QUASI-VERTICAL SCHOTTKY-STRUCTURES FOR THZ-APPLICATIONS

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Abstract—This paper presents the results of a systematical work on the improvement of high-frequency performance of quasi-vertical structures for THz-applications. Three versions of structure-design based on a quasi-vertical concept were successfully fabricated and characterized. The anti-parallel mixer-diode pair demonstrated a high performance at frequencies up to around 200 GHz. Measurements at frequencies about 600 GHz of a single diode structure mounted in a heterodyne mixer revealed a voltage responsivity of more than 1500 V/W and conversion loss (SSB) of bellow 10 dB. Microwave-noise measurements of such structure revealed typical values of the junction noise to be lower than 300 K at frequencies between 2.1 GHz and 4.8 GHz and at a bias current up to 3 mA. Low-frequency noise of these diodes is typically about 4 $\mu V/Hz^{1/2}$ at 1 Hz. Achieved DC-characteristics are as follows: series resistance $R_s < 7\ \Omega$, ideality factor $\eta < 1.2$ and junction capacitance at 0 V $C_{0j} < 2.3$ fF. The total capacitance of this structure is $C_0 < 7$ fF. These data result in a calculated cut-off-frequency of well above 3 THz.

Index Terms—Schottky diodes, quasi-vertical structure, THz-applications.

INTRODUCTION

Schottky diodes based on n-GaAs have been shown to be the best-performing devices at room temperature up to several Terahertz for both mixing and multiplying applications [1-3]. In recent decades GaAs whisker-contacted structures were found to be an optimum solution for THz-frequency operation due to their small parasitic capacitance and series resistance, with a vertical current flow providing an uniform field and current density distribution over the whole anode area [2,3]. Because whisker contacted diodes are very sensitive to mechanical influences and the contacting procedure is very difficult and time consuming, ever-widening application fields and the potential commercial market push the development of planar devices suitable for monolithic integration.

But planar technology is usually related to certain limitations which mainly consist of an additional parasitic capacitance, series resistance and thermal difficulties. Due to the fact that Schottky and Ohmic contacts are situated on the same plane, a current overloading of the anode region closest to the Ohmic contact may occur. High local current density may heat electrons considerably above their thermal energy, causing excess noise in the device.

An alternative to a planar structure is a quasi-vertical structure, whose relevant features can diminish some of these problems.

DESIGN CONSIDERATIONS

One of the main advantages of a quasi-vertical structure is a vertical current flow, as in the case of whisker-contacted [3] or substrate-less[2,4] structures, namely, from the anode on the top of the epitaxial layer to the back-side Ohmic-contact (see Fig. 1). In this case, the field distribution is kept uniform across the entire anode area excluding current overloading of the anode region closest to the Ohmic contact, which may generate additional noise in traditional planar structures due to high current density.

Secondly, since the GaAs mesa, as thin as 1.5 µm, is enclosed between the Ohmic-contact and Schottky-contact, a very good heat sink from the Schottky contact to the back-side Au-bump and other massive metallic elements of the circuitry is organised. This considerably increases the power capability of the quasi-vertical structure.

Gold-bumps deposited on back-side Ohmic-contacts (which are specific to this kind of structures) may be used as contact

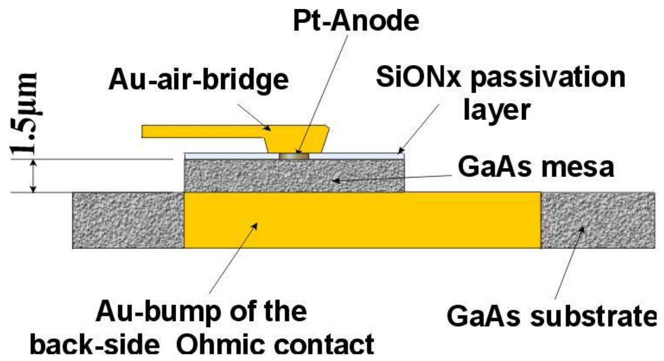


Fig. 1. Sketch of single planar quasi-vertical diode.

pads for mounting on corresponding filter structures. This means that in contrast to the traditional flip-chip mounting approach, where the structure is mounted up-side-down, a quasi-vertical structure may be mounted also in a up-side-up position. In such a position anode fingers are automatically taken away from the filter-substrate which may reduce the influence of the substrate to the structure performance. This is an alternative mounting approach and represents a potential advantage of the quasi-vertical concept.

