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Microwave Characteristics of Amplifiers on Nanoheterostructures of Gallium Nitride in the 80–100 GHz Frequency Range

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Abstract—The results of measuring the microwave characteristics of experimental samples of a monolithic integrated circuit of a gallium nitride amplifier in the frequency range 80–100 GHz, which are promising for use in communication and radar systems, are presented.

Keywords: millimeter wavelength range, monolithic integrated circuits, amplifier, gallium nitride, silicon carbide, communication, radar

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There are a number of areas of radio electronics that require achieving the maximum output power in the microwave range in the absence of additional heat-removing elements. In such modules, to ensure the minimum weight and size characteristics of the devices, heat transfer is provided exclusively from the amplifier crystal. Such requirements primarily arise among developers of robotic devices and spacecraft.

The frequency characteristics of semiconductor devices are largely determined by the mobility of charge carriers, and the most promising ones are microwave devices using semiconductor materials with high electron mobility transistors (HEMTs). Among them, a special place is occupied by gallium nitride (GaN) and AlN/GaN heterostructures, which are formed on substrates such as silicon carbide, sapphire, and silicon, which ensure their operation at high temperatures and a high level of radiation.

This is due to the unique electrophysical properties of GaN: wide band gap, mobility and fast speed of electron saturation, high breakdown fields, sufficiently high thermal conductivity, and other useful properties. This makes it possible to create powerful high-frequency transistors based on such structures. The use of wide-gap materials and heterostructures is currently a priority for the development of transistors and integrated products based on them.

Microwave transistors made using GaN technology have a high specific power per millimeter of gate width of up to 8 W/mm, which is almost an order of magnitude higher than the specific output power of microwave transistors made using GaAs technology and are the core of ultrafast solid state electronics modules.

A three-stage gallium nitride amplifier was fabricated at the Institute for High-Temperature Physics, Russian Academy of Sciences, according to a scheme with the summary of the power on a silicon carbide substrate for the W band (frequency range 84–96 GHz) on HEMTs and a gate length of 90 nm on AlGaN/AlN/GaN/SiC heterostructures manufactured by ZAO Elma-Malachite (Fig. 1).

The low-signal S-parameters and the output power of the amplifier were measured in conjunction with AO NPP Shokin Istok. For measurements, we used the contact method based on the contact of microwave and power probes with the studied crystals of amplifiers located on an unshaded and uncut plate with monolithic integrated circuit (MIC) structures.

The results of measuring the low-signal S-parameters of the experimental samples of three-stage amplifiers at a supply voltage of 10 V are shown in Figs. 2–4 and have a gain coefficient ($S21$) of at least 12 dB with the standing wave coefficient (SWC) at the input and output of not more than 2 in the 84–96 GHz band; the unevenness does not exceed 1 dB and the maximum gain of 14.5 dB is achieved at frequencies of 85 and 92 GHz.

For measuring the output power of the experimental amplifier samples the stand at AO NPP Istok was used. The microwave signal from the generator is fed to the input of the MIC being tested through a waveguide microwave probe and a waveguide rotary section.

