IF-noise improvement of the GaAs Schottky diodes for THz-frequency mixer applications

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***Abstract* - GaAs-Schottky-diodes are a key-element of millimetre-, submillimetre-wave and THz-frequency mixer and multiplier systems. This paper presents the evaluation of sub-micrometer-size Pt/n-GaAs anode fabrication technology based on electrochemical metal deposition for planar Schottky-diodes. The technological approach for low-noise Pt/n-GaAs Schottky diode fabrication has been first optimised for whisker-contacted diodes and then successfully transferred to the fabrication of planar structures using a "dummy anodes" structural approach. The IF-noise temperature of planar diodes is significantly lower than that of whisker-contacted diodes. Excess noise of whisker-contacted anodes is attributed to temperature effects which are reduced in the planar quasi-vertical design. The effect of thermal annealing on IF noise temperature of planar structures is investigated using a "single step" method. In contrast to non-annealed samples, no evident threshold of the noise temperature is observed up to 3mA of bias current for thermally annealed samples. This strongly suggests that RIE-induced defects in the GaAs surface may generate trap noise at a few GHz. However this can be effectively reduced by thermal annealing. The optimisation of the fabrication technology results in very good DC-characteristics and excellent noise temperature of planar Schottky diodes for THz mixer applications.**

I. INTRODUCTION

Schottky diodes remain widely used for non-cryogenic submillimetre wave mixer applications [1]-[3]. In order to minimize conversion loss at higher frequencies the junction capacitance has to be minimized, which is mainly achieved by anode area reduction. This results in very high current densities through the anode, heating the electrons considerably above their thermal energy and causing excess noise in the device.

An important part of THz-device fabrication is the anode formation [4]. Reactive Ion Etching (RIE) is commonly used for small anode area definition due to plasma's unique properties. However RIE is accompanied by processes like back-deposition and damage, which may strongly degrade diode performance [5]. Particularly, radiation damage induced by RIE becomes apparent in the displacement of Ga and As atoms at the GaAs surface [6]. It is well known that surface states and impurities are mainly responsible for low-frequency noise generation whereas hot-electron and intervalley scattering noise predominate in the microwave frequency range [7]. It has been also suggested that additional noise sources may contribute to the total excess noise in the intermediate frequency (IF) range [8], [9]. Since processes at the Schottky interface can not be exactly predicted theoretically, iterative experimental verification of various technological processes is required for fabrication of high quality Schottky devises.

A systematic process optimisation and characterisation of planar devices is very costly and time-consuming due to fabrication complexity and reduced yield of the fabrication process. However the use of a structural approach, described in [5], allows optimisation on simple whisker-contacted structures and transfer of parameters to the fabrication of planar structures.

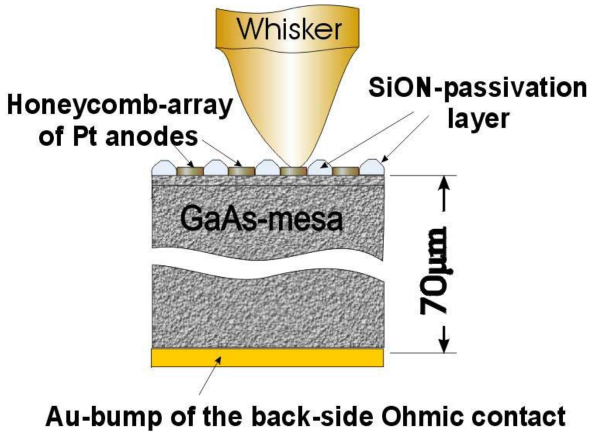
This paper presents results of systematically performed IF-noise optimisation for whisker-contacted diodes and planar structures for THz-applications. A "single step" method permits investigation of the effect of thermal annealing on planar structure performance.

II. EXPERIMENTAL DETAILS

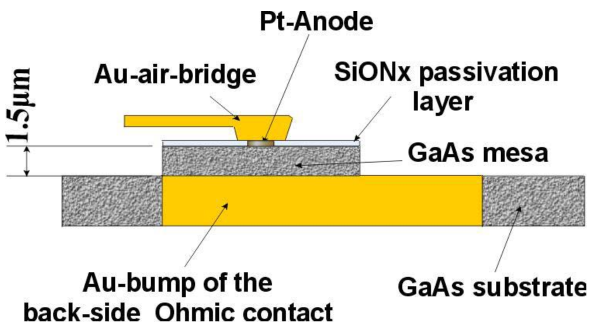
A sketch of fabricated whisker-contacted diodes and planar quasi-vertical structures is shown in Figure 1a and Figure 1b respectively.

One of main advantages of a quasi-vertical structure is vertical current flow, as in the case of whisker-contacted structures, from the anode on the top of the epitaxial layer to the back-side Ohmic contact. 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 Au-bump and other massive metallic elements of the circuitry is organised. Since the mesa for whisker-contacted anodes fabricated in this work is about 70µm-thick, these diodes are deprived of this advantage.

Overall descriptions of the technological process for fabrication of whisker-contacted diode and that of planar quasi-vertical diode fabrication are given in [10] and [5], respectively. Anodes of planar structures on the samples



(a)



(b)

Figure 1. Sketch of fabricated structures: a) whisker-contacted anode array; b) single planar quasi-vertical diode.

"m1" and "m2" are fabricated in a similar way to of whisker-contacted diodes using "dummy anodes" structural approach [5] and an optimised technological approach for anode formation. The optimisation includes SF_6-RIE process for anode area opening in SiON passivation layer, thermal annealing and wet chemical surface processing. Thermal annealing of whisker-contacted diodes and planar structures (sample "m2") is performed at 400°C for 20 min. in a H_2 ambient. The effect of thermal annealing on the noise temperature of planar structures is investigated using a "single step" method that implies the fabrication of two samples ("m1" and "m2") in a similar way except thermal annealing, which is performed only for the sample "m2". All anodes have a diameter of 1µm and are metallised using Pt as a contact metal deposited by a pulsed electrochemical method. A "dummy anodes" approach [5] permits anode fabrication of planar structures in a similar manner to whisker-contacted ones. This yields more than 50% of high quality diodes with negligible deviation in DC-characteristics over a sample. This provides statistically significant data directly related to the technology modification. DC-characterisation and IF-noise temperature measurements of both, whisker-contacted and planar diodes, are performed using an automated measurement system [11], which permits measurement of many tens of whisker-contacted anodes in the same way as planar structures.

III. RESULTS AND DISSCUTIONS

Measured microwave noise of fabricated whisker-contacted diodes reveal remarkably low values of diode noise temperatures. Figure 1 illustrates the dependence of the noise temperature on applied current bias from 0.3mA up to 3mA at six different frequencies (2.1GHz, 2.8GHz, 3.1GHz, 3.8GHz, 4.8GHz and 5.6GHz).

Generally noise characteristics are in good agreement with theory showing lower noise temperature at higher frequencies. An apparent increase of the noise temperature at 5.6GHz is attributed to a measurement system mismatch [11].

In order to establish a correlation between the noise temperature and the DC-characteristics of planar structures, twelve non-identical planar structures from both samples ("m1" and "m2") were chosen for IF-noise measurements. Extracted DC parameters of these diodes are listed in the table 1. The ideality factor of all elected diodes do not substantially differ, whereas the serial resistance Rs differs from 11,46 Ω up to 17,74 Ω for diodes from the sample "m1"and from 6,38 Ω up to 11,6 Ω for diodes from the sample "m2".

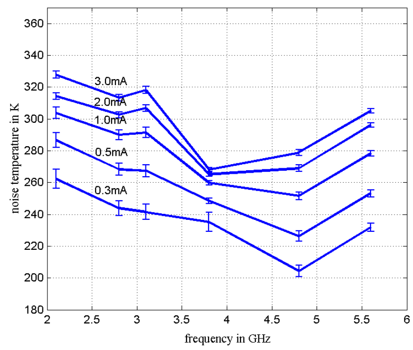


FIGURE 1. Measured IF-noise temperature of optimised whisker-contacted mixer diodes. Anode diameter is 1µm.

For each investigated diode, noise measurements are performed at 3 different frequencies using 5 different bias currents. These are 2.1GHz, 3.1GHz, 4.8GHz and 0.3mA, 0.5mA, 1.0mA, 2mA, 3mA respectively. Figure 2. shows noise measurement results at 3.1GHz for all planar diodes under investigation. Symbols from the left-hand column indicate measured and calculated values of diodes from the sample "m2" and those from the right-hand column – of the sample "m1".

At low bias currents, noise temperature of both samples are similar and tend to the theoretically predicted value $\eta T_0/2$ of the shot and thermal noise where η is the ideality factor and T_0 is the ambient temperature.

TABLE I. DC characteristics of planar diodes under investigation.

