A STUDY OF RELIABILITY AND PHYSICAL PROPERTIES OF SCHOTTKY BARRIERS WITH RESPECT TO THZ APPLICATIONS

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Abstract

Whisker contacted GaAs Schottky barrier diodes are the standard devices for mixing and multiplier applications in the THz frequency range. With the decreasing size of Schottky diodes for operation at higher frequencies, the reliability and the physical understanding of the Schottky barrier becomes increasingly important.

In this contribution, we present new results concerning the reliability of Schottky diodes and new insight into the physical properties of Schottky junctions, especially at low current densities. For these purposes a number of different Schottky diodes have been fabricated with varying epi-layer doping concentrations and anode diameters.

It can be inferred from the measured I/V characteristics that the diode current deviates normally considerably from the ideal thermionic current behavior with decreasing diode diameter. This deviation shows an exponential dependance on the diode voltage and is a function of the doping concentration. For a given doping concentration in the epi-layer and decreasing anode diameter, this phenomenon shifts the minimum of the ideality factor towards higher current densities. It is speculated that this is caused by the crystallinity difference of the polycrystalline Pt films on the GaAs films for decreasing SiO_2 aperture size when the Pt mobility in the electrolyte of the hole is reduced.

The reliability of Schottky barrier diodes under thermal and electrical stress has been investigated on different THz Schottky diode structures. The results show that the barrier height and the ideality factor of the fabricated structures is not affected by thermal stress. Electrical stress induced by large forward currents up to a current density of 10 kA/mm^2 even leads to a slight increase of the barrier height and a reduction of the series resistance.

Introduction

The physical properties of Schottky contacts on GaAs are well-known and have been a subject of investigation since the beginning of GaAs technology [1]. But this is not the case for small-area Schottky barrier junctions which are the key element for mixing applications at far infrared frequencies. Diodes for this purpose usually have the so called honeycomb design [2]with anode areas of less than 1 μm^2 [3].

For this study a number of different diodes has been fabricated in order to investigate the influence of the diode diameter and the epi-layer doping concentration on the physical diode properties determined from the I/V characteristics. When talking about Schottky barriers, the most important parameter is the barrier height Φ_b or the current-dependent ideality factor $n_{(I)}$ which describes the lowering mechanisms of the barrier. It has been already shown earlier that the current through Schottky diodes for THz applications at medium and high forward bias can be described by thermionic emission and thermionic field emission when effects such as current spreading, heating of electrons etc. are taken into account [4, 5, 6, 7]. In the range of small currents (less than approx. 100 nA), a considerable deviation from the above theory can be observed, especially for small and highly doped diodes.

With the decreasing diode diameter of Schottky diodes for THz mixing applications, the reliability and stability of the contacts become more important. This is mainly due to the increased current densities under mixing conditions where a typical bias current between 200 and 500 μA leads to current densities of up to 1000 A/mm^2. Another problem with small anode areas is the semiconductor surface technology which becomes more critical with decreasing Schottky contact area. Therefore, it is necessary to know how Schottky diodes behave under extreme thermal and electrical conditions.

Diode fabrication and characterization

The epitaxial layers for the diodes were all grown by the same supplier [1]. Layers with doping concentrations between $2 \cdot 10^{16}$ cm^{-3} and $3 \cdot 10^{17}$ cm^{-3} have been used for the fabrication of Schottky diodes with diameters between 7 and 0.8 μm. All diodes investigated in this study have been fabricated with the same process making use of in situ anodic pulse etching and electrolytic Pt deposition. The features of this technique have been presented earlier and are described in [7, 8, 9]. The only exception is the diode D_{ox} which has been exposed to air for

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10 *min* prior to the electrolytic Schottky metal deposition. Therefore, this diode is expected to have an interfacial native oxide layer of about 1 *nm* thickness.

