# New Approach to the Design and the Fabrication of THz Schottky Barrier Diodes

Andrzej Jelenski, Andreas Grüb, Viktor Krozer, and Hans L. Hartnagel

***Abstract*—GaAs Schottky barrier diodes with near-ideal electrical and noise characteristics for mixing applications in the THz frequency range are described.**

**The conventional formulas describing these characteristics are valid only in a limited forward bias range, corresponding to currents much smaller than the operating currents under submillimeter mixing conditions. Therefore, generalized analytical expressions for the $I$–$V$ and $C$–$V$ characteristics of the metal-semiconductor junction in the full bias range are given. A new numerical diode model is presented which takes into account not only the phenomena occuring at the junction, such as current dependent recombination and drift/diffusion velocities, but also the variations of electron mobility and electron temperature in the undepleted epi-layer.**

**A diode fabrication process based on the electrolytic pulse etching of GaAs in combination with an in situ platinum plating for the formation of the Schottky contacts is described. Schottky barrier diodes with a diameter of 1 $\mu$m fabricated by this process have already shown excellent results in a 650 GHz waveguide mixer at room temperature. A DSB conversion loss of 7.5 dB and a DSB mixer noise temperature of less than 2000 K have been obtained at an intermediate frequency of 4 GHz. The noise and $I$–$V$ characteristics of Schottky diodes with a smaller diameter of 0.8 $\mu$m are presented.**

**The measured noise and $I$–$V$ characteristics of these diodes show an excellent agreement with calculated values, confirming the validity of the proposed model.**

## I. Nomenclature

| | |
|---|---|
| $A$ | Diode (anode) area. |
| $C_j$ | Junction capacitance. |
| $C_{j0}$ | Zero bias junction capacitance. |
| $E$ | Electric field. |
| $e_h$ | Thermal noise. |
| $I$ | Diode current. |
| $I_{fb}$ | Flat-band current. |
| $I_{\text{sat}}$ | Saturation current. |
| $i_j$ | Shot noise. |
| $i_t$ | Trap noise. |
| $k$ | Boltzmann constant. |
| $m_e^*$ | Effective electron mass. |
| $N_{De}$ | Epi doping concentration. |
| $N_T$ | Trap concentration. |
| $n$ | Ideality factor. |
| $q$ | Electron charge. |
| $R_s$ | Series resistance. |
| $R_j$ | Junction resistance. |
| $R_T$ | Trap noise resistance. |
| $T$ | Temperature. |
| $T_n$ | Diode noise temperature. |
| $V$ | Diode voltage. |
| $V_D$ | Flat-band voltage. |
| $V_T$ | Thermal voltage. |
| $v_{\text{drift}}$ | Electron drift velocity. |
| $v_{r0}$ | Zero bias electron velocity. |
| $v_{rI}$ | Electron recombination velocity. |
| $v_{\text{sat}}$ | Electron saturation velocity. |
| $\Delta f$ | Bandwidth. |
| $\epsilon$ | Dielectric permittivity of GaAs ($\epsilon_0\epsilon_{\text{GaAs}}$). |
| $\mu_0$ | Low-field electron mobility. |
| $\mu_{00}$ | Intrinsic electron mobility. |
| $\mu_{\text{epi}}$ | Electron mobility in the epi-layer. |
| $\tau$ | Time constant of traps. |
| $\tau_\epsilon$ | Energy relaxation time. |
| $\omega$ | Frequency ($2\pi f$). |
| $\omega_j$ | Cutoff frequency. |

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## II. Introduction

SCHOTTKY-BARRIER diodes have been recently applied to heterodyne receivers in the frequency range up to a few THz [1], the interesting point being how their realization and technology can be improved to obtain still better results at higher frequencies. Much effort has been done to reduce the feature sizes, and recently 0.25 $\mu$m GaAs Schottky diodes were developed [2], [3]. Since maximizing of the conversion efficiency requires a resistive mixing, the junction resistance at the operating point has to be much smaller than its capacitive reactance to avoid losses related with parametric downconversion [4].

In practical mixers for the highest frequencies, despite the decreasing diameter, the dc bias current at the operating point is always of the order of 0.3–0.5 mA, leading to an increased current density. Therefore, THz Schottky diodes usually have to be operated at bias conditions approaching the so called flat-band voltage.

However, the commonly used formulas for the design and calculation of the Schottky diode junction resistance and the junction capacitance are not valid near the flat-band voltage [5]. To avoid discrepancies between calculated and measured results, some authors were forced to make unphysical assumptions like assuming that the flat-band voltage $V_D$ equals the barrier height $\phi_b$ [6] and neglecting the $V_T/V_D$ term [7]. But these assumptions still do not solve the problem which results from the fact that under the so called flat-band condition, when the depleted layer disappears, according to the conventional model the junction capacitance becomes infinite, while the junction resistance is still finite and greater than zero. This phenomenon results from the approximations made in the derivation of this Schottky diode model. These approximations can be avoided if the transport equations in the diode are solved with the proper boundary conditions. Such work has been done on $I$–$V$ [8] and $C$–$V$ characteristics [9] at high biases and the results show the limitations of the conventional approach.

