2}Ga_{0.8}N/GaN$ structure (solid lines). The inset illustrates the band diagram of the dual channel structure. The insertion of the thin $Al_{0.2}Ga_{0.8}$ N interlayer (2 nm) between the GaN and the AlN layers modifies the profile in that it becomes wider and, despite of higher 2DEG density, the highest 3D electron density becomes lower (Fig. 1, solid line at a 300 K). At elevated hot-electron temperatures, the 3D density decreases further, and the camelback profile develops (solid lines).

The experimental component of this study was carried out on nominally undoped $Al_{0.82}In_{0.18}N/AlN/Al_{0.1}Ga_{0.9}N/GaN$ structures grown in a vertical low-pressure metal-organic chemical vapor deposition system on a 2-in. sapphire substrate. The results are presented for a structure that contains a 2-μm thick GaN buffer layer, a 3-nm thick AlGaN interlayer, a 1 nm AlN spacer, and a 17-nm thick AlInN barrier.

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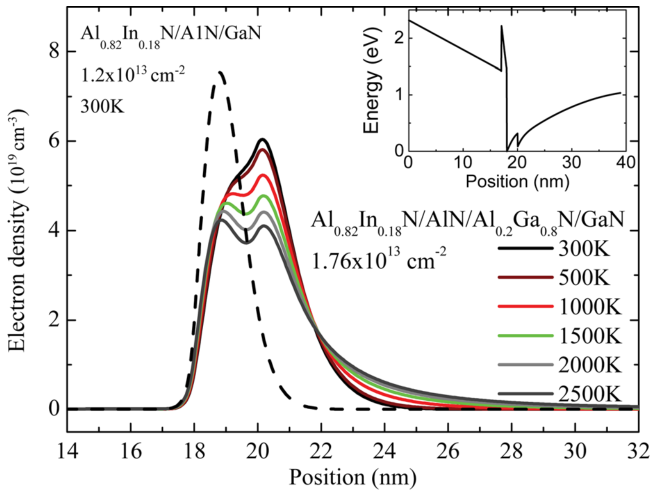

FIG. 1. (Color online) Calculated electron 3D density profiles for a standard structure (dashed line) and the camelback structure (solid lines) at different hot-electron temperatures.

Schottky diodes were formed for density profile measurements, transfer length model (TLM) patterns with coplanar ohmic contacts composed of Ti/Al/Ni/Au, and transistors were fabricated for noise and unity gain cutoff frequency measurements, respectively. The electron sheet density is 1.8×10^{13} cm^{-2} and the mobility is 530 cm^2 V^{-1} s^{-1}.

The measured electron density profiles for the $Al_{0.82}In_{0.18}N/AlN/Al_{0.1}Ga_{0.9}N/GaN$ (solid line) and the $Al_{0.82}In_{0.18}N/AlN/GaN$ (dashed line[13]) structures are compared in Fig. 2. While the peak 3D densities are comparable, the electron sheet density is considerably higher in the design where some electrons occupy the $Al_{0.1}Ga_{0.9}N$ interlayer even at equilibrium (solid line, shoulder). A weak shoulder is also resolved in the reference channel (dashed line).[13] This shoulder may be associated with an *unintentionally* grown interlayer in the nominally single-channel structure.

The LO-phonon lifetime is extracted from the hot-electron microwave noise measurements in the same manner as described elsewhere.[9,10,16] Figure 3 shows the results for the $Al_{0.82}In_{0.18}N/AlN/Al_{0.1}Ga_{0.9}N/GaN$ gateless structure with the

