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Nonlocal electron dynamics in GaN / AlGaN transistor heterostructures

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The processes of nonlocal electron heating in transistor heterostructures based on gallium nitride and gallium arsenide were compared. It has been shown that, in the case of GaAs double doped pseudomorphic heterostructures, the real space transfer of electrons significantly reduces their drift velocity overshot in the region of a strong field as compared with pure bulk GaAs, while in GaN−based heterostructures the decrease in the drift velocity overshot does not exceed 30% in the studied cases.

Keywords: Real space transfer, field-effect transistor, gain factor

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The main tendency in the modern high power solid−state millimeter−range electronics is development of the gallium nitride technologies. The GaN−based transistors exhibit record values of specific power in different frequency ranges [1], they have made lodgement in the W-range [2] and advanced to almost terahertz values [3]. In this connection, positive forecasts are being made for achieving even higher operating frequencies. Literature continuously presents new information on the ways for improving characteristics of gallium nitride devices: increasing their power and steepness, improving the linearity [4–6]. The reasons for the GaN transistors predominance as regards to specific power are evident: high thermal conductivity of the silicon carbide substrates, wide band gap, and high surface density of electrons. The latter quantity reaches about 10^{13} cm^{-2} [7] even in undoped AlGaN / GaN heterostructures. Along with this, paper [6] informs that introduction into the heterostructure of AlGaN gradient layers in which the aluminum mole fraction is represented as a function of coordinate also ensures additional increase in the surface concentration. However, the quite high gain factor of these devices raises certain questions. As it has been shown many times [8,9], pure bulk gallium nitride is well behind pure bulk gallium arsenide in frequency characteristics. At the same time, comparison of high power GaAs transistors based on pseudomorphic heterostructures (DpHEMT) with devices based on GaN-heterostructures shows that the GaN-transistor gain factor often appears to be not lower than that of analogous GaAs transistors provided their short gate lengths are equal. Thus, transistors based on the AlGaN / GaN heterostructures are almost no worse than devices based on conventional pseudomorphic heterostructures with respect to maximal operating frequencies, and sometimes are even better. Explanation of this effect by that the strong−field electron drift velocity is higher in GaN than in GaAs does not stand up to scrutiny [9]. Attempts also failed to quantitatively explain this by closer proximity to the channel gate in GaN devices, as well as by the corresponding reduction of edge effects and increase in the source−gate characteristic steepness. To clarify this situation, it will be interesting to consider nonlocal electron transport in heterostructures of up−to−date UHF transistors fabricated based on different materials, since hot electron dynamics in heterostructures differs significantly from their behavior in bulk materials. For instance, in analyzing nonlocal electron heating in GaAs−based structures, it is quite important to take into account electron transitions between the heterostructure layers (real space transfer) [10] which essentially decrease the electron drift velocity beneath the transistor gate.

The calculations were performed according to the model presented in [10]. The longitudinal hot electron transport was described using a set of hydrodynamic equations with phenomenological times of electron energy and momentum relaxation. To describe the real−space electron distributions at various electron gas temperatures, the solution of the conventional self−consistent set of Schrodinger-Poisson equations was used. Finally, the set of hydraulic equations and the set of Schrodinger-Poisson equations were solved self-consistently.

The applied hydrodynamic model describes well the electron dynamics in bulk materials [8,11]; however, it is evident that scattering mechanisms in heterostructures are essentially different from those in bulk materials. Moreover, the electron dynamics may be of a rather complex character [12–17]. It is possible to assume that sufficiently correct numerical description of the electron transport in such systems can be achieved based on at least the kinetic equation solution. In this field a great progress has been achieved [18], however, models of this kind appear so far to be too complex to allow comprehensive analysis of the problems under consideration. Therefore, the used model describes the hot electron dynamics rather roughly most likely just because of its simplicity. In addition, the electric field distribution in the real transistor channel is of not stepwise but of some other character depending on the

specific operating mode of the device, which significantly affects the distributions of the electron drift velocities. This is why the used model provides only qualitative results as concerning limiting frequencies of field transistors.