N°	Structure	Ideallity factor η	Series Resistance Rs (Ω)	Reverse current Ir (mA)
1	m1a	1,179	17,74	1,34E-17
2	m1b	1,17	11,46	2,76E-17
3	m1c	1,201	12,93	1,28E-15
4	m1d	1,215	11,94	1,42E-15
5	m2a	1,209	6,38	2,16E-16
6	m2b	1,184	8,18	7,89E-17
7	m2c	1,179	8,31	2,87E-16
8	m2d	1,189	6,82	1,21E-16
9	m2e	1,194	8,18	1,12E-16
10	m2f	1,179	11,6	6,00E-17
11	m2g	1,201	6,95	1,29E-16
12	m2h	1,202	7,68	1,25E-16

However, at current bias above 0.5mA, where actually the diode "operation point" have to be chosen, the measured noise temperature for diodes from sample "m1" is significantly higher compared to those from sample "m2". Additionally, the noise temperature of diodes from sample "m1" strongly depends on the current bias and is proportional to the diode serial resistance, especially at higher bias current. Normally, this could be attributed to the well known thermal noise on the series resistance. However, values measured on structures from sample "m2" remain well below 300K even at a bias current of 3mA and they are neither strongly correlated to bias current nor to diode series resistance.

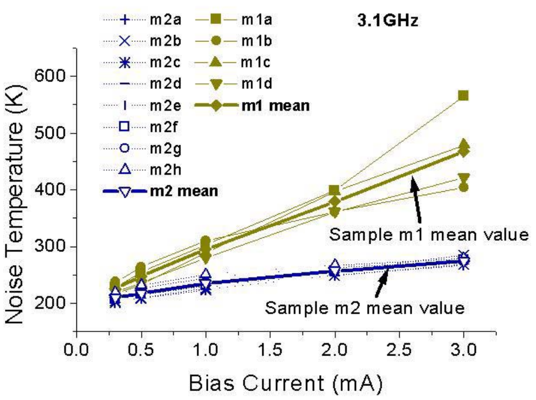


FIGURE 2. Measured noise temperature of 12 investigated planar diodes and their mean value at 3.1GHz versus diode bias current. Symbols from the left-hand column indicate measured and calculated values of diodes from sample "m2" and those from the right-hand column – of sample "m1".

For comparison, mean noise temperature values of all investigated samples at three different frequencies versus the logarithm of the bias current are shown in figure 3. An evident threshold of the noise temperature of the sample "m1" may be easily observed at current bias above 1mA. Such a noise behaviour is frequently observed and commonly attributed to the excess noise generated by hot electron effects [8]. However, no evident threshold of the noise temperature may be observed for thermally annealed samples (neither whisker-contacted nor "m2") at current bias up to 3mA. This strongly suggests the existence of defects generating the excess microwave noise of sample "m1" at higher current bias which may be effectively removed by means of thermal annealing. Jelenski et al. [12] and Miranda et al. [9] suggested that Microwave trap noise is generated at the Pt/n-GaAs interface by RIE induced defects like the generation of dislocations at the first atomic layer of the semiconductor and the reduction of Ga coverage at the surface. Note that both groups used CHF_3 as a process gas for RIE, which is able, although with a low rate, to etch GaAs and therefore definitely induces structural changes on the surface. In contrast, no detectable etching profile is observed on GaAs samples exposed to SF_6-plasma at microwave power of 100W with etching times longer as used for our diode fabrication.

Hara et al. revealed CF_4-RIE-induced *radiation* damage on a GaAs surface [6]. These defects result in a drastically reduced Schottky barrier height. However, similar to the results for CHF_3-plasma reported in [9], no appreciable influence of the SF_6-RIE-process to the barrier height of our diodes is observed. This suggests that although SF_6-plasma does not etch GaAs, it introduces defects at the semiconductor surface similar to what a CHF_3-plasma does. Probably due to their high chemical activity, F-ions, which are the main components of both, the CHF_3- and SF_6-plasma, do preferentially remove Ga atoms from a GaAs surface. Unbounded As atoms at the metal-semiconductor interface excite a strong 1/f excess noise [13] which stretches to a broad frequency spectrum and likely reaches a few GHz. On the other hand, As may form clusters which lead to local current crowding with locally occurring warm-electron noise [7]. The role of thermal annealing on a SF_6-plasma affected surface is to increase the Ga/As ratio [14] and thereby significantly reduces the excess microwave noise [9].

Although sample "m2" is fabricated in a similar way as whisker-contacted diodes (Figure 3) with identical anode diameter of 1µm, the noise temperature of planar diodes is significantly lower. These results do not contradict our expectations. The main reason of this discrepancy may lie in the structure design. Since the GaAs mesa is enclosed between the Ohmic and the Schottky contact of the planar quasi-vertical structure and is as thin as 1.5µm (see Figure 1), a highly efficient heat sink from the Schottky contact to the back-side Au-bump and other massive metallic elements of circuitry is realised. The fact that our quasi-vertical structures with anode diameter of 0.8µm could be biased up to 5mA (current density up to $1MA/cm^2$), without any changes in I-V-curves, confirm this assumption. Therefore the junction temperature does not significantly exceed the ambient temperature at 3mA of current bias for an anode diameter of 1µm, excluding additional noise generated by high-temperature effects [8].