The diodes were characterized by I/V and C/V measurements using a *HP4151B Semiconductor Parameter Analyzer* and a *HP4279A C/V-Meter*, respectively. Additionally, noise measurements at 1.5 GHz have been carried out using a *HP8970B Noise Figure Meter*. The noise temperature of the THz diodes A, C, E is shown in fig. 1. A comparison of the diode parameters is given in the following table:

diode	diameter $[\mu m]$	N_{de} 10^{17} $[cm^{-3}]$	d_e $[nm]$	C_{j0} $[fF]$	$R_s^{(1)}$ $[\Omega]$	n_{min}	$-V_{br}^{(2)}$ $[V]$
A	0.8	3	70	1	20	1.23	4.9
B	0.8	2	100	0.9	25	1.18	6.3
C	1	2	100	1.2	15	1.18	6.3
D	1.3	2	100	2.1	12	1.15	4.9
D_{ox}	1.3	2	100	2.1	14	1.25	5.5
E	0.8	$gr^{(3)}$	90	0.8	28	1.15	6.5
F	1.1	$gr^{(3)}$	90	1.1	21	1.13	6.4
G	1.3	$gr^{(3)}$	90	2.2	19	1.10	7.0
H	2.2	0.8	100	5.6	12	1.11	7.1
I	1.3	0.2	100	1.2	18	1.08	9.0
J	3	0.2	100	6.3	13	1.06	9.1
K	7	0.2	100	33	6	1.04	9.1

$^{(1)}$: minimum of the differential measured I/V characteristic

$^{(2)}$: measured at a reverse current of $-1\,\mu A$

$^{(3)}$: graded doping, from $2 \cdot 10^{16}\,cm^{-3}$ at the surface to substrate doping within 90 *nm*

Physical properties

Diodes fabricated according to the above in-situ electrochemical etching and deposition process show near-ideal I/V characteristics. The measured I/V characteristics were used to characterize and to determine the physical properties of the diodes. One of the most suitable parameters for the characterization of the physical properties is the diode ideality factor n. Schottky diodes with large contact areas can be described in a wide current range by a more or less constant

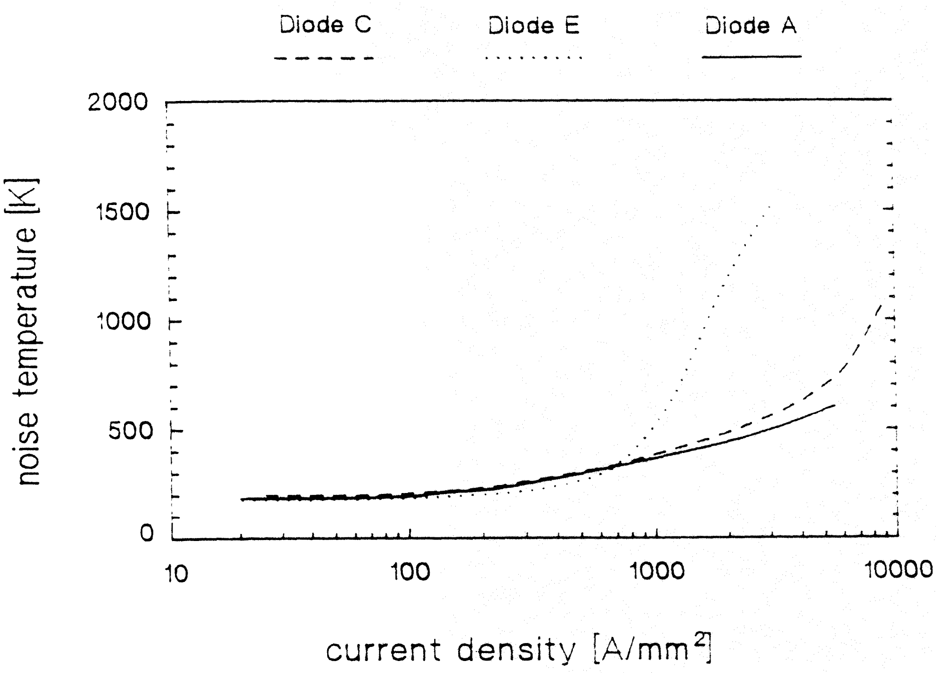

Fig. 1: The noise temperature of various THz mixer diodes measured at 1.5 GHz as a function of the diode current density

ideality factor. This approach is not applicable for diodes with small junction areas such as utilized for THz mixing applications. The current-dependance of the ideality factor cannot be neglected for these diodes. The current-dependant ideality factor $n_{(I)}$, which physically means the sum of barrier-lowering mechanisms, can easily be obtained from the measured I/V characteristics according to eq. 1.

