Noise Characterization of Schottky Barrier Diodes for High-Frequency Mixing Applications

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Abstract—**The noise performance of Schottky barrier diodes for mixing applications is the most important aspect when operating at millimeter and submillimeter wavelengths. Therefore, the understanding and characterization of the diode noise sources plays an important role for the modeling of the diode performance. Experimental noise characteristics of diodes with different parameters are presented and discussed with respect to the dominant noise sources. It is shown that diodes with high doped epi-layers cannot be described by the common noise sources. Excellent agreement with measured and calculated results can be achieved for all diodes when the noise contribution due to interfacial traps in the epi-layer is taken into account. The separate sections are devoted to discuss the basic noise model of mm-wave Schottky barrier diode and a concept of the noise temperature measurement.**

I. Introduction

Noise temperature is one of the most important parameters of mm-wave Schottky barrier diodes for the mixer applications. The noise model, which takes into account thermal noise, shot noise and noise due to hot electrons describes often pretty well Schottky diodes noise characteristics in the wide range of currents [1], [2]. However, several papers reported noise characteristics deviating seriously from the above model values. The purpose of this letter is to establish the origin of this excess noise.

II. Noise Model of MM-Wave Schottky Diode

Noise behavior of mm-wave Schottky barrier diodes was discussed in many papers [3]–[5]. The Schottky diode noise temperature can be expressed by (1), which takes into account thermal noise in the undepleted part of epi-layer, shot noise in the junction, hot electrons noise and noise due to traps located in the depleted part of epi-layer, as was described in [5]:

$$T_n = \frac{\frac{\eta T_o}{2}(R_j + R_{\text{tr}}) + T_o R_s (1 + K_h I^2)[1 + (\omega\tau_j)^2]}{R_j + R_s[1 + (\omega\tau_j)^2]}, \tag{1}$$

I is the diode bias current, R_j and R_s — junction and series resistances, T_o — ambient temperature, η — ideality factor, ω — pulsation, and $\tau_j = R_j C_j$ —junction time constant. K_h is the factor related to the hot electron noise, defined by

$$K_h = \frac{2\tau_e}{3kq\mu_n N_d^2 S^2}, \tag{2}$$

where: k — Boltzman constant, q — electron charge, μ_n — mobility of electron, N_d — doping concentration, S — diode area. R_{tr} is the equivalent trapping resistance, representing excess noise at the junction due to trap loading and unloading processes:

$$R_{\text{tr}} = \frac{\eta V_o S_{nj}}{2qN_d^2 V^2}. \tag{3}$$

V_o is the thermal voltage

$$V_o = \frac{kT}{q}. \tag{4}$$

S_{nj} is the spectral density of fluctuations of number of carriers at the junction caused by one specific type of trapping mechanism:

$$S_{nj} = \alpha N_T V \cdot \frac{\tau_{\text{tr}}}{1 + (\omega\tau_{\text{tr}})^2}. \tag{5}$$

$N_T V$ is the number of traps, V is the considered volume,τ_{tr} is the time constant related to these traps, and α is a constant adjusted to fit the data. For low frequencies $\omega\tau_j \rightarrow 0$ and the formula (1) can be rewritten as

$$T_n = \frac{\frac{\eta T_o}{2}(R_j + R_{\text{tr}}) + T_o R_s (1 + K_h I^2)}{R_j + R_s}. \tag{6}$$

III. Measurement Methods

The measurement system for determining Schottky diode noise temperature at frequency 1.5 GHz is presented in Fig. 1. The assumptions that the circulator and the bias circuit are matched and the isolation of the circulator is high enable to write (7), which joins the output noise temperature T_{out} with Schottky diode noise temperature T_d:

$$T_{\text{out}} = T_o + \frac{T'_{ns} \mid \Gamma_d \mid^2 + T_d(1 - \mid \Gamma_d \mid^2) - T_o}{L_{32}}, \tag{7}$$

where Γ_d — Schottky diode reflection coefficient, L_{32} is the attenuation from the port 2 to the port 3, and T'_{ns} is joined with T_{ns} by

$$T'_{ns} = T_o + \frac{T_{ns} - T_o}{L_{21}}, \tag{8}$$

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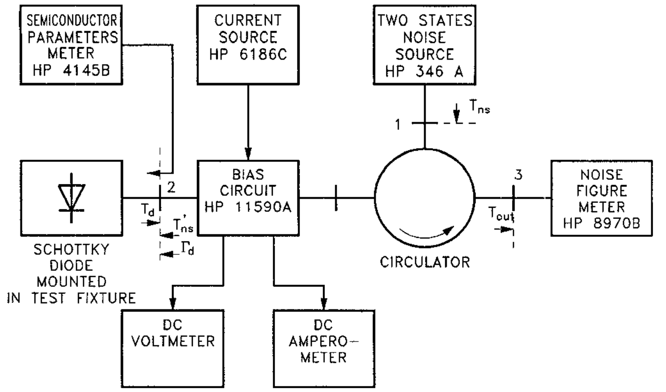

Fig. 1. Measurement system for determining Schottky diode noise temperature at 1.5 GHz.

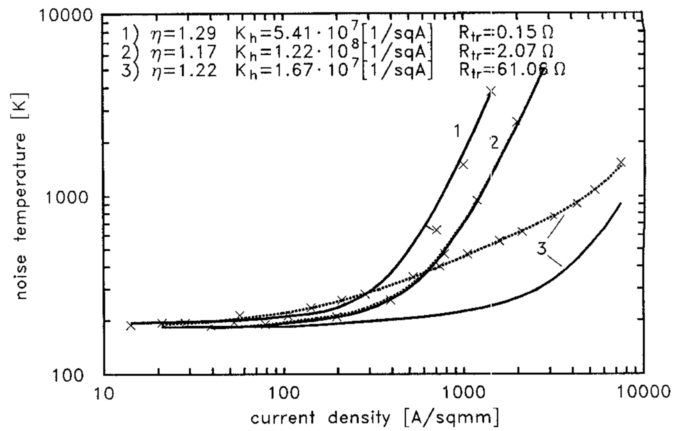

Fig. 2. Measurement and theoretical noise characteristics at 1.5 GHz.

where L_{21} is the attenuation from the port 1 to the port 2.

The taking of the two different values of the noise source temperature T_{ns1}, T_{ns2} and the measuring the output noise temperatures T_{out1}, T_{out2} related to these values enable to create of a system of equations with two unknowns $| \Gamma_d |^2$ and T_d. The solving of the system yields $| \Gamma_d |^2$ and T_d:

$$| \Gamma_d |^2 = \frac{L_{32}(T_{\text{out1}} - T_{\text{out2}})}{T'_{ns1} - T'_{ns2}} \tag{9}$$

$$T_d = \frac{T_o + L_{32}\,(T_{\text{out1}} - T_o) - T'_{ns1} \mid \Gamma_d \mid^2}{1 - \mid \Gamma_d \mid^2}. \tag{10}$$

The parameters L_{32}, T'_{ns1}, T'_{ns2} are determined during the calibration of the measurement system [6].

IV. Experimental Results

In order to investigate the noise properties of the Schottky diodes fabricated at the University of Darmstadt according to the process described in [7], several diodes with different parameters were measured [6]. The measurements were done at $f = 1.5$ GHz.

The investigation of the influence of the doping concentration level upon the Schottky diode noise properties was the first fundamental purpose of the measurements. Three groups of diodes with different doping concentration ($2 \cdot 10^{17}$ cm^{-3}, $4 \cdot 10^{16}$ cm^{-3}, $2 \cdot 10^{16}$ cm^{-3}) were tested. The crosslets on the Fig. 2. relate to the typical for each of the groups measurement results. All of the characteristics have been measured at the ambient temperature $T_o = 298$ K. In order to compare the results for diodes with different diameters, the characteristics are presented as a function of current density. The parameters of the measured diodes are the following:

1. $N_d = 2 \cdot 10^{16}$ cm^{-3}, $\phi = 3.0$ μm, $R_s = 6$ Ω, $\eta(I \approx 10\ \mu\text{A}) = 1.08$,
2. $N_d = 4 \cdot 10^{16}$ cm^{-3}, $\phi = 1.8$ μm, $R_s = 16$ Ω, $\eta(I \approx 10\ \mu\text{A}) = 1.09$,
3. $N_d = 2 \cdot 10^{17}$ cm^{-3}, $\phi = 1.1$ μm, $R_s = 15$ Ω, $\eta(I \approx 10\ \mu\text{A}) = 1.18$.