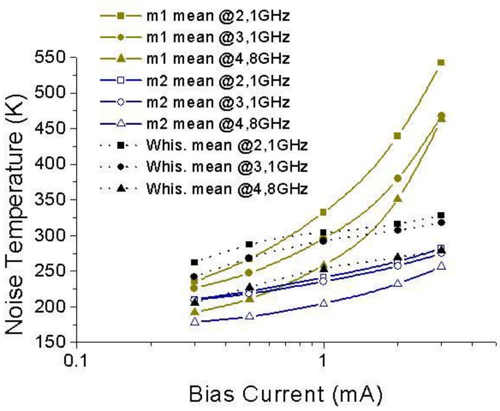


FIGURE 3. Calculated mean values of the noise temperature versus logarithmic scale of the diode current bias for all samples at three different frequencies.

IV. CONCLUSIONS

1) Planar structures are fabricated using the technological approach for anode formation as optimised for comparatively cheap and easy-to-fabricate whisker-contacted diodes using the “dummy anodes” approach. Measurement results show very good and uniform characteristics with a yield of above 50% which allows acquisition of statistically significant data.

2) SF_6-plasma induced defects result in a rise of excess noise at IF frequency. Similarly to CHF_3, SF_6-plasma probably leaves an As-enriched surface which, after Pt-metallisation, generates trap noise at frequencies up to a few GHz. Statistical data directly related to the technology modification show that this noise can be effectively reduced by sample thermal treatment at 400°C for 20 min. in H_2 atmosphere before Schottky metallisation.

3) Among a higher power capability, the quasi-vertical concept is promising for fabrication of a low-noise Schottky diodes because of good thermal properties.

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REFERENCES

[1] V. S. Mottonen, P. Piironen, J. Zhang, A. V. Raisanen, C. -I. Lin, A. Simon and H. L. Hartnagel; Microwave and Opt. Technol Lett.Vol.27, No.2, Oct. 2000. pp. 93-97.

[2] P. H. Siegel, R. P. Smith, M. C. Gaidis and S. C. Martin; IEEE Transactions on Microwave Theory and Techniques, Vol.47, No.5, May 1999. pp. 596-604.

[3] D. S. Kurtz, J. L. Hesler, W. Growe and R. M. Weikle; IEEE Trans. on Microwave Theory and Techniques, Vol.50, No.11, November 2002. pp. 2610-2617.

[4] A. Grub, V. Krozer, A. Simon and H. L. Hartnagel; Solid-State Electronics Vol. 37, No. 12, 1994, pp. 1925-1931.

[5] O. Cojocari, B. Mottet, M. Rodriguez-Girones, S. Biber, L. Marchand, L. –P. Schmidt and H. L. Hartnagel; Semicond. Sci. Technol. 19 (2004), 237-242.

[6] T. Hara, H. Susuki, A. Suga, T. Terada N. Toyoda; J. Appl. Phys. 62 (10), 15 November 1987, pp. 4109-4113.

[7] H. L. Hartnagel, R. Katilius, A. Matulionis; A Wiley-Intercience Publication, John Wiley & Sons, INC., USA, 2001.

[8] Herbert Zirath,; J. Appl. Phys. 60 (4), 15 August 1986, pp. 1399-1407.

[9] Miranda J M, Lin C -I, Brandt M, Rodriguez-Girones M, and Hartnagel H L, Sebastian J L; IEEE Electron Device Letters, vol.21 (11) 2000, pp.515-517.

[10] O. Cojocari, S. Biber, B. Mottet, M. Rodriguez-Girones, H. L. Hartnagel and L. -P. Schmidt; submitted to SST, 2004

[11] Biber S, Cojocari O, Rehm G, Mottet B, Schmidt L -P, Hartnagel H L *“A Novel System for Systematic Microwave Noise and DC Characterization of THz Schottky Diodes”.* IEEE Transactions on Instrumentation and Measurement, VOL.53, NO.2, APRIL 2004, pp. 581-587.

[12] A. Jelenski, E. Kollberg and H. Zirath; IEEE Trans. Microwave Theory Tech., vol. MTT-34, pp. 1193-1201, 1986.

[13] H. W. Hübers and H. P. Röser; Proc. 23-th Int. Conf. Infrared and mm-Waves, Colchester, U.K., 1998.

[14] J. Szuber, G. Hollinger and E. Bergignat; Electron. Technol., vol.31, pp. 1-10, 1998.