Hot-electron transport in AlGaN/GaN two-dimensional conducting channels

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We report on experimental studies of high-field electron transport in AlGaN/GaN two-dimensional electron gas. The velocity–electric field characteristics are extracted from 10 to 30 ns pulsed current–voltage measurements for 4.2 and 300 K. An electron drift velocity as high as 1.7×10^7 cm/s was obtained in the fields 150 kV/cm. Estimates of thermal budget of the system show that overheating of the electrons exceeds 1700 K at highest electric fields achieved in the experiment. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1830078]

Group III-nitride materials possess unique physical properties, which allow one to suggest that the materials have excellent potential for applications in high-power, high-frequency, and high-temperature electronics.[1] These suggestions are based mainly on theoretical results on high-field transport [see, for example, Refs. 2–4]. To date, there is a lack of experimental data on specific characteristics of both bulklike and heterostructure nitrides under high fields.

For the nitride materials, large electron concentrations are rather typical. This provides a dominance of electron–electron collisions over other scattering mechanisms, and implies that the distribution function of the electrons under nonequilibrium occurs in the form close to the *shifted Maxwellian function*. Such a distribution is characterized by two parameters: an effective electron temperature T_e and a drift velocity V_{dr}. The achieved drift velocity is of fundamental importance, since it determines the current, high-speed capability, and high-frequency operation. For nitrides, the theory predicts V_{dr} as high as 2×10^7 to 3×10^7 cm/s in dc fields about 130–150 kV/cm. Time-resolved measurements[5] of electroabsorption in GaN confirm achieving very high velocities for ultrashort (~200 fs) time intervals. However, for steady-state or quasi-steady-state conditions, direct measurements of the drift velocity meet considerable difficulties. Particularly, high electric fields and currents in the nitrides give rise to high dissipative power and a large Joule heating. The latter, in turn, induces additional electron scattering and limits V_{dr}, masking truly nonequilibrium hot-electron effects.[6] Thus, correct measurements of this characteristic have to be done in pulse regimes.[7–9] Another parameter, the electron temperature, determines stochastic characteristics of the electrons, their fluctuations, and current noise. In this letter, we present experimental results on the velocity–field characteristics in AlGaN/GaN heterostructures obtained by using 10–30 ns pulse current–voltage measurements in the range of electric fields up to 150 kV/cm. We also estimate and discuss the electron temperature of nonequilibrium electrons.

The investigated devices were fabricated from $Al_{.33}Ga_{.67}N$/GaN undoped heterostructures of 1.1 μm GaN and 23 nm AlGaN covered with a 320 nm Si_3N_4 passivation layer. The structures were grown by metalorganic chemical vapor deposition on sapphire substrate with a 40 nm $Al_{.16}Ga_{84}N$ intermediate nucleation layer. The transmission line model (TLM) patterns of different conduction channel lengths L and of the same channel width W were used. The channel length varied from 1 to 35 μm, while the width was 100 μm. The TLM ohmic contacts were processed by Ti/Al/Ti/Au metallization annealed for 40 s at 800 °C. Since the contacts contribute to the voltage drop along the sample, for correct determination of the average electric field in the device, the contact resistance was carefully measured in the low-field regime.

To determine the electron drift velocity, we used the relationship

$$V_{dr} = I/enW, \tag{1}$$

where I is the current, e is the electron charge, and n is the carrier concentration. This method of determination of V_{dr} relies on the knowledge of the electron concentrations and on the assumption that the concentration remains constant as the electric field changes.

First we conducted the low-field measurements. By applying the Van der Pauw method, we found the low-field mobility equals 4000 cm^2/V s at 4.2 K and 1250 cm^2/V s at 300 K. The measured temperature dependence of the mobility is presented in Fig. 1. For the sheet electron concentration we found $n \approx 1\times10^{13}$ cm^{-2} in the entire measured temperature range (4–400 K). We conducted also magnetotransport measurements. The strong Shubnikov–de Haas (SdH) oscillations appeared at relatively low magnetic fields, which is evidence for the good quality of the AlGaN/GaN heterointerface. The sheet carrier concentration determined from the SdH oscillations was nearly the same as the value the Van der Pauw method yielded.[10]

The high-field experiments, particularly the current–voltage characteristic measurements, were carried out by using nanosecond voltage pulses applied to the sample. This pulse regime minimizes the self-heating effects. To conduct such measurements, we used a specially designed electric circuit minimizing the load mismatch altered with electric

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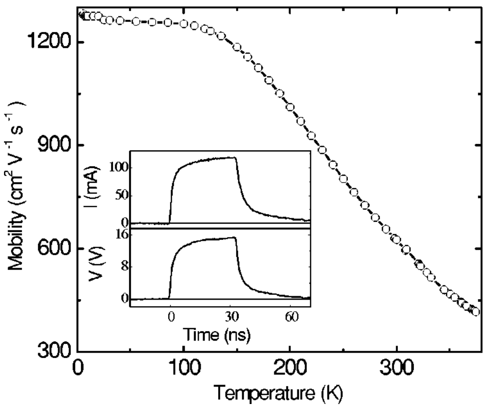

FIG. 1. Electron mobility versus ambient temperature. In the inset: examples of the wave forms of the current and the applied voltage.

pulse magnitude. The typical wave forms of the current and the applied electric voltage pulse are shown in the inset to Fig. 1. The wave form coincidence of both signals was observed at all temperatures of the experiment; importantly, it did not alter with electric pulse magnitude. The measurements were performed in temperature range 4.2 to 300 K, the sample was immersed into the liquid helium, while at elevated temperature measurements the helium gas flow was used for better electrical isolation.

