ISSN 1062-8738, Bulletin of the Russian Academy of Sciences. Physics, 2016, Vol. 80, No. 4, pp. 476–478. © Allerton Press, Inc., 2016.
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Promising Materials for an Electronic Component Base Used to Create Terahertz Frequency Range (0.5–5.0 THz) Generators and Detectors

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Abstract—A THz transistor based on a metamorphic nanoheterostructure with generation frequency $f_{\max}$ = 0.63 THz and a zigzag-shaped gate L_g = 46 nm long is developed. A series of low-temperature GaAs structures are produced, and photoconductive antennas with generation frequencies above 1.5–2 THz are developed on their basis.

DOI: 10.3103/S1062873816040109

INTRODUCTION

Terahertz devices and instruments could change the principles and theoretical approaches to early medical diagnostics (especially of malignant tumors) and the treatment of chronic diseases. The demand for research and development in this field is also due to countermeasures against terrorism in public places and in mass transit systems. The automobile, aviation, and space industries require improved systems for nondestructive monitoring and positioning [1].

Field effect transistors based on nanoheterostructures with two-dimensional electron gas [2] are used as THz signal sources (generators). Such THz-range HEMTs (high electron mobility transistors) can have generation frequencies of ~0.5–0.7 THz, depending on their topology. A photoconductive antenna is one of the most popular THz signal generators (and detectors) [3]. It is a system consisting of a semiconductor (usually GaAs or InGaAs), grown via molecular beam epitaxy at low temperatures of ~200–400°C, and two electrodes. When an ultrashort laser pulse hits such an antenna, the concentration of carriers in this low-temperature semiconductor grows sharply in a very short time on the order of picoseconds. The resulting free carriers are accelerated by the field applied to the gap, thus forming a short current pulse that serves as the source of THz radiation. An ultrashort laser pulse is thus a superfast switch for the antenna, moving it from the insulating to the semi-insulating state.

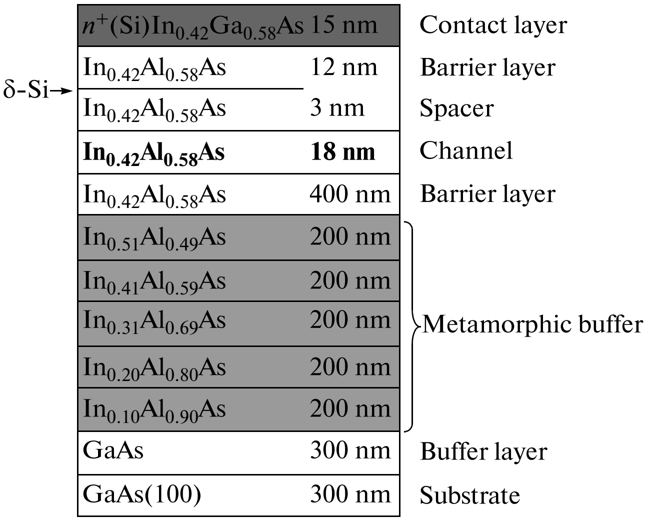
DEVELOPING NANOHETEROSTRUCTURES AND THz TRANSISTORS BASED ON THEM

To improve the frequency characteristics of sub–mm range devices, a series of nanoheterostructures with a graded metamorphic buffer (MB) of two inverse grades and superlattices inside the MB [4, 5] were developed at the Russian Academy of Sciences' Institute of Ultra High Frequency Semiconductor Electronics. In developing such structures, the effective electron mass in the transistor channel must be reduced as a result of the increased molar fraction x(InAs) in the active layer of $In_xGa_{1-x}As$. This improves the mobility of electrons and their drift velocity in the transistor channel [6]. It is also necessary to move the active region to the heterostructure's surface, which improves the controllability of the field-effect transistor. A schematic diagram of the epitaxial layers and their widths for the transistor's metamorphic HEMT (MHEMT) nanoheterostructure is shown in Fig. 1.