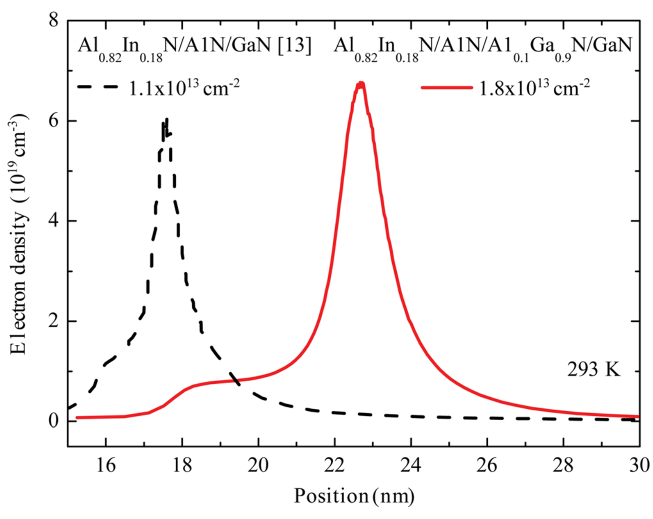

FIG. 2. (Color online) Capacitance–voltage measurements of electron 3D density profile in the camelback structure (solid line) and a standard channel (dashed line, see Ref. 13).

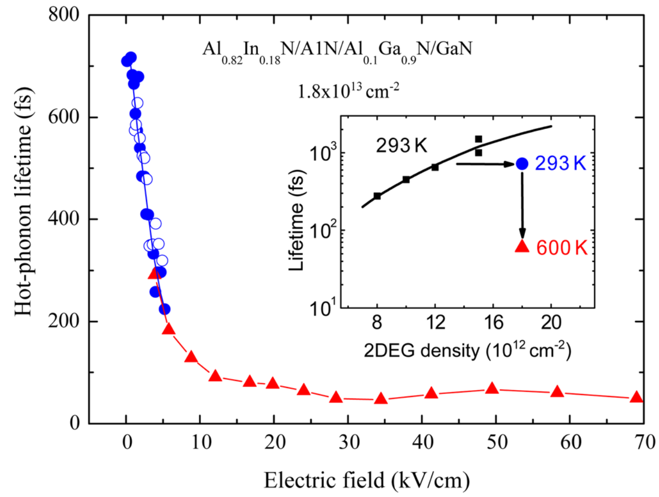

FIG. 3. (Color online) Field-dependent LO-phonon lifetime in the camelback channel for voltage pulse lengths of 2.7 μs (circles) and 100 ns (triangles). Open and closed circles stand for two samples from the same wafer. Inset compares the camelback channel at 293 K (circle) with single channels (squares, see Ref. 16); triangle is the lifetime for the camelback channel at hot-electron temperature of 600 K. Curves guide the eye.

camelback channel. The value of ~700 fs is found at low fields (circles) followed with a rapid decrease down to ~60 fs as the field increases (triangles). A good uniformity of the wafer is demonstrated from results for two samples of different length (open and closed circles). The channel self-heating is weak at fields below ~5 kV for a pulse length of 2.7 μs as illustrated by the negligible dependence on voltage pulse duration for 2.7 μs (circles) and 100 ns (triangles) pulses in the field range (4–5) kV/cm. In a similar manner, the voltage pulses of 50 ns are used to control the self-heating at higher fields.

The squares[16] (Fig. 3, inset) illustrate the density dependence of the LO-phonon lifetime at low fields for the standard GaN-based single channels at electron densities above the resonance value. The lifetime increases with the 2DEG density, and a value of ~1.8 ps is expected for a single channel at 1.8×10^{13} cm^{-2} (solid line). The camelback design shows a shorter lifetime of ~700 fs at this 2DEG density (inset, circle). Notably, a considerably lower 2DEG density of 1.2×10^{13} cm^{-2} is needed to obtain approximately the same lifetime in the standard $Al_{0.82}In_{0.18}N/AlN/GaN$ structure.[10]

The dependence of the LO-phonon lifetime on the applied electric field can be explained in terms of the LO-phonon–plasmon resonance. The LO-phonon and plasmon energies are equal near 1×10^{19} cm^{-3} in GaN if the plasma is uniform and infinite, but neither is true for 2DEG channels. According to a slab model, the in-plane plasma frequency is lower and the resonance 3D density is higher. Moreover, the plasma frequency depends on slab thickness. Since the channel half-width changes with the hot-electron temperature (Fig. 1), the LO-phonon–plasmon resonance can be tuned electrically.[10,16]