$$n_{(I)} = \frac{1}{V_T} \frac{\delta V}{\ln \delta I} \tag{1}$$

The ideality factor of near-ideal diodes can be described by contributions due to the image force n_{if} (eq. 2, 3) and the thermionic field emission n_{tf} (eq. 4, 5, 6) [7, 10]. The ideality factor due to these two mechanisms is close to one and depends only on the doping concentration. Other barrier lowering mechanisms for example due to interfacial states can then be neglected. The ideality factor can be calculated according to the following set of equations [10].

$$n_{if} = \frac{1}{1 - \frac{\Delta\Phi_b}{4 V_{fb}} \left(1 - \frac{V}{V_{fb}}\right)^{-3/4}} \tag{2}$$

with

$$\Delta\Phi_b = \left[\frac{q^3\, N_{de}\, V_{fb}}{8\,\pi^2\,\epsilon_s'^2\,\epsilon_s\,\epsilon_0^3}\right]^{1/4} \tag{3}$$

$$n_{tf} = \left[\frac{V_T}{E_0} - \frac{V_T}{2\,(V_{fb}-V)}\right]^{-1} \tag{4}$$

with

$$E_0 = E_{00}\, coth\left(\frac{E_{00}}{V_T}\right) \tag{5}$$

and

$$E_{00} = \frac{h}{4\,\pi}\left[\frac{N_{de}}{m^*\,\epsilon_0\,\epsilon_s}\right]^{1/2} \tag{6}$$

In eq. 2– 6 the following nomenclature has been used: Flat–band voltage V_{fb}, barrier lowering $\Delta\Phi_b$, epi–layer doping concentration N_{de}, thermal voltage V_T.

The combination of eq. 2– 6 leads to

$$n = 1 + (n_{if} - 1) + (n_{tf} - 1) \tag{7}$$

It could be shown that Schottky diodes with diameters larger than $3\,\mu m$ which are fabricated on low doped epitaxial layers ($N_{de} = 2\cdot10^{16}\,cm^{-3}$) can be completely described by the above theory. This reveals that the fabrication process for the diodes does not create any other interfacial surface states than these required for Fermi–level pinning. However, for doping concentrations larger than $N_{de} = 2\cdot10^{17}\,cm^{-3}$ the ideality factor determined from the I/V characteristics is slightly higher ($\Delta n \approx 0.05$) than predicted by eq. 7. The corresponding current for ideal diodes I_{id} is given by eq. 8.

$$I_{id} = I_s\,\exp\left(\frac{V}{n_{(I)}\,V_T}\right) \tag{8}$$

Although all diodes have been fabricated according to the same fabrication techniques, a comparison of the different I/V characteristics reveals that diodes with a smaller diameter than approx. 3 μm exhibit a considerable deviation from the simple theory, especially at low bias voltages. Fig. 2 shows the ideality factor as a function of the diode current density. The small diode exhibits a large increase in n at low current densities which cannot be explained in terms of image force and thermionic field emission.

Fig. 2 also shows that the small diode has a minimum in the ideality factor. The current corresponding to this value of n depends on the doping concentration and the diode diameter.

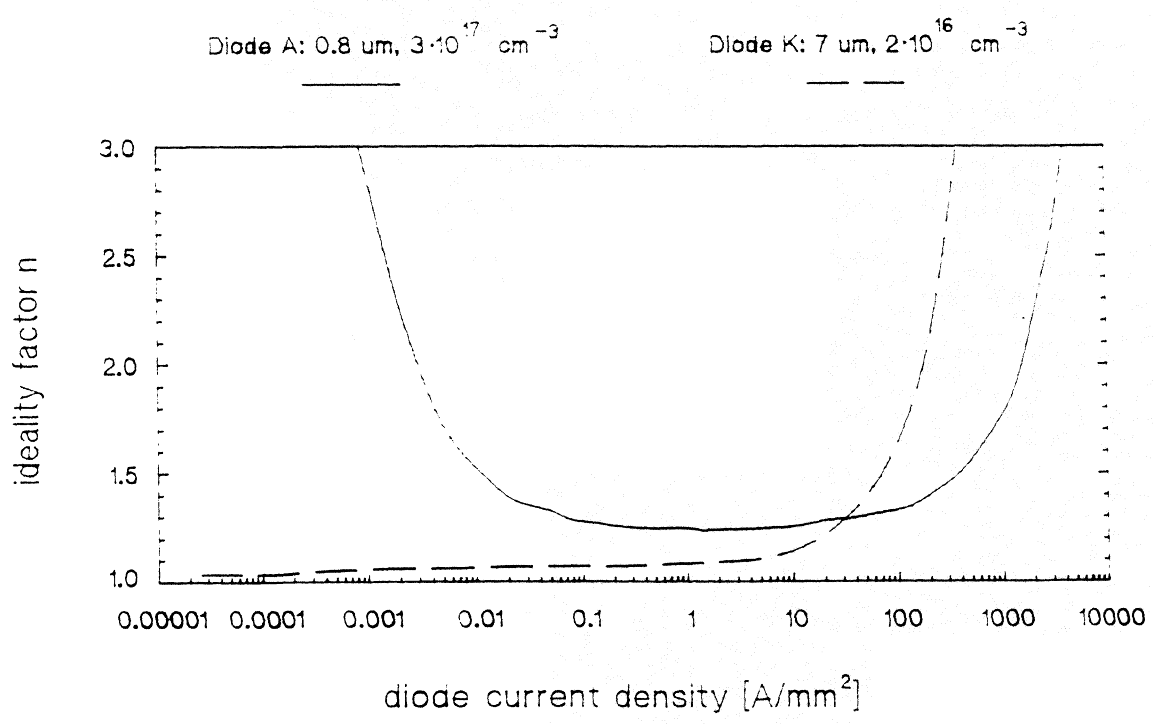

Fig. 2: The diode ideality factor as a function of the diode current density

For larger forward currents the ideality factor can be calculated according to eq. 7. The current range towards small current densities can be described by an additional current contribution ΔI to the diode current I_{id}.

$$I = I_{id} + \Delta I \tag{9}$$

In fig. 3 this additional contribution ΔI is presented for different diodes as a function of the diode voltage. Fig. 3 clearly demonstrates the exponential behavior of ΔI with the diode voltage. This implies that ΔI can be described by the following equation:

$$\Delta I = I_{sm} \exp\left(\frac{V}{m\, V_T}\right) \tag{10}$$

I_{sm} is the intercept of ΔI with the ΔI-axis and m is the slope parameter of ΔI.

The corresponding values for the slope parameter m are in the range of $m \sim 2...5$. Such large values cannot be explained by barrier lowering through image force and thermionic field emission. This means that the contribution ΔI does not originate from a simple parallel parasitic diode. However, the fact that ΔI is more pronounced in small diodes suggests that this additio-

