Mechanisms of a negative differential conductivity in a short-channel $\text{In}_{0.52}\text{Ga}_{0.48}\text{As/In}_{0.53}\text{Al}_{0.47}\text{As}$ HEMT

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Mechanisms of a negative differential conductivity in a short-channel In$_{0.52}$Ga$_{0.48}$As/In$_{0.53}$Al$_{0.47}$As HEMT

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Abstract. The effect of negative resistivity observed at anomalously low voltages in output characteristics of modulation-doped In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As field-effect transistors is considered. In the discussed experiments, the threshold for appearance of negative resistivity depends not only on the gate length, which was mentioned before, but also on the gate–drain voltage. It is shown that the negative differential resistivity observed at output characteristics of the short-channel In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As field-effect transistor at anomalously low threshold voltages is related to the formation of the second transport channel. This effect is a result of resonance transition of hot electrons from upper levels of the quantum well to the above-barrier layer via the states of ionized donor impurity.

1. Introduction

One of the mechanisms most actively discussed in recent years is the one related to the formation of a descending section in the transistor’s output characteristic; this effect can be caused, by example, by interlayer transport of hot electrons in the heterostructures with two-dimensional (2D) electron gas [1]. The most interesting features of this effect are observed in transistors fabricated on the basis of the In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As heteropair. The distinctive feature of such transistors in comparison with a traditional GaAs/GaAlAs high electron mobility transistor (HEMT) is the deeper quantum well ($U_{QW} \approx 0.5eV$) (that forms the transport channel in the InGaAs layer), and the absence of side valleys within the depth of the quantum well (the energy distance between the valleys $\Gamma$ and $L$ is $E_{1L} \geq 0.55eV$); these valleys make possible the manifestation of effects related to the transport of electrons between the valleys. In these structures, the effects related to the interlayer electron transport manifest themselves most clearly, which was shown by Mensz et al. [2]. Moreover, they found for the first time that, in the case of the gate length $L_C < 1\mu m$, one observes a decrease in the value of the threshold voltage $U_D$ for the formation of the descending section in output characteristics of a transistor from $U_D = U_{QW} = 0.5V$ at $L_C \geq 1\mu m$ to the value of $U_D \approx 0.35V$ at $L_C \approx 0.6\mu m$. Even smaller values of the threshold voltage, $U_D \leq 0.1V$, were observed for field effect transistors (FETs) [3]. However, possible mechanisms of formation of a section with negative differential resistivity (NDR) in output characteristics of a transistor at low voltages applied between the source and drain of the transistor were not discussed in available publications so far.
2. Effect of a negative differential conductivity in a short-channel transistor

In this study, we analyze the results of measurements of output characteristics of a short-channel In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As transistor fabricated using the traditional technological scheme [3] with high-mobility 2D electrons in the transport channel. Conducted experiments show that it is possible to observe the NDR section in the output characteristics of transistors at anomalously low threshold voltages, $U_D < 0.1V$, at a lowered temperature [3] for negative and positive voltages $U_G$ at the gate. The conducted measurements show not only that, as the length of the transistor gate is decreased, the threshold voltage decreases but also that this voltage depends directly on the gate–drain voltage. In what follows, we consider possible causes of appearance of features in experimental curves.

In figure 1, we show the output characteristics $J_D (U_D)$ of the transistor that belongs to the same series of structures that were used in the studies reported in [3]. Measurements were carried out at temperature $T = 4K$ for several voltages applied to the transistor electrodes. The presented results and ones obtained by other groups show that the low-field NDR ($U_D < U_{OW}$) is observed in a wide range of temperatures and applied voltages; however, the minimum voltage at the gate $U_G$, at which the NDR section appears, is significantly different for different structures. The section of negative resistivity at output characteristics of the transistor represents the source of noise in the structure. Therefore, an analysis of possible causes of the NDR formation in the transistor channel and the effect of NDR on the emission spectrum of a transistor require careful consideration.

![Figure 1. Experimental (points) output characteristics of a short-channel In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As transistor at $T = 4K$ and for the voltage at the transistor gate $U_G = 0.1V(1), 0.05V(2), 0V(3)$. Lines represent the theoretical dependences obtained in the context of two-temperature transport model.]

