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# From Honey-Comb to SMMIC: Schottky Diodes at TU Darmstadt

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**Abstract** – GaAs Schottky diode proved itself to be one the main semiconductor device used in THz-electronics. This contribution describes the evolution of THz-devices from honey-comb whisker-contacted Schottky diodes to sub-millimetre monolithically integrated circuits (SMMIC) at University of Technology (TU) Darmstadt. Short description of each device and integration type is given together with pointing technological and device particularities.

## I. INTRODUCTION

The interest to THz radiation grows with enormous speed due to the wide range of frequencies and their suitable applicability to various fields, from atmospheric, earth, medical and biological studies to automobile and industrial involvement. The main units in heterodyne mixer systems are the local oscillator and the mixer. Mixing and frequency multiplying in THz region requires the use of very fast non-linear devices with high cut-off frequency. GaAs Schottky diodes represent ones of the fastest electronic semiconductor devices known nowadays due to the high electron mobility, absence of minority carriers and very simple structure. Due to the non-linearity of the current-voltage-characteristics and the capacitance-voltage-characteristics, GaAs Schottky diodes are often used in heterodyne mixers and frequency multipliers in the THz region, respectively. Their device configuration varies from single diodes for hybrid integration to monolithically integrated circuits. In this contribution we will discuss the device configuration of GaAs Schottky diodes available at TU Darmstadt, and consequently the evolution of their technology.

## II. SINGLE SCHOTTKY DIODES

Schottky varactor diodes are the key element for all-solid-state local oscillator sources at frequencies higher than 100 GHz. A single Schottky diode represents itself as a highly efficient for varactor applications. For hybrid integration, both whisker-contacted and single planar Schottky diodes are successfully used. Although planar diode technology improved substantially, whisker contacted Schottky diodes still provide the highest efficiencies and output powers at frequencies above 300 GHz. The conventional form of whisker-contacted diodes was modified into a substrateless device configuration [1] by reducing the odd part of  $n^+$ -GaAs from hundreds to only a few micrometers. There is a large number of advantages of the latter against the conventional one, among which: less influence of skin effect, better heat sink, small semiconductor volume, and vertical current flow.

All that leads to significant improvements in performance, which were shown from RF-measurements for frequency multipliers and mixers using substrateless diodes [2]. As a logical sequence of vertical configuration is the Quasi-Vertical structure of planar Schottky diode (QVD), developed at TU Darmstadt. Fig. 1 presents schematically the technology evolution from the conventional whisker-contacted diode to QV-configuration of a planar diode.

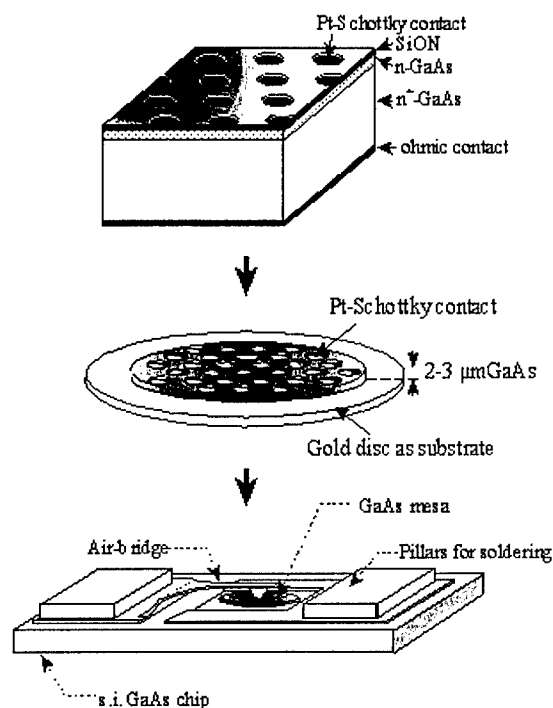


Fig.1: The way from a whisker-contacted diode to a quasi-vertical planar Schottky diode

Fig. 2 offers some examples of substrateless and planar Schottky diode fabricated according to the principle described above. Let us attend your attention here for some details of device particularities and parameters of both substrateless and planar Schottky diodes.

### A. Substrateless Whisker-Contacted Schottky Diode

Substrateless Schottky diodes, proposed in 1995 [1], offer the prospect to increase the power handling capabilities and to receive a minimum series resistance. Compared with the conventional diode chip the thickness of the  $n^+$ -GaAs (gallium arsenide) substrate is strongly reduced from 100  $\mu\text{m}$  to 2 $\mu\text{m}$ .

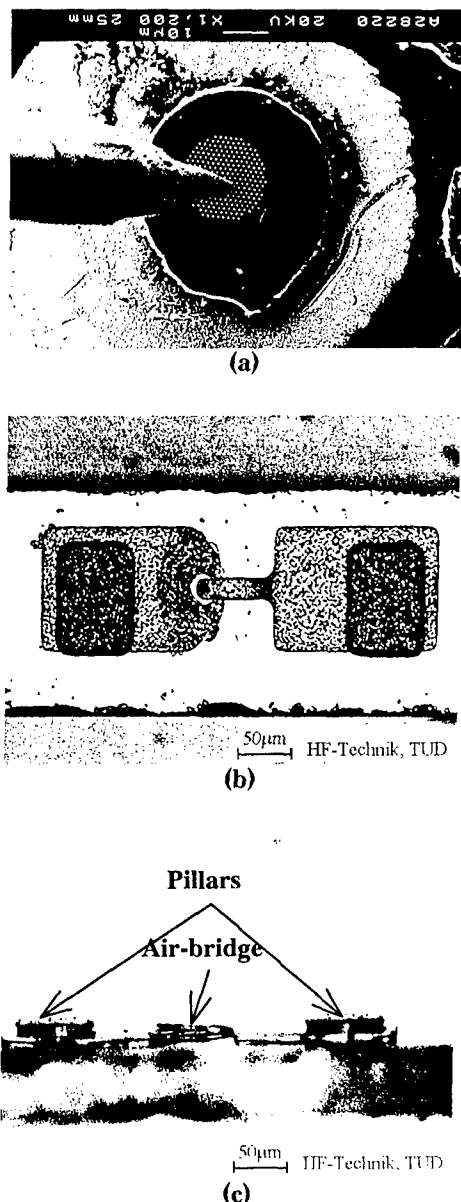


Fig.2: (a) Anode array placed in a honey-comb manner on a gold disk and contacted with a NiAu-whisker. (b) Top-view and (c) side view of a single planar Schottky-diode chip

A 5-10 μm thick gold disk promotes the mechanical stability of the device and simplifies the handling. Due to the reduced geometry, substrateless Schottky diodes offer several advantages compared with a conventional whisker contacted Schottky diodes. Due to minimised dimensions the structure is less affected by the skin effect [2]. The  $n^+$ -substrate thickness is reduced to a few microns reducing its contribution to the resistance. Small distance between the active n-layer and the backside metal provides a good heat sink. Therefore, substrateless Schottky diodes can operate more reliably at high current densities without thermal degradation and the contribution to the system noise is reduced. Reduced semiconductor surface area decreases the leakage current. Reduced device volume allows a better coupling of the input signal into the diode within the waveguide. Due to these advantages substrateless Schottky diodes give a prospect to attain improved performance of mixers and frequency multipliers in the sub-millimetre wave regime.

In co-operation with the research group by Prof. Brand at the University of Erlangen-Nürnberg, a 2.5 THz corner cube mixer using substrateless whisker contacted diode is realised. Fig. 2 (a) shows a picture of a substrateless diode with an anode diameter of 0.5 μm contacted with a whisker in the corner cube mixer set-up. Different diodes were under investigation of the video sensitivity. The best one with a doping level of  $3 \times 10^{17} \text{ cm}^{-3}$  and a anode diameter of 0.5 μm was applied to further rf measurement. A mixer noise temperature of 16000 K at 2.5 THz was achieved which is even little lower than the best result published in 1999, which is measured in a waveguide mixer and had a noise temperature of 16500 K [3]. Some of multipliers built with substrateless varactor diodes yielded record output power and efficiency. The efficiency of a tripler of almost 19% has been achieved at frequencies close to 300 GHz. With optimised complex doping structures we could achieve a very high capacitance modulation ratio. Recently, the doubler efficiency of 40% that has been achieved with this diode is the highest reported value for a single diode multiplier.