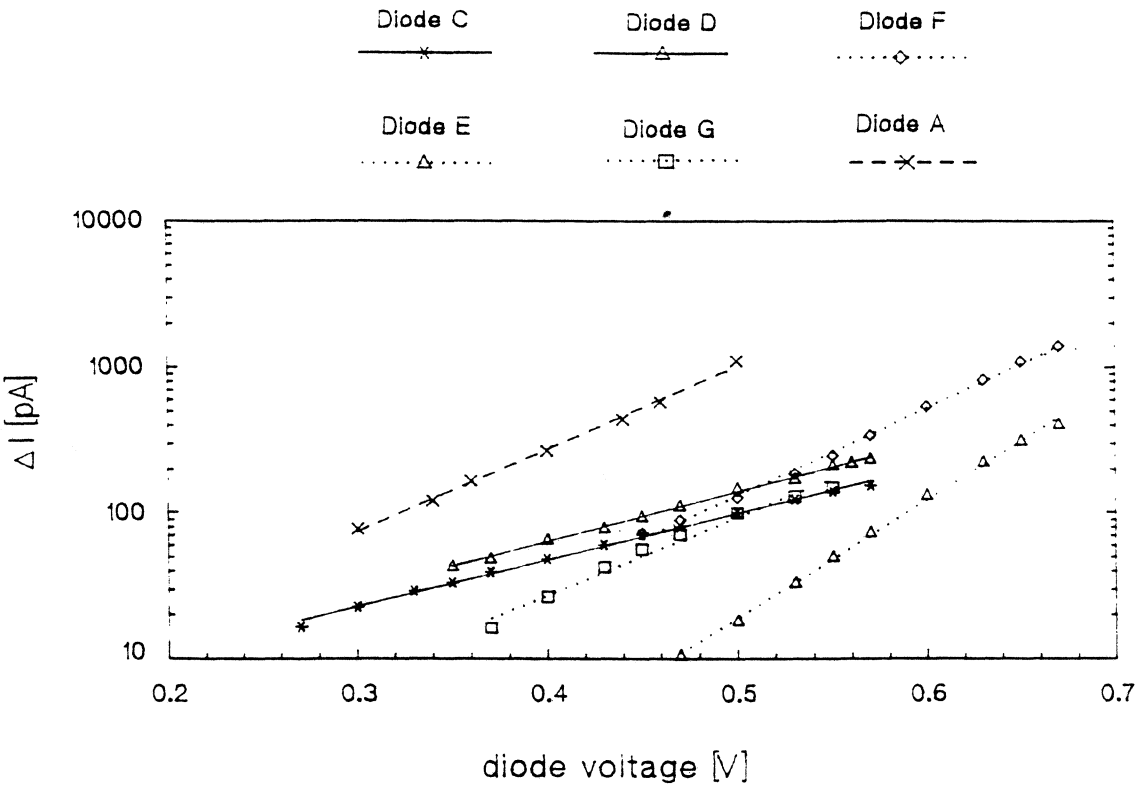

Fig. 3: The additional current contribution ΔI as a function of the diode voltage for different diodes

nal current is caused by edge effects. The area of the possible parasitic diode can be determined from I_{sm} in eq. 8. Assuming a realistic barrier height for the parasitic diode between 0.5 - 1.2 eV yields areas in the range of several square nanometers. This corresponds to a ring around the original contact with a width of less than 1 Å. Therefore, the additional contribution ΔI cannot be due to simple edge effects. We suggest that ΔI is caused by interface effects at the metal semicondutor junction. This assumption is supported by experimental results which are presented in fig. 4. This shows the ratio of the additional current contribution ΔI to the total diode current I as a function of the diode voltage for a number of diodes with different diameters and a doping concentration of $2 \cdot 10^{17}\,cm^{-3}$. At low bias voltages the diode current is entirely determined by the parasitic contribution ΔI. This behavior is more pronounced for diodes with small diameters which suggests that this effect is dependant on the junction area. Furthermore, fig. 4 indicates that the contribution ΔI to the total diode current depends on the metal semiconductor transition. This can be inferred from the comparison of the diodes D and D_{ox}. These diodes are identical but diode D_{ox} has an interfacial oxide layer. The change in the interface morphology and therefore a deviation from the ideal metal semiconductor junction leads to an increase of the influence of this parasitic effect on the diode current.

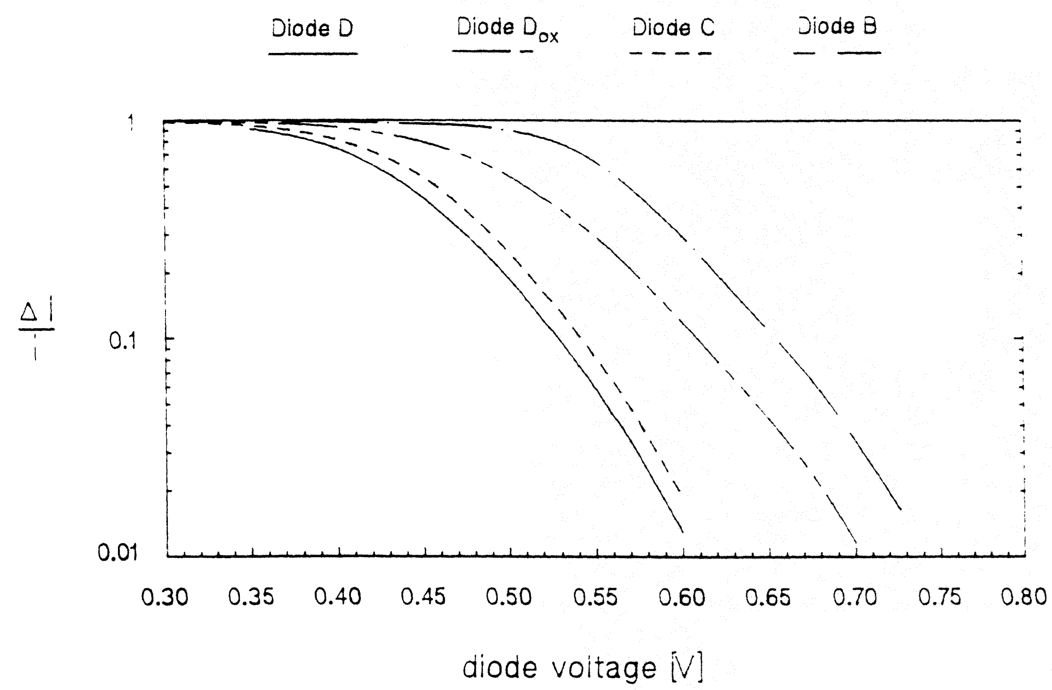

Fig. 4: $\Delta I/I$ as a function of the diode voltage

A possible explanation for the area–dependance of the parasitic current contribution ΔI could be a change of the size and number of Pt growth centers resulting in differences in crystallite sizes and intercrystalline boundary material at the interface to GaAs with decreasing Schottky contact diameter. These differences are produced by different mobilities of the Pt in the electrolyte before deposition for narrow and wide SiO_2 apertures. The adhesion of Pt during the electrolytic deposition depends on the potential distribution between the semiconductor surface and the electrolyte. The inhomogeneous field pattern at the edge of the SiO_2 window affects the Pt growth centers and therefore the Schottky metal morphology [11].

Reliability

The diodes A, D, D_{ox} have been thermally stressed under various conditions. Diode A has been tested for instrument survival with all power off in a temperature cycle ranging between -30 C and +65 C for 24 h [12]. No change in the ideality factor, the barrier height and the overall I/V characteristic could be observed. The noise temperature measured at 1.5 GHz shows that there occurs no degradation of the contacts due to the thermal stress. In order to get additional information about the influence of a thermal stress with all power off, the diodes D and D_{ox} were stressed for 1000 h in an experiment with temperatures between -50 C and

+100 C (duty cylcle 2 h). The results are illustrated in fig. 5 where the ideality factor is shown as a function of the diode current. Diode D which was fabricated according to the optimized process shows no changes in the electrical performance. For diode D_{ox} a slight increase of the ideality factor is observed in the overall forward bias range. This indicates that the in situ etching and deposition techniques utilized for the fabrication of diode D is more suitable for reliable diodes than fabrication techniques where the GaAs surface is in contact with air prior to the Schottky metal deposition.

