Schottky-Structures for THz-Applications based on Quasi-Vertical Design-Concept

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***Abstract*—This work presents results of systematically performed optimizations of a quasi-vertical Schottky-structure for THz-applications. Three versions of structure-design based on a quasi-vertical concept were successfully fabricated and characterized. The first-developed anti-parallel mixer-diode pair demonstrated a high performance at frequencies below 200GHz. Measurement results show a conversion efficiency (DSB) of 5.1dB, 5.8dB, 6.3dB and a system noise-temperature (DSB) of 940K, 950K and 1450K at frequencies of 140GHz, 150GHz and 183GHz respectively. A room-temperature power-sensitivity of about 3000V/W has been attained at frequencies between 75GHz and 95GHz of a single-diode structure fabricated with the second design-version in combination with a broadband planar logarithmic-periodic antenna. Measurements at frequencies about 600GHz of a similar structure mounted in a heterodyne mixer revealed a voltage responsivity of about 1500V/W and conversion loss (SSB) of about 10dB. Microwave-noise measurements of such a structure revealed typical values of the junction noise-temperature to be lower than 300K at frequencies between 2.1GHz and 4.8GHz and at a bias current up to 3mA. Low-frequency noise of these diodes is normally about 4µV/Hz$^{1/2}$ at 1Hz. Typical DC-characteristics of the third design-version of a single-diode-structure are as follows: series resistance Rs<7Ω, ideality factor η<1.2 and junction capacitance at 0V C_{0j}<2.3fF. The total capacitance of this structure is C_0<7fF. These data result in a calculated cut-off-frequency of well above 3THz.**

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

I. 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 optimal 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.

First quasi-vertical structures are developed and fabricated at TUD a few years ago [4]. They demonstrated good mixing performance at millimetre waves [5]. However measurements of a similar structures at 650GHz revealed deficient results [6]. The most significant frequency-limiting factor of these structures is suggested to be the parasitic capacitance [7]. In order to make a quasi-vertical structure suitable for applications in a high-THz-frequency region further structure optimisations are required.

In this work we present and discuss some results of systematically performed optimisations of quasi-vertical structures in order to improve their high-frequency performance.

II. Design considerations

One of main advantages of a quasi-vertical structure is a vertical current flow, as in the case of whisker-contacted [3] or substrate-less[2,8] 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 1.5µm, is enclosed between the Ohmic-contact and Schottky-contact, a very good heat sink from the Schottky contact to the back-side

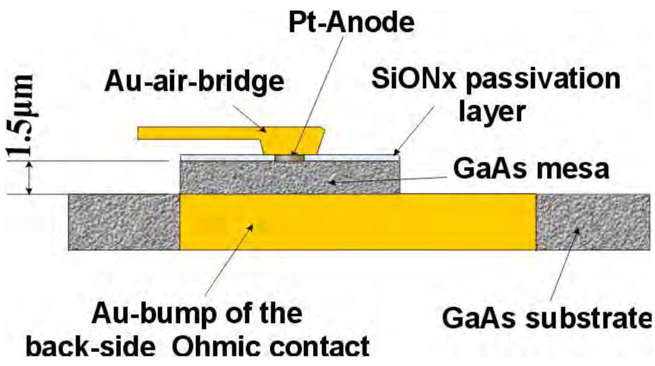


Fig. 1. Sketch of single planar quasi-vertical diode.

Au-bump and other massive metallic elements of the circuitry is organised. This considerably increases the power capability of the quasi-vertical structure.