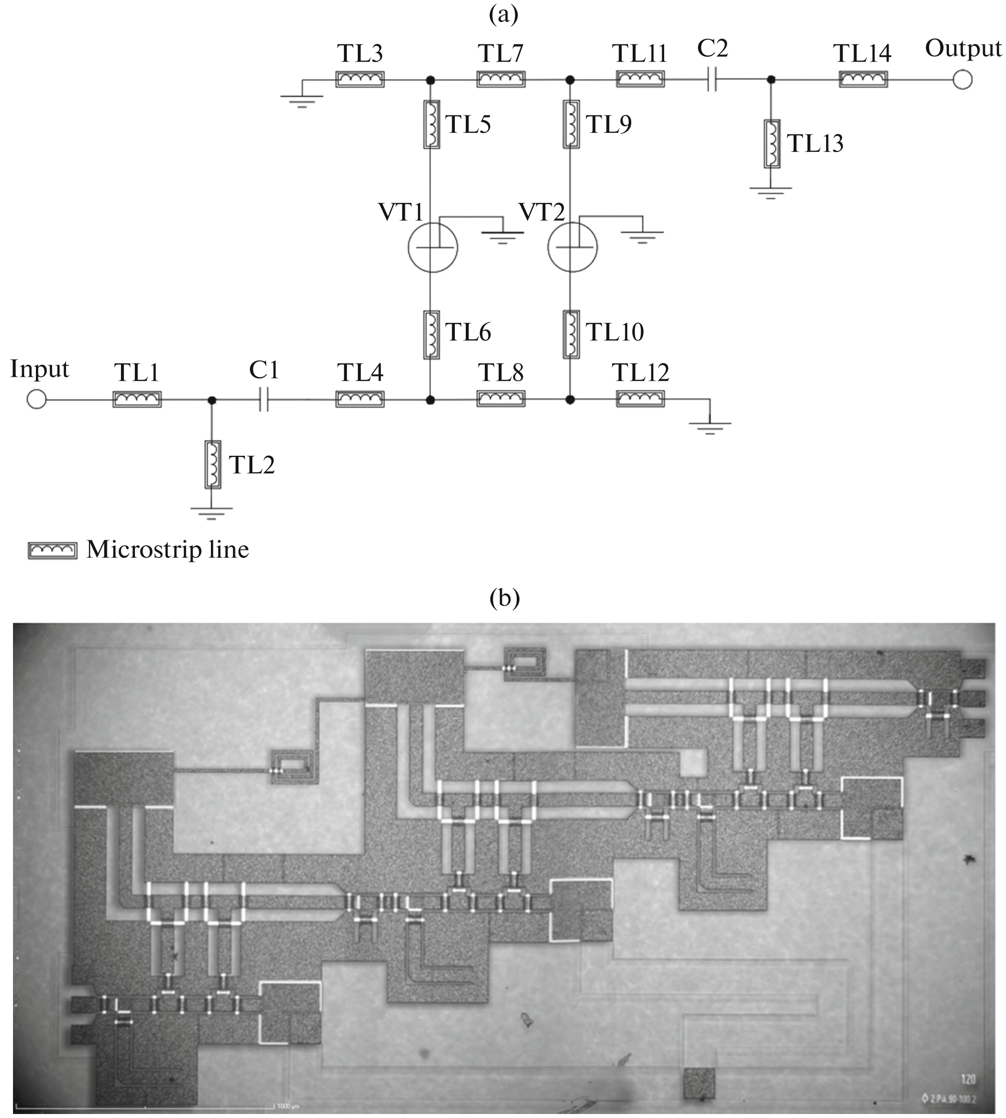


Fig. 1. Scheme of basic amplifier for three-stage amplifier (a); photograph of a manufactured three-stage amplifier for the frequency range 84–96 GHz (b).

As a microwave generator, a technological generator of the 90–94 GHz range with a constant output power was used. An adjustable polarization attenuator with an adjustment range of 0 to 50 dB was installed at the generator's output.

The output power of the experimental samples of three-stage amplifiers was measured at an output power of the generator of 30 and 52 mW at frequencies of 92 and 94 GHz respectively.

Figure 5 shows the dynamic response of an amplifier at a frequency of 92 GHz. Figure 6 shows the dependence of the output power of the amplifier on the voltage at the drain at frequencies of 92 and 94 GHz.

During measurements of the output power of the amplifier in the waveguide path, the maximum saturated power of 20.26 dBm (106 mW) was recorded at an input power of 12.2 dBm and a supply voltage of 14 V (Fig. 6). The specific output power of the output stage of the amplifier with the total gate width of transistors of 200 μm in this case reached 530 mW/mm.

Mokerov Institute of Microwave Semiconductor Electronics, Russian Academy of Sciences (MIMSE RAS), together with ZAO Elma-Malachite and the National Research Center, Kurchatov Institute, carried out work on creating heterostructures (h/s) with a reduced thickness of the barrier layer t_B. The parameters of the heterostructures are presented in Table 1.