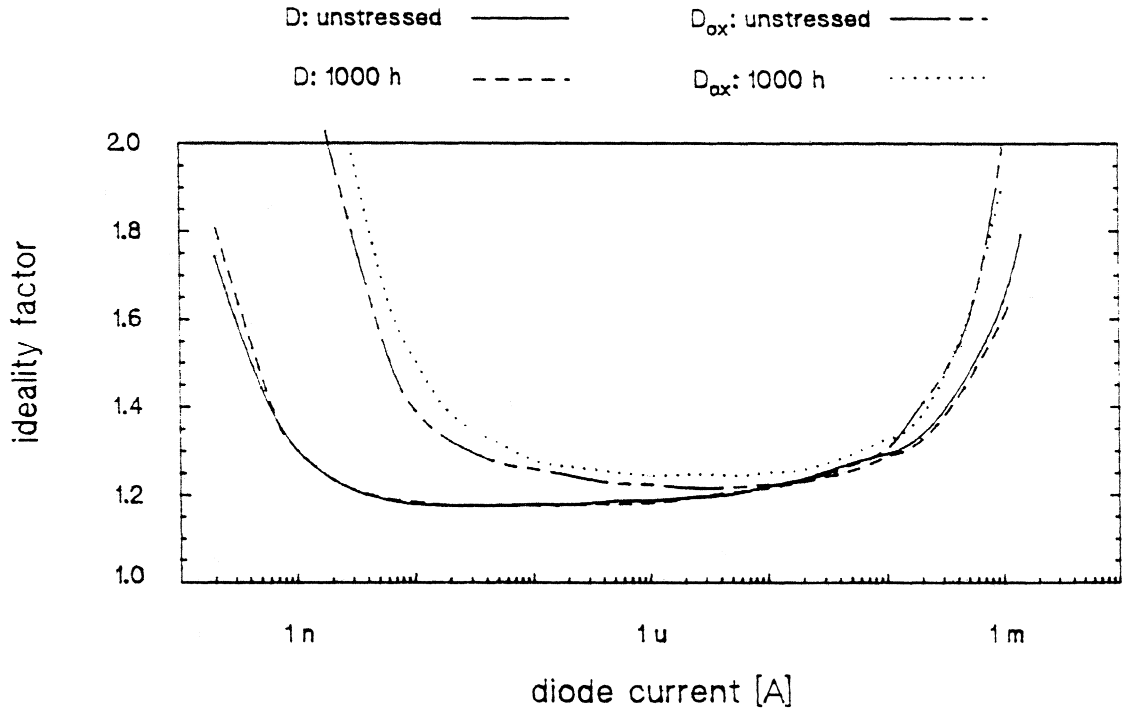

Fig. 5: Ideality factor as a function of the diode current for different diodes before and after thermal stress

The high current densities (up to 1000 A/mm^2) at which THz diodes are operated require diodes which show stable performance under electrical stress. Diode A has been stressed clearly beyond the maximum operating current densities. Operated for 48 hours at 2 mA (4000 A/mm^2) and subsequently for 48 hours at 5 mA (10000 A/mm^2), the diodes show no degradation. Even a slight reduction of the series resistance ($\sim$ 2 Ω) in combination with a decrease of the ideality factor was observed ($\Delta n \sim 0.05$) (fig. 6). These improvements are probably due to a modification of the Pt morphology at the Schottky interface. A further increase of the current density to 14000 A/mm^2 leads to a strong degradation of the Schottky contact within 30 minutes. Fig. 6 illustrates these results. All observed changes (improvements as well as degradations) occured within 30 min after the application of the electrical stress.

