Design Optimization of Schottky Barrier Diodes at THz Frequencies

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Abstract

Whiskered GaAs Schottky barrier diodes are still the key elements in mixing applications at frequencies higher than 1000 GHz. It is obvious that envisaged operating frequencies of e.g. 2.5 THz, which are necessary for environmental studies, require sub-halfmicron anode diameters with all the encountered problems such as whisker stability, fabrication and reliability. Therefore, it is essential to optimize diode parameters such as epi layer thickness and doping concentration in order to achieve improved performance of the device and the overall receiver system.

The common optimization approaches make use of the cut-off frequency f_c which has several drawbacks. Therefore, we propose a new optimization procedure which takes into account the complete diode equivalent circuit. The I/V, C/V, and noise characteristics are calculated and a new cut-off frequency f_{cn} is defined. The calculations are based on an analytical diode model [1,2]. The new cut-off frequency f_{cn} is bias dependent and takes into account $R_s(I)$, $R_j(I)$ and $C_j(I)$. f_{cn} in conjunction with the diode noise temperature $T_n(I)$ is utilized to obtain a design procedure for the fabrication of whisker contacted as well as planar diode structures.

The results demonstrate that the epi layers should be thinner than currently used for the fabrication of THz Schottky diodes in order to improve the diode performance.

Introduction

The requirement of atmospheric studies (ozone depletion) has caused a strongly increased interest in heterodyne receivers for applications at frequencies higher than 1 THz. The OH molecule for example plays an important role in the catalytic ozone destruction process. This molecule has a transition frequency of 2514.3 GHz which corresponds to the lowest energy level. Other important molecules in this respect are O_3 (2510.6 GHz) and H_2O (2529.3 GHz) [3].

Heterodyne receivers at frequencies above 1 THz have to use whisker contacted Schottky barrier diodes as mixing element. The application of SIS junctions as well as planar Schottky diodes are presently restricted to lower frequencies due to material and technology problems.

The application of whisker contacted Schottky diodes at THz frequencies requires an optimized diode design in order to achieve the optimum mixer performance. The diode design parameters are the anode diameter d_{an}, the epi doping concentration N_e and the epi thickness t_e. Recently, several groups have made contributions to the optimization of Schottky diodes [2,4,5,6,7]. The main task of the optimization procedure is to define an appropriate criterium for the parameter optimization. Commonly accepted is the figure-of-merit cut-off frequency which makes use of constant values of the diode series resistance and the zero bias junction capacitance for the optimization. It is obvious that these assumptions are very different from the conditions in a mixer where the diode is biased strongly in the forward direction. This paper introduces a more realistic cut-off frequency which is based on bias dependent parameters and takes into account all elements of the diode equivalent circuit.

Diode model

A diode model for the simulation of THz Schottky diodes has to include the following items:

- field emission and thermionic field emission
- current spreading in the different layers
- current dependent recombination velocity
- field dependent electron mobility
- equations for R_j and C_j which are valid near flat-band

Our analytical diode model has the above mentioned features and details have been presented earlier [1,2].

Optimization Approaches

For a successful diode parameter optimization procedure one has to know how a variation of the parameters affects the diode performance. One possibility is to investigate the influence on the elements of the diode equivalent circuit which is shown in fig.1 . For the resistive down conversion of a THz signal only the nonlinear junction resistance R_j is necessary. All other elements such as the junction capacitance C_j and the series resistance R_s which has contributions due to the resistance of the undepleted epi layer R_{epi}, the substrate resistance R_{sub} and the contact resistance R_{con} are parasitics which influence the diode performance negatively and therefore have to be minimized. Additionaly, noise sources due to thermal noise u_{th}, hot electron noise u_{hot}, shot noise i_{shot} and noise due to traps i_{trap} have to be considered.

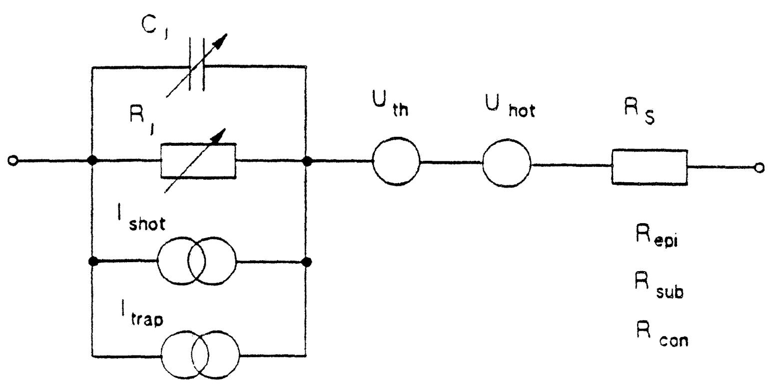

Fig.1: The diode equivalent circuit

The basic influence of the diode design parameters on the different elements of the diode equivalent circuit is summarized in the following table:

	R_j and η	C_j	R_s	i_{shot}	u_{th}	u_{hot}
d_{an}	+	−	+			
N_e	−	−	+	−	+	+
t_e	(+)	+	−		−	

The +/− in the table mean that the corresponding design parameter should be chosen as large/small as possible in order to minimize the parasitics. The first column corresponds to the nonlinearity of the junction resistance which should be as large as possible. In every row there exist + and - at the same time which means that a compromise has to be found. The problem of diode optimization finally focusses on the question of defining an appropriate criterium for these compromises. In the following sections two optimization criteria will be described and discussed.

The figure-of-merit cut-off frequency f_c (in the following referred to as standard cut-off frequency) is a wellknown and commonly accepted parameter for the optimization of high-frequency devices. For Schottky diodes the cut-off frequency is defined as follows.

$$f_c = \{2\pi R_s C_{j0}\}^{-1} \tag{1}$$

The above definition takes into account only constant values for the series resistance R_s and the zero bias junction capacitance C_{j0} of the diode. These two parameters are both dependent on the anode diameter, the epi layer doping concentration and thickness. The cut-off frequency f_c can be determined by either measuring the corresponding values of R_s and C_{j0} or by utilizing a diode model for the calculation. The diode design parameters are then chosen such that the cut-off frequency becomes as large as possible.

This approach has several drawbacks which make the use as optimization procedure questionable:

- R_j is neglected
- no bias dependence is considered

Since THz Schottky diodes have to be biased at large forward currents near the flat-band condition, these drawbacks are quite severe. At the operating bias the diode junction resistance is only a few times larger than the series resistance and, therefore, has to be considered in the optimization procedure. Furthermore, the elements of the diode equivalent circuit such as junction resistance, junction capacitance and series resistance are strongly bias dependent. Therefore, the cut-off frequency varies also with the applied bias.

The new approach takes into account all elements of the diode equivalent circuit. The impedance of the diode is given by

$$Z_d = R_s + \frac{R_j}{1 + j\omega R_j C_j} \tag{2}$$

For the definition of a new cut-off frequency the following relationship is used which is similar to the definition of the standard cut-off frequency.

$$Re\{Z_d\} = Im\{Z_d\}$$

This condition leads to a second order equation. The solution provides a condition for the junction resistance (eq. 3) and results in an efficient definition of a new cut-off frequency f_{cn} (eq. 4).

$$R_j \geq (2+\sqrt{8})R_s \tag{3}$$

$$f_{cn} = \{4\pi\, R_s(I)\, C_j(I)\}^{-1} \tag{4}$$

The smallest value for the junction resistance which is equal to $R_j = (2+\sqrt{8})\, R_s$ defines an operating bias which corresponds perfectly to experimentally obtained values in receiver systems. Therefore, this smallest value of R_j is used to define the diode operating bias. The proposed optimization process includes the following steps:

1. choose a set of design parametesrs d_{an}, N_e, t_e
2. calculate diode I/V, C/V and noise characteristics
3. extract R_s for high currents
4. define operating bias
5. check current density and noise temperature at this bias
   if $J \geq 10000\, A/mm^2$ or $T_n \geq 250\, K$ goto 1.
   else
6. calculate new cut-off frequency

Discussion

This section shows the results which have been obtained by applying of the two previously described optimization procedures. All calculations are made for a substrate doping concentration of $2 \cdot 10^{18}$ cm^{-3} and a substrate thickness of 50 μm (including a 1 μm, $3 \cdot 10^{18}$ cm^{-3} buffer layer). These are also the values currently used for diode fabrication in our laboratory.

Standard cut-off frequency:

Fig.2 and fig.3 show the standard cut-off frequency as a function of the epi thickness and epi doping for an anode diameter of 0.8 and 0.4 μm.