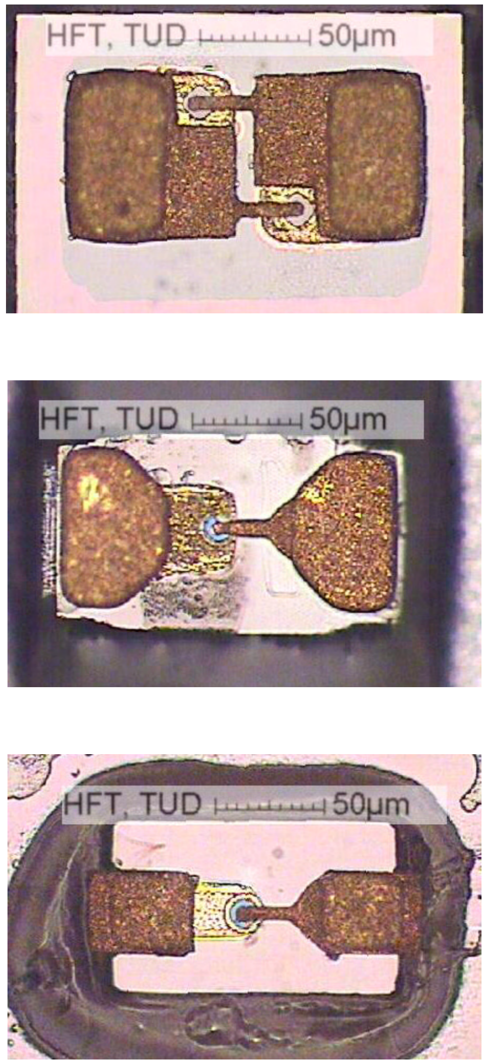
Gold-bumps deposited on back-side Ohmic-contacts (which are specific to these kind of structures) may be used as contact pads for mounting on corresponding filter structures. That means that in contrast to the traditional flip-chip mounting approach, where the structure is mounted up-side-down, a quasi-vertical 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 represents an alternative mounting approach and represents an 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 [9] and in more details in [10].

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 (0.8µm 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.



a)

b)

c)

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

III. Results and Discussions

A. First Design-Version.

The first-developed design of quasi-vertical structures includes both single diode (SD) and anti-parallel diode-pair (APD). However only an APD for frequency mixing application is considered in this work (Fig. 2a.). This structure was designed to be mounted in a subharmonically-pumped waveguide mixer operating at frequencies around 200GHz. For a minimum loss, the structure is carried out on a 8µm to 10µm thick semi-insulating GaAs-membrane. For a comparison to the sketch of a quasi-vertical structure illustrated in Fig. 1 a SEM picture of a mesa-region prepared by Focused Ion Beam (FIB) is shown in Fig. 3. Here one can distinguish a thin GaAs-mesa encapsulated between Au-air-bridge and a massive Au-bump of a back-side Ohmic-contact.

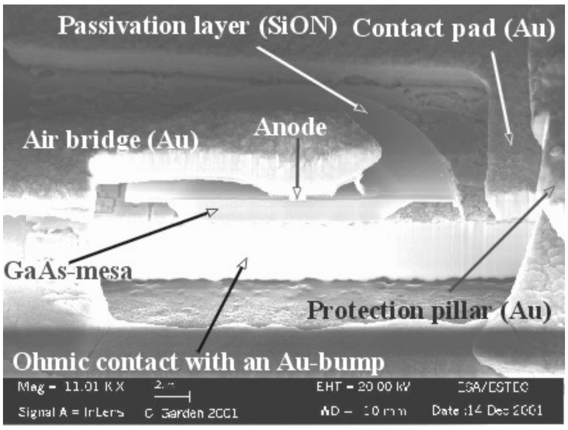


Fig. 3. SEM picture of an APD prepared by Focused Ion Beam (FIB).

Electrical parameters of this structure with an anode diameter of d=0.8µm are as follows: junction capacitance at 0V C_{j0}=1.6fF to 2.1fF (for two anodes switched in parallel), series resistance R_s<15Ω, ideality factor η<1.18, pad-to-pad capacitance C_{tot}=16fF to 18fF. These values resulted from various on-waver DC- and S-parameters-measurements and simulations.

In order to determine a complete S-Parameter matrix of the structure mounted in a waveguide, detailed simulations are performed in Electro-Magnetic Field-Solving software (HFSS). The structure is modelled entirely, including air bridges, mesas, embedded back-side Ohmic-contacts, oxide layers and GaAs substrate. In such a way an accurate analysis, including all parasitics is obtained. A non-linear diode simulation is performed in a Harmonic Balance analysis package (Microwave Office), where the S parameter file is imported from the HFSS-model. Diode-parameters such as C_{j0}, R_s η are varied to ensure the tolerance of the design to small changes of diode-parameters. For our simulations starting values as follows are chosen: C_{j0}=2.5fF, R_s=14Ω and η=1.2. Real diode-parameters can vary somewhat, however the chosen starting values are deliberately pessimistic.

The mixer is designed in such a way that the RF bandwidth is kept as large as possible and it typically achieves 25% at frequencies bellow 200GHz. For mixer fabrication, split-block technology was used with suspended substrate micro-strip technology for couplers and filters. This design allows easy assembly with minimal handling of the substrate and diode. Mixer blocks are lapped flat, the waveguide polished and electrochemically plated with gold for a minimum loss.
Just before mounting all diodes are tested on a Gel-Pack for good I-V-characteristics.

Several Mixers were made and measured at three frequencies, namely 140GHz, 150GHz and 183GHz. Measurements revealed broadly repeatable results of different mixers and their typical values are shown in Table I. Measurement results at 150GHz 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 16GHz).

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 [5]	9.2 (SSB)	3500(SSB)	_	3.5

Our results compare well to those reported in [5] which are evaluated by another group and by different measurement set-up (also summarized in the Table I). This just confirms a very good diode performance at frequencies up to around 200GHz. However, the HFSS computer model pointed to parasitic capacitance of the structure being a significant limiting factor at higher frequencies, where additional inductive tuning devices have to be employed (reducing bandwidth). An increase in the required LO power for optimal pumping in our measurements and increasing conversion loss and noise temperature at 183GHz and 215GHz also suggest capacitance effects. Measurements of a similar structure in a 650GHz-mixer revealed poor results [6], which just confirms our assessments.

B. Second Design-Version.

The second quasi-vertical structure is designed for mixer and multiplier applications in the frequency range from 200GHz to 400GHz. In order to improve operational capability of the structure at higher frequency some changes in the design are 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 x 10^{-3} mm^2 to 3 x 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 using a network analyser exhibited following electrical parameters: C_{j0}=1.3fF to 1.6fF, R_s<10Ω, η<1.18, C_{tot}=10fF to 12fF. 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.

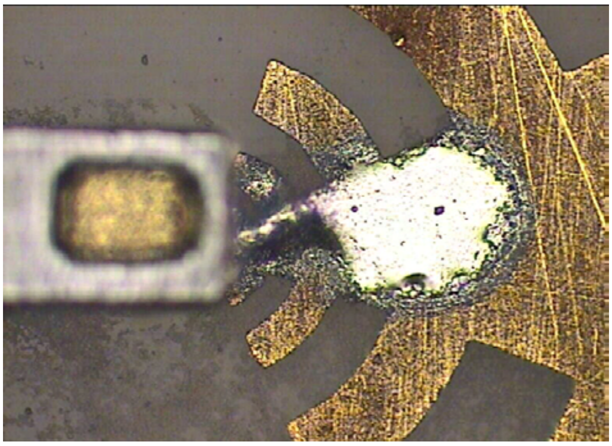


Fig. 4. Optical microscope picture of the soldered diode chip on an antenna arm.

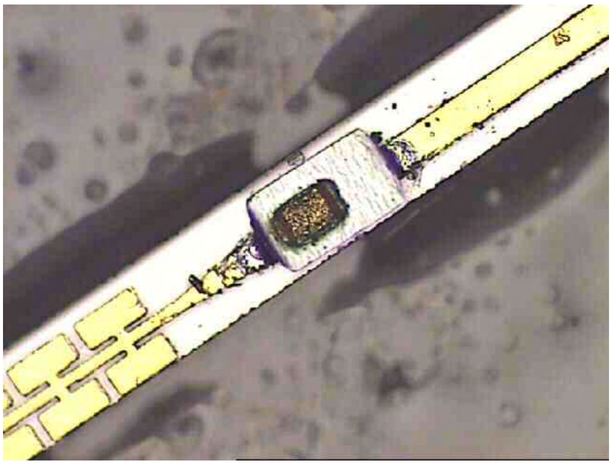


Fig. 5. Optical microscope picture of the soldered diode chip on filter-structure. The filter-substrate is glued with wax on a glass-carrier.

