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Optimization of heterostructure transistor parameters for the monolithic integrated circuits of the amplifying path of a medical radiothermograph

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Abstract. The amplifying path of a modern miniature medical radiothermograph should provide a gain of about 80 dB with minimal intrinsic noise levels. The construction of such a path, even on the most modern element base, requires the use of several microcircuits with a significant resulting current consumption. The existing problem can be solved by creating new active elements of specialized monolithic microcircuits - low-noise transistors, for which the requirements of high energy efficiency will be taken into account when designing heterostructures. The paper presents the results of optimizing the design of a heterostructure low-noise transistor for use in microcircuits of the amplifying path of a miniature medical radiothermograph.

Keywords: medical radiothermography, heterostructure transistor, optimization, amplifying path

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Оптимизация параметров гетероструктурного транзистора для монолитных интегральных схем усилительного тракта медицинского радиотермографа

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Аннотация. В работе представлены результаты оптимизации конструкции гетероструктурного малошумящего транзистора для применения в микросхемах усилительного тракта миниатюрного медицинского многоканального многочастотного радиотермографа. Достигнуто значительное повышение крутизны передаточной характеристики предложенной конструкции малошумящего транзистора.

Ключевые слова: медицинская радиотермография, гетероструктурный транзистор, оптимизация, усилительный тракт

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Introduction

Very high requirements are traditionally placed on the amplifying path of a radiothermograph. In addition, radiothermographs for medical use have a number of other features (for example, the requirements for a very small error in determining body temperature, not exceeding tenths of a kelvin, a record low level of intrinsic noise in the microwave range, etc.), which further tightens the characteristics of the amplifying path. Moreover, there are additional limitations when designing a miniature medical radiothermograph. Indeed, to provide a gain of about 80 dB with minimal levels of intrinsic noise, designing of such a path even on the most modern Monolithic Integrated Circuit (MIC) Low Noise Amplifier (LNA) requires several chips with a total current consumption in the operating mode of the order of hundreds of milliamps. Such current consumption of amplifying stages in a miniature case of a radiothermograph leads to a significant increase in temperature inside the case with the reference noise source located there. This is a significant problem for designers of modern miniature medical radiothermographs. The existing problem can be solved by creating new active elements of specialized monolithic microwave microcircuits - low-noise transistors, for which the requirements of high energy efficiency, primarily low current consumption, low heat release into the surrounding space, low noise level and sufficient gain factor will be taken into account when designing heterostructures [1–2].

Results and Discussion

A promising system of materials for solving the above problem can reasonably be considered heterostructures of semiconductors of the A3-B5 group. The experience accumulated by the author of successful mathematical modeling and practical implementation of heterostructural microwave transistors with high electron mobility allows to speak about the reasonable probability of successfully solving the above problem of creating a special low-noise microwave transistor with reduced current consumption [3].

Analysis of the possibility of reducing the energy consumption of the amplifying tract of a miniature medical radiothermograph suggested that one of the most significant resources for reducing the energy consumption of the amplifying tract is a change in the design of the active elements of monolithic integrated circuits of low-noise amplifiers. Indeed, almost all modern monolithic integrated circuits of low-noise microwave amplifiers are based on heterostructural pseudomorphic transistors with high electron mobility based on gallium arsenide with an indium channel [4]. The basic structure of the transistor (Fig. 1) is formed on a semi-insulating GaAs substrate, on which a buffer layer is created in the form of an AlAs/GaAs superlattice, an InGaAs channel layer and an AlGaAs n-type barrier layer. Above and below the channel layer adjoins the so–called spacer, a thin layer of unalloyed AlGaAs. The concentration of conduction electrons in the channel reaches $1.0x10^{12}$ cm^{-2}, and their mobility is 6500 $cm^2/V{\cdot}s$. As a result, the maximum current of the transistor channel can be 600 mA/mm (at a channel voltage of 1.5 V), the breakdown voltage is 13 V, the boundary frequency f_t is 60 Hz, the maximum power amplification frequency f_{max} is 150 Hz. The optimal operating voltage of the transistor is 6 V.

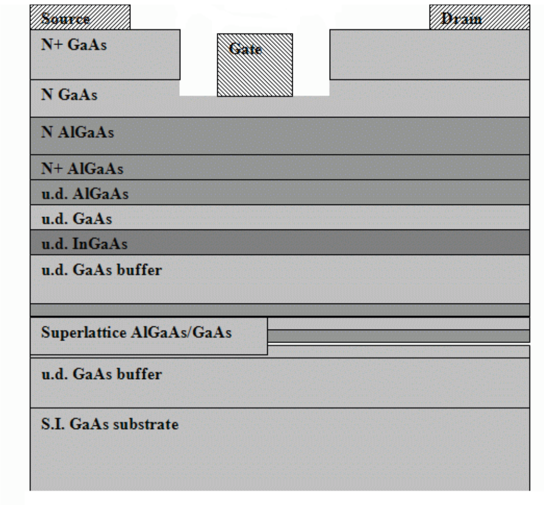


Fig. 1. Schematic cross section of a base transistor with high electron mobility based on gallium arsenide with an indium channel

In order to reduce the current consumption of the active element of such MIC, while maintaining a high gain, which means a high transconductance of the transfer characteristics along the gate, attention should be paid to an effect that is almost imperceptible in other conditions, seriously hindering the reduction of current consumption in such devices. Indeed, as the estimates of the behavior of charge carriers in the transistor channel show, with an increase in the locking potential at the gate, the shape of the quantum well is distorted and some of the electrons can move away from the gate and react less to the controlling effects of its electric field.

