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Double-channel heterostructure with additional digital potential barriers for high-power field-effect transistors

© S.A. Bogdanov, S.N. Karpov, A.B. Pashkovskii

JSC „RPC „Istok"named after Shokin", Fryazino, Moscow oblast, Russia
E-mail: solidstate10@mail.ru

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The first results of double-channel heterostructures with donor-acceptor doping and systems of alternating thin layers of AlAs/GaAs forming additional digital potential barriers study are presented. It is shown that due to the peculiarities of real space electron transfer in the proposed design, when the surface density of electrons with high mobility is doubled compared to traditional single-channel bilaterally doped heterostructures, even in the absence of digital barriers, the drift velocity overshot does not decrease. The introduction of digital barriers significantly increases the of electrons drift velocity overshot when they fly into the region of a strong field, bringing the drift velocity overshot in the corresponding heterostructures closer to the theoretical limit for the model used — the drift velocity overshot in the undoped bulk material of the channel.

Keywords: double-channel structure, digital barriers, field-effect transistor, real space transfer.

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The current advancement of high-power semiconductor devices toward the millimeter wavelength range is driven largely by the progress in epitaxial gallium nitride technology [1–4]. However, while these studies of gallium nitride heterostructures on silicon carbide substrates are undeniably promising, the use of structures on silicon substrates for the same purpose raises questions. Indeed, a silicon substrate with a thickness of just $50\,\mu$m reduces (under otherwise equal conditions) the specific power of a transistor by a factor of at least 1.5 [5], since the thermal conductivity of silicon is lower than the one of silicon carbide. At the same time, it is estimated (see below) that virtually the same levels of specific power are feasible in gallium arsenide heterostructures. This may both solve all the problems inherent in the „gallium nitride on silicon" technology and help raise several-fold the gain of a transistor at a constant gate length.

Owing to the specifics of localization of electrons in channels of traditional gallium arsenide heterostructures, the surface density of electrons is approximately equal to $3 \cdot 10^{12}\,\mathrm{cm}^{-2}$. This surface density corresponds to a specific power level of $1-1.2$ W/mm. If the heterostructure design remains essentially unchanged, a further increase in the surface density leads to a significant reduction in the gain factor. However, heterostructures based on gallium arsenide have ample opportunities for improvement. An example here is provided by heterostructures with donor-acceptor doping (DA-DpHEMT [6]), which made it possible to raise the specific power of commercial devices to above 1.5 W/mm and achieve a two-fold gain enhancement, and heterostructures with donor-acceptor doping and digital barriers (Q-DpHEMT [7]), which provided an almost two-fold enhancement of the gain factor of transistors based on them. However, the surface density of high-mobility electrons in the channel of such heterostructures cannot be increased uncontrollably, since the Fermi level may match the position of upper valleys in GaAs. Apparently, the overall surface density may be enhanced only by increasing the number of channels in a transistor heterostructure. This idea is not a new one: multichannel heterostructures have already been proposed in the early days of development of high-power heterostructure transistors [8]. However, it is known that the real space electron transfer exerts a strong negative influence on the characteristics of heterostructure transistors [9]. At the first stage of development of multichannel heterostructures (i.e., before the implementation of reliable delta doping techniques), there were no efficient ways to mitigate real space transfer. At subsequent stages, this issue was apparently disregarded [10]; channels were spaced too widely apart, and the result was adequate to these conditions.

A double-channel heterostructure (Q-DCpHEMT), where the influence of the real space electron transfer on hot electron dynamics is suppressed significantly owing to the introduction of digital potential barriers, was designed based on the results reported in [6,7,9]. Its band diagram is presented in Fig. 1. Three short-period AlAs/GaAs superlattices with layer thicknesses of 3 and 4 ML, respectively, distinguish this design from the traditional ones. Six digital potential barriers form a lattice on the substrate and gate side, and channels are separated from each other by a superlattice with four digital potential barriers.

The surface density of electrons in each channel (channels are separated by a set of digital potential barriers) is $n_s = 4 \cdot 10^{12}\,\mathrm{cm}^{-2}$. Additional donor-acceptor doping is introduced on the substrate side in order to suppress the drift of electrons into the substrate and their accumulation in the short-period AlAs/GaAs superlattice located at the base

of the active region of the heterostructure. It is suggested to introduce no acceptors on the gate side; an equivalent effect is produced by surface states in the presence of a superlattice. If no superlattice is present, the field of surface states cannot confine hot electrons within a channel. The typical band bending magnitude is 0.2−0.3 eV. This is the reason why donor-acceptor doping at the heterostructure surface was used in [6,7]. The gate field interferes with the accumulation of charge in the superlattice beneath the gate.