As the t_B heterostructures and gate technologies were thinned, an increase in the frequency parameters of HEMTs was observed (Fig. 7) as a result of the increase in the aspect ratio L_G/t_B for a fixed gate length of the transistor L_G.

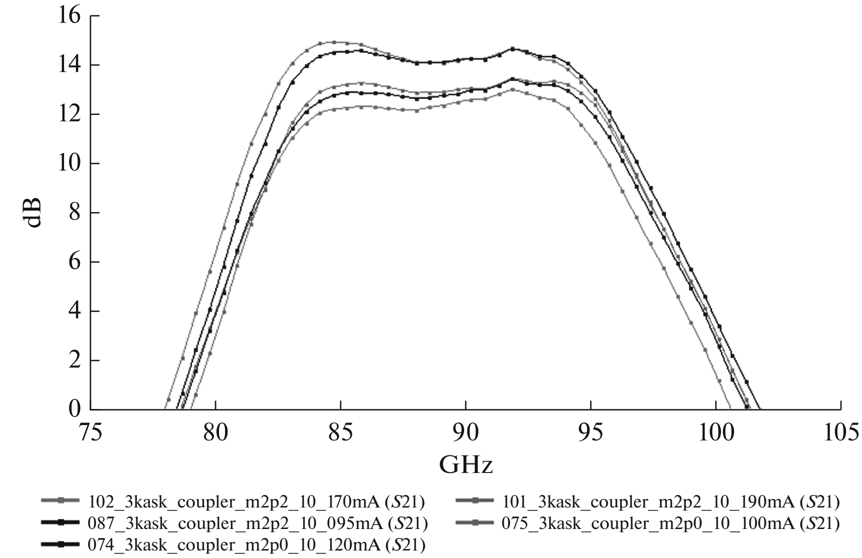


Fig. 2. Results of measuring transmission coefficient *S*21 of five experimental samples of a three-stage amplifier.

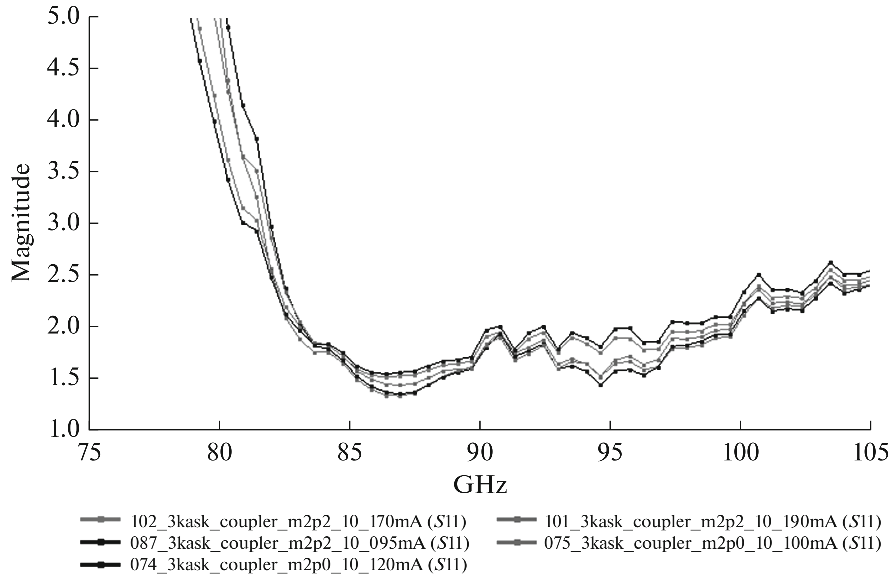


Fig. 3. The results of measuring the SWC at the input of five experimental samples of a three-stage amplifier.

It is interesting to note that the best HEMT microwave parameters of the maximum current gain $f_T > 100$ GHz at the maximum power gain $f_{MAX} > 200$ GHz (Fig. 8) were obtained on a V-1911 heterostructure not with the minimum thickness t_B but with the maximum value of mobility, which implies a large value of the drift velocity of electrons. The maximum achievable gain of HEMTs at the frequency of 90 GHz in this case was 7 dB. The best microwave parameters of the amplifier were obtained on the same V-1911 heterostructure.