One of the main problems in developing THz transistors is the mechanical instability of the gates as the size diminishes. If a mushroom-like gate is used, leg length L_g is limited to 50–55 nm. For further reduction of L_g we must have a developed profile in which the lower layer has a shape close to the one shown in Fig. 2 (example 3). It can be divided into a number of independently developed sublayers for reliable monitoring of the size and shape of this region.

Our solution to this problem is to form the lower layer from three PMMA/PMGI/PMMA resist sublayers. The gate then has a zigzag shape. Schematic diagrams of the deposition of metal into a narrow gap (the isochronous metal boundaries during deposition are shown) are shown in Fig. 2 along with some sample aspect ratio values.

The five-layered system of resists that we developed allows us to form various profiles in the lower layers by varying the development time in the corresponding



	n^+(Si)$In_{0.42}Ga_{0.58}As$	15 nm	Contact layer
	$In_{0.42}Al_{0.58}As$	12 nm	Barrier layer
δ-Si→	$In_{0.42}Al_{0.58}As$	3 nm	Spacer
	$In_{0.42}Al_{0.58}As$	**18 nm**	Channel
	$In_{0.42}Al_{0.58}As$	400 nm	Barrier layer
	$In_{0.51}Al_{0.49}As$	200 nm	Metamorphic buffer
	$In_{0.41}Al_{0.59}As$	200 nm	
	$In_{0.31}Al_{0.69}As$	200 nm	
	$In_{0.20}Al_{0.80}As$	200 nm	
	$In_{0.10}Al_{0.90}As$	200 nm	
	GaAs	300 nm	Buffer layer
	GaAs(100)	300 nm	Substrate

Fig. 1. Schematic diagram of the epitaxial layers in the transistor's structure.

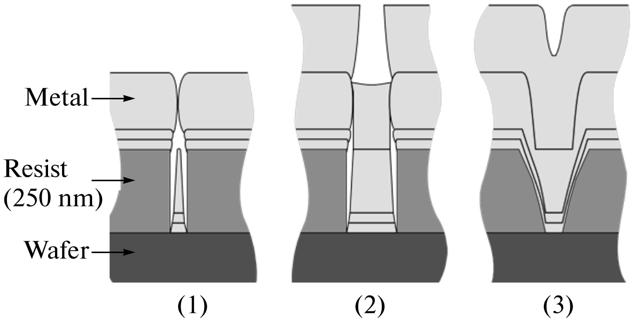


Fig. 2. Examples of different aspect ratio values: (1) 1 : 5; (2) 2 : 3; (3) smooth wall profile (the lower part is shorter than the resist thickness by a factor of five).