The results of calculations performed using the model from [9] demonstrate (Fig. 1) that the majority of electrons are located within narrow-band channels of this structure even at an electron gas temperature of 1500 K. This, in turn, translates into a considerable drift velocity overshot of electrons entering the region of a strong field (Fig. 2): it is almost equal to the drift velocity overshot of electrons in undoped $In_{0.2}Ga_{0.8}As$, which is the theoretical limit for the model used. While this result is somewhat predictable in

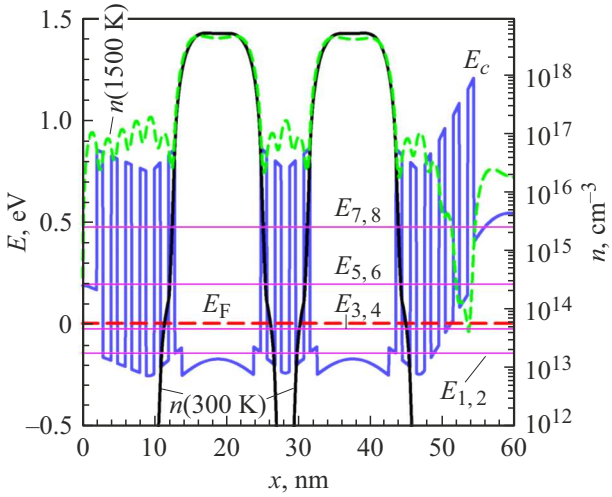

Figure 1. Band diagram and electron density distributions in the structure with two channels and digital barriers. The electron gas temperature is 300 K (solid curve) and 1500 K (dashed curve).

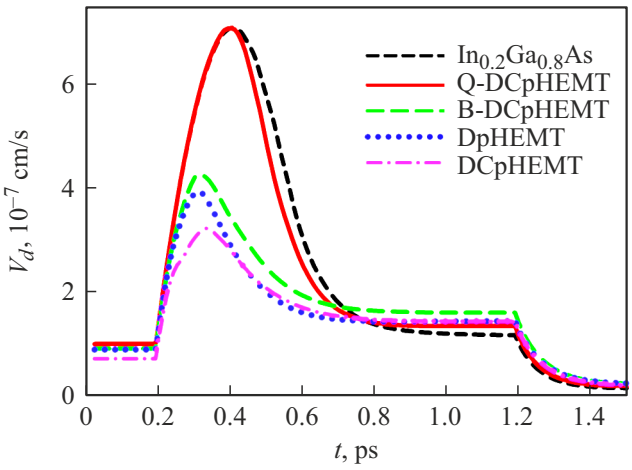

Figure 2. Time dependences of the drift velocity of electrons entering the region of a strong field. $E = 1$ kV/cm at $t < 0.2$ ps; $E = 20$ kV/cm at $0.2 < t < 1.2$ ps; and $E = 1$ kV/cm at $t > 1.2$ ps.

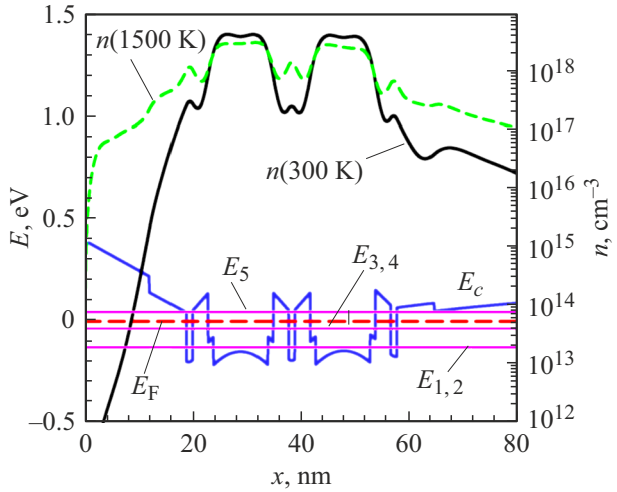

Figure 3. Band diagram and electron density distributions in the structure with two channels and without digital barriers. The electron gas temperature is 300 K (solid curve) and 1500 K (dashed curve).

the context provided by [7,9], the outcome of a comparison (see Fig. 2) between the drift velocity overshot in an ordinary single-channel bilaterally doped structure (traditional DpHEMT) and a double-channel structure without digital barriers and donor-acceptor doping on the substrate side (B-DCpHEMT; see Fig. 3) is entirely unexpected. It turns out that the drift velocity overshot of electrons in this double-channel structure is no smaller in magnitude than the one in the traditional DpHEMT transistor structure. This is likely attributable to the fact that, in contrast to previous studies into multichannel transistors, the region of intense scattering was made fairly narrow through the use of delta doping. Naturally, the scattering intensity increases notably (Fig. 2) and the drift velocity overshot of electrons gets suppressed strongly (DCpHEMT) if one removes the internal spacers (barriers at the boundaries of the internal delta layer).

Thus, with the results reported in [6] taken into account, the specific output power of devices based on heterostructures with a double channel without digital barriers may be estimated theoretically at 3−4 W/mm (at a gain factor close to the one of traditional DpHEMT transistors). Introducing digital barriers and donor-acceptor doping on the substrate side into the design of heterostructures with a double channel, one may raise the gain factor by at least 3−4 dB while preserving the same level of specific output power (or even increasing it slightly). Naturally, if the design of a gallium arsenide device remains unchanged, thermal effects make it impossible to reach these power levels anywhere outside of pulsed operation modes. In order to enable continuous operation at high specific output power levels, one needs at least to reduce the substrate thickness to 25 μm and increase the distance between the „fingers“ of a device accordingly.

Conflict of interest

The authors declare that they have no conflict of interest.

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