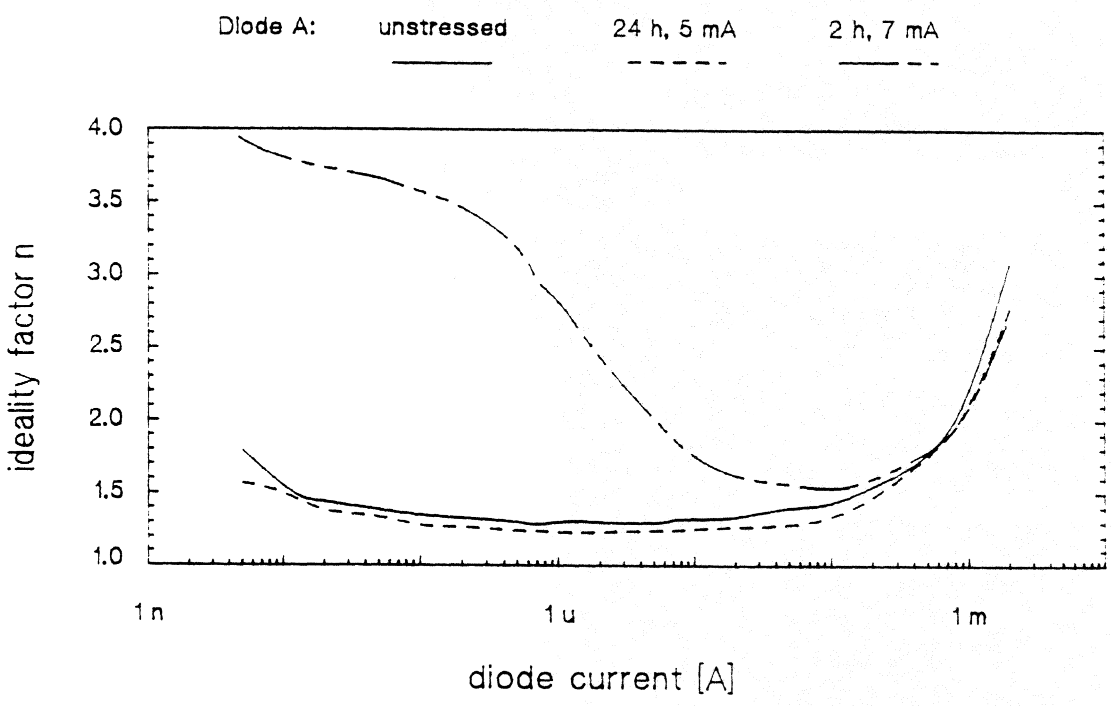

Fig. 6: The ideality factor of diode A as a function of the current before and after electrical stress

Conclusions

It has been demonstrated that small area diodes such as utilized in THz mixers can only be described in a relatively small current range by an ideality factor which is calculated according to the image force and thermionic field emission. At low bias voltages there exists a deviation from the theoretical ideality factor which is the more pronounced the smaller the diode area is. There exists experimental evidence that this deviation depends on the interface morphology of the metal/semiconductor junction.

THz mixer diodes which have been fabricated by the optimized in situ electrochemical process show no degradation after 1000 h of thermal stress. It has been also demonstrated that the diodes are reliable under long–time electrical stress up to a current density of 10000 A/mm^2.

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References

[1] L. Brillson, "Chemical reaction and charge redistribution at metal–semiconductor interfaces," *J. of Vacuum Science & Technology*, vol. 15, (1978), no. 4, pp. 1378–1383.

[2] D. Young and J. Irvin, "Millimeter frequency conversion using $Au-n$–type $GaAs$ Schottky barrier epitaxial diodes with a novel contacting technique," *Proceedings of the IEEE*, vol. 53, (1965), pp. 2130–2131.

[3] W. Peatman and T. Crowe, "Design and fabrication of $0.5\mu m$ $GaAs$ Schottky barrier diodes for low–noise Terahertz receiver applications," *Int. J. Infrared and Millimeter Waves*, vol. 11, (1990), no. 3, pp. 355–365.

[4] A. Jelenski, A. Grüb, V. Krozer and H. Hartnagel, "A new approach to the design of Schottky barrier diodes for THz mixers," *Proc. 3rd Symp. on Space Terahertz Technology*, (1992), pp. 631–642.

[5] V. Krozer, *Verfahren der Kleinsignal- und Großsignal-Analyse und Charakterisierung von Mikrowellenschaltungen und Bauelementen mit Hilfe der Volterra Reihe.* VDI–Verlag, series 9, nr. 142, Düsseldorf, (1992).

[6] V. Krozer and A. Grüb, "A novel fabrication process and analytical model for $Pt/GaAs$ Schottky barrier mixer diodes," *Solid-State Electronics*, (submitted).

[7] A. Jelenski, A. Grüb, V. Krozer and H. Hartnagel, "New approach to the design and fabrication of THz Schottky barrier diodes," *IEEE Trans. Microwave Theory & Techniques*, vol. MTT–41, (1993), no. 3.

[8] A. Grüb, *Technologieentwicklung für THz–Schottkydioden und Nanometerstrukturen.* VDI–Verlag, series 21, nr. 110, Düsseldorf, (1992).

[9] A. Grüb, K. Fricke and H. Hartnagel, "Highly controllable etching of epitaxial $GaAs$ layers by the pulse etching method," *J. of Electrochemical Society*, vol. 138, (1991), no. 3, pp. 856–857.

[10] E. Rhoderick and R. Williams. *Metal–Semiconductor Contacts. Monographs in Electrical and Electron. Eng., No. 19*, Oxford Science Publ., 2 ed., (1988).

[11] F. Walsh and M. Herron, "Electrocrystallization and electrochemical control of crystal growth: Fundamental considerations and electrodeposition of metals," *J. Phys. D: Applied Physics*. vol. 24, (1991), pp. 217–225.

[12] P. Siegel *private communication.*