In this paper we present a new model for the $I$–$V$ and noise characteristics of Schottky diodes, which is valid also in the flat-band region and accurately models the noise contributions from the different noise sources. In the following sections we first will describe the new model for the junction resistance and capacitance. Subsequently, the new model for the noise characteristics of the Schottky diode and the fabrication procedure will be described. Finally, we will present theoretical and experimental results for the $I$–$V$ and noise characteristics for the conventional and optimized Schottky-barrier diode structures.

## III. Schottky Diode Model

The expressions for the $I$–$V$ and the $C$–$V$ characteristics of uniformly doped Schottky diodes are usually determined by the following well known formulas:

$$I = I_{\text{sat}}\left(\exp\left(\frac{V}{nV_T}\right) - 1\right) \quad \text{giving} \quad R_j \approx \frac{nV_T}{I} \quad (1)$$

$$C_j = A\sqrt{\frac{q\epsilon N_{De}}{2(V_D - V_T - V)}} = \frac{C_{j0}}{\sqrt{1 - \frac{V_T}{V_D} - \frac{V}{V_D}}} \quad (2)$$

The above formulas describe very well the uniformly doped Schottky diode behavior for moderate forward bias conditions which correspond to the operating point for RF and microwave mixers, however in the case of mm-wave or submm-wave mixers, the operating point is near the flat-band voltage where the above equations can not be utilized. This situation occurs when the difference between the bias and the flat-band voltage is smaller than $3V_T = 3$ kT/$q \sim 80$ mV at room temperature [5].

The examination of the $I$–$V$ characteristics of the fabricated diodes shows that the dominating carrier transport mechanism is the thermionic field emission in the reverse bias and the thermionic emission and thermionic emission/diffusion for forward biases. In the frame of the diffusion theory, which determines the diode behavior near flat-band, (1) is just an approximation of the solution given by the Dawson integral [5] valid for $V \leq V_D - 4V_T$. A better approximation of this solution can be derived from the exact solution of the Poisson equation, which determines the depletion region and the maximum electric field. A similar expression has been already given by Schottky [10], also leading to $R_j = 0$ for $V = V_D$ [11]. In this case the current is given by

$$I = I_{\text{sat}} \exp\left(\frac{V}{nV_T}\right) \cdot \left[\frac{1}{1 - \exp\left[-\frac{2(V_D - V)}{nV_T}\right]}\right] \quad (3)$$

Replacing $I_{\text{sat}}$ by the flat-band current $I_{fb} = I_{\text{sat}} \exp \cdot (V_D/nV_T)$, the following expression for the diode current is obtained

$$I = I_{fb}\left[\frac{1}{2\sinh\left(\frac{V_D - V}{nV_T}\right)}\right]. \quad (4)$$

The junction resistance $R_j$ can be evaluated from (4):

$$R_j = \frac{\partial V}{\partial I} = \frac{nV_T}{I}\tanh\left(\frac{V_D - V}{nV_T}\right) \quad (5)$$

These equations show that at flat-band, when the depletion layer disappears, the junction resistance decreases to zero. A zero junction resistance can only be reached when the diode current tends to infinity, which obviously for real diodes can not be reached, due to the limited voltage drop across the series resistance. This means that the series resistance is dominating the $I$–$V$ characteristic already at lower forward bias conditions than those predicted by the conventional expressions ((1) and (2))

In this bias range the depletion approximation utilized in the derivation of (2) is also not valid any more and the mobile electron charge must be taken into account. In this case the maximum electric field at the junction becomes

$$E_{\max}^2 = \frac{2qN_{De}}{\epsilon} \cdot \left(V_D - V - V_T\left[1 - \exp\left(-\frac{V_D - V}{V_T}\right)\right]\right) \quad (6)$$

The calculation of the total charge in the depletion region according to (6) yields a novel expression for the junction capacitance.

$$C_j = \frac{C_{j0}\left[1 - \exp\left(-\frac{V_D - V}{V_T}\right)\right]}{\sqrt{1 - \frac{V}{V_D} - \frac{V_T}{V_D}\left[1 - \exp\left(-\frac{V_D - V}{V_T}\right)\right]}} \quad (7)$$

For $V < V_D$ this expression reduces to (2) and for $V \rightarrow V_D$ the junction capacitance approaches a constant value of $C_j = C_{j0}\sqrt{2V_D/V_T}$.