Two structures were considered: a typical structure of the GaAs DpHEMT transistor and structure of the gallium–nitride HEMT transistor. In the $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As/Al_{0.3}Ga_{0.7}As$ structure, the quantum well width was 12 nm, surface–channel distance was 31.5 nm, and surface electron density was $3.4 \cdot 10^{12}\,cm^{-2}$. The GaN transistor structure comprised an undoped layer of $Al_xGa_{1-x}N$ with thickness $d = 22$ nm at mole fraction $x = 0.18$ and a GaN layer with thickness $d = 450$ nm. The channel effective width proved to be approximately 4 nm, while the design surface density of charge carriers was about $9.6 \cdot 10^{12}\,cm^{-2}$. Notice that, according to this model, electron dynamics weakly depends on the distance to the surface in both cases.

The calculations were performed for electrons that moved first during 0.2 ps in a weak field of 1 kV/cm, and then during 1 ps in a strong field, and then in a weak field again. The strong field strength was selected so that it was approximately equal to the mean field strength in the channel of a short–gate transistor. For clarity, Figs. 1 and 2 present time dependences of electron drift velocity in the heterostructures under consideration which were obtained by strict calculations according the used model (curves for DpHEMT and $Al_{0.25}Ga_{0.75}N/GaN$) and approximate calculations in which the probability of the electron location in the wide–gap material was not determined based on the self–consistent task solution but was initially assumed to be 20% (curves designated as $p(Al_{0.3}Ga_{0.7}As) = 20\%$ and $p(Al_{0.25}Ga_{0.75}N) = 20\%$), and also time dependences of electron drift velocity in bulk materials (curves for $In_{0.2}Ga_{0.8}As$, $Al_{0.3}Ga_{0.7}As$ and GaN, $Al_{0.25}Ga_{0.75}N$) allowing theoretical estimation of the lower and upper limits of the drift velocity.

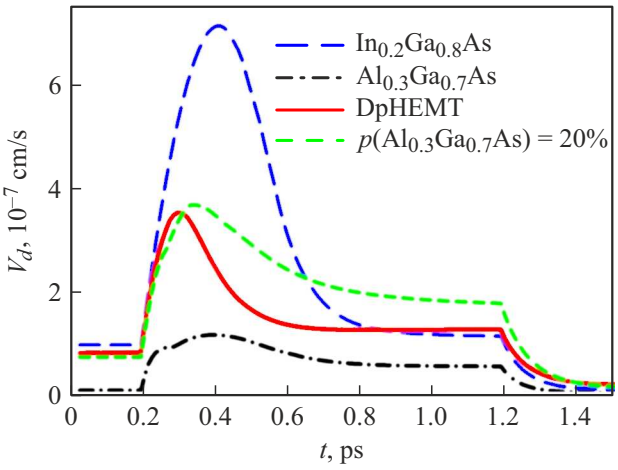

Figure 1. Electron drift velocity versus time for the DpHEMT structure. Electrical field strength: $E = 1$ kV/cm at $t = 0–0.2$ and 1.2–1.5 ps, $E = 20$ kV/cm at $t = 0.2–1.2$ ps.