Figure 4 illustrates the LO-phonon lifetime as a function of the excess noise temperature. The results for the camelback channel (circles) are compared with those available for the reference channel (squares[10]). The lifetime decreases as the temperature increases. The decrease from the ~600 fs down to the ~60 fs of the reference channel (squares) has been interpreted in terms of the hot-phonon decay enhanced

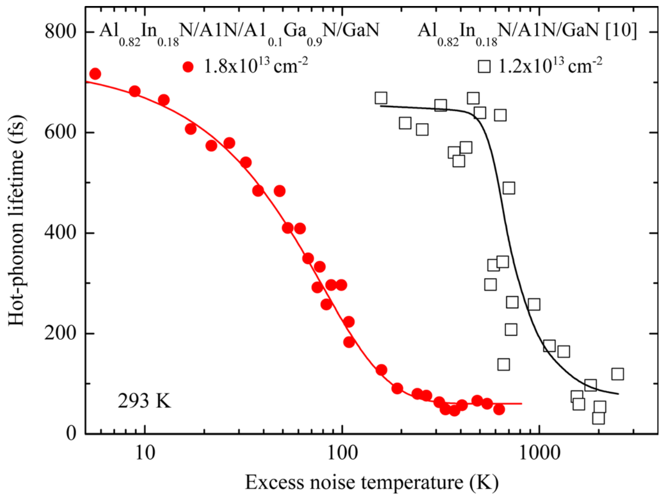

FIG. 4. (Color online) The hot-phonon lifetime as a function of the excess noise temperature in the reference channel (squares, see Ref. 10) and the camelback channel (circles). Curves guide the eye.

when the LO-phonon–plasmon resonance is approached upon electron heating.[10] Since the equilibrium plasma frequency exceeds the LO-phonon frequency considerably, strong electron heating is needed to bring the system to the resonance in the reference channel. The camelback channel contains even higher 2DEG density. Nevertheless, the density profile (Fig. 2, solid line) is designed to make the plasma frequency close to the LO-phonon frequency. As a result, the decrease of the hot-phonon lifetime is observed at moderate hot-electron noise temperatures (Fig. 4, circles).

The resonance can be tuned with the electron temperature or the supplied power at the electron densities higher than the resonance value. However, if the electron sheet density is too high, no resonance can be reached for reasonable applied power levels before the catastrophic breakdown sets in. On the other hand, below the breakdown, the shorter hot-phonon lifetime in the camelback channel should ensure lower LO-phonon temperature as compared to the standard channel supposing that the both channels operate at the same power level or, alternatively, at the same LA-phonon temperature (the lattice temperature). If the high-field electron transport is limited by the scattering on the LO phonons, the camelback structure is beneficial for reaching higher electron drift velocity at a given high electric field.

The main drawback of the investigated camelback channel is alloy scattering in the $AlN/Al_{0.1}Ga_{0.9}N$ interlayer: the measured mobility is lower than typical values at this electron density. As a result, the access resistance of the source–drain part of the channel of the camelback heterostructure field-effect transistor would exceed that in the control transistor grown without the interlayer at the same conditions with similar sheet electron densities. However, since transistor operation depends to a relatively large extent on the high-field mobility, note that the low and high field mobilities are governed by different scattering mechanisms, the fabricated camelback field-effect transistor demonstrates a 70% higher $f_T n_{2D}$ product (where f_T is the cutoff frequency and n_{2D} is the sheet electron density) as compared to the same product of the control device, which bodes well for the structure under discussion.

Power transistors are known to suffer from degradation under DC and particularly RF stress, and hot phonons are known to be responsible, in part, for device degradation.[15] The camelback channel demonstrates ultrafast decay of hot phonons at elevated hot-electron temperatures. Therefore, this design should mitigate degradation and increase reliability of device operation.

In conclusion, a camelback channel confined in the GaN heterostructure is grown and investigated experimentally. Ultrafast decay of LO phonons is demonstrated at a high sheet density of mobile electrons. The electron sheet density is increased without sacrificing the rate of the hot-phonon decay, which is critical for high performance GaN heterostructure field effect transistors. The benefits of the camelback density profile are evident: the approach is sufficiently flexible to allow for engineering of the channel composition in order to achieve the fastest decay of hot phonons under whichever supplied power one expects to apply under operation.

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