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Analytical model for the TeraHertz current noise in nanometric Schottky-barrier diodes and heterostructure barrier varactors

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Abstract. In this paper we propose an analytical model for the calculation of the spectral density of current fluctuations in Heterostructure-barrier varactors. The structures of the calculated spectra are analyzed in terms of physical processes useful to optimize the device parameters for the extraction of the high-order harmonics.

1. Introduction
The varactor devices, like the Schottky barrier diode (SBD) and the heterostructure barrier varactor (HBV) diode, are nonlinear elements able to generate high-frequency signals by frequency multiplication [1]. More recently, the HBV diodes have emerged as interesting competitors of SBD as frequency multipliers due to their symmetric capacity-voltage (C-V) and antisymmetric current-voltage (I-V) characteristics [2,3], which lead to produce only odd harmonics compared to the SBD [1]. Under high-frequency large-signal operation, a critical parameter assessing their electrical performances is the intrinsic current noise, which constitutes also an important limit for the extraction of the high-order harmonics at the basis of terahertz generation. In this contribution we present an extension of the analytical model proposed in Ref. [4] which gives a description of the resonances appearing in the high frequency region.

2. Analytical Model
We apply the analytical model described in Ref. [4] to calculate the intrinsic high-frequency noise spectrum in a typical $n^+n – barrier – nn^+$ HBV structure shown in Fig. 1. Here $l_i$ is the length of the i-regions with $N_2$ and $N_4$ the dopings of the first and second $n$ regions, respectively, $N_1$ and $N_3$ the dopings of the first and second $n^+$ regions, respectively, and $l_d$ the length of the depletion region (see, e.g. [3]).
Here the homogeneous part of the global perturbation previous system of equations (1) and (2) can be rewritten in matrix form as:

\[
\begin{align*}
\delta E \equiv & \begin{cases} 
\Delta E - \left(\frac{e}{\epsilon_0}\right) N_1 \delta x_1 & 1^{st} n^+ \text{ region} \\
\Delta E - \left(\frac{e}{\epsilon_0}\right) N_2 \delta x_2 & 1^{st} n^- \text{ region} \\
\Delta E - \left(\frac{e}{\epsilon_0}\right) N_3 \delta x_3 & \text{depletion region} \\
\Delta E - \left(\frac{e}{\epsilon_0}\right) N_4 \delta x_4 & 2^{nd} n^+ \text{ region} \\
\end{cases} 
\end{align*}
\]

(1)

Here the homogeneous part of the global perturbation \( \Delta E = \frac{e}{\epsilon_0 L} \sum_{i=1}^{4} N_i \delta x_i \) is determined under constant applied voltage operation and the variation of the voltage drop equals to zero \( \delta U = 0 \), where \( i = 1, 2, 3, 4 \) is the number of regions. According to the symmetry of HBV structure \( l_1 = l_3 = l_+ \), \( l_2 = l_4 = l_- \) and \( l = 2l_+ + 2l_- + l_d \) is the total length of the HBV [2,3]. To describe evolution of these shifts we take the advantage of the Langevin approach formulated by the following system of equations:

\[
\frac{d^2}{dt^2} \delta x_i + \nu_i \frac{d}{dt} \delta x_i = \frac{e}{m} \delta E_i(x) + f_i
\]

(2)

where \( f_i \) is the Langevin force in the \( i \)-region. For the numerical results we assume that \( N_1 = N_3 = N_+ \), \( N_2 = N_4 = N_- \) and the plasma frequency is defined as \( \omega_n^2 = (e^2/\epsilon_0 m)N_i \). The previous system of equations (1) and (2) can be rewritten in matrix form as:

\[
\begin{pmatrix}
\begin{pmatrix}
a_{11} & a_{21} & a_{31} & a_{41} \\
a_{12} & a_{22} & a_{32} & a_{42} \\
a_{13} & a_{23} & a_{33} & a_{43} \\
a_{14} & a_{24} & a_{34} & a_{44}
\end{pmatrix} & \begin{pmatrix}
\delta x_1(\omega) \\
\delta x_2(\omega) \\
\delta x_3(\omega) \\
\delta x_4(\omega)
\end{pmatrix}
\end{pmatrix}
\begin{pmatrix}
f_1(\omega) \\
f_2(\omega) \\
f_3(\omega) \\
f_4(\omega)
\end{pmatrix}

(3)

The expressions of the matrix elements are: \( a_{11} = a_{33} = -\omega^2 + i\omega\nu_+ + \omega_+^2(1 - r_+) \), \( a_{12} = a_{41} = a_{24} = a_{32} = a_{34} = a_{42} = -\omega \omega_+ \), \( a_{13} = a_{21} = a_{31} = a_{43} = -r_+ \omega_+ \), \( a_{22} = a_{44} = -\omega^2 + i\omega\nu_- + \omega_-^2(1 - r_-) \), \( r_+ = \frac{l_+}{l} \) and \( r_- = \frac{l_-}{l} \) are the relative lengths of the \( n^+, n^- \) regions. In accordance with the conservation law of the total current, the current fluctuation \( \delta J \) in the external circuit is determined by the rate of change of the surface density \( \delta \sigma_M = \epsilon_0 \Delta E \) [4]:

\[
\delta J = \frac{eA}{L} \sum_{i=1}^{4} N_i l_i \frac{d}{dt} \delta x_i
\]

(4)

For uncorrelated (in time and space) Langevin forces their spectral density normalized to the total number of free carriers in the \( i \)-th region takes the form:

\[
S_{ij} = 4kT \left( \frac{1}{Am} \frac{\nu_i}{N_i l_i} \right)
\]

(5)
By using the equations (4) and (5) and the $b_{ij}$ elements of the inverse matrix of equation (3) the spectral density can be represented as:

$$S_{ii}(\omega) = \left( \frac{e\lambda}{L} \right)^2 \sum_{j=1}^{4} \sum_{i=1}^{4} N_{i} l_{i} b_{i,j} S_{jj}^{2}$$  \hspace{1cm} (6)$$

Let us stress that by keeping in equation (3) only the elements $a_{11}, a_{12}, a_{21}, a_{22}$ we obtain the analytical model for the SBD noise developed in [4].

3. Results and discussion

The intrinsic current noise obtained for a GaAs SBD is illustrated in Figure 2, with a carrier momentum relaxation rate $\nu = 1.364 \times 10^{12}$ s$^{-1}$ similar to the value obtained by Monte Carlo simulation [5]. The results of figure 2 obtained by this analytical model are compared by the results of SBD device in article [5].

**Figure 2.** Spