A Novel Micron-Thick Whisker Contacted Schottky Diode Chip

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Abstract

Although planar diode technology recently has improved significantly, whisker contacted Schottky diodes are required for applications above 1 THz. This paper presents a novel whiskered substrate-less diode chip which exhibits a significantly reduced DC series resistance. Due to the extremely small chip geometries, these diodes are also expected to be more suitable for operation at THz frequencies than the conventional diode chips because of the reduced skin effect resistance.

The novel diode chip consists of a 100-250 µm wide gold foil with a 10-30 µm wide and 3 µm high GaAs mesa on it. The typical honeycomb-array of anodes is located on top of the mesa.The diameters of the gold foil and the GaAs mesas can be varied according to the mixer geometry.

Up to now, diode chips with 0.8 µm and 0.5 µm anodes have been fabricated and compared to conventional diode chips with identical epi-layers and anode diameters. The novel device shows a DC series resistance which is reduced by ~3 Ω.

The fabrication process for these devices is presented which requires a number of additional steps compared to the conventional devices.

Introduction

A number of optimisation approaches for whiskered Schottky diodes have improved the performance of heterodyne receivers for use at frequencies as high as 2.5 THz. The traditional chip structure consists of a chip which is typically 100-200 μm square and 80-100 μm thick, with ohmic contacts on the back and a honeycomb anode array on top.
The optimisation of a diode covers the following items:

- reduction of the zero-bias junction capacitance and the series resistance which mainly determine the high-frequency performance
- GaAs growth and fabrication techniques for a high-quality Schottky contact which mainly determines the noise behaviour
- layer design according to the application
- structurisation of the entire chip

With respect to a decrease in zero-bias junction capacitance of less than one fF the anode diameters have been reduced to 0.25-0.5 μm [1]. Plating techniques for a high-quality Schottky metal deposition providing an oxide-free contact have been investigated [2,3]. The quality of the epitaxial layers has improved significantly and the structure of the layers have been optimised with regard to the specific needs of the radiometer developers [4,5]. In this paper we investigate the optimisation and fabrication of improved chip structures with respect to THz applications. There are several reasons why the structure of the entire chip could be optimised:

- at highest frequencies the skin effect adds significant parasitic resistance to the diode which degrades the receiver sensitivity
- the diode chip is mounted in different embedding circuits and the ideal chip shape might differ.

Diode Design

The skin effect confines the current within a few microns of the outer boundary of the chip for frequencies higher than a few hundred gigahertz. Fig. 1 shows the skin effect resistance vs. diode diameter at 600 GHz, 1Thz and 2.5 THz [6] for a traditional diode chip geometry indicating that at highest frequencies the skin effect becomes an important factor. Especially at 2.5 THz, the most important frequency for the investigation of the OH molecule, the skin effect adds 8 Ω (d = 0.5 μm) to the series resistance and therefore decreases the receiver sensitivity.

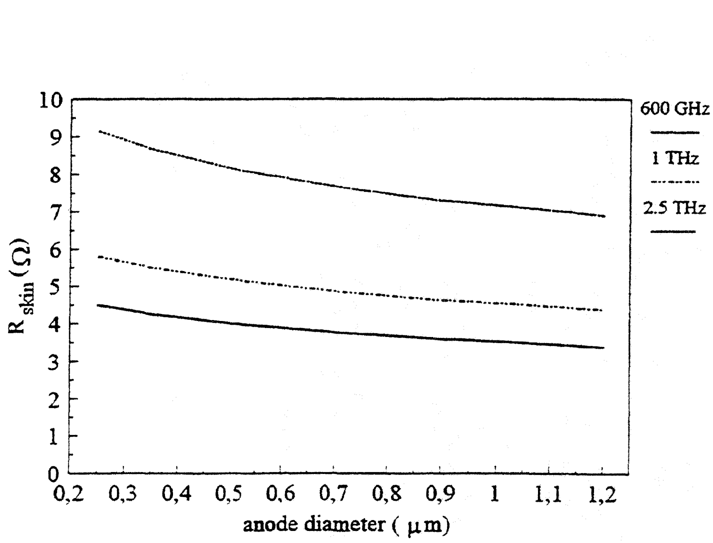

Fig. 1 skin effect resistance vs. diode diameter for several operating frequencies