The output power of an amplifier can be increased in two ways.

The first method is to increase the total gate width of the transistors of the output stage in a conventional or balanced switching circuit. With a specific output power level of 530 mV/mm, this will require an output stage with a periphery of 1.9 mm, which is equivalent to using 10 basic transistor cells with a configuration of 4×50 μm. In this case, potential difficulties may arise both with the heat sink and with the construction of a large number of dividing and summing power circuits, leading to an increase in losses and a decrease in the absolute output power and efficiency. In addition, in this configuration, it is difficult to ground a large number of transistor sources.

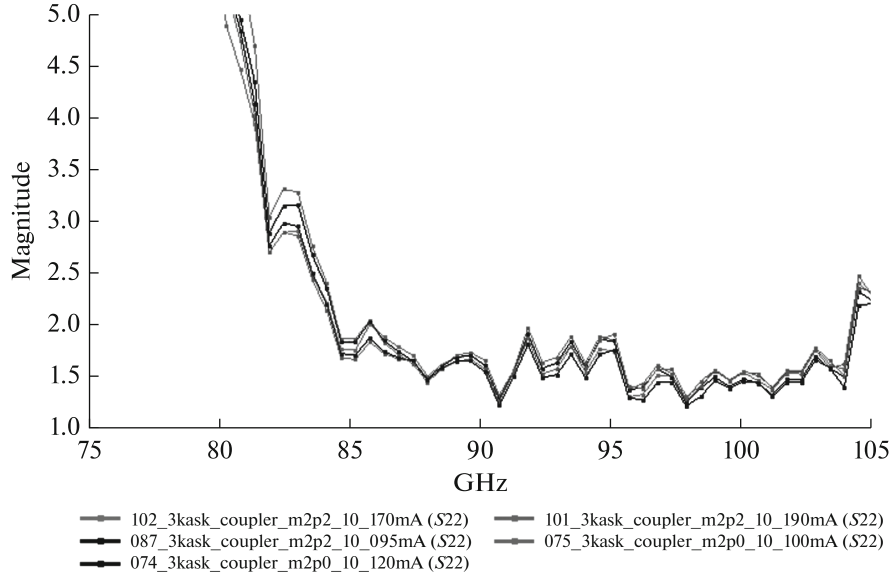


Fig. 4. The results of measuring the SWC for the output of five experimental samples of a three-stage amplifier.

We note the difficulty of etching through-holes in SiC substrates in manufacturing MICs using microstrip technology. The use of coplanar technology without grounding through-holes, in our opinion, is not advisable due to the difficulty in ensuring the stability of an amplifier with a high output power.

The solution to the problem can be the use of the technology of forming a ground plane above the front surface of the crystal on top of the layer of dielectric material, which has been successfully applied in a number of works at the Institute for High-Temperature Physics RAS [1, 2]. In this case, the corresponding elements are grounded through holes in the layer of the dielectric material.

The second method, which seems to us more promising, is related to the improvement of heterostructures. Figure 9 shows the calculated dependences of the specific output power of nitride HEMTs in the W range on the thickness of the heterostructure barrier t_B in the 100–300 nm range of shutter lengths L_G, based on the dependences obtained in [3]. The asterisk in the figure shows the level of the developed amplifier. It follows from the figure that when thinner heterostructures with a thickness of, for example, 6 nm are used, a significant increase (up to 3.4 W/mm) in the specific power of transistors in the W range can be expected. This will allow us to raise the output power of the developed MIC AM to a value of about 500 mW, which is extremely desirable for practical use. It is important that this does not require the development of a new amplifier. The power is increased using the same chip topology. With the further thinning of the