ϕ is the diode diameter.

The figure shows that for the diodes with high doping concentration the increase of noise temperature due to hot electrons is at higher value of current density than for the diodes with low doping concentration. It enables to shift the rapidly increasing of the diode noise temperature outside of the operated Schottky diode region of current density. This value is determined by the value of a magnitude of the diode reflection coefficient, and by the shape of diode I/V characteristic. The optimal operated region of current density lies between 700 and $1000[A/sqmm]$. The increase of diode doping concentration involves the decrease of diode diameter in order to assure the small junction capacitance. It is clearly that this fact causes many troubles during the diode fabrication. On the other hand, the increase of the diode doping concentration is limited by the correctness of the Schottky contact.

The identification of the noise sources in the Schottky diode structures was the second fundamental purpose of the noise measurements.

The continuous lines on the Fig. 2. relate to the noise temperatures predicted from the noise model, which takes into account thermal noise, shot noise and noise due to hot electrons — formula (6) with $R_{\text{tr}} = 0$. The comparison between the measurement results and the results predicted from this model shows very good agreement for diodes with $N_d = 4 \cdot 10^{16}$ cm^{-3}. For diodes with $N_d = 2 \cdot 10^{16}$ cm^{-3} the agreement is also good, but the increase of the measured diode noise temperature is faster than I^2 in the high currents region. This phenomena for low doped diodes was reported in [5], [8]. For high doped diodes the same comparison shows that the measured noise temperature is substantially higher. One of the possible reasons of these differences is the fact that the effects concerned with the trapping of electrons were not taken into account. The full formula (6) enables to take into account the trapping effects in the depleted part of epi-layer. In the situation in which the traps are located in the volume of the depleted epi-layer, number of the active traps ie. R_{tr} is dependent on the bias current. If the traps are located at the interface metal-semiconductor number of active traps is independent from the diode current in the wide range of currents.

The calculations show that the best agreement between measurement results and the results predicted from (6) is for the situation in which the volume V is independent from current (the equivalent trapping resistance R_{tr} is also independent from current). It suggests that the traps are situated at the interface metal-semiconductor. In this situation number of active traps is independent from diode bias current for "small currents". As "small currents" is defined situation when all of the traps are located in the depleted part of epi-layer, in practice I should be smaller than $\approx$ 3 mA. The dotted lines on the Fig. 2. refer to the results calculated from this model.

The presented results show very good agreement between the measurement results and the results predicted from the model with trapping effects for high-doped diodes. For low-doped diodes the dotted and continuous lines almost coincide. In this situation the contribution of diode noise temperature due to traps is very small. The excess diode noise temperature due to traps is proportional to the equivalent trapping resistance R_{tr}, which is proportional to the number of traps. Obtained results suggest that the R_{tr} increases when the diode doping concentration increases and the diode diameter decreases.

The simulation results were obtained in the optimization way with three parameters η, K_h, R_{tr}. This optimization was based on the equation (6). The values of the optimization parameters are given on the Fig. 2. The optimization of ideality factor η was done to take into account the increase of this parameter together with the increase of the diode bias current [5]. Further information concerning with τ_{tr} and N_T can be obtained by the investigation of the frequency dependence of this noise. Measurements of other GaAs Schottky diodes reported in [5] suggest that these time constants are of the order of fractions of ns, dependent upon technology and support the conclusion about the trapping origin of the observed excess noise.

V. Conclusion

It has been shown that the noise model, which takes into account thermal noise, shot noise and noise due to hot electrons describes pretty well noise characteristics of low-doped diodes. The comparison between the measurement results and the results predicted from this model shows however that for small diodes using highly doped material the measured diode noise temperature is substantially higher. Very good agreement can be obtained by taking also into account the trapping mechanisms in the diode noise model. Further work is needed to determine the origin of these traps and their dependence upon diode diameter, technology, and doping of the epi-layer.

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