In a first attempt Seidel and Crowe [7] calculated and fabricated a membrane diode with a thickness of about 2 microns which should be capable to reduce the series resistance. Using an improved finite difference calculation Bhapkar and Crowe [8] have shown that a reduction of the substrate significantly reduces the influence of the skin effect. Neglecting the ohmic contact, the series resistance should be reduced by more than 30 % at 1 THz compared to a traditional diode chip if the thickness of the substrate does not exceed the skin depth. Taking into accout reasonable specific ohmic contact resistivities, a substrate thickness of at least 2 microns has been proposed. At 2.5 THz even with a thickness of two microns most of the current is forced to flow in the outer boundaries of the chip and therefore the benefit of a thin substrate is reduced.

As a second approach to reduce the influence of the skin effect the diameter of the chips can be reduced. Kelly et al. [9] fabricated 30 μm diameter cylindrical Schottky diode chips which should result in a decrease of the skin resistance of about 10 %.

To reduce the influence of the Skin effect most effectively we decided to fabricate devices which are drastically reduced in height and width illustrated in Fig. 2. With a substrate thickness of 2 - 3 microns a reasonable effective ohmic contact area still is provided. In combination with a diode chip diameter of 15 - 35 microns the influence of the skin effect is significantly reduced. Such diode chips would be extremely difficult or maybe impossible to handle. Therefore, the diode is located on top of a metal disk which is providing the ohmic contact. The diameter of this disk is 120 - 250 microns with a thickness of at least 10 microns to obtain mechanical stability of the whole structure and to guarantee a facilitated soldering of the diode into a mixer mount.