Additionally this kind of structures enables the use of the anode formation technology as-optimised on relatively simple and easy-to-fabricate whisker-contacted structures, as described in [5] and in more details in [6].

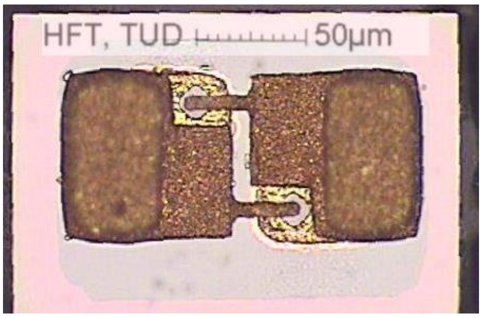
Fig. 2 illustrates top view of all three versions of fabricated structures with a proportional magnitude. At this stage chips are just separated from the carrier wafer but are not cleaned yet. Nevertheless, overall changes in dimensions and design are obvious.

All three structures have similar geometrical features, which are as follows:

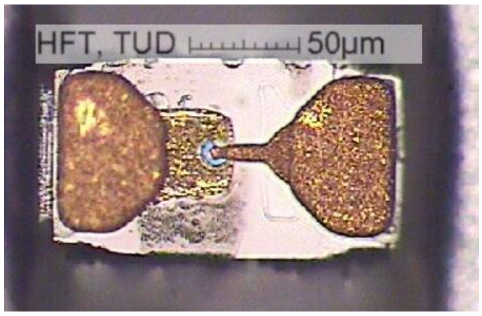
- The active device is fabricated on a 1.5 µm thick GaAs mesa placed on a few µm thick gold cathode;
- Pt-Au anodes have a circular geometry with the diameter of about 1µm (0.8 µm for first structure);
- Anodes are defined in a $SiON_x$-passivation layer and are situated in the centre of mesas;
- Anodes are connected to an anode contact-pad through an air bridge running 4 µm above the substrate;
- Contact-pads are plated to a height of 6 – 8 µm above the top of the GaAs-substrate, offering significant mechanical protection for air bridges;
- The backside gold cathode is embedded in a few µm thick GaAs/AlGaAs substrate and offers a direct connection to a cathode contact-pad on the top of the chip.

RESULTS AND DISCUSSIONS

An anti-parallel diode-pair (APD) structure for frequency mixing application (Fig. 2a.) based on quasi-vertical-concept was designed to be mounted in a subharmonically-pumped



a)



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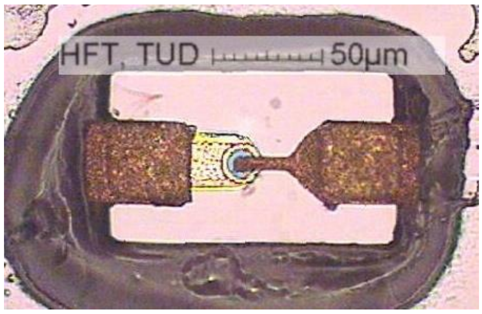

c)

Fig. 2. Optical pictures of structures fabricated by first (a), second (b) and third (c) design versions.

waveguide mixer operating at frequencies up to 200 GHz. For a minimum loss, the structure is carried out on 8 to 10 µm thick semi-insulating GaAs-membrane. Electrical parameters of this structure with an anode diameter of $d = 0.8$ µm are as follows: junction capacitance at 0 V $C_{j0} = 1.6$ to 2.1 fF (for two anodes switched in parallel), series resistance $R_s < 15\ \Omega$, ideality factor $\eta < 1.18$, pad-to-pad capacitance $C_{tot} = 16$ to 18 fF. These values resulted from various on-waver DC- and S-parameter-measurements and simulations.

