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Optimization of the Planar Schottky Diode Structure in THz Range

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Abstract: *Optimization of the structure of a planar Schottky diode with a whisker and an air anode lead allowed to obtain 198 GHz bandwidth (fractional bandwidth of 16.5 %) at a central frequency of ~1200 GHz and reduce insertion losses of ≤3.4 dB at a noise temperature of ~3300 K.*

Keywords: *planar Schottky diode, compact model, THz-range, small-signal S-parameters.*

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1. Introduction

The terahertz frequency range is one of the broadband frequency ranges currently includes electromagnetic oscillations from hundreds of gigahertz (GHz) to hundreds of terahertz (THz) [1]. According to general electrophysical concepts and current position, there are no trivial structural and technological solutions for diode chips on the ECB market allow to overlap such chips performance in the entire terahertz frequency range.

Since that, one possibility to solve this problem is a set of design solutions of diode chips optimized for operating in narrower (e. g. 1103–1301 GHz) overlapping frequency ranges [2].

Despite the relatively large amount of literature data in public sources on terahertz frequency converters, information on transfer characteristics of terahertz range diode chips is extremely limited. In this regard, the aim of work is optimization of structural and technological solutions for planar Me/n- n^+- GaAs packageless Schottky diode with a whisker and an air anode lead performed by "Mesa-Mesa" method (hereinafter referred to as planar diodes) for operating in the frequency range f_T=1103–1301 GHz [3].

2. Design methodology

The small-signal characteristics of a planar Schottky diode in the THz range were obtained using previous designed and improved small-signal (linear) compact model (LCM) (Fig. 1) [1]. The designed LCM verification in the range 0.1–50 GHz showed a good agreement with experimentally obtained frequency dependences of small-signal scattering parameters (S-parameters) of a planar Schottky diode. The optimization procedure ensured the accuracy of restoring the values of parameters (nominal values) of improved LCM equivalent elements (hereinafter referred to as elements) by more than 95 %. The feature of this LCM is a larger number of elements (22 equivalent elements), which is sufficient for more accurate consideration of device constraints on the limit (physically possible f_L (L – limit)) operating frequencies of such diodes in the THz frequency range [1].

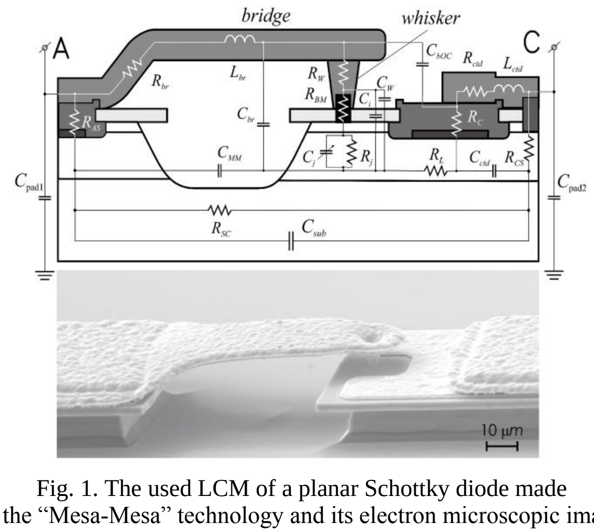

Fig. 1. The used LCM of a planar Schottky diode made
using the "Mesa-Mesa" technology and its electron microscopic image [1]

The limit frequency estimation of the Schottky contact operation $f_L=1/\tau$, where $\tau=\tau(E)$ – time of ballistic transport of electron with energy E through the thin diode base, was carried out using the theory of ballistic transport of the charge carriers, which allows to take into account not only the amplitude characteristics of the electron scattering parameters at the potential Schottky barrier, but also the phase ones, unlike diffusion and thermionic theories [1]. Doing so, not only the entire form of potential barrier, but also the scattering during the above-barrier transport was taken into consideration. The evaluation showed, that for base length $x_b \leq 0.1$ μ*m* $N_d^+ = 7\times10^{16}$ cm^{-3} the average value $\tau \approx 2\times10^{-15}$ *s*, which corresponds to the frequencies $f_L \approx 5\times10^{14}$ Hz = 500 THz.

The design and research of structural and technological solutions using the "Mesa-Mesa" technology in a three-dimensional (3D) projection was carried out using the computer-aided design (CAD) for devices technological design "TCAD SYNOPSYS", which allows to obtain static and high-frequency characteristics of individual structural elements of a diode chip and compare them with the LCM model values.

The modeling and optimization of small-signal S-parameters frequency dependencies of an optimized equivalent circuit (EC) in the THz range with zero biased anode was carried out using CAD AWR Microwave Office. Input and output matching was implemented by adjusting the matching capacities C_{pad1} и C_{pad2}. When choosing the values of the parameters of equivalent LCM elements (hereinafter referred to as LCM parameters), the electromagnetic interaction influence on the inductance value L_{br} of air bridge and substrate bottom metallization system inductance was taken into consideration. The input reflection coefficient $S_{11} \leq -10$ dB (VSWR ≤ 1.95) was taken as the criterion of bandwidth estimating.

After that, the diode chip structural elements were corrected in the CAD "TCAD SYNOPSYS", the static and high-frequency charasteristics of individual structural elements were obtained and verified with model values.

3. Results

The static current-voltage (IV) and capacity-voltage (CV) characteristics of the anode non-ohmic metal-semiconductor (M-S) contact with the Schottky barrier were calculated using the theory of ballistic transport with the influence of series resistance R_s consideration (Fig. 2). Despite that the calculation were performed using quantum-mechanical concepts of electrons transfer, the $C=C(V)$ and $I=I(V)$ curves have a typical form for Schottky diodes, which shows consistency of the ballistic theory.

Regardless of the fact than the skin depth at such frequencies is about ~0.01 μm, the n+-GaAs contact layer thickness was set to be 7 μ to ensure the necessary values of series resistances R_s. The fact is that the localization of alternating current in the skin layer is caused by superposition of the main current J and Foucalt currents J_F throughout the semiconductor. Although the resulting alternating current in the internal volume of conductive material is zero, its equal in magnitude and opposite in direction components J and J_F are far from zero values in the conductor. Therefore, even if the skin layer provides the main flow of resulting alternating current, the internal volume of semiconductor also takes a direct part in the series resistance R_s formation.

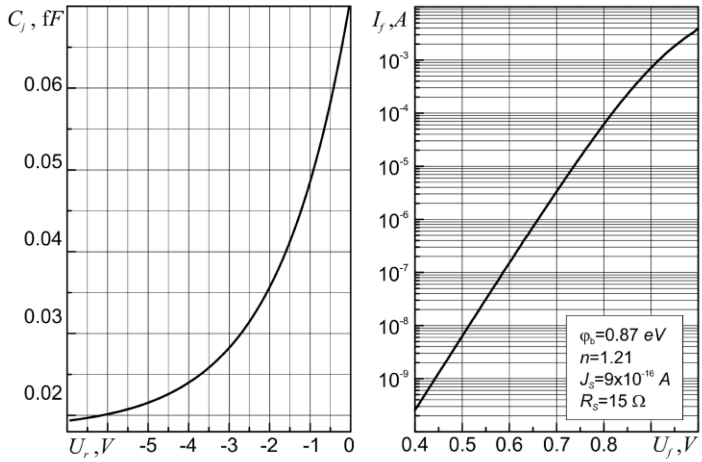

Fig. 2. Static CV and IV characteristics of the M-S anode contact with the Schottky barrier

According to analysis results, all elements of the LCM may be classified under two groups: 1 – elements which impact is significant on the device limitations of the operating frequency range, 2 – elements with insignificant impact. The S-parameters absolute values (magnitude) relative change was taken as the impact indicator when the LCM elements nominal values were changed by ±10% and ±50 %.

In either case (for ±10% and ±50%), a decrement of majority of the 2nd group element values leads to a change in the S-parameters magnitude, f_T and the bandwidth Δf_T does not exceed 2–3%. The impact of half of the 2nd group elements is not greater than 1%.

The 1st group elements, whose impact exceeds tens of percent, merit special mention. Among these are an air bridge inductance L_{br} and whisker capacity C_w, which influence on f_T and Δf_T is obvious. The “Mesa-Mesa” technology make possible to change over a wide range an air bridge length, width, thickness and height in relation to chip bottom metallization. Taking into consideration the influence of the structural element’s electromagnetic interaction, one can vary the bridge inductance L_{br} in a fairly wide range from hundreds (e. g., 200 pH) to fractions (e.g., 0.02 pH) of picohenry. The whisker capacity Cw has the lowest possible values, since its cross section is almost equal to Schottky contact size, so the enlarged contact capacity impact, which is represented in many analogs [4], is completely eliminated.

The high impact of the anode pad resistance RAS on the frequency characteristics, which might be greater than 20% for this structure, is appeared to be nontrivial. Its exclusion from the structure leads to a significant transfer characteristics degradation.

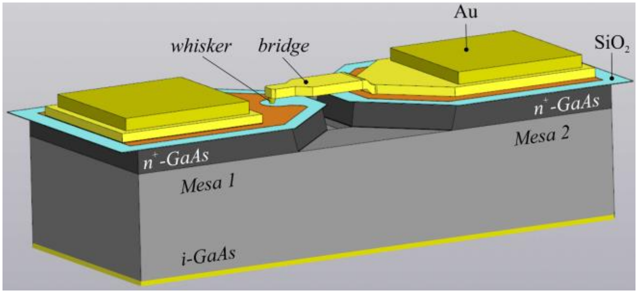

Fig. 3. The "Mesa-Mesa" structural solution of the planar Me/n- n^+- GaAs Schottky diode with a whisker and an air lead (bridge) optimized for operation in the frequency range f_T=1103–1301 THz

Thus, the planar diode structure optimized in the frequency range 1103–1301 GHz has an anode terminal in the form of a shorter and wider air bridge, a higher whisker and a deeper mesa (Fig. 3). For the formation of mesa a special etcher was designed. This structural and technological solution provides for the possibility of forming a grounding metallized via to the anode pad.

According to the modeling results, the proposed planar diode structure has the bandwidth of 198 GHz at a central frequency of ~1200 GHz (fractional bandwidth of a 16.5%), insertion losses of ≤3.4 dB and noise temperature ~3300 K (Fig. 4).

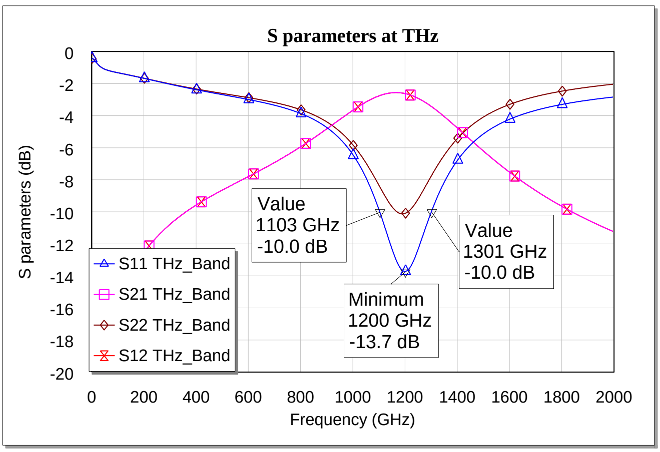

Fig. 4. Small-signal S-parameters of a planar diode (calculation)

A comparative analysis with existing technological and schematics solutions (e. g., [5]) suggests the feasibility of the structural and technological solutions of the wideband (up to 200 GHz) mixer at a frequency of ~1200 GHz with conversion losses (CL) of 9.5–10.0 dB and characteristics that meet global standards based on obtained design solutions.

Acknowledgement

The optimization of a planar Schottky diode structure with a whisker and an air anode lead allowed to expand the bandwidth to 198 GHz (16.5% fractional bandwidth) at a central frequency ~1200 GHz and reduce insertion losses of ≤3.4 dB at a noise temperature of ~3300 K.

The obtained structural solutions make it possible to significantly improve the planar diodes reliability by increasing its mechanical strength, power dissipation and electrostatic discharge tolerance, provide significantly expand applicability of these diodes in generating, converting and detecting of electromagnetic signals devices in different physical, chemical, biological sciences and technologies: genetic and molecular level interaction with living and nonliving objects of a nature, spectral analysis, monitoring and control of transition processes, detection of radiation quanta and elementary particles, ultrafast data transformation and transferring in high-frequency fiber- and quantum-communication lines, short-range and space location, radio imaging, energy-efficient devices for converting and transferring radiant energy, and also make a notable contribution to overcoming the significant lag of electronic component base behind optoelectronics in terahertz frequency range.

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