The typical results of measurements of the current are illustrated in Fig. 2(a), where the current–voltage characteristics are presented for two samples with $L=5$ μm and $L=10$ μm at different ambient temperatures. General features of these results are: a rapid increase in the current from 0 to 0.15A at low voltage bias (<10 V) and an extended portion with a slow increase in the current at larger biases. Slightly higher currents occur at lower ambient temperature. Currents in excess of 1.5 A/mm are achieved at high voltages. These values are larger by one order of magnitude than the currents observed in heterostructure field effect-transistor (HFET) and metal oxide semiconductor heterostructure field effect transistor (MOSHFET)-nitride structures,[11] which can be explained by the absence of both the spillover effect and the gate leakage currents.

The results on the current–voltage characteristic and measured electron concentrations n can be used to calculate V_{dr} according to Eq. (1). To present V_{dr} as a function of the electric field E, we calculated the average field in the conduction channel taking into account the voltage drop on the contacts. We found that the dependences $V_{dr}(E)$ are very similar for the devices with different lengths L. Typical results are presented in Fig. 2(b). It is seen from Fig. 2(b) that V_{dr} increases linearly up to the fields of about 5 kV/cm, whereas at higher fields a sublinear dependence is observed. It is remarkable that, although the nitride structures under consideration had relatively small low-field electron mobilities, we obtained magnitudes of the drift velocity above 10^7 cm/s. The maximum of achieved drift velocity equals 1.7×10^7 cm/s at $E=150$ kV/cm ($T=4$ K) and 1.1×10^7 cm/s at $E=80$ kV/cm ($T=300$ K). These magnitudes of V_{dr} obtained for the 30 ns electric pulses are larger than those we measured for the longer pulses. Interestingly, despite the moderate value of the low-field mobility in the studied nitride samples, the velocity magnitudes found are close to the V_{dr} values measured for the *perfect modulation-doped* AlGaAs/GaAs structures. Indeed, for lightly doped AlGaAs/GaAs structures ($n\approx4\times10^{11}$ cm^{-2}) with a mobility of 7600 cm^2/V s at $T=300$ K, it has been found $V_{dr}\leqslant1.7\times10^7$ cm/s.[12] For another relevant comparison, we calculated $V_{dr}(E)$ dependence in the model of the shifted Maxwellian distribution, taking into account known scattering mechanisms, particularly, electron–optical phonon interaction. In Fig. 2(b), these results are shown for the ambient temperature 300 K. The theoretical values are slightly larger than the measured ones. This can be explained by the fact that, for the 30 ns electric pulses, the Joule heating still exists. Estimates show that a decrease in the duration pulse to 1–2 ns should lead to somewhat higher velocity.

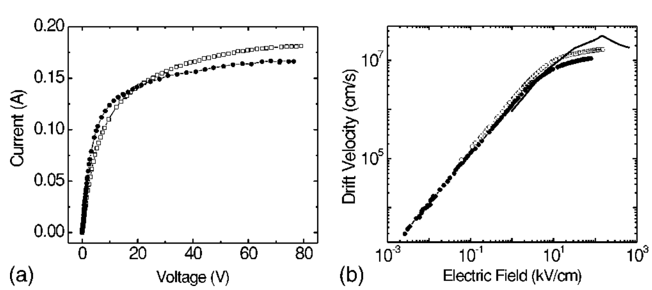

FIG. 2. (a) Current–voltage characteristics for two TLM samples. Open symbols correspond to $L=5$ μm, $T=4.2$ K, solid symbols correspond to $L=10\mu$m, $T=300$ K. (b) Electron velocity versus electric field for the same samples and temperatures as in case (a); solid curve represents the theoretical dependence.

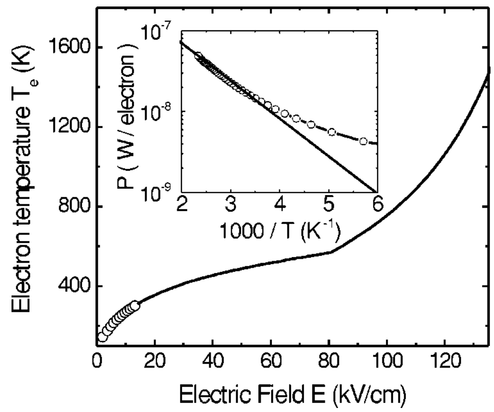

FIG. 3. Estimated electron temperature versus electric field: open symbols corresponds to experimental results, solid line to calculated values. Inset: Dissipated power as a function of inverse electron temperature.