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 4µV/Hz$^{1/2}$ at 1Hz under current bias of 1mA. The 1/f-noise value is bellow 100nV/Hz$^{1/2}$ at frequencies above 500Hz.

For the evaluation of DC-performance of fabricated diodes a similar structure was centrally flip-chip-soldered with indium into waist of a circularly-toothed planar logarithmic-periodic antenna fabricated on a 50µm-thick fused-silica substrate, as shown in Fig. 4. The height of about 12µm moves the diode out of the microscope focus but the diode chip and the Au-bump of the back-side Ohmic-contact are still observable.

In such a way we fabricated a millimetre-wave power-detector. With this approach room-temperature sensitivities of more than 3000V/W are attained at frequencies between 75GHz and 95GHz [11]. These tests and attained results assume a very good quality of fabricated Schottky-contacts. The structure appears to be stable and withstood to handling and mounting procedures.

As a next step, being convinced in the Schottky-contact quality and the structure robustness, we proceeded to a high frequency test. For that we soldered a similar structure with indium on 40µm-thick quartz substrate with a previously defined filter structure as illustrated in Fig. 5. The filter-structure was embedded in a 600GHz heterodyne mixer. The mixer characterization included measurements of DC-performance and conversion loss. These measurements revealed a best value of voltage responsivity of 1690V/W at frequencies between 592GHz and 602GHz for a signal-power of 40µW [12]. To measure single sideband (SSB) conversion loss of the mixer we used an LO-power of 2.2mW at 600.5GHz and a RF signal-power of 40µW at frequencies between 592.0GHz and 601.5GHz. Best results showed an IF signal with a dynamic range of about 60dB and a conversion loss (SSB) of 9.4dB [12].

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 [13]. Results showed typical values of the junction noise-temperature significantly lower than 300K at frequencies between 2.1GHz and 4.8GHz and at a bias current up to 3mA. A remarkable low microwave noise at high current-bias is suggested to be a benefit of quasi-vertical design [14].

C. *Third Design-Version.*

The third quasi-vertical structure is dedicated to operate in a 600GHz heterodyne mixer. For an irreproachable operation at this frequency requirements to the structure-parameters considerably increase. In order to minimise the total parasitic capacitance and the series resistance following changes in the design are made:

- The backside gold cathode and contact pads dimensions are further reduced.
- GaAs-substrate is replaced by AlGaAs-layer and the substrate thickness is reduced down to 4µm.
- The R_s of the Schottky contact is reduced by reducing the thickness of the active n-GaAs epi-layer.
- Chip dimensions are 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 a total capacitance of the structure with an anode diameter of 1µm is C_{tot}=6.35fF. Then few structures were fabricated and the capacitance was measured using an network analyzer at 1GHz. An accurate measurement of such a small capacitance is not trivial. Nevertheless, it resulted in a C_{tot}<7fF, 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 a thinner n-GaAs active layer of the structure 3. The last is even thinner as depletion layer of the Schottky contact at 0V which probably result 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 [15]. Instead, a significant decrease of the series resistance of the structure 2 is obvious. According to our computer model of a 600GHz mixer block, modelled by a 3D field solver Microwave Studio from CST, a variation of R_s with 2Ω may influence the mixer performance at 600GHz with approximately the same magnitude as the variation of the C_{tot} with 1fF does. A simple calculation reveals a gain of a thinner active layer as in the case of structure 3.

