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The electrons drift velocity overshot in inverted transistor heterostructures with donor–acceptor doping and additional digital potential barriers

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The first results of the electrons drift velocity study in inverted AlGaAs/InGaAs/GaAs pseudomorphic heterostructures with donor–acceptor doping and short–period AlAs/GaAs superlattices are presented. It is theoretically shown that the introduction of superlattices significantly, up to one and a half times, increases the electrons drift velocity overshot when they enter the region of a strong field. Localized states in the superlattice between the quantum well and the substrate have been found. It is shown that this effect leads to an additional increase in the electrons drift velocity overshot up to the theoretical limit for the model used, i.e., a drift velocity overshot in the bulk material of the quantum well.

Keywords: inverted heterostructure, digital barriers, field-effect transistor, gain.

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Continuous intensification of information flows requires an increase in the communication channel carrying capacity and, hence, an increase in the reception and transmission operating frequencies. It is assumed that one of the possible communication standards 6 G will operate at about 300 GHz. This, in its turn, needs sufficiently powerful, reliable and, if possible, low–cost power amplifiers. At present, driving of high–power semiconductor transistors to the millimeter wavelength range is connected mainly with improving the gallium nitride epitaxial technologies [1–4]. However, commercial use of such devices at frequencies considerably higher than 100 GHz looks yet rather problematic [4]. Therefore, in fabricating field transistors and amplifiers for operation at wavelengths below 2 mm there are mainly used metamorphic heterostructures AlGaAs/InGaAs on the GaAs substrates and heterostructures AlInAs/InGaAs on the InP substrates [5,6] with the narrow–band $In_xGa_{1-x}As$ channel with the indium mole content of $x = 0.8$ and higher. With respect to their amplification characteristics, transistors based on such structures are at present beyond competition. However, the narrow band gap of the channel causes low breakdown voltages and, hence, low specific output powers. At the same time, there is one more promising way of extending to the higher frequency range, which allows a sharp increase in the field transistor specific power and gain [7,8]. This way is to use pseudomorphic heterostructures with the $In_xGa_{1-x}As$ $(x > 0.15)$ channel on the GaAs substrates with barriers raised due to selective doping with donors and acceptors. It appeared to be especially useful in the case of inverted heterostructures [9] that evolved from almost dysfunctional [10] to extremely promising ones [11]. The main distinguishing feature of these structures, namely, doping of the barrier near the quantum well on the side of substrate, allows moving the transistor channel maximally close to the gate and, thus, significantly increasing the source–gate slope, which is especially important just in the millimeter wavelength range. Elementary estimates show that transition to the inverted structure leads to the following increase in the maximum current amplification frequency:

$$\frac{\Delta f_t}{f_t} = \frac{C_p}{C_{gs}}\left(\frac{d-h}{d}\right) \Big/ \left(1 + \frac{C_p}{C_{gs}}\frac{h}{d}\right),$$

where C_{gs} is the source–gate input capacity of the „intrinsit“ field transistor on the pseudomorphic heterostructure with high electron mobility (pHEMT), C_p is the gate parasitic power, d is the distance between the gate and quantum well center in pHEMT, h is the distance between the gate and quantum well center in the inverted structure. The frequency increment in short T-shaped gates may be 20–30%, which approximately matches with the gain increase to 2 dB.

In addition, such structures possess one more potential possibility of improving the characteristics, and can seriously compete with conventional metamorphic and InP–matched heterostructures in terms of high–power devices designed for the short–wavelength part of the millimeter wavelength range.