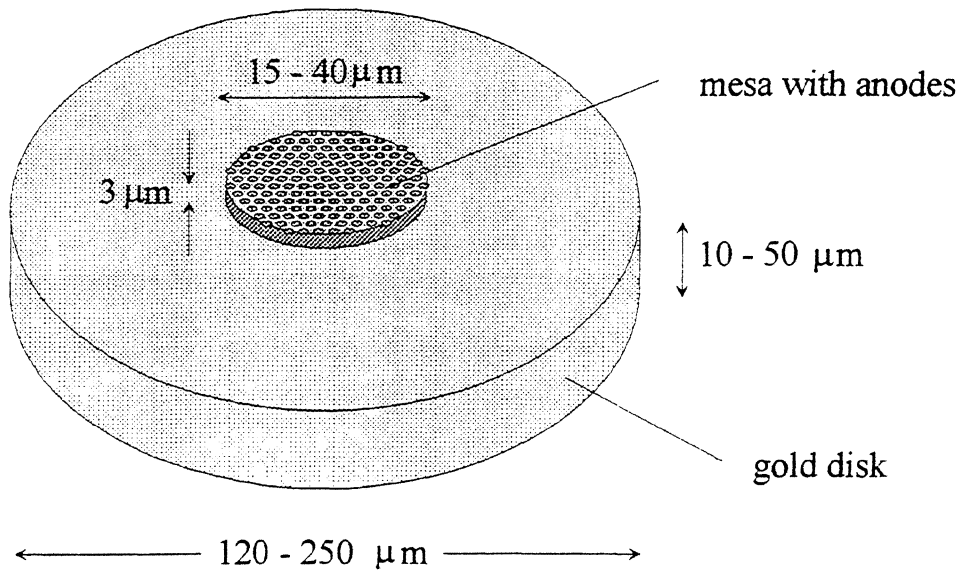

Fig. 2 "Substrateless" diode chip

Device Fabrication Process

The material is composed of four layers. A 1 µm $Ga_{0.45}Al_{0.55}As$ - layer is grown on top of a semi insulating GaAs substrate to incorporate an etchstop layer into the structure. A 3 µm n^+ GaAs with a doping level of $N_D = 3 \times 10^{18}$ cm^{-3} is used to create the ohmic backside contact. A 50-100 nm ($N_D = 3\text{-}10 \times 10^{17}$ cm^{-3}) n-GaAs active layer completes the structure. A 300 nm layer of SiO_2, which is necessary for the definition of submicron anodes, is deposited on the active layer. The wafers are lapped to a thickness of about 100-120 µm. With a selective via-hole etching using H_2O_2 / NH_4 OH (pH = 7.9) and a modified spray etching technique, small holes with diameters of ∅ = 120 - 250 µm are defined from the backside. The AlGaAs layer is etched selectively with J_2:KJ:H_2O. Ohmic contacts which have been formed at the original interface between GaAs and AlGaAs often offered a high contact resistance. Therefore, prior to the deposition of a Ni/AuGe/Ni contact 100-200 nm of this interfacial layer is removed with a nonselective etchant. A rapid thermal annealing step with a subsequent electroplating of the contact areas to a thickness of 10 - 30 µm completes the backside fabrication steps.

The fabrication processes for the anode definition are the same as utilised for conventional whiskered diode chips. For the formation of the anodes the samples are processed by standard contact UV lithography. The honeycomb pattern is transferred to the oxide by reactive ion etching. To achieve near ideal electrical and noise performance a homogeneous metal/semiconductor contact, free of interfacial layers, is required. Using anodic pulse etching in a Pt- electrolyte some nm of the epitactical layer are removed. Within the same electrolyte 100 - 150 nm of Pt is deposited [10]. A final 150 nm Au overlayer deposition completes the anode formation.

The mesas are defined by a two-step etch process: Firstly, the SiO_2 mesh regions between the mesas is etched in buffered HF. Finally, with an H_2O_2 / NH_4OH (pH = 7.9) etchant small mesas remain on the Au backside metallisation. The mesas then are covered with wax and the remaining substrate is removed using H_2O_2 / NH_4OH (pH = 8.4).

Fig. 3 shows a mesa with a diameter of 16 µm and 1 µm anodes on top of a 120 µm metal disk prior to the substrate removal. This shows that very small mesa and metal disk diameters are possible. The main limitation for these geometrical aspects is not the fabrication technology but the handling of the devices and the contacting of the anodes. In Fig. 4 a 35 µm diameter mesa with 0.5µm anodes is shown. Fig. 5 shows a device with seven diode mesas after substrate removal. Devices with only one mesa utilize less than 1 % of the wafer surface. Therefore, our recent devices have been fabricated with seven mesas. The Au-disc and the mesas offer high mechanical stability and the handling is even easier as with the traditional chips.

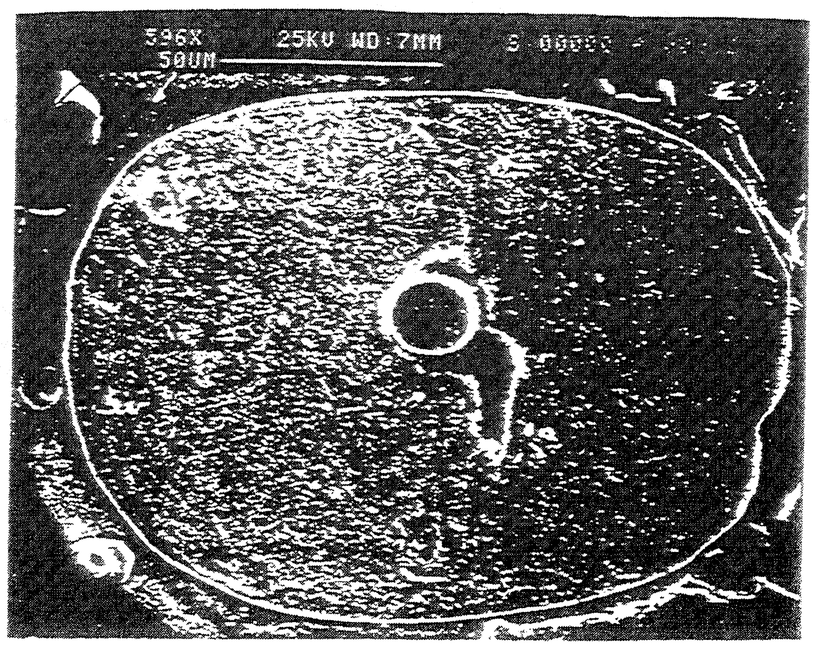

Fig. 3 mesa, ∅=16 µm with 1 µm anodes on top of a ∅=120 µm Au-disc

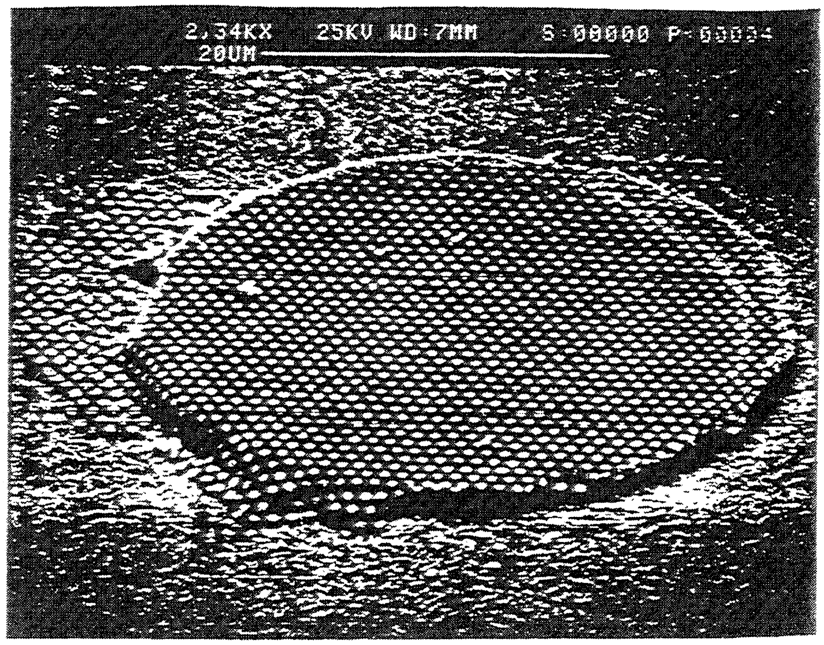

Fig. 4 mesa, ∅= 35 μm with 0.5μm anodes

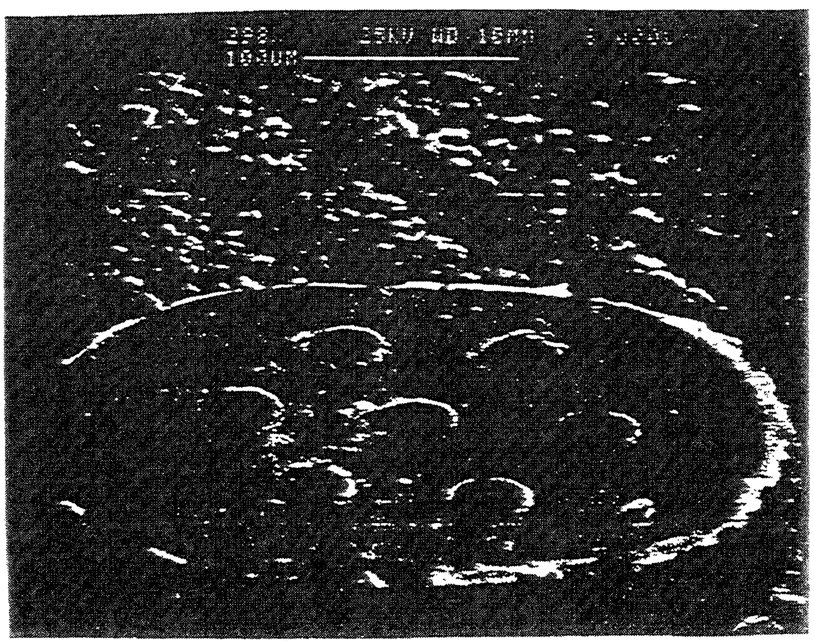

Fig. 5 device with seven mesas

Device Characteristics

A batch of prototype diodes has been fabricated with different epi-layer doping concentrations and anode diameters. Table I shows a comparison of a conventional chip and four substrateless devices.

	DA560	DASL038	DASL037	DASL055	DASL107
parameter					
type	conventional	substrateless	substrateless	substrateless	substrateless
N_{epi} (cm^{-3})	3×10^{17}	3×10^{17}	3×10^{17}	5×10^{17}	1×10^{18}
d_{anode} (μm)	0.8	0.8	0.6-0.7	0.5-0.6	0.7
R_S (Ω)	13	10	20	30	30
C_{j0} (fF)	1	1	(0.6)	(0.5)	(1)
η	1.1	1.1	1.12	1.21	1.32

Table 1 DC characteristics of different diodes

The first substrateless diode, the DASL038 offers the same barrier characteristics of the corresponding standard whiskered diode DA560 (also fabricated at TH Darmstadt) but a 3 Ω lower series resistance. Assuming that the crystal quality of the wafers is the same and with the prospect of a reduced skin resistance the high frequency results performance of the new devices is very likely to be even better. First results (measured at RPG) are shown below. At 545 GHz a mixer noise temperature of T_M=1300 K has been achieved. There is only one result with a conventional whiskered diode (DA560 at 570 GHz) which has achieved a better performance.