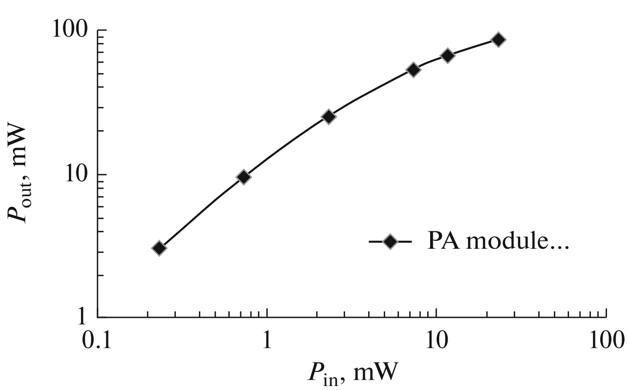


Fig. 5. The dynamic response of an amplifier at 92 GHz.

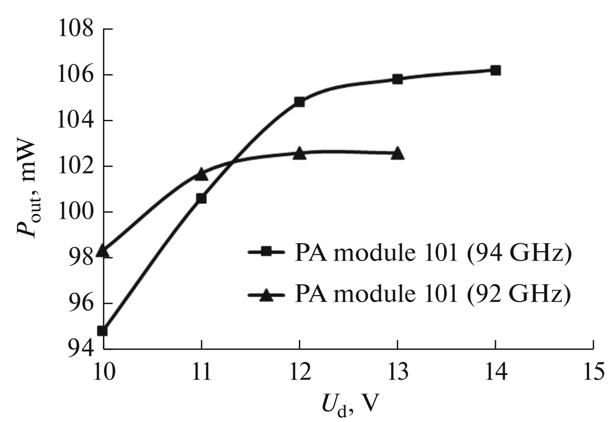


Fig. 6. The dependence of the output power of the amplifier on the voltage at the drain at frequencies of 92 and 94 GHz with an input power of 16.87 mW.

Table 1. Characteristics of the studied heterostructures

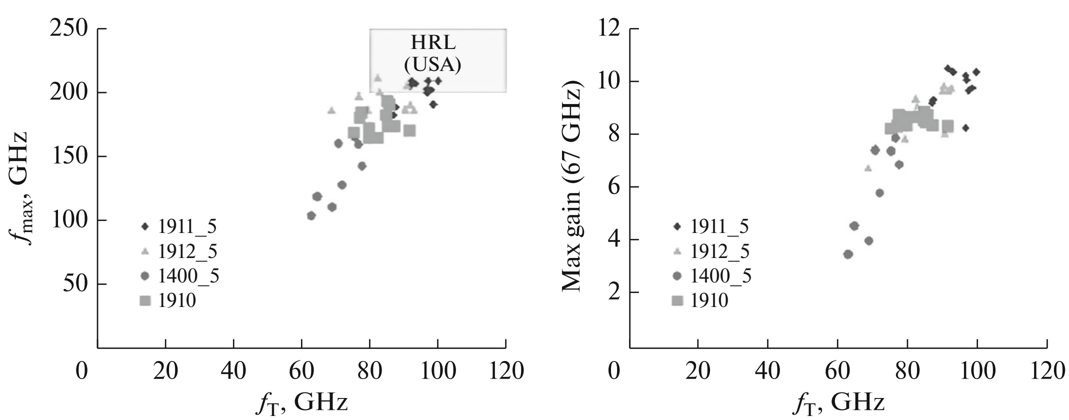
No.	Heterostructure number	Barrier thickness Al-GaN/AlN, nm (X_{Al})	The mobility of electrons in the channel, $cm^2/V\,s$	The concentration of electrons in the channel, cm^{-2}	Layer resistance, Ω/kV	Saturation current (calculation), A/mm	The initial current of the transistor (at $U_g = 0$), A/mm
The growth method is MOCVD, the substrate is SiC (ZAO Elma-Malachite)							
1	V-1909	26.7 (29%)	2055	1.11×10^{13}	274	1.77	1.0
2	V-1915	25.7 (28%)	2100	1.17×10^{13}	254	1.87	1.1
3	V-1910	15.7 (31%)	1880	1.28×10^{13}	259	2.05	1.2
4	V-1440*	15.3 (32%)	1880	1.3×10^{13}	260	2.08	1.2
5	V-1911	13.7 (31%)	2300	1.28×10^{13}	212	2.05	1.1
6	V-1966	13.2 (38.7%)	1944	1.34×10^{13}	240	2.14	1.3
7	V-1990	13.2 (39%)	2000	1.32×10^{13}	237	2.11	–
8	V-1991	11.7 (39%)	1720	1.43×10^{13}	254	2.29	–
9	V-1912	11.2 (31%)	2040	1.16×10^{13}	264	1.86	0.85
Growth method, MBE; substrate, Sapphire (National Research Center, Kurchatov Institute)							
10	58_4	10 (40%)	1462	1.55×10^{13}	237	2.48	
11	60_1.2	3.5 (100%)	1220	1.8×10^{13}	284	2.88	