Several mixers were fabricated and characterized at different frequencies. Some results are summarised in Table I. The results of characterization at 150 GHz are rating along-side with the best achieved.

All mixers exhibit extremely flat sensitivity with IF frequency and a good IF match up to high IF frequencies (typically 16 GHz).

Our results compare well to those reported in [7] (also shown in the Table I) which were evaluated by another group using different measurement set-up but with a similar structure

TABLE I
TYPICAL VALUES OF THE MEASURED RESULTS

Frequency (GHz)	Conversion efficiency (dB)	Tsys (K)	Tmix (K)	LO Level (mW)
140	5.1(DSB)	940(DSB)	650(DSB)	3.5
150	5.8(DSB)	950(DSB)	650(DSB)	3.0
183	6.3(DSB)	1450(DSB)	870(DSB)	4.0
215 [7]	9.2 (SSB)	3500(SSB)	_	3.5

fabricated at TU Darmstadt. This confirms a very good diode performance at frequencies up to around 200 GHz.

A single diode (SD) structure shown in Fig. 2b was designed for frequency-mixing operation in the frequency range from 200 to 400 GHz. In order to improve operational capability of the structure at higher frequencies some changes in the design were implemented. The most significant of them in respect to the previous version are listed below:

- Pad-to pad capacitance is reduced in two ways: on the one hand pad area is reduced from 5×10^{-3} mm^2 to 3×10^{-3} mm^2; on the other hand the pads are chamfered;
- The GaAs-substrate is reduced down to 6µm...8µm
- The parasitic inductance of the bridge is considerably reduced since the bridge is shortened;
- Chip dimensions are also reduced (see Fig. 2 b).

S-parameter-measurements up to 110 GHz using a network analyser exhibited following electrical parameters: C_{j0} = 1.3 to 1.6 fF, $R_s < 10\ \Omega$, $\eta < 1.18$, C_{tot} = 10 to 12 fF. Since a similar wafer is used for the diode fabrication, the ideality factor did not significantly change in comparison to previous structures, whereas R_s and C_{tot} are smaller and compare well to our simulation results.

In order to check the quality of the Schottky-contact the low-frequency noise is measured by means of a HP 3562A Dynamic Signal Analyzer. The results show a 1/f-noise of these diodes of about 4 μV/Hz$^{1/2}$ at 1 Hz under current bias of 1 mA. The 1/f-noise value is bellow 100 nV/Hz$^{1/2}$ at frequencies above 500 Hz.

For high-frequency measurements we soldered a similar structure with indium on 40 µm-thick quartz substrate with a previously defined filter structure as illustrated in Fig. 3. The filter-structure was embedded in a 600 GHz heterodyne mixer. The mixer characterization included measurements of DC-performance and conversion loss. These measurements revealed a best value of voltage responsivity of 1690 V/W at frequencies between 592 and 602 GHz for a signal-power

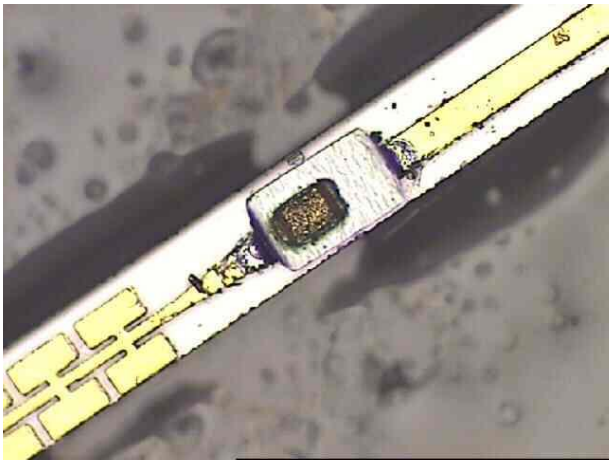

Fig. 3. Optical microscope picture of the soldered diode chip on filter-structure. The filter-substrate is glued with wax on a glass-carrier.

of 40 µW [8]. To measure single sideband (SSB) conversion loss of the mixer we used an LO-power of 2.2 mW at 600.5 GHz and a RF signal-power of 40 µW at frequencies between 592.0 and 601.5 GHz. Best results showed an IF signal with a dynamic range of about 60 dB and a conversion loss (SSB) of 9.4 dB [8].