Although devices with 0.5-0.7 micron anodes have shown low series resistances there is no striking decrease in DC series resistance compared to traditional chips. To classify these devices in Fig. 6 the plot of log(I) against V and the differential resistance against V of the DASL055 and the IT12 and IT6 from the University of Virginia are shown. The IT12 and IT6 which have shown excellent performance [11], are the most established half-micron whiskered diodes with nearly the same doping levels as the DASL055. It can easily be seen that the three diodes exhibit almost identical I/V curves. Small differences occur in the R_S curves which are probably due to variations in the anode diameters. Taking into account the prospect of reduced dependence on the skin effect the substratless devices offer very promising DC- characteristics.

	Freq (GHz)	L(dB)	T_{Sys} (K)	T_M (K)
DA560	570	6	1550	1250
DASL055	545	6.1	1680	1300

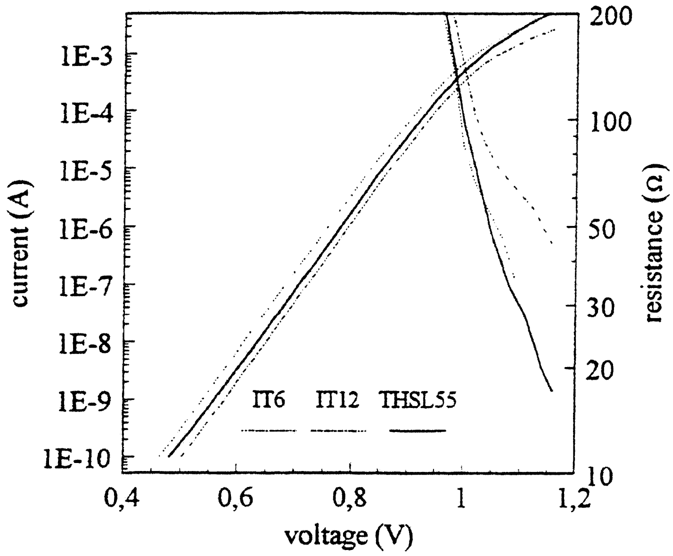

Fig. 6 DC-characteristics of the DASL055, IT12 and IT6

Besides these pros there are some serious cons, which will however be overcome in the future. The uniformity of different batches and even diodes on different mesas still show some variations. There are several reasons for this:

- the quality of available wafers varies much more than that for standard diodes
- the AlGaAs etchstop layer creates dislocations in the following grown GaAs layers which are essential for good diode performance
- the formation of a good ohmic contact is much more difficult

Therefore, the fabrication has not yet achieved the maturity of standard devices and up to now there are only prototype chips available. To obtain a higher reproducibility we will substitute the AlGaAs by an InGaP etchstop layer. InGaP can be grown lattice matched and due to its higher selectivity a reduced layer thickness can be chosen. Both aspects should positively affect the crystal quality and therefore the performance of the diodes.

Conclusion

A fabrication process for Schottky barrier diodes with reduced overall dimensions has been developed. These devices should offer a drastically reduced influence on skin effect and therefore could offer advantages in the THz frequency range. Prototype devices have been fabricated and the DC characteristics show that the same or even slightly reduced series resistance values and the same ideality factors with respect to traditional diode chips can be achived.

The fabrication has not yet achieved the maturity of the standard whiskered chips. This is mainly due to the AlGaAs etchstop layer which decreases the quality of the essential layers significantly and makes the formation of a reasonably good ohmic contact much more difficult.

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References

[1] P. A. D. Wood, D. W. Porterfield, W. L. Bishop, T. W. Crowe, "GaAs Schottky Diodes for Atmosperic Measurements at 2.5 Thz", Fifth International Symposium on Space Terahertz Technology, pp 355-367, 1994

[2] T. W. Crowe,"GaAs Schottky Barrier Mixer Diodes for the Frequency Range 1-10 THz", Int. Journal IR and Millimeter Waves, Vo. 10, No. 7,pp.765 -777, 1989

[3] A. Grüb, C. Lin, H.L. Hartnagel," Electrolytic Deposition Techniques For The Fabrication Of Submicron Anodes", this prceedings

[4] A. Jelenski, A. Grüb, V. Krozer, H. L. Hartnagel," New Approach to the Design and Fabrication of THz Schottky Barrier Diodes", IEEE Tans. Microwave Theory Tech., Vol 41, No. 4, pp. 549-557, 1993.

[5] A. Grüb, V. Krozer, A. Simon, H.L. Hartnagel, "Reliability and Micro-Structural Properties of GaAs Schottky Diodes for Submillimeter-Wave Applications", Solid-State Electronics, Vol 37, No. 12, pp 1925-1931, 1994

[6] L.E. Dickens,"Spreading Resistance as a Function of Frequency", IEEE Transactions, Vol. MTT-15, No. 2, pp 101-109, Feb. 1967

[7] L.K.Seidel, T. W. Crowe, "Fabrication and Analysis of GaAs Schottky Barrier Diodes Fabricated on Thin Membranes for Terahertz Applications", Int. Journal IR and Millimeter Waves, Vol. 10, No 7, pp. 779-787, 1989

[8] U. V. Bhapkar, T. W. Crow,"Analysis of the High Frequency Series Impedance of GaAs Schottky Diodes by a Finite Difference Technique", IEEE Trans. Microwave Theory Tech., Vol. 40, No.5, pp. 886-894, 1992

[9] W. M. Kelly, S. Mackenzie, P. Maaskant, "Novel Chip Geometries For THz Schottky Diodes", Fifth International Symposium on Space Terahertz Technology, pp. 404-408, 1994

[10] A. Grüb, R. Richter, H. Hartnagel, "Electrolytic Processes for Etching and Metal Deposition towards Nanometre Quantum Structures", Electr. Letters, vol. 27, no.4 pp. 856-857, 1991

[11] W. C. B. Peatman, T. W. Crowe,"Design and Fabrication of 0.5 Micron GaAs Schottky Barrier Diodes for Low-Noise Terahertz Receiver Applications", Int. Journal IR and Millimeter Wa ves, Vo. 11, No. 3,pp. 355 -365, 1990