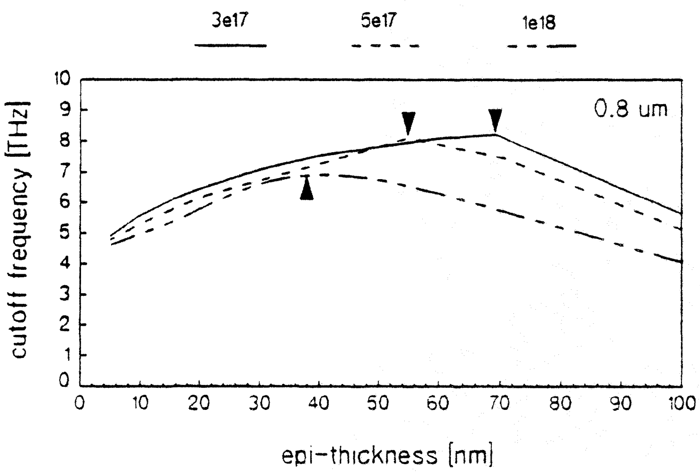

Fig.2: Standard cut-off frequency for 0.8 μm anode diameter

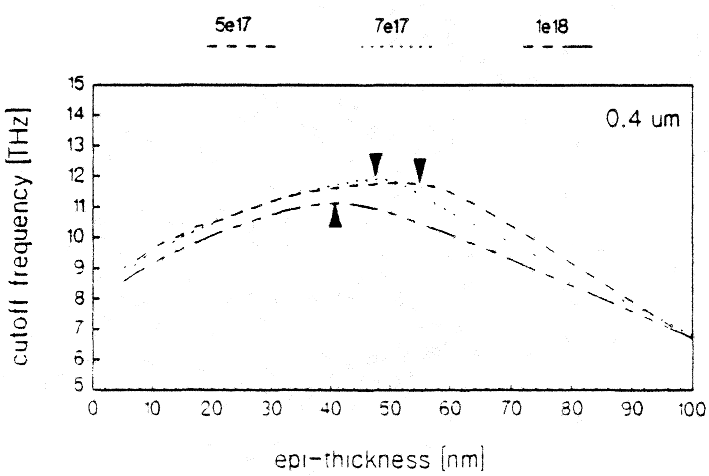

Fig.3: Standard cut-off frequency for 0.4 μm anode diameter

The first result is that the maximum of the cut-off frequency for all epi doping concentrations and anode diameters is obtained for an epi layer thickness which is equal to the zero bias depletion width (dark triangles in fig.2,3). A comparison to some of the commercially available diodes reveals that so far all these diodes have been designed according to this optimization criterium.

diode	d_{an} $[\mu m]$	N_e $[10^{17} cm^{-3}]$	t_e $[nm]$
$1I7^*$	0.8	3	70
$1T12^*$	0.5	4	75
$1I12^*$	0.45	4.5	60
$1T14^*$	0.25	10	60
$DAC3-08^+$	0.8	3	70
$DAC10-08^+$	0.8	10	30

* fabricated at the University of Virgina
\+ fabricated at the University of Darmstadt

It can also be seen that with decreasing anode diameter the maximum cut-off frequency is achieved with higher epi doping densities which approach a value of 10^{18} cm^{-3} for sub-halfmicron diodes.

New cut-off frequency:

The situation is quite different for the new cut-off frequency. Fig.4 and fig.5 show the new cut-off frequency as a function of the epi thickness and epi doping for an anode diameter of 0.8 and 0.4 μm.