Unfortunately, noise characteristics of this mixer are not investigated yet. However, we performed microwave-noise measurements of several similar structures using a set-up described in [9]. Results showed typical values of the junction noise-temperature significantly lower than 300 K at frequencies between 2.1 GHz and 4.8 GHz and at a bias current up to 3 mA. A remarkable low microwave noise at high current-bias is suggested to be a benefit of quasi-vertical design [10].

In order to further improve the performance of our structures for a proper operation at higher frequencies a new structure design of a SD was elaborated. An optical microscope picture of a fabricated structure is shown in Fig. 2c. For minimising of the total parasitic capacitance and series resistance of the structure the following changes in the design were made:

- The backside gold cathode and contact pads dimensions were further reduced.
- GaAs-substrate was replaced by AlGaAs-layer and the substrate thickness was reduced down to 4 µm.
- The R_s of the Schottky contact was reduced by reducing the thickness of the active n-GaAs epi-layer.
- Chip dimensions were reduced as well (see Fig. 2c).

The structure was firstly simulated and the total capacitance was calculated using a 3D electromagnetic solver from CST (Computer Simulation Technologies). Accordingly to our simulations the total capacitance of the structure with an anode diameter of 1 µm is C_{tot} = 6.35 fF. Then few structures were fabricated and the capacitance was measured using a network analyzer at 1 GHz. An accurate measurement of such a small capacitance is not trivial. Nevertheless, it resulted in a C_{tot} < 7 fF, which well agrees with simulation results. On-wafer measurements and calculations exhibited structure-parameters shown in Table II under structure signed as 3/SD.

Comparing parameters of the third structure with those of the other two also summarised in Table II, one can observe a higher junction capacitance of the structure 3 in respect to that of the structure

2 whereas the anode diameters are the same.

TABLE II
TYPICAL PARAMETERS OF CONSIDERED STRUCTURES.

Structure version/typ	Series resistance Rs (Ω)	Ideality factor η	Anode diameter (μm)	Junction capacitance at 0V Cj0 (fF)	total capacitance Ctot (fF)
1/APD	< 15	< 1.20	0.8	1.6-2.1	16-18
2/SD	< 10	< 1.20	1.0	1.3-1.6	10-12
3/SD	< 7	< 1.25	1.0	1.8-2.3	< 7

Most probably this is due to the thinner n-GaAs active layer of the structure 3. The last is even thinner as depletion layer of the Schottky contact at 0 V which probably results in a slightly higher ideality factor of the structure 3 in comparison to other two structures. A slight increase of the ideality factor does not significantly affect the mixer performance [11]. Instead, a significant decrease of the series resistance of the structure 2 is obvious. According to our computer modelling of a 600 GHz mixer block, modelled by a 3D field solver Microwave Studio from CST, a variation of R_s with 2 Ω may influence the mixer performance at 600 GHz with approximately the same magnitude as the variation of the C_{tot} with 1 fF does. A simple calculation reveals a gain of a thinner active layer as in the case of structure 3.

CONCLUSIONS AND OUTLOOK

Due to an apparent relatively high capacitance of back-side cathodes and the absence of a surface channel, quasi-vertical structures seemed to be not suitable for operation in a high-THz frequency-region side-along with surface-channel structures, described for instance in [12]. However, recently obtained mexperimental results at frequencies up to 600 GHz are encouraging. Various computer models of a quasi-vertical structure suggest a possible reduction of the parasitic capacitance (junction capacity not included) to bellow 1.5 fF for an APD and bellow 1 fF for a SD. Monolithically-integrated structures (i.e. substrateless) can have even less capacitance without a significant increase of the inductance. Such structure would have a cut-off frequency of above 7 THz. However, in order to demonstrate a full potential of this kind of structures additional investigations and technology developments are needed.

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