The comparison of the commonly utilized formulas for the junction resistance and capacitance with the novel expressions presented in this paper are indicated in Fig. 1 and Fig. 2, respectively. These expressions should be used to describe the junction if one wants to calculate the mixer performance when the diode is operating near flat-band conditions. They can be easily inserted into the generalized mixer analysis programs, such as those described by Held *et al.* [11] or Hegazi *et al.* [12] in which excess noise sources discussed in the next paragraph were also taken into account. This should also improve the accuracy of THz multiplier efficiency calculations which use similar programs. The above expressions enable the analysis of simple Schottky diodes. For the analysis of more sophisticated diode structures, such as diodes with a graded doping profile in the epi-layer a computer program was developed. This program solves the drift/diffusion equations taking into account the field dependent mobility and electron heating at high forward bias, the current dependent recombination velocity and field-emission. The utilized program proceeds as follows. As the first step in the calculation of the $I$– $V$ characteristic, the current spreading is taken into account by the introduction of an effective equivalent radius, instead of the physical diode radius, for the epi- and substrate layers, respectively. We have developed a new formula for the spreading resistance of a two layer structure using correct boundary conditions [13]. We utilize a doping dependent low-field mobility

$$\mu_0 = \mu_{00}\left(1 - C\log_{10}\left(\frac{N_D}{B}\right)\right)^F \tag{8}$$

where $N_D$ is the doping concentration in $m^{-3}, \mu_{00} = 0.8m^2/Vs$ is the intrinsic electron mobility, $C = 0.2083, B = 10^{21}\,m^{-3}$ and $F = 23$. The expression for the field-dependent mobility is due to Chang and Fetterman [14]:

$$\mu(E) = \begin{cases} \mu_0 & \text{for } E \le E_L \\ \dfrac{\mu_0}{\sqrt{1 + \left(\dfrac{E - E_L}{E_c}\right)^2}} & \text{for } E > E_L \end{cases} \tag{9}$$

with

$$E_c = \frac{v_{\text{sat}}}{\mu_0} \tag{10}$$

and

$$E_L = \frac{1}{2}(E_{\text{crit}} + \sqrt{E_{\text{crit}}^2 - 4E_c^2}) \tag{11}$$

$E_{\text{crit}} = 3600$ V/cm denotes the critical field for maximum drift velocity and $v_{\text{sat}} = 0.7 \cdot 10^7$ cm/s the high-field saturation velocity.

A drifted Maxwellian distribution, similar to that in [4] is assumed at the junction and the drift velocity for the

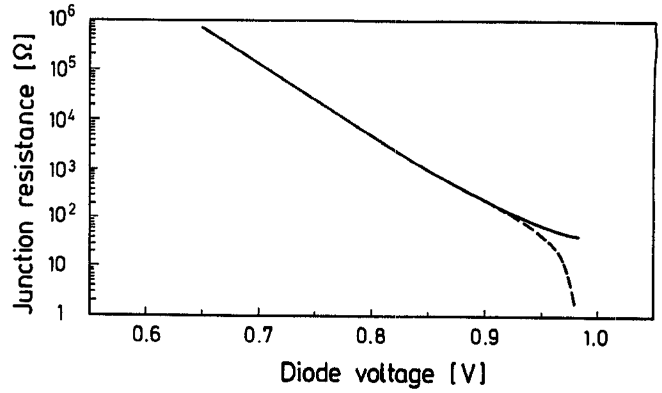


Fig. 1. Comparison of the conventional (solid line) and the new formula (broken line) for the junction resistance of the Schottky-barrier diode as a function of voltage. The parameters are: $I_{\text{sat}} = 2 \cdot 10^{-17}$ A, $n = 1.19$, $V_D = 0.982$ V, $V_t = 25.51$ mV.

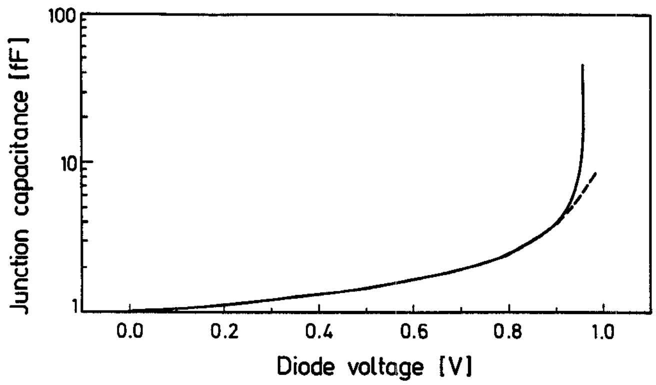


Fig. 2. Comparison of the conventional (solid line) and the new formula (broken line) for the junction capacitance of the Schottky-barrier diode as a function of voltage. The parameters are: $C_{j0} = 1.0$ fF, $R_s = 20\,\Omega$. $V_D = 0.982$ V, $V_T = 25.51$ mV.

Maxwellian shift is obtained using the following expression.

$$v_{\text{drift}} = \mu_{\text{epi}}(E)E_x(I). \tag{12}$$

We have systematically derived the formula for the current dependent velocity $v_{rI}$, which meets the zero bias velocity proposed by Sze [15].

$$v_{rI} = \frac{v_{\text{drift}}}{2}\left[1 + \text{erf}\left(\frac{v_{\text{drift}}}{v_{r0}}\right)\right] + \frac{v_{r0}}{2}\exp\left(-\frac{v_{\text{drift}}^2}{v_{r0}^2}\right) \tag{13}$$

where

$$v_{r0} = \sqrt{\frac{2kT}{m_e^*\pi}} \tag{14}$$

with $m_e^*$ the effective electron mass, $k$ the Boltzmann constant and $T$ the junction temperature in $K$. The advantage of the proposed approach is, that the current dependent velocity function is continuous in the overall velocity space and can

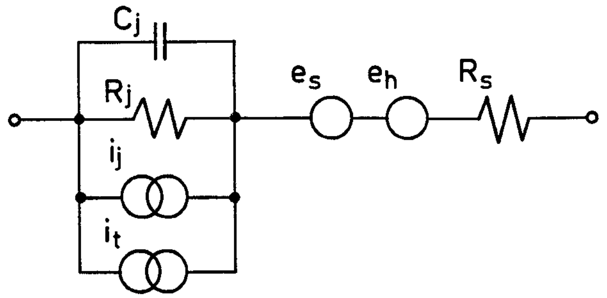


Fig. 3. The equivalent circuit of the Schottky-barrier diode with noise sources.

be directly evaluated from the operating current, without the need for iterative solutions.

## IV. Noise Characteristics

The noise generating mechanisms in Schottky-barrier diodes are well understood and are indicated in Fig. 3. The basic noise generating mechanisms are: a) shot noise in the junction with $i_j^2 = 2qI\Delta f$ and b) thermal noise in the series resistance with $e_s^2 = 4kT_0R_s\Delta f$.

The well-known expression first derived by Weisskopf in 1943 [16] gives the diode noise temperature for frequencies much lower than the junction cut-off frequency $\omega_j = 1/(R_jC_j)$:

$$T_n = \frac{nT}{2}\left(\frac{R_j}{R_s + R_j}\right) + T\left(\frac{R_s}{R_s + R_j}\right) \tag{15}$$

For higher forward biases and diodes with low doped epi-layers, electrons are heated by the high electric field in the undepleted epi-layer and the excess noise source $e_h^2$ due to the increased electron temperature $T_h$ has to be added to the thermal noise [17], [18].

$$e_h^2 = 4kTK_hI^2R_s\Delta f \tag{16}$$

with

$$K_h = \frac{2}{3}\frac{\tau_\epsilon}{kTq\mu_{\text{epi}}N_{De}^2A^2} \tag{17}$$

stands for the hot electron noise and can be considered as a constant for moderate currents, when $\mu_{\text{epi}}(E) \sim \mu_0$.

In some diodes an excess noise can be observed due to trapping effects at the interface. This phenomenon has been described by [18], [19] and the noise source $i_t$ should be added to $i_j$ for one type of traps.

$$i_t^2 = 2I^2\frac{N_T}{N_{De}}\left(\frac{\tau}{1 + (\omega\tau)^2}\right) \tag{18}$$

where $N_T$ is the trap concentration and $\tau$ is the time constant of this process.

The general expression for the diode noise temperature including this additional noise sources was derived in [18]. For the experimental verification it can be written as follows.

$$T_n^* = \frac{nT}{2}\left(\frac{R_j + R_T}{R_s + R_j}\right) + T\left(\frac{R_s}{R_s + R_j}\right)(1 + K_hI^2) \tag{19}$$

where $R_T$ represents the excess noise due traps at the interface.

$$R_T = \frac{nV_T}{q}\frac{N_T}{N_{De}}\frac{\tau}{1 + (\omega\tau)^2} \tag{20}$$

As will be shown later, the noise characteristics of different fabricated diodes can be very well described by the above simple noise model.

## V. Diode Fabrication

The first major requirement for GaAs Schottky diodes for mixing applications in the submillimeter frequency range is a small Schottky contact area in order to achieve junction capacitances in the low fF or even subfemtofarad region. Secondly, a homogeneous metal/semiconductor contact free of interfacial layers is required in order to achieve near-ideal electrical and noise performance. Since practical submm Schottky diodes have a metal/semiconductor contact area of less than 1 $\mu m^2$, the GaAs surface treatment and Schottky metal deposition techniques are much more important than for other semiconductor devices. Therefore, the fabrication of low-noise Schottky diodes requires an especially optimized device technology in order to avoid any damage to the GaAs surface. The diodes presented in this paper have been fabricated by applying a novel GaAs etching technique which is called anodic pulse etching [20], [21]. Since the initial fabrication steps such as $SiO_2$-deposition, ohmic backside contact and $SiO_2$-structuring are the same as commonly used, the main subject of the fabrication section will be the description of the anodic pulse etching in combination with the electrolytic Pt deposition for the formation of near-ideal small-area Schottky contacts.

For the fabrication of the diodes high-quality MBE-grown layers have been used [22]. Besides the diode diameter, thickness and doping concentration of these layers are the important process parameters for optimum device performance. Epitaxial layers having doping concentrations of $2 \cdot 10^{16}\,\text{cm}^{-3}, 8 \cdot 10^{16}\,\text{cm}^{-3}$ and $2 \cdot 10^{17}\,\text{cm}^{-3}$ with an original epi-layer thickness of 200 nm have been used. In addition, one epi-layer with a graded doping profile has been used. This layer has a surface doping concentration of $2 \cdot 10^{16}\,\text{cm}^{-3}$ which is increased exponentially to $6 \cdot 10^{18}\,\text{cm}^{-3}$ within 90 nm. By controlled etching of the GaAs surface any surface doping concentration can be achieved.

After thinning the $n^+$-substrate to a thickness of 50–70 $\mu$m by mechanical lapping and polishing in order to reduce the substrate resistance, a 500 nm thick $SiO_2$ layer is deposited onto the epitaxial side by e-beam evaporation. The $SiO_2$ is necessary in order to avoid As outdiffusion during the following formation of the ohmic backside contact and finally separates the single Schottky diodes and serves as a mechanical guide for the whisker contact. The ohmic backside contact is formed by evaporation of Ni/AuGe/Ni followed by a rapid thermal annealing step in $H_2$-atmosphere. Subsequently, the honeycomb diode structure is transferred to a photoresist layer on the $SiO_2$ by conventional UV-lithography. The structured photoresist serves as an etch mask for the reactive ion etching of the $SiO_2$. The applied RIE-process with $CHF_3/O_2$ and 400 W assures highly anisotropic etching of the $SiO_2$. Thus, honeycomb structures with smallest hole diameters of 0.8 $\mu$m have been defined. The RIE-process is followed by a short dip in buffered HF in order to remove any possible $SiO_2$ residues.

The next step is the formation of the small-area Schottky contacts which is of course most important since it defines the quality of the Schottky contact. Because of the introduced GaAs surface damage due to the $SiO_2$ e-beam evaporation and the plasma etching, it is necessary to remove several hundred Angstroms of GaAs before the deposition of the Schottky *et al.*

The etching step usually is performed by wet chemical etching [23], [1] or anodic oxidation of the GaAs surface with subsequent dissolution of the anodic oxide in an electrolytic Pt solution [24]. Since wet chemical etching is isotropic it leads to an enlargement of the contact area in the case of metal plating and thus to larger junction capacitances. Furthermore, the etched GaAs surface is in contact with air, leading to the formation of a thin interfacial oxide layer. Another possibility is to use an isotropic etch in conjunction with metal evaporating techniques. However, the e-beam evaporation of Pt introduces surface damage [25] and degrades the Schottky barrier. The anodic oxidation process allows the in situ Pt plating avoiding the surface damage and interfacial layers. The anodic oxidation process has become the standard technique for the fabrication of GaAs Schottky diodes for submm applications.

The major advantages of the novel pulse etching technique are the rather anisotropic etching, making it suitable also for the fabrication of very small structures and the excellent control of the removed amount of GaAs [20].

The principle of this technique is outlined below. The GaAs surface is brought into contact with a Pt electrolyte. The electrolyte/GaAs junction which behaves like a Schottky junction is driven into the avalanche breakdown by the application of short voltage pulses. During the impact ionization in the space charge region electron-hole pairs are generated. The holes drift to the electrolyte/GaAs interface where they are essential for the anodic dissolution of GaAs. The short pulse width of 300 ns therefore enables an excellent control of the removed GaAs thickness by the number of applied voltage pulses. The short pulses are also essential for the anisotropic etching since saturation effects due to diffusion limited transport of reaction species are avoided. Since the solution for the anodic pulse etching is the same which is used for the electrolytic Pt deposition, the in-situ metallization is possible. The most important aspects of this technique are summarized below.

1) anisotropic etching ⇒ suitable for fabrication of sumicron structures;
2) excellent control and reproducibility ⇒ suitable for process-oriented modelling;
3) in situ metallization ⇒ suitable for fabrication of near-ideal Schottky contacts because surface damage and interfacial layers are avoided.

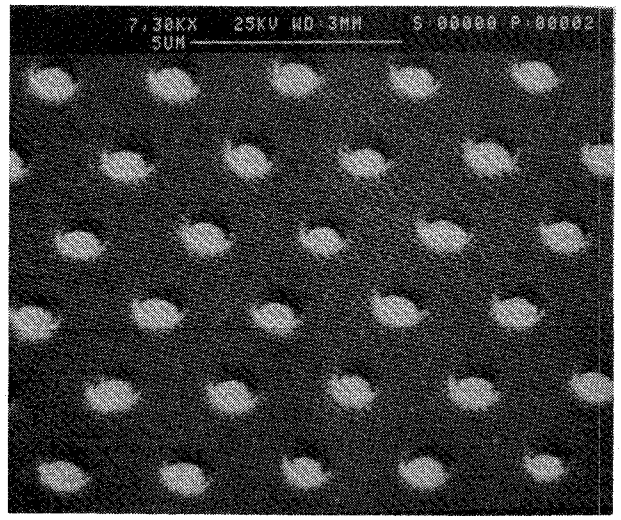


Fig. 4. SEM photograph of the fabricated Schottky diode chip with 0.8 $\mu$m diodes.

By application of the anodic pulse etching technique, 100 nm of epitaxial GaAs have been removed, followed by the in-situ Pt deposition of 150 nm and a final electrolytic 150 nm thick Au deposition. The optimization of the Schottky diode structure has shown that an epi-layer thickness of 50–100 nm should be used, instead of the utilized 200 nm thick epi-layers. A SEM photograph of the completely fabricated diode chip is given in Fig. 4. After the formation of the Schottky junctions the samples are cut into single diode chips of $100 \cdot 100\,\mu m^2$.

*I–V* and *C–V* characteristics were recorded by whisker contacting the diode chips soldered to a BeCu post. The whisker consists of a 15 $\mu$m AuNi wire with an electrochemically etched tip. The whisker is soldered to another BeCu post, which is mechanically advanced to the diode chip by a micromanipulator for contacting. Noise measurements were performed using the setup described in [26], [27]. The signal was taken from the IF port of a mm-wave mixer and measurements were performed at 1.5 GHz.

## VI. Experimental Results

Several Schottky diodes having different diameters, doping concentrations and doping profiles have been fabricated. All diodes show very good *I–V* characteristics in agreement with parameters predicted by the thermionic-field emission for reverse bias and ideality factors close to unity for forward bias and for low doped diodes. Fig. 5 shows the measured and calculated values of the forward *I–V* characteristic of a Schottky diode with 1 $\mu$m diameter and $2 \cdot 10^{17}\,cm^{-3}$ doping concentration. The higher values of the ideality factor are due to thermionic-field emission for higher doping concentrations and probably due to interfacial states, as it can be inferred from Fig. 6 in which ideality factors of several diodes manufactured at the Technical University of Darmstadt and at the University

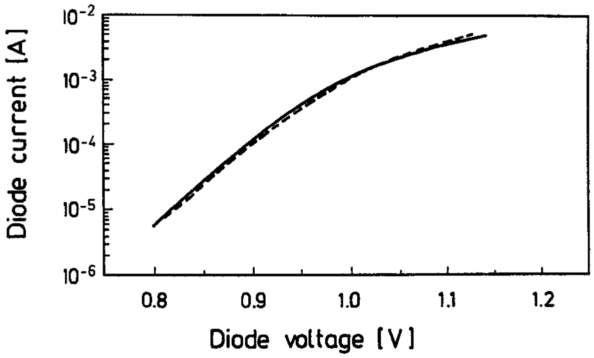


Fig. 5. Measured and calculated values of the forward $I$–$V$ characteristic for a diode with 1.1 $\mu$m diode diameter, $C_{j0} = 1.2$ fF zero-bias junction capacitance, $R_s = 15\,\Omega$, and $2 \cdot 10^{-17}\,\text{cm}^{-3}$ doping concentration.

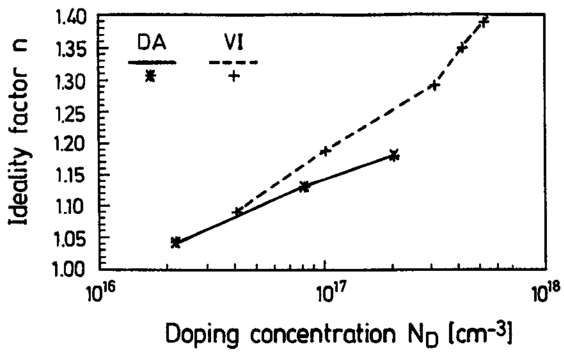


Fig. 6. The ideality factor of Schottky-barrier diodes as a function of the doping concentration for diodes fabricated at the Technical University of Darmstadt (DA) and the University of Virginia (VI) calculated from measurements at standard conditions.

of Virginia are presented as a function of doping concentration.

In Figs. 7–9 the noise temperatures of various diodes are presented. The diode examined in Fig. 7 does not exhibit any trap noise, however due to the low doping concentration, hot electron noise becomes appreciable at a relatively low current density. Its characteristic is well described by (8) with negligible trap noise. The constant $K_h$ calculated for this diode is $5.5 \cdot 10^4\,A^{-2}$, and from (17) a value for $\mu$ of $4.7 \cdot 10^3\,\text{cm}^2/Vs$ is obtained if an energy relaxation time of $\tau_\epsilon = 0.5$ ps is assumed. Although this diode exhibits ideal $I$–$V$ and noise performance, which means that $n$ and $T_n$ are determined by intrinsic effects (image force, field emission, electron heating) with negligible parasitic effects (interfacial layer, traps), low doped Schottky diodes are not suitable for low-noise submm-wave mixer realizations. It can be inferred from Fig. 7 that at the required operating conditions the noise temperature exceeds already 1000 K.

The opposite situation can be inferred from Figs. 8 and 9, where the doping concentration has been increased up to $2 \cdot 10^{17}\,\text{cm}^{-3}$. Due to the increased doping concentration, the hot-electron noise is shifted towards higher current densities, well beyond the usual operating conditions. Fig. 8 shows the measured and calculated noise characteristics of a 0.8 $\mu$m Schottky diode with 1.0 fF zero-bias junction capacitance ($R_s = 20\,\Omega$) and a small contribution of the excess noise can be seen at small current densities. Another diode with a diameter of 1.1 $\mu$m and 1.2 fF zero-bias junction capacitance ($R_s = 15\,\Omega$) exhibits a much larger excess noise contribution.

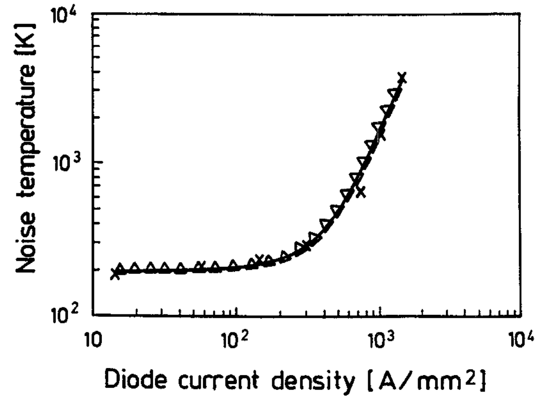


Fig. 7. Comparison between measured and calculated (from (8)) noise characteristics of a low doped Schottky diode as a function of current density. The crosses indicate the measured data, the solid line stands for $T_n + T_h$ and the triangles are $T_n + T_h + T_t$. The parameters of these diodes are: $N_D = 2 \cdot 10^{16}\,\text{cm}^{-3}, \emptyset = 3.0\,\mu\text{m}, R_s = 6\,\Omega$ and $n = 1.07$.

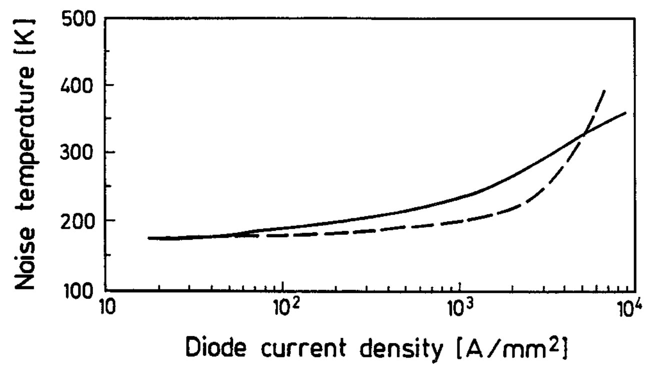


Fig. 8. Comparison between measured and calculated (from (8)) noise characteristics of a highly doped Schottky diode as a function of current density. The dashed line indicates the calculated results according to $T_n + T_h$ and the solid line stands for the measured data. The parameters of these diodes are: $N_D = 2 \cdot 10^{17}\,\text{cm}^{-3}, \emptyset = 0.8\,\mu\text{m}, R_s = 20\,\Omega$ and $n = 1.19$.

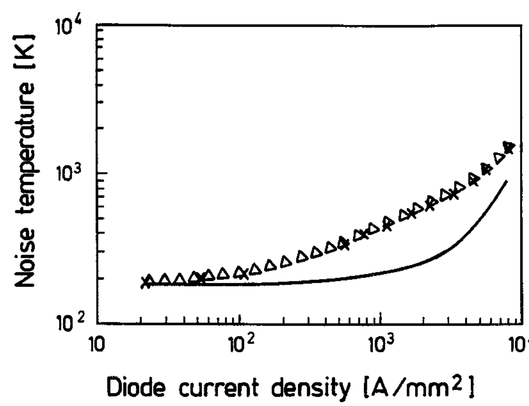


Fig. 9. Comparison between measured and calculated (from (8)) noise characteristics of a highly doped Schottky diode as a function of current density. The crosses indicate the measured data, the solid line stands for $T_n + T_h$ and the triangles are $T_n + T_h + T_t$. The parameters of these diodes are: $N_D = 2 \cdot 10^{17}\,\text{cm}^{-3}, \emptyset = 1.1\,\mu\text{m}, R_s = 15\,\Omega$ and $n = 1.18$.

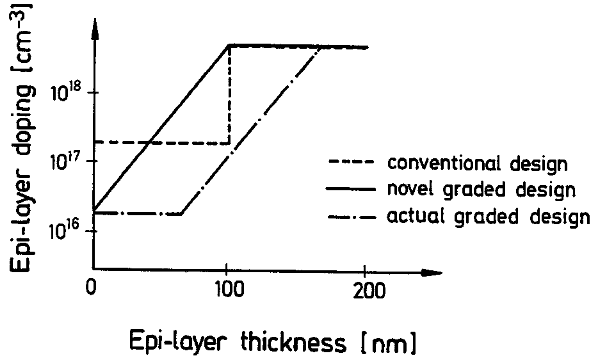


Fig. 10. Comparison of the new graded doping profile in the epi-layer and the constant doped material as used for the new Schottky diodes as a function of epi-layer thickness. The doping concentration is in logarithmic scale.

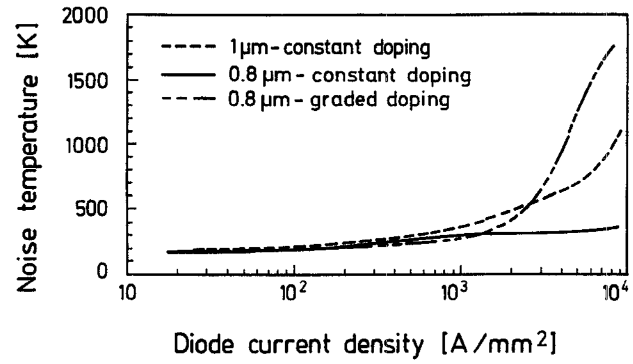


Fig. 11. Noise characteristics of a 0.8 $\mu$m diode with graded junction ($C_{j0}$ = 1.1 fF, $R_s$ = 30 $\Omega$) in comparison to the 1 $\mu$m and 0.8 $\mu$m diode with constant ($2 \cdot 10^{17}$ cm$^{-3}$) doping concentration as a function of current density.

As already discussed in [26], this noise can be accurately described by (19) indicating that this noise is due to traps at the interface. Noise measurements at three distinct frequencies give an estimation for the value of $\tau$ of 0.2 ns, corresponding to very shallow traps at the interface. Using this value it is possible to evaluate the trap density $N_T$ according to (20). For this diode $N_T/N_D = 1.5 \cdot 10^{-6}$ which gives a reasonable value for the trap density of $N_T = 3 \cdot 10^{11}\,\text{cm}^{-3}$.

Additionally, a new approach to the design of Schottky diodes has been pursued in order to achieve low-noise Schottky diodes with ideality factors close to those of the low doped diodes. On the other hand, these new Schottky diodes are expected to exhibit similar noise performances as the highly doped diodes.

It is shown that the above requirements can be accomplished by utilizing the doping profile according to Fig. 10. This epi-layer has been grown by a novel technique using the same MBE facility as for the other fabricated diodes. Noise characteristics of a Schottky diode realized with the new material can be inferred from Fig. 11. The minimum noise temperature level, which is dependent on the surface doping densities, is lower than that of the highly doped diodes which are usually used in THz mixer applications. The strong increase of the noise temperature due to hot electrons is shifted from 300 A/ mm$^2$, which is typical for low doped diodes (see Fig. 7), to 1400 A/mm$^2$ for the diode with the graded epi-layer. For the common operating conditions of the Schottky diodes in THz mixers (700–1000 A/mm$^2$) the novel diodes exhibit a lower noise temperature than that of Schottky diodes fabricated on epi-layers with constant doping concentrations. However, the diodes fabricated on highly doped material show less hot electron effects at very high current densities.

The fabricated diodes with graded epi-layer have a diameter of 0.8 $\mu$m, an ideality factor of $n = 1.15$ and a zero-bias junction capacitance of 1.1 fF. The series resistance of the diodes on the graded epi-layer material is stronger dependent on the bias conditions as compared to the standard Schottky diodes with constant epi-layer doping. Therefore, only a typical value of $R_s \sim 30\,\Omega$ can be given.

The 1 $\mu$m diode has already shown excellent results in a 650 GHz DSB waveguide mixer at room temperature. A noise temperature smaller than 2000 K and a corresponding conversion loss of 7.5 dB have been obtained at an intermediate frequency of 4 GHz [28]. These results are comparable to others obtained with smaller diodes. A further improvement can be expected from diodes fabricated on the optimized graded doping profile as indicated in Fig. 10, because of the smaller series resistance for the optimized graded doping.

## VII. Conclusions

GaAs Schottky barrier diodes for mixing applications in the THz frequency range were theoretically and experimentally investigated. Diodes with a diameter of 1 $\mu$m fabricated by the described process have already obtained a DSB mixer noise temperature of 2000 K and a DSB conversion loss of 7.5 dB in a 650 GHz waveguide mixer at room temperature, which is an excellent result.

The new generalized Schottky diode model, which is valid also at high current densities, allows now the further optimization of the diode structure and technology. Analytical expressions are presented which can be easily inserted into existing THz mixer and frequency multipliers calculation programs to improve their accuracy.

Calculated diode $I$–$V$ and noise characteristics show an excellent agreement with measured values. Thus, the diode model offers the possibility of a further diode improvement and the prediction of the diode performance under mixing conditions at THz operating frequencies.

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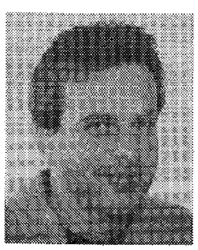

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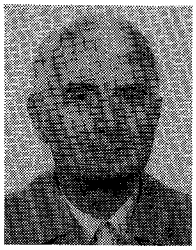

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