barrier layer of the heterostructure to 4 nm, the specific output power of 6 W/mm, at which the output power of the amplifier can increase to 1.2 W, is theoretically expected.

The use of thinner heterostructures, as was shown in [4], should not only increase the output power of the amplifier but also reduce the noise coefficient.

In addition, to increasing the output power of the amplifier, a combination of the two above methods is possible. For example, when the thickness of the heterostructure is reduced to 10 nm, the specific output power increases to 1.2 W/mm, which allows the use of five basic transistor cells with a configuration of 4 × 50 μm instead of ten, required with a barrier layer thickness of 13.7 nm, which will greatly simplify the chip's topology. With a further decrease in thickness to 6 nm using only two basic transistor cells with a configuration of 4 × 50 μm it is theoretically possible to obtain an output power of 1.3 watts.

Thus, in order to increase the output power of the amplifier to 1–2 W, it is necessary for the manufacturers of heterostructures to work on the creation of a new class of effective nitride heterostructures with a barrier layer thickness of 5 to 10 nm for the W range.



Increase in the limiting frequencies | Increase in gain

Fig. 7. Increase in f_T and f_{max} of HEMTs with the thinning of the barrier of heterostructures.

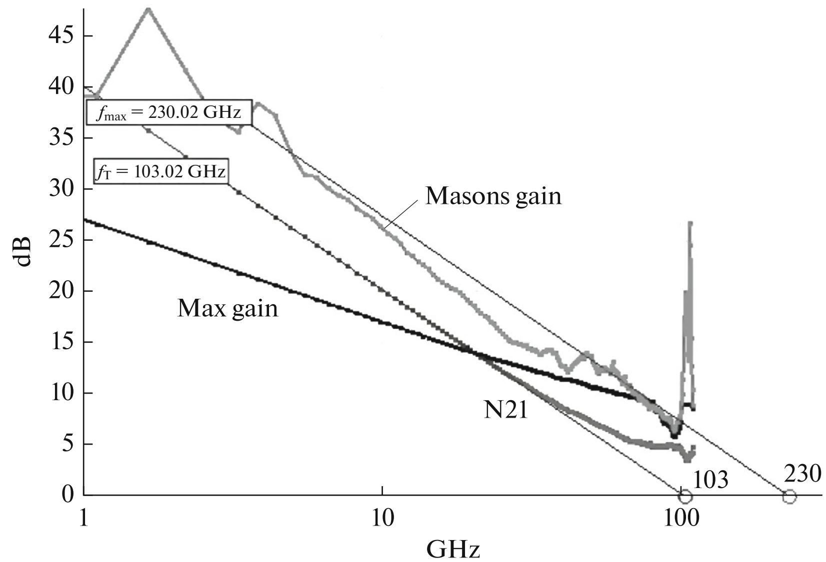


Fig. 8. Microwave parameters of nitride HEMTs on V-1911-5 heterostructure (ZAO Elma-Malachite).