This leads to the fact that in the area of low currents, the transconductance of the transfer characteristic becomes insufficient to maintain a high gain of the base active element of the MIC LNA.

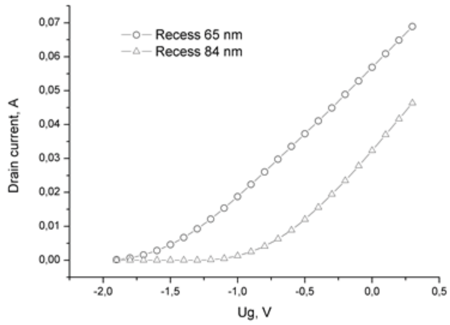
In modern devices, in order to reduce the effect of this effect, it is necessary to increase the quiescent current of the operating mode of a low-noise transistor, which leads to an increase in the total current consumption of the MIC, which is usually tolerated against the background of significantly higher current consumption by other elements of the path, for example, the MIC of a power amplifier [5].

However, in our case, it is here that the main reserve for improving the efficiency of a low-noise transistor, as a basic element of a microcircuit, as part of a microwave MIC, can be concentrated, without changing its schematic diagram and manufacturing technology.

By analyzing the effect of changes in the thickness of various layers on the transfer characteristics of the device, we were able to determine the topological parameter that most effectively affects the transfer characteristic of the transistor. This parameter turned out to be the depth of etching of the gate groove. Fig. 2 shows the main results of the analysis.

Analyzing the results shown in Fig. 2, it can be clearly seen that in order to achieve the same transconductance, a new version of the transistor design requires about half the value of the quiescent current. So, for a transistor with a gate width of 100 microns, to reach the transconductance of the characteristic in the region of 400 mSm/mm, it was required to have a quiescent current of about 20 mA. In our proposed version of a transistor with increased energy efficiency, to achieve the same transconductance (static gain), it is sufficient to provide a quiescent current in the region of 10–15 mA. As a result, we can expect a significant reduction in the current consumption of the entire chip, which also depends on typical circuit solutions. Among the disadvantages of the proposed solution, it can be noted that the upgraded transistor design will require increasing the accuracy of the etching processes of the barrier layer.

a)



b)

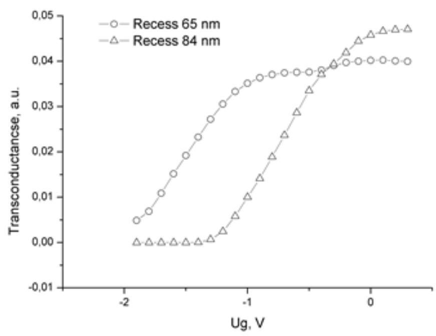


Fig. 2. Effect of the depth of the gate electrode on the transfer characteristic (*a*) and static transconductance (*b*)

As a result of optimizing the transistor design based on these requirements, a calculated slope characteristic was obtained, clearly showing the good amplifying capabilities of the proposed transistor in the low current region, which directly leads to the possibility of a significant reduction in the current consumption of the entire microcircuit. The results of calculated characteristics are shown in Fig. 3.

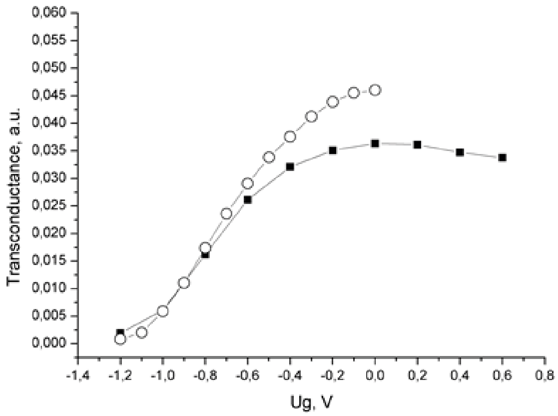


Fig. 3. Calculated characteristic of the slope of the transistor transfer characteristic (squares correspond to conventional design; circles to topology-optimized design)

Conclusion

Thus, the paper presents the results of optimization by numerical simulation of a low-noise p-HEMT transistor based on a domestic heterostructure. A significant increase in the transconductance of the transfer characteristic of the proposed transistor design indicates the possibility of using this promising element base as part of microwave radiometers, which will allow combining the principles of multichannel, multifrequency and miniaturization in one radiometric complex and will lead to the expansion of its functionality and a significant reduction in size.

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