D. Monolithically-Integrated Structure.

According to our computer models any substrate is able to considerably increase the pad-to-pad capacitance of the structure. As is described bellow, even the 4µm-thick AlGaAs-membrane increases a total capacitance of our structure with up to 1fF which is already a significant value at THz-frequency. In order to exclude an additional capacitance and losses in an AlGaAs-membrane we proceeded to develop a monolithically-integrated diode with a transition-line and filter-structures on a quartz-substrate. An optical microscope picture of such a structure is shown in Fig. 5. Due to the structure height, the top details of the structure are out of the focus, however one can still distinguish the Au-cathode, mesa, air-bridge and protection pillars. Unfortunately, this structure is not characterized yet but since the anode fabrication technology does not significantly differ from that of the structure 3 we believe that their DC-characteristics are also comparable (see Table II). Our computer model (CST EM-Studio) of such a structure revealed a capacitance of C_{tot}=5.45fF for a structure with an anode diameter of 1µm (substrate and filters are not included). Reduction of the anode diameter considerably reduces C_{tot}.

IV. CONCLUSIONS AND OUTLOOK

The main conclusions on this work can be drawn as follows:

- Devices designed for operation at frequencies up to 200GHz were successfully fabricated and characterized at several frequencies. They demonstrated good mixer-performance at frequencies up to around 200GHz. However, at higher frequencies parasitic pad-to-pad capacitance becomes a significant limiting factor affecting structure performance.
- A second structure-version designed for operation at frequencies between 200GHz and 400GHz is successfully fabricated and characterized. A test in a 600GHz-mixer demonstrated good performance. Although the substrate is thinner these structures appear to be stable and withstood to various handling and mounting procedures. Various measurements revealed excellent quality of Schottky contact.
- A third version of quasi-vertical structure designed for operation in a 600GHz-mixer is also fabricated and partially characterized. Measured and calculated values of electrical parameters of this structure result in a calculated cut-off frequency of well above 3THz.
- A technology is developed for the fabrication of a monolithically integrated diode with transmission-line and filter structures on a quartz-substrate.

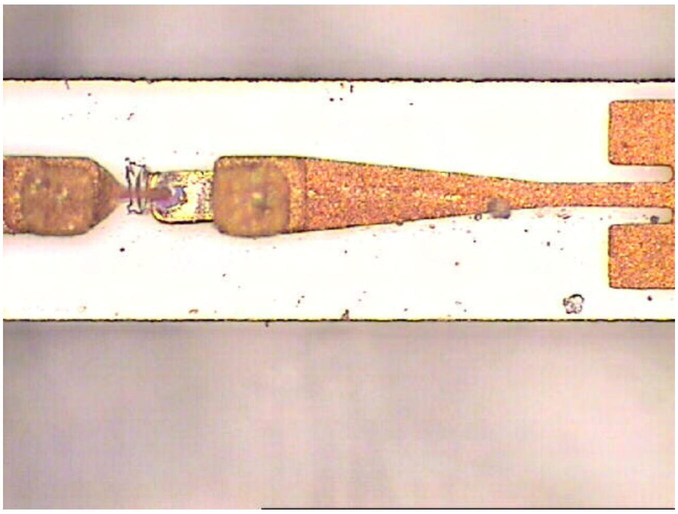


Fig. 5. A single monolithically-integrated diode with filter-structures and transition-line (not shown) on a quartz-substrate. The quartz-substrate dimensions are 40X120X2000µm.

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 [16]. However, recently obtained measurement results at frequencies up to 600GHz are encouraging. Various computer models of a quasi-vertical structure suggest a possible reduction of the parasitic capacitance (junction capacity not included) to bellow 1.5fF for an APD and bellow 1fF for a SD. Monolithically-integrated structures (i.e. substrateless) can have even less capacitance without a significant increase of the inductance. Such a structure would have a cut-off frequency of above

7THz. However in order to demonstrate a full potential of this kind of structures additional investigations and technology developments are needed.

ACKNOWLEDGMENT

The authors want to acknowledge Mr. R. Zimmerman, A. Walber and H. Gibson Radiometer Physics GmbH (RPG) for qualitative mixer measurements and fruitful discussions.

The authors would like also to thank the company CST for providing the MST Microwave Studio and EMS electromagnetic Studio software packages.

This work was partly supported by European Space Agency (ESA) and Deutsche Forschungsgemeinschaft (DFG).

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