The main idea of the selective donor–acceptor (DA) doping of the double pseudomorphic heterostructure (DpHEMT) is to increase the extent of electron localization in the channel by creating sharp p–i–n potential barriers

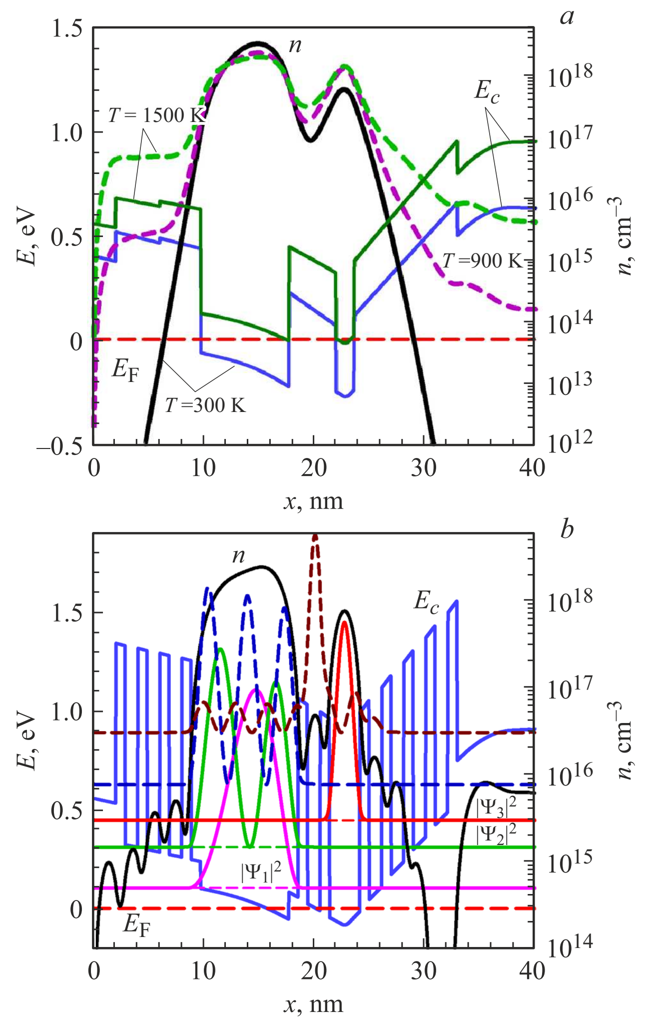

Figure 1. Band diagrams and electron concentration distributions. a — a structure with averaged layer parameters at the electron gas temperatures of 300, 900 and 1500 K. b — with additional potential barriers at the electron gas temperature of 1500 K (in calculations, 20 quantum levels were considered).

on both channel sides (heterostructure DA-DpHEMT) [7]. These additional potential barriers reduce the electrons real space transver from the channel to the wide–bandgap AlGaAs layers and considerably increase the electron drift velocity [12] and its overshot when electrons enter the strong field region beneath the transistor gate [11]. Evidently, the extent of electron localization in the channel drastically depends on both the band discontinuity at the interfaces between layers with different elemental compositions [13] and potential profile of the additional barriers formed by the electric field of p–i–n transitions. Therefore, the interface band discontinuity will increase if the uniform AlGaAs spacers between the channel and n–δ-layer and between the δ-layer and thin p-layer are replaced with thin AlAs/GaAs superlattices several monolayers in period. Such superlattices are often referred to as digital (analogously to the binary code sequence) since their average elemental composition is defined by the ratio between the numbers of AlAs and GaAs monolayers. What is important for transistors is that the digital barriers can raise the hot electron localization in the channel.

In this work, the effect of digital barriers on the electron spectrum and transport characteristics of heterostructures in a strong electric field was studied theoretically. Three heterostructure types were considered: conventional inverted heterostructures with one δ-layer between the channel and substrate; inverted heterostructures selectively DA–doped on the substrate side; inverted heterostructures with a DA–doped region surrounded by digital barriers. The mean Al mole fraction in the spacer was approximately equal in all the structures. The calculation was performed via a model based on self–consistently solving the Schrodinger and Poisson equations and a set of hydrodynamic equations [11].

Fig. 1 presents band diagrams and carrier concentration distributions for the DA–doped structure at different electron gas temperatures (a) and for the structure with digital barriers at the electron gas temperature of 1500 K (b). One can see that the digital barriers enhance the electron localization in the channel. This, in its turn, leads to a significantly greater (by 1.5–2 times) drift velocity overshot (Fig. 2).

The structures with digital barriers exhibit (at least in calculations) one more effect that is extremely interesting and useful for designing microwave transistors: when the electron gas temperature increases under the thermodynamic equilibrium conditions, electrons transfer from a number of quantum well levels to the states localized in the vicinity of digital barriers (Fig. 1, b). The wave function of these localized states in the channel is almost zero. This means that in the millimeter–wavelength transistor elec-

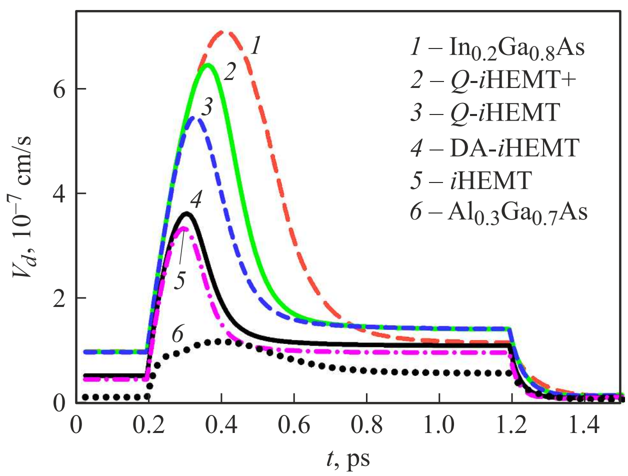

Figure 2. Electron drift velocity versus time when the electrons enter the strong field region ($t < 0.2$ ps, $E = 1$ kV/cm; $0.2 < t < 1.2$ ps, $E = 20$ kV/cm; $t > 1.2$ ps, $E = 1$ kV/cm). iHEMT — the inverted structure, DA-iHEMT — the inverted structure with donor–acceptor doping, Q-iHEMT =— the inverted structure with donor–acceptor doping and digital barriers, Q-iHEMT+ — the calculations accounting for the localized states.

trons will hardly transfer to those levels during their almost ballistic [14] flight under the gate. Fig. 2 demonstrates the estimate time distributions of the electron drift velocity overshot calculated with considering this effect. Levels localized within the AlAs/GaAs short–period superlattice (in this case, this is the third level) were merely ignored in the calculations. Evidently, in this case the overshot increases significantly thus approaching the theoretical limit of this model, namely, the drift velocity overshot in the bulk channel material. This means that in transistors based on the structures with digital barriers this may be an additional mechanism for a considerable increase in their operating frequencies.

In principle, the calculations performed provide an answer to the main question of study [15] on what is the source of excess amplification in the transistors based on the earlier developed DA-DpHEMT heterostructure as compared with the previously obtained estimates. Taking into account the results of [15] and above–presented calculations, simple estimates show that, when the transistor gate is shrunk to 0.05 μm, optimization of the inverted structures with DA doping and additional digital barriers may enable the transistors to work at frequencies of up to 300 GHz with retaining quite high specific powers that are several times higher than those of modern transistors with the $In_xGa_{1-x}As$–based channels with high mole content of In.

Thus, the obtained results show that the use of digital barriers is a quite efficient way of improving characteristics of transistors based on inverted DA–doped heterostructures. This makes possible a two–fold increase in the operating frequencies and, hence, four–fold increase in the gain as compared to those of conventional DpHEMT transistors with retaining high values of other parameters, e. g., specific power. Thus, the transistors based on inverted heterostructures with donor–acceptor doping and digital barriers can compete with GaN–based devices and transistors with $In_xGa_{1-x}As$–based channels with high mole content of indium, especially in the millimeter and submillimeter wavelength range.

Conflict of interests

The authors declare that they have no conflict of interests.

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