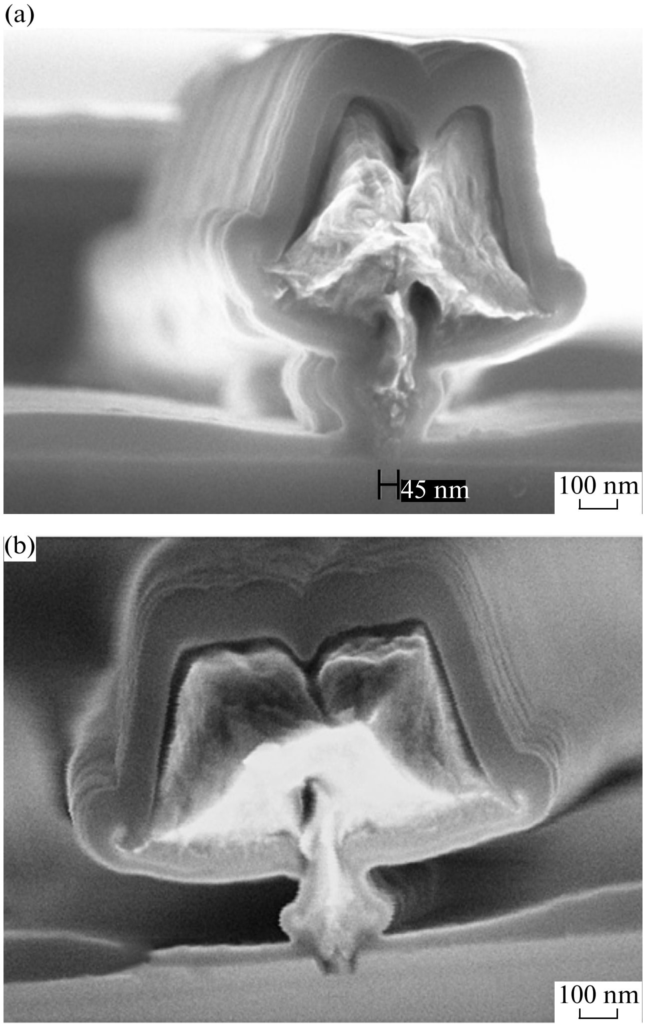


Fig. 3. Raster electron microscopy images of our zigzag-shaped gates.

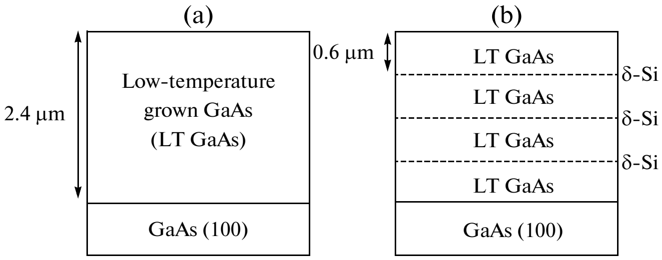


Fig. 4. Schematic diagram of epitaxial layers in LT GaAs structures of two types produced at the Institute of Ultra High Frequency Semiconductor Electronics.

developers without the use of the dose profiling. The developed technology ensures precise reproduction of a given gate size and a reduction in size to $L_g \sim 36$ nm. The gates were formed via electron beam nanolithography on a Raith 150 TWO nanolithography system. Examples of gates with $L_g = 46$ nm are shown in Fig. 3.

The *S*-parameters of the test transistors were measured in a circuit with a common source in the range of 0.1–67 GHz. An Agilent E8361A vector analyzer was connected directly to the MHEMT transistors on the plate using a pair of three-contact probe heads. Low limiting amplification frequencies with respect to current and power were obtained for the MHEMT transistors with gate widths of 2 × 80 μm: $f_T = 0.13$ and $f_{\max} = 0.63$ THz [7, 8].

DEVELOPING STRUCTURES BASED ON LOW-TEMPERATURE GaAs AND PHOTOCONDUCTIVE ANTENNAS

We produced structures of low-temperature GaAs (LT GaAs) of two types that differed by having silicon layers in structures of the second type [9]. These layers divided the LT GaAs into four equidistant domains with thicknesses of 0.6 μm each. The introduction of such layers can contribute to the accumulation of excessive arsenic in the form of precipitates. Figure 4 shows a schematic diagram of the epitaxial layers in the produced structures.

We also developed and produced a photo pattern containing several types of antennas with areas of contact. The distance between them was 4 mm, and the band width was 5 μm. The polarization vector was in the plane of the plate. A two-layered LOR5A/S1813 photoresist system and a SUSS MJB4 contact photolithography unit were used to form the pattern. The resulting photoconductive antennas were tested using a TDS spectrometer in which they replaced the standard source of THz radiation. Depending on the developed topology, the generation frequencies of such antennas were ~1.5–2 THz [10].

CONCLUSIONS

A MHEMT transistor based on a metamorphic nanoheterostructure with two inverse grades, generation frequency $f_{\max} = 0.63$ THz, and transistor gate length $L_g = 46$ nm was developed. A five-layer system of electron resists for forming a zigzag-shaped gate with high mechanical stability was developed. A series of low-temperature GaAs structures was grown via molecular beam epitaxy; photoconductive antennas with generation frequencies of 1.5–2 THz were produced on the basis of these structures.

ACKNOWLEDGMENTS

This work was supported in part by the Russian Science Foundation, project no. 14-29-00277.

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Translated by E. Baldina