### B. Planar Single Schottky Diode

Like substrateless diodes, the QVD's possess also the geometrical advantages as the substrateless ones and are expected to be very promising for applications in the THz regime. Fig. 2 (b) and (c) show top and side view of a single planar Schottky diode after separation from the substrate. Within the ESA/ESTEC-Kasimir project we co-operate with Radiometer Physics GmbH (RPG) to build a 650 GHz waveguide mixer using planar Schottky diodes. Single quasi-vertical planar Schottky mixer diodes were used for this purpose. The diodes with doping level  $5 \times 10^{17} \text{ cm}^{-3}$  and anode diameter 0.8 μm have shown series resistance of 16 Ω, zero junction capacitance  $C_{j0}$  of 1.2 fF, saturation current of  $2 \times 10^{-17} \text{ A}$ , ideality factor of 1.15, and finally, breakdown voltage of -4 V. The diodes were submitted to noise measurements at 1.5 GHz. The mixer noise temperature was of  $T_{\text{mixer}}^{\text{DSB}} = 2500 \text{ K}$  with a conversion loss of  $L_{\text{mixer}}^{\text{DSB}} = 10 \text{ dB}$  which proves the high quality of the diode.

## III. MONOLITHICALLY INTEGRATED CIRCUITS FOR THZ APPLICATIONS

Using planar techniques it is possible to integrate several diodes and other elements for special applications. The first step to integration is to produce chips with a number of diodes connected or placed together in one unit. Such integration of diodes permits to avoid parasitic effects introduced by not-reproducible hybrid techniques and ensures acceptable circuit performance. In this section, we will discuss different types of integration performed at TU Darmstadt.

### A. Anti-Parallel Diode

One of the elementary integration methods is to connect a few diodes together in parallel or in series in dependence of the purpose of their use. For mixing, two diodes should be connected in anti-parallel manner, so that at least one diode is always forward-biased. This regime is for frequency mixing. An anti-parallel diode pair performed according to the Quasi-Vertical approach is shown in Fig. 3. The noise temperature measurements at 1.4 GHz

carried out on each diode of the mounted diode pair at different biases were reported in Ref. [4]. At a typical bias current of 500  $\mu\text{A}$  for a single mixer diodes, the noise temperature was determined as 350 K which is comparable to whisker-contacted diodes.



Fig. 3. Anti-parallel planar diodes pair

### B. Schottky-Diode Array for Quasi-Optical Frequency Multipliers

For frequency multipliers, Schottky diodes can be put in series in order to increase the total breakdown voltage of the circuit, which is important for efficient performance of a frequency multiplier. Monolithically integrated balanced groups of Schottky diodes of various number and dimensions are currently produced and investigated at TU Darmstadt. Another possibility to integrate diodes for frequency multiplication in the THz-range is to fabricate a non-linear element array for quasi-optical frequency multiplier [5].

Monolithic Integration of several non-linear elements offers the possibility to increase the efficiency of quasi-optical frequency multipliers. At the University of Technology Darmstadt, several of such systems have been fabricated. In one approach, an array of non-linear elements are fabricated on a ground plane, and slot antennas are used to feed them. This represents an advanced integration, where the chip contains apart Schottky diodes also other elements such as antennas and filters.

Another example of such integration is strip-line technology. In this case electrical dipoles are used to feed the non-linear elements, which in turn deliver the multiplied signal to a further electrical dipole, orthogonal to the first. Orthogonal polarisation is used for incoming and outgoing power. Fig. 4 shows such a circuit featuring seven Schottky diodes with their corresponding dipole antennas for reception of fundamental signal and emission of the second harmonic.

### C. Integrated Circuits of Atmospheric Observations

Another field in which monolithic integration can have many advantages is in atmospheric sensing. Traditional heterodyne receivers use waveguide mixers fed by horn antennas incorporating waveguide-mounted single diodes. The integration of the front-end in one single chip should have not only the electrical advantages mentioned above but also lower the costs.