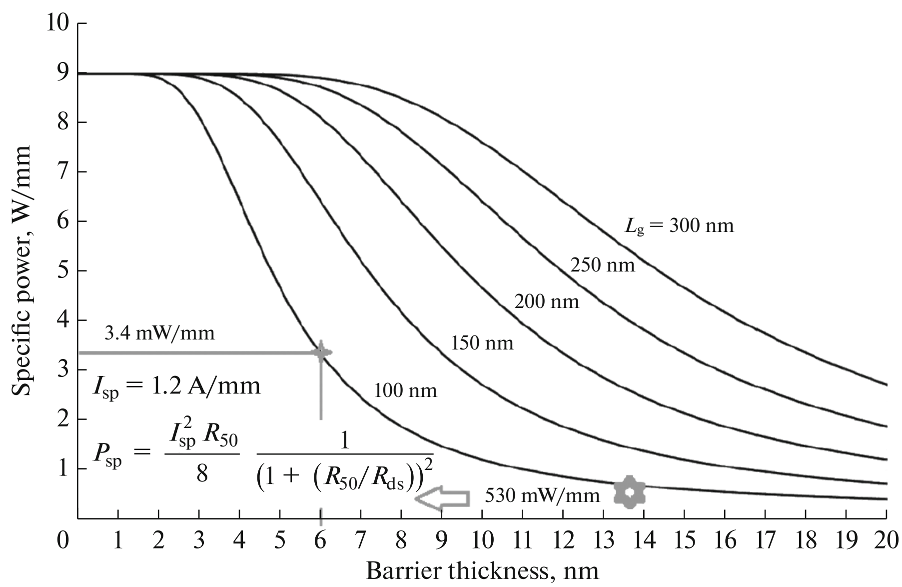


Fig. 9. The calculated dependences of the specific output power of nitride HEMTs in the W range on the thickness of the barrier of the heterostructure t_B in the range of gate lengths L_g from 100 to 300 nm.

The review [5] analyzed more than 20 foreign sources and considered options for constructing monolithic integrated circuits for the W band, which is attractive to use in communication and radar systems. Particular attention is paid to the possibility of using gallium nitride in microcircuits.

In order to assess the level of MICs developed at MIMSE RAS, an analysis was carried out. Table 2 presents a comparison of the obtained parameters with the achievements of world leaders in the millimeter wavelength range—the Fraunhofer Institute and Raytheon [6–8].

From the analysis of the information presented, it follows that the parameters of the developed W-range amplifiers on nitride heterostructures are in good agreement with the best foreign samples in terms of the gain and specific output power but inferior in terms of the parameter of the absolute output power. This is explained by the use of transistors with a total width of 200 μm in the output stage compared with the width of foreign analogues of 720 to 800 μm [6, 7], and 320 μm [8], respectively. It should be noted that the experimental samples developed at the Institute for High Frequency Analytical Chemistry, RAS have input and output SWC

Table 2. Comparison of the experimental samples of MIMSE RAS with foreign analogues

	[5]	[6]	[7]	MIMSE RAS
Low signal gain, dB	14–18	16–21	10	14
Output power, W	0.4 0.43	1.2–1.7	0.19	0.1
Specific output power, mW/mm	566 606	There is no data	530	530
SWC for input	<2	<3	<2	<2
SWC for output	<3	<3	3	<2
Supply voltage	20	15–20	12	14

values of less than 2 in the frequency band 10–11 GHz wide, whereas for foreign analogues this value often lies in the range from 2 to 3 (Table 2).

CONCLUSIONS

As a result of the measurements, it was found that the amplifiers have a uniform gain in the frequency band 84–96 GHz. The maximum gain reaches 14.5 dB with an SWC at the input and output of less than 2. Thus, the output power of the three-stage experimental samples of amplifiers reaches 100 mW.

The MIC amplifiers manufactured based on gallium nitride nanoheterostructures are intended for use in promising systems of wireless data transmission and communication in the millimeter-wavelength range and to ensure the collection and transmission of information streams at speeds of up to 10–100 Gbit/s.

At MIMSE RAS certificates were obtained of the state registration of topologies of integrated circuits [9–12] for the frequency range 84–96 GHz.

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