08.3;13.4

AlGaAs/InGaAs/GaAs heterostructures for pHEMT switching transistors

© D.Yu. Protasov[1,2], D.V. Dmitriev[1], K.S. Zhuravlev[1], G.I. Ayzenshtat[3], A.Y. Yushchenko[3], A.B. Pashkovsky[4]

[1] Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
[2] Novosibirsk State Technical University, Novosibirsk, Russia
[3] Scientific and Research Institute of Semiconductors, Tomsk, Russia
[4] JSC „RPC „Istok"named after Shokin", Fryazino, Moscow oblast, Russia
E-mail: protasov@isp.nsc.ru

Received May 26, 2022
Revised July 14, 2022
Accepted July 16, 2022

The pHEMT heterostructures optimized in this work to improve the parameters of switching microwave transistors have a one-sided δ-doping at $6 \cdot 10^{12}\,\text{cm}^{-2}$ and an AlAs/GaAs spacer. Such heterostructures were used to fabricate the monolithic integrated circuits of single-pole double throw pHEMT switches with gate length and width of $0.5\,\mu$m and $100\,\mu$m, respectively. The resulting transistors had the following parameters: $g_{\max} = 400$ mS/mm, saturation current $I_D = 380$ mA/mm, ON-state resistance $1.0\,\Omega \cdot$ mm, OFF-state capacitance 0.37 pF/mm. The switch parameters at 20 GHz are: insertion loss -2.2 dB, isolation -56 dB, return loss -11.7 dB, linearity $P_{1\,\text{dB}} = 21$ dBm and $\text{II}P_3 = 40$ dBm.

Keywords: Single-side doping, spacer design, maximal conductivity, pHEMT, switches.

DOI: 10.21883/TPL.2022.09.55075.19260

The rapid development of technology of detection, communication, and positioning systems and the heightened requirements imposed on military and commercial high-frequency equipment necessitate the engineering of more and more advanced solid-state components of microwave electronics. Monolithic integrated circuits (MICs) of microwave switches fabricated based on pHEMT (pseudomorphic high electron mobility transistor) heterostructures are one of the components of this kind [1]. A number of requirements are imposed on the parameters of pHEMT switching transistors for such circuits. The key requirement consists in minimizing the on-state transistor resistance (R_{on}) and the off-state capacitance (C_{off}).

It has been demonstrated via mathematical modeling that transistors with a donor density in the δ-layer closest to the heterostructure surface being 4–6 times higher than the one in the lower δ-layer provide the best switching characteristics [2,3]. Compared to heterostructures with double-sided δ-doping, the electron density maximum in heterostructures with a single δ-layer close to the surface shifts away from the inverted InGaAs/AlGaAs heterointerface, which has a higher roughness than a direct AlGaAs/InGaAs heterointerface [4]. The electron mobility increases as a result, while the heterostructure resistance decreases (at comparable electron densities) [5]. All this suggests that heterostructures with one-sided δ-doping should be suitable for the fabrication of switching transistors.

In order to reduce resistance R_{on} further, one needs to alter the electron density by raising the donor impurity density. However, the mobility of electrons decreases when their density exceeds $(1.5-1.8) \cdot 10^{12}\,\text{cm}^{-2}$ [6]. This feature of electron mobility may lead to a reduction in conductivity. Therefore, one needs to investigate the dependence of conductivity of pHEMT heterostructures with one-sided doping on the dopant impurity density in the region above $2 \cdot 10^{12}\,\text{cm}^{-2}$.

In the present study, the influence of both the method and level of doping and the spacer design on the resistance of a pHEMT heterostructure with one-sided doping is examined. Models of integrated circuits of double-throw pHEMT switches are fabricated based on heterostructures with the optimum resistance, and their parameters are measured. It is demonstrated that heterostructures with a spacer in the form of a short-period AlAs/GaAs superlattice and δ-doping at the level of $6 \cdot 10^{12}\,\text{cm}^{-2}$ are the optimum ones for switching transistors. The parameters of switching transistors fabricated based on such heterostructures are on par with the ones of transistors based on heterostructures with double-sided doping.

The studied heterostructures were grown by molecular beam epitaxy on semi-insulating GaAs substrates. The temperature of growth of the buffer GaAs layer was varied within the range of $550-600^\circ$C to obtain an atomically smooth surface. The growth temperature for the InGaAs layer was reduced to 510°C. In the process of spacer growth, the substrate temperature was raised to $530-550^\circ$C; δ-doping with silicon was performed at this temperature. AlGaAs layers were grown at a temperature of 620°C. Four series of heterostructures differing in the method of doping and the spacer design were examined (Fig. 1). The AlAs/GaAs superlattice was structured as follows: 3 monolayers (ML) of GaAs/3 ML AlAs/3 ML GaAs/3 ML AlAs/2.5 ML GaAs (the overall thickness was 4.2 nm). This spacer had a mean molar content of aluminum

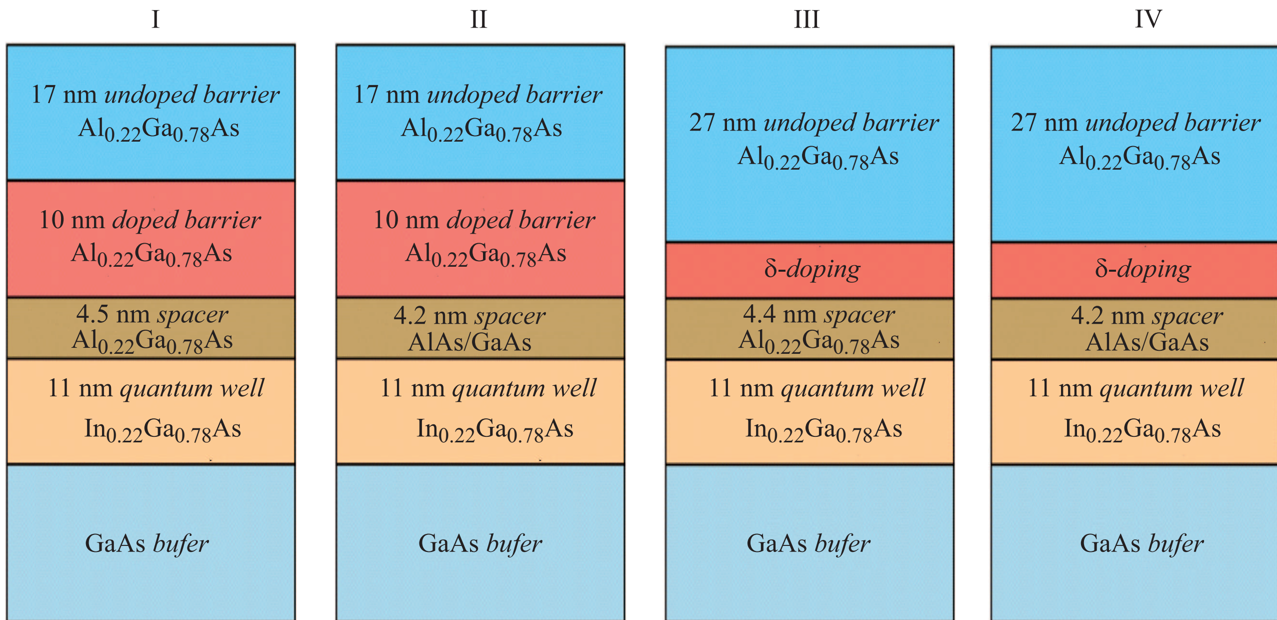

Figure 1. Variation of the spacer design and the doping method in series I–IV heterostructures.

of 0.59, which is almost two times higher than the molar content of aluminum in the AlGaAs spacer.

The sheet density of silicon atoms (N_{Si}) was set by varying the silicon flux, which depends on the temperature of the silicon source, in heterostructures with modulation doping and by increasing the silicon deposition time at a constant source temperature in heterostructures with δ-doping. The value of N_{Si} varied from $2.5 \cdot 10^{12}$ to $9.0 \cdot 10^{12}\,\mathrm{cm}^{-2}$. Prior to heterostructure growth, dependences of the density of conduction electrons in GaAs and AlGaAs layers on the silicon source temperature were determined. These dependences were then used to calculate the density of silicon atoms in grown heterostructures. The mobility and density of electrons and the resistivity values were determined based on the data of van der Pauw measurements of the Hall effect and the resistance of samples 5×5 mm in size in a magnetic field of 0.2 T. The error of the determined electron mobility and density values is due to the procedural error of the van der Pauw method. The error of measurement for square samples with small Ohmic contacts at the edges (the ratio of characteristic sizes of contacts to the sample size is approximately 1:5), which were used in the present study, is 2.5% for the resistivity and 10% for the Hall voltage [7].

The measured dependences of resistivity of heterostructures on the dopant impurity density are presented in Fig. 2. The resistivity of heterostructures needs to be minimized in order to reduce resistance R_{on}. The dependence of resistivity on the donor density is nonmonotonic; the lowest resistance values in the majority of the studied series of samples were achieved at $N_{\mathrm{Si}} = 6 \cdot 10^{12}\,\mathrm{cm}^{-2}$. The mobilities and densities of electrons measured in heterostructures with this doping level are listed in Table 1.