The specific feature of the transistor manifests itself in the dependence of the threshold voltage on the gate voltage in the transistor (figure 1) and was not taken into account in previous studies. The threshold voltage in the short-channel structure increases as the gate potential is increased at a constant gate length; i.e., an anomalously low threshold for appearance of NDR in the $I–V$ characteristic of a short-channel transistor structure is a consequence of a decrease not only in the effective gate length but also in the transverse electric field applied to the structure. It is also worth noting that, as the gate voltage $U_G$ is varied, the voltage $U_{DG}$ between the drain and gate remains unchanged, which indicates that the resonance mechanism of formation of low-threshold NDR can manifest itself in the sample.

3. Transfer mechanism of the hot electrons in a short-channel FET

We now discuss the mechanisms that can be responsible for experimentally observed phenomena. In accordance with numerous previous studies [2] where it was shown in a conclusive way that the formation of NDR in output characteristics of In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As FETs with a long channel ($L_G > 1\mu m$) is related to the effect of interlayer transport of hot electrons in real space. In order to assess the NDR effect in the structures considered here, we assume that there is the transport of hot electrons between two spatially separated channels in the system; these channels differ in transport properties of electrons. Possible causes of the appearance of additional transport channels in the samples will be considered separately.

In order to analyze the observed current dependences, we use the two-temperature model of electron transport; this model showed itself to be an advantage in practice [4]. In figure 1 with the
solid lines we show the results of calculations of the current $J_D$ flowing through the structure in relation to the voltage $U_D$ between the drain and source of the transistor. The final theoretical dependences obtained as a result of the considered calculation procedure are in excellent agreement with experimental data shown in figure 1. Although the appearance of two transport channels in the real space and the redistribution of electrons between these channels ensuring the descending portion in the $I–V$ characteristic of the structure are established beyond doubt, the position of the second channel and causes bringing about its appearance remain the subject of discussions.

Figure 2. (a) The structure of the conduction-band bottom and (b) the distribution of potential in the vicinity of heteroboundary of the quantum well (QW) with the upper barrier layer doped at a level of $N_D = 2 \times 10^{18}$ cm$^{-3}$; $T = 5$K. The spectrum of energy levels in the quantum well, the position of the Fermi level $E_F$, and positions of the levels of shallow donor centers are shown (dashed lines). $x_0 = 22.5$nm is the Debye screening radius.

A possible cause of the appearance of NDR in the $I–V$ characteristic can be related to transitions of electrons heated by an electric field from lower subbands of quantum confinement $E_{21} \approx eU_{D1}$ to upper subbands. If electrons remain within the quantum well as a result of interlevel transitions, then, due to the fact that the electrons’ effective masses are the same in different subbands of quantum confinement, the only possibility for appearance of NDR in the structure is related to a significant difference in characteristic times of scattering of electrons at the upper and lower levels. The electrons that reside at the lower level of dimensional quantization and are localized in the center of the quantum well are scattered only slightly by the potential of impurity atoms in barrier layers. The maxima of the wave function of the electrons at the second level of dimensional quantization are located near the boundaries of barrier layers; as a result, these electrons experience more pronounced scattering and their mobility is much lower compared with the mobility of electrons at the first level of the quantum well. However, according to the model under consideration, formation of NDR in the $I–V$ characteristic is impossible if we have only a reduction in the electron mobility as a result of the transition of electrons to the second level of the quantum well (compare curves 1 and 3 in figure 1). The required variation in the density of states $N_{1(2)}$ can be attained only as a result of transport of 2D electrons in the real space from the quantum well to the states in the barrier layer. On the other hand, estimations of the position of the Fermi level in the structure with the quantum-well thickness of 20 nm and the electron concentration higher than $2 \times 10^{18}$ cm$^{-3}$ show that the two lower subbands of dimensional quantization are filled. In the case under consideration, the electron concentration in the transistor channel was as high as $n \approx 4 \times 10^{12}$ cm$^{-2}$ and the Fermi energy equalled $E_F = \pi n \hbar^2 / m^* \approx 220$meV; i.e., the Fermi energy vastly exceeded the energy of the dimensional-quantization level $E_2$ ($E_2 - E_1 \approx 60$meV). Thus, the considered mechanism of formation of the descending section in the $I–V$ characteristic is possible only in the region of low electron concentrations in the transistor channel.
In the case of experiments under consideration (figure 1), it is more reasonable to assume that, as a result of heating of the charge carrier by an electric field, electrons from the Fermi level transfer to the third energy level \( E_3 \) in the quantum well \( (E_3 - E_F = 300\text{meV}, E_3 - E_F \approx 80\text{meV}) \). Numerical analysis of the structure of the energy band in the system (figure 2) on the basis of the Poisson equation shows that only electrons from the third energy level in the quantum well can transfer to the neighboring barrier layer. Calculations show that, at the doping level \( N_D \approx 10^{18}\text{cm}^{-3} \) of the barrier layer with the thickness \( d_D \), the potential arising in the structure as a result of redistribution of charges due to their transfer from the impurity centers to the quantum well has the amplitude \( \sim 200\text{mV} \). The value of the potential \( \varphi \) modulating the bottom of the quantum well can be estimated on the basis of the following considerations. Ionized donors and electrons in the structure are spatially separated and their charges are equal by magnitude. In addition, as a result of quantization of electrons in the potential well of the InGaAs layer, their charge is almost uniformly distributed over the layer’s thickness. It is quite reasonable to replace the charge of electrons in the right-hand side of the Poisson equation by an equivalent charge of ionized acceptors \( (N_A = N_0) \). In this case, a solution of the Poisson equation at the half-period for a structure with a completely compensated charge of free carriers can be written as