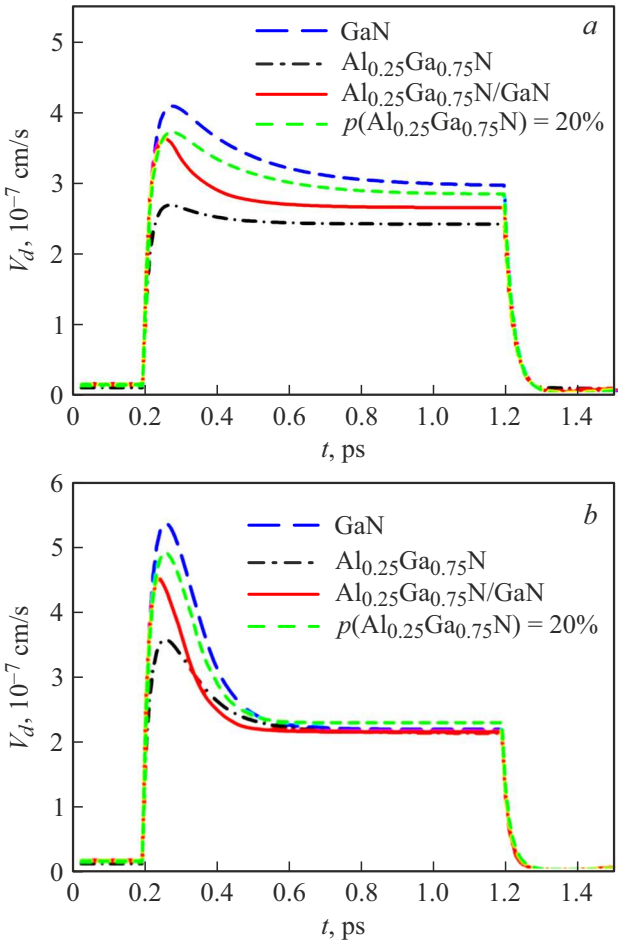

Figure 2. Electron drift velocity versus time for the AlGaN/GaN structure. Electrical field strength: $E = 1$ kV/cm at $t = 0–0.2$ and 1.2–1.5 ps, $E = 200$ (a) and 300 kV/cm (b) at $t = 0.2–1.2$ ps.

Fig. 1 presents the calculations for the first heterostructure. One can see that layer–to–layer electron transitions in the GaAs–based heterostructure strongly affect the electron drift velocity. This is obviously caused by that electron velocities in $In_{0.2}Ga_{0.8}As$ and $Al_{0.3}Ga_{0.7}As$ differ significantly, especially in the case of nonlocal dynamics. For instance, when finally 20% of electron transfer into the wide–gap material (with the preset probability), the overshot decreases almost twice. When the probability depends on the electron temperature (self–consistent calculation), the decrease is even larger. Moreover, the overshot duration also decreases twice. At the same time, in the GaN–based structures there is an absolutely different situation. Nonlocal electron dynamics in GaN and $Al_{0.25}Ga_{0.75}N$ differ from each other only slightly (Fig. 2).

The time dependence of the drift velocity for the $Al_{0.25}Ga_{0.75}N/GaN$ heterostructure is to be approximately between such dependences for pure GaN and $Al_{0.25}Ga_{0.75}N$. Accordingly, dependences of the electron drift velocity overshot in both the self–consistent calculation for the heterostructure and calculation at the preset probability of

location in 20% in the wide−gap material quite slightly differ from a similar dependence in pure GaN. Thus, the maximum drift velocity reduction is less than 30% in all the considered cases. Notice that, generally speaking, the aluminum mole fraction in such structures may change somewhat; therefore, the scattering frequencies for the dynamics calculation were set to the values for $x = 25\%$, i. e, the worst variant was considered.

Thus, one of important factors explaining high gain characteristics of GaN−based heterostructures is appropriate heteropair composition (dynamics in the narrow−gap and wide−gap materials differ poorly). Based on this, the following conclusions may be made. On the one hand, the electron velocity in GaN−based heterostructures can hardly be essentially increased without using fundamentally new approaches; vice versa, this is possible in GaAs heterostructures [10]. Surely, this will prevent further progress in elevating frequency bands of devices based on GaN heterostructures. On the other hand, GaN−based transistor heterostructures, contrary to those based on GaAs, exhibit a weak dependence of the electron drift velocity on the profile of the heterostructure conductivity band bottom. This opens for GaN−based HEMTs great opportunities for improving their purely „transistor" properties, e. g., for reducing the effective width of the hot electron channel in order to decrease the gate−drain transconductance, minimizing the gate−channel distance in order to increase the gate−source transconductance and thus reduce the influence of parasitic elements, etc.

Conflict of interests

The authors declare that they have no conflict of interests.

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