The possibility to realise microstrip structures adequate for very high frequencies on the same chip as the Schottky diode suggested the system [5] pictured in Fig. 5. A microstrip-fed double-slot antenna supplies the diode with the signal to be detected as well as with pumping power.

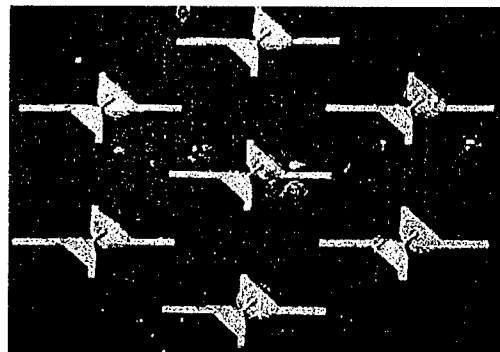


Fig. 4: SEM image of a 7-Schottky diode array for Frequency Doubling

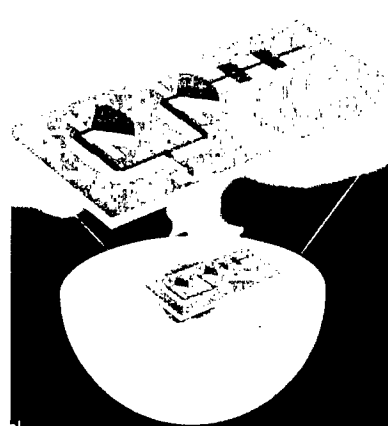


Fig. 5: Sketch of an integrated front-end for atmospheric observation

### D. Integrated Multi-Channel Mixer Circuits for Imaging Applications

Monolithic integration of THz circuits may also find a very promising application in the development of detector arrays for imaging of electron cyclotron in fusion plasmas.

The basic problem presented here is the high pumping power requirements in a system with several mixer diodes. The LO loss can be reduced by a factor of about 10 dB in a system with on-chip LO-power distribution as opposed to quasi-optically fed systems, which might be the best solution for single-receiver systems.

On-chip coupling of LO power may be improved through the use of sub-harmonic pumping, which brings about a significant reduction of the attenuation in the microstrip. Therefore, antiparallel diode pairs are selected as mixer elements to improve sub-harmonic performance [6].

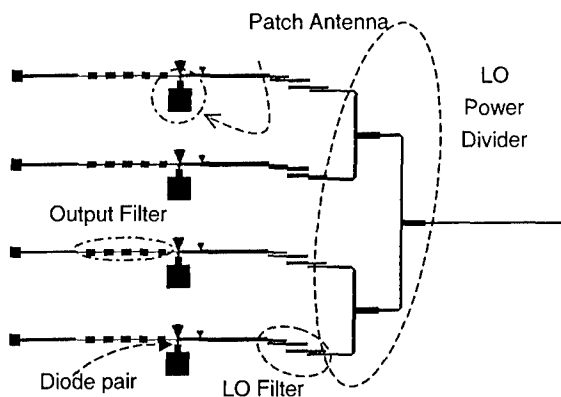


Fig. 6: Layout of a 4-receiver array for imaging of electron temperature in fusion plasmas

The circuit, sketched in Fig. 6, is realised on a multi-substrate technology and includes aperture-coupled patch antennas for the reception of the plasma signal. Cross-talking between channels may be reduced by isolation of patch antennas through trench etching.

System calculations show a minimum expectable value of conversion loss between 6 and 8 dB for input LO powers ranging from 5 to 10 dBm per diode pair. The ripple throughout the IF band (9 to 18 GHz) is less than 4 dB.

#### IV. CONCLUSION

In the THz range, both single devices as whisker contacted and planar Schottky diodes to partially integrated circuits and SMMIC techniques are essential to satisfy high requirements of complex designs and reproducible characteristics of modern science, electronics and research. In this paper, the present research activities in the THz region at Darmstadt are highlighted. Fabrication technologies as well as simulation techniques are being further optimised in order to match the high demands of THz Electronics.

#### ACKNOWLEDGEMENTS

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