\[
\varphi_{\text{max}} - \varphi_{\text{min}} = (1/8)N_A^*d_D^2/\varepsilon_0, \quad \text{where} \quad \varphi^* = \varphi / kT, \quad d_D^* = d_D / x_0, \quad x_0 = (\varepsilon_0 kT / 4 \pi n_e^2)^{1/2}, \quad \text{and} \quad N_A^* = N_D / n_1.
\]

For the values of the parameters \( N_D = 2 \times 10^{18}\text{cm}^{-3} \), \( d_D = d_{ch} = 2 \times 10^{-6}\text{cm} \), and \( \varepsilon_0 = 14 \), we correspondingly obtain \( e\varphi_{\text{max}} - e\varphi_{\text{min}} = 260\text{meV} \), which is quite consistent with the results of a more precise numerical analysis (figure 1). This value of the potential is quite sufficient to ensure the possibility of resonance transitions of electrons from the third level of the quantum well to ionized shallow impurity centers in the upper barrier layer of the structure. These electrons pass to the conduction band as a result of breakdown in the pulling electric field. The resonance model of electron transitions between the layers is supported by the experimentally observed (see figure 1) dependence of the threshold voltage on the gate voltage and existence of a threshold voltage \( |U_{GD}| = 50\text{mV} \) for a transistor with the \( I-V \) characteristic shown in figure 1). The above field gives rise to a threshold for tunneling of electrons between the states in the main and additional channels. An increase in the voltage at the transistor gate by \( \Delta U_G \) at a specified voltage at the transistor drain brings about the disappearance of the NDR in the \( I-V \) characteristic. However, as the current through the structure is increased, i.e., as the voltage at the drain electrode is increased, the system again transfers to the resonance state if the condition \( \Delta U_D = \Delta U_G \) is satisfied (see figure 1). Differences in the geometry of the structural elements of specific devices also give rise correspondingly to different values of \( U_{GD} \) and \( \Delta U_D \) for different transistors. The probability of formation of resonance electronic states in the potential well of the \( \delta \)-doped InGaAs:Si layer is low as a result of scattering of electrons by the impurities’ potential (the free path \( l_p = N_D^{1/3} \approx 10\text{nm} < d_{QW} \approx 20\text{nm} \)). As a consequence of the multivalley character of the electron spectrum in the InAlAs layer and different electron masses in 2D (InGaAs) and 3D (InAlAs) channels in the system, the condition \( R = N_2 / N_1 >> 1 \) required for observation of NDR in output characteristics of the transistor is easily satisfied.

So, the new resonance mechanism of the hot electron transfer in a short-channel FET, that explains the peculiarities of the observed NDR effect, is proposed.

References