Now, we shall briefly discuss the electron temperatures T_e in the nitride samples. For moderate electric fields, when the drift velocity is small in comparison to the thermal electron velocity ($V_{dr}\ll\sqrt{2k_BT_e/m}$, k_B and m are the Boltzmann constant and the effective mass, respectively), T_e can be estimated by the "mobility comparison" method.[8] This method consists in the measurement of the low-field mobility at different ambient temperatures $\mu(T)$ and the measurement of the hot-electron mobility as a function of the electric field $\mu_{he}(E)$. Since the distribution function of the electrons is approximately described by the Maxwellian function with substitution $T\to T_e$, equating the found dependences $\mu(T_e)=\mu_{he}(E)$, one can estimate the function $T_e(E)$. We used the results presented in Fig. 1 on $\mu(T)$ in the interval 4.2–350 K to determine $T_e(E)$ dependence for the field range 0–18 kV/cm, as presented in Fig. 3. By using this dependence, one can calculate dissipated electrical power per one electron P_e as a function of $1/T_e$. The corresponding data are shown in the inset to Fig. 3. The high-temperature portion of these data $(200\ \mathrm{K} < T_e < 350\ \mathrm{K})$ can be compared to the energy relaxation rate via optical phonon emission $P_e = (\epsilon_0/\tau_O)\exp[-\epsilon_0/k_B T_e]$, where ϵ_0 is the optical phonon energy, and τ_O is the characteristic time of optical phonon emission. This equation agrees well with the data presented in the inset at the parameters $\epsilon_0 = 92$ meV and $\tau_O = 25$ fs (compare to Refs. 8 and 9). Remarkably, the latter value can be calculated via the Frölich coupling constant α: $\tau_O = \hbar/(2\alpha\epsilon_0)$. For GaN parameters[1] we calculated $\alpha = 0.41$ and $\tau_O = 20$ fs; both estimates coincide very well.

For high fields and $T_e > 350$ K, we estimate T_e by exploiting the following consideration. Under the finite drift velocity, the energy balance equation has the form $eEV_{dr} = Q_\epsilon(T_e, V_{dr})$, where Q_ϵ is the rate of energy relaxation, which is dependent, generally, on both parameters T_e and V_{dr}. The particular form of Q_ϵ depends on scattering mechanisms and will be published elsewhere. Using measured dependence $V_{dr}(E)$, we can estimate high-field $T_e(E)$ dependence assuming that the optical phonon scattering is dominant. The estimate is presented in Fig. 3. Although these estimates illustrate the behavior of T_e in two limiting cases of relatively low fields and high fields, they allow one to make several important conclusions. The $T_e(E)$ dependence consists of three different portions: an increase in the temperature up to 350 K at low fields (<20 kV/cm), an extended portion with slow temperature variation from 350 to 500 K in the field range 20–80 kV/cm, and a fast increase in T_e at higher fields. The first portion corresponds to electron heating by the field at dominant energy relaxation through the acoustic phonons. A linear dependence of $V_{dr}(E)$ and increase in $T_e(E)$ at $E < 5$ kV/cm is characteristic for acoustic scattering of two-dimensional electrons populating the lowest subband, while at $E > 5$ kV/cm the electrons start to be redistributed over excited subbands. The second extended portion with a moderate increase in T_e corresponds to hot electrons under the dominant energy relaxation through optical phonon emission. Finally, the third portion with a fast temperature increase up to 1700 K is due to a weakening optical phonon scattering characteristic for the electron with high energy,[13] and can be interpreted as a rudiment of the so-called runaway effect.[13,14] Further temperature increase is to be suppressed at the fields above 140 kV/cm by the electron transfer to the high-energy side valleys. Large temperatures estimated for $E > 120$ kV/cm can have an impact on performance of nitride-based devices exploiting the high fields. Particularly, this "overheating" should lead to large hot-electron noise spreading up to the terahertz frequency range.

In conclusion, by applying 10–30 ns electrical pulses to AlGaN/GaN gateless heterostructures, we experimentally measured low-field and high-field transport phenomena, including the drift velocity dependence on the applied electric field up to 150 kV/cm. Particularly, a current density in excess 1.5 A/mm was measured at high voltages. These values are greater by one order of magnitude in comparison with the currents observed in gated nitride structures. For the measured samples, high electron concentrations are typical, which implies that the electron distribution function is determined by the shifted Maxwellian distribution with two parameters: the electron temperature and the drift velocity. Estimates of thermal budget of the system show that overheating of the electrons exceeds 1700 K for highest electric fields achieved in the experiment. It is remarkable that, although the measured nitride structures had moderate values of low-field electron mobility, we obtained a magnitude of the drift velocity of 1.7×10^7 cm/s at the field 150 kV/cm. This magnitude is still lower than the limit predicted by theory ($\sim 3 \times 10^7$ cm/s); however, it very close to the V_{dr} values measured for the perfect modulation-doped AlGaAs/GaAs structures.[12]

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