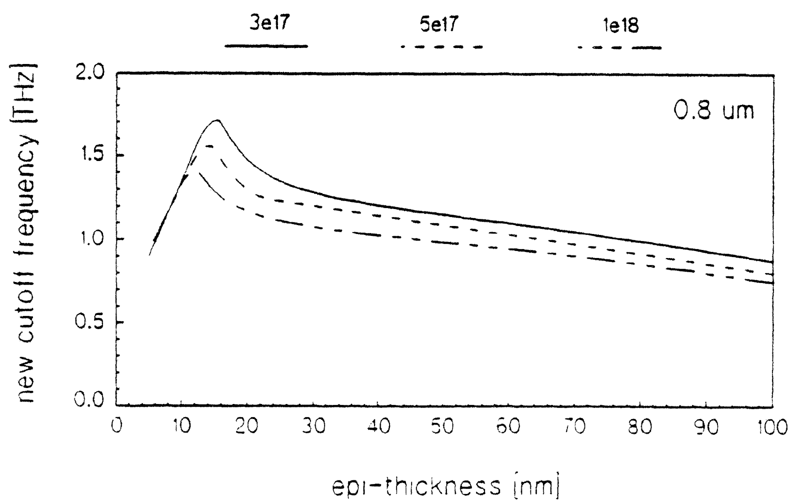

Fig.4: New cut-off frequency for 0.8 μm anode diameter

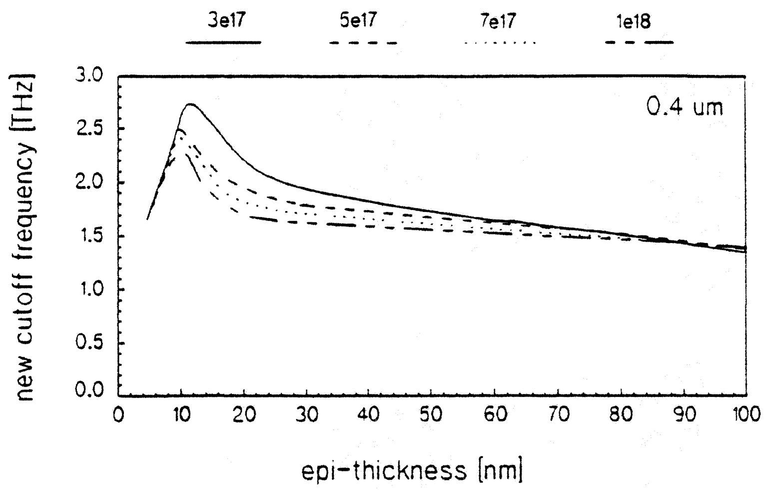

Fig.5: New cut-off frequency for 0.4 μm anode diameter

First, one can see that for epi layers thinner than $\approx$ 10 nm f_{cn} does not depend on the doping concentration any more because the junction capacitance is more or less dominated by the substrate doping. The maximum of the cut-off frequency f_{cn} occurs at values for the epi layer thickness between 11 and 15 nm. A closer look at the simulation results reveals that these values correspond to an epi layer which is just becoming depleted at the operating bias. This epi layer depletion leads to a minimization of the series resistance because R_{epi} becomes zero for this special bias condition.

A second important result is that lower doping concentrations lead to higher cut-off frequencies f_{cn}. This is different from the results which are obtained from the standard approach where high doping concentrations are preferred. Since the noise due to hot electrons increases inversely to the doping concentration, which has to be considered, the optimum N_e should be $3 \cdot 10^{17}$ cm^{-3}. For this doping concentration the noise contribution due to hot electrons is still neglectable at the calculated bias. Currently, no diodes with such thin epi layers have been fabricated but similar simulation results have been obtained by a different approach [6].

Fig.6 illustrates the dependence of the standard and new cut-off frequency on the anode diameter for a given epi doping concentration. Both cut-off frequencies increase with decreasing anode diameter, as expected. Even for anode diameters as small as 0.1 μm there is no saturation visible. However, anodes smaller than 0.1 μm are not reasonable. Besides the difficulties of reliable fabrication and contacting, the required operating current densities exceed 10000 A/mm^2 leading to a degradation of the Schottky contact during operation [8].

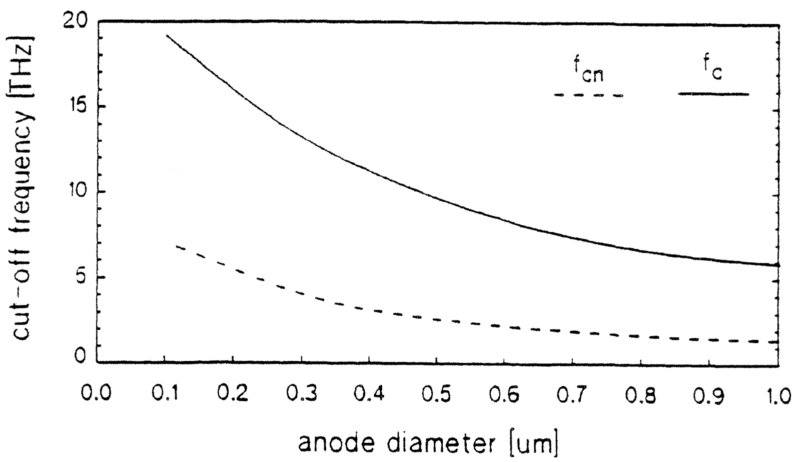

Fig.6: Standard and new cut-off frequency as function of the anode diameter

Conclusions

A new optimization approach for THz Schottky diodes has been presented. This approach makes use of a new cut-off frequency which is based on the complete diode equivalent circuit. The bias dependence of every single circuit element is taken into account. The results show that the thickness of the epi layer should be chosen such that at the operating point the epi layer is just depleted. Currently, diodes with epi layers of about 15 nm are under fabrication for a comparison with diodes designed according to the standard approach.

Acknowledgements

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