The electron mobility in series II and IV heterostructures with a superlattice spacer increases relative to the one in

Table 1. Mobilities and densities of electrons in series I–IV heterostructures at sheet donor density $N_{\mathrm{Si}} = 6 \cdot 10^{12}\,\mathrm{cm}^{-2}$

Parameter	Series			
	I	II	III	IV
Density, $10^{12}\,\mathrm{cm}^{-2}$	2.6	2.4	5.9	4.6
Mobility, $\mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}$	6100	6480	2190	3150

series I and III, respectively. In contrast, the electron density decreases when a superlattice spacer is used. Owing to their increased electron mobility, heterostructures with

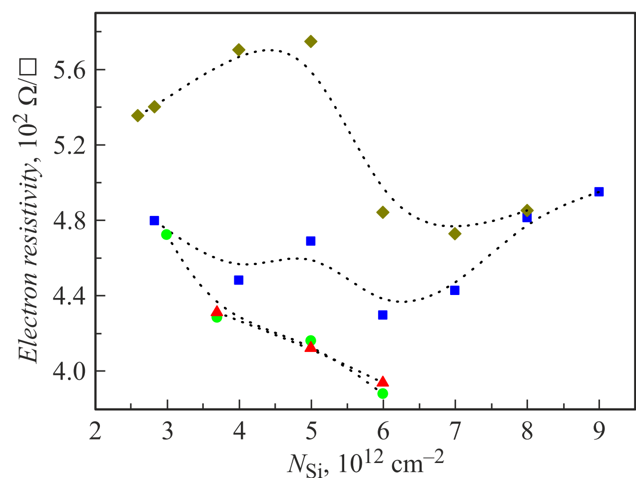

Figure 2. Variation of resistivity of heterostructures with sheet donor density N_{Si} for different types of heterostructures. Circles — series I, triangles — series II, diamonds — series III, squares — series IV. Curves were drawn for clarity.

modulation doping (series I and II) feature the lowest resistivity ρ. The values of ρ corresponding to these two series are essentially the same (the discrepancy is no higher than 1.5%).

When choosing the type of heterostructures for switching transistors, one needs to find a compromise between resistance R_{on} and other parameters of a transistor (specifically, its transconductance). Potential diagrams and wave functions were calculated for series II and IV heterostructures in order to estimate the degree of control over the electron density in the channel of transistors with modulation doping and δ-doping. It was found that an electron density comparable to two-dimensional electron gas density n_{2D} is retained in the donor region in the heterostructure with modulation doping at a voltage of -1.5 V, while this conduction channel in the structure with δ-doping is almost completely depleted. Therefore, as the gate bias increases, the current in series II heterostructures should decrease more slowly than the current in series IV heterostructures. Dependences of derivative $\partial n_{2D}/\partial U_g$ on the gate voltage varying in the range from -0.7 to -0.3 V were calculated to estimate the transconductance. It was found that derivative $\partial n_{2D}/\partial U_g$ assumes a value of $1.5 \cdot 10^{11}\,\mathrm{cm^{-2} \cdot V^{-1}}$ and $4.5 \cdot 10^{11}\,\mathrm{cm^{-2} \cdot V^{-1}}$ at the center of the indicated range (-0.5 V) in series II and IV heterostructures, respectively. Since the transconductance is proportional to the product of $\partial n_{2D}/\partial U_g$ and the electron mobility, series IV heterostructures should feature a higher transconductance even though the mobility is two times lower. This was the reason why series IV heterostructures were chosen to be used for transistor fabrication.

MICs of double-throw switches were fabricated in accordance with the 0.5 μm pHEMT process. Figure 3 shows the typical current–voltage curve of a test switching transistor with gate width $w = 100\,\mu$m (the gate and the switch MIC were fabricated in the same process). Series IV heterostructures with donor density $N_{\mathrm{Si}} = 6 \cdot 10^{12}\,\mathrm{cm^{-2}}$ in

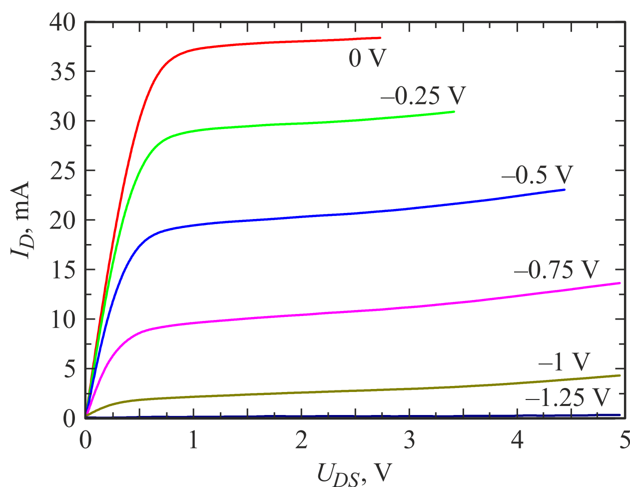

Figure 3. Current–voltage curve of a test transistor ($w = 100\,\mu$m).

Table 2. Parameters of double-throw switch MICs based on pHEMT transistors

Parameter	Present study	[8]	[9]
$g_{\max}$, mS/mm	400	250	280
$R_{on} \cdot C_{off}$, fs	370	272	360
Insertion loss, dB	−2.2	−0.85	−1.7
Isolation loss, dB	−56	−31.5	−40
Return loss, dB	−11.7	−12.7	–
$P_{1\,\mathrm{dB}}$, dBm	21	25	30
$\mathrm{II}P_3$, dBm	40	42	–

the δ-layer and barrier layer thickness $d = 25$ nm were used to fabricate test transistors. In addition to the layers shown in Fig. 1, these heterostructures featured a surface n^+-layer that helped reduce the contact resistance. The on-state transistor resistance was $R_{on} = 1.0\,\Omega \cdot$mm, and the off-state transfer capacitance was $C_{off} = 0.37$ pF/mm. The maximum transistor transconductance was $g_{\max} = 400$ mS/mm, the maximum saturation current was $I_{\mathrm{D}} = 380$ mA/mm, and the cutoff voltage was $U_{th} \geqslant -1.3$ V.

The frequency range of double-throw switch MICs was 0–20 GHz. The absolute insertion loss did not exceed 2.2 dB within this range, while the maximum absolute return loss was 11.7 dB. The absolute isolation loss was no less 56 dB, the 1dB compression point was $P_{1\,\mathrm{dB}} = 21$ dBm, and the third-order intercept point was $\mathrm{II}P_3 = 40$ dBm. The obtained parameters of switching transistor MICs are listed in Table 2. It can be seen that they are largely comparable to the parameters of similar switching transistors with a gate length of 0.5 μm reported in [8,9].

Thus, the results of optimization of the pHEMT heterostructure design for switching transistors were reported. The resistivity of all types of heterostructures reaches its minimum at a dopant impurity density of $(6-7) \cdot 10^{12}\,\mathrm{cm^{-2}}$. Heterostructures with a superlattice spacer have a lower resistivity than heterostructures with a bulk spacer. Although heterostructures with δ-doping have a somewhat (9%) higher resistance than heterostructures with modulation doping, their higher transconductance makes them better suited for fabrication of microwave switching transistors.

The parameters of monolithic integrated switching circuits fabricated based on heterostructures with one-sided δ-doping and a superlattice spacer are largely on par with the parameters of similar circuits based on more complex heterostructures with double-sided doping.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] L. Zhao, W.-F. Liang, J.-Y. Zhou, X. Jiang, IEEE Microwave Wireless Comp. Lett., **27** (5), 485 (2017).
DOI: 10.1109/LMWC.2017.2690834
[2] J.-H. Oh, J.K. Mun, J.-K. Rhee, S.-D. Kim, ETRI J., **31** (3), 342 (2009). DOI: 10.4218/etrij.09.0208.0348
[3] J.K. Mun, H.G. Ji, H. Ahn, H. Kim, C.-O. Park, Semicond. Sci. Technol., **20** (8), 677 (2005).
DOI: 10.1088/0268-1242/20/8/005
[4] T. Baba, T. Mizutani, M. Ogawa, J. Appl. Phys., **59** (2), 526 (1986). DOI: 10.1063/1.336663
[5] D.Yu. Protasov, K.S. Zhuravlev, Solid-State Electron., **129**, 66 (2017). DOI: 10.1016/j.sse.2016.12.013
[6] D.A. Safonov, A.N. Vinichenko, N.I. Kargin, I.S. Vasil'evskii, Tech. Phys. Lett., **44** (2), 145 (2018).
DOI: 10.1134/S106378501802027X.
[7] R. Chwang, B.J. Smith, C.R. Crowell, Solid-State Electron., **17** (12), 1217 (1974). DOI: 10.1016/0038-1101(74)90001-X
[8] Q. Xiao, G. Samiotes, T. Galluccio, B. Rizzi, in Proc. *39th Eur. Microwave Conf.* (IEEE, 2009), p. 1673.
DOI: 10.23919/EUMC.2009.5296295
[9] J.-K. Mun, J.-H. Oh, H.-K. Sung, C. Wang, Solid-State Electron., **114**, 121 (2015). DOI: 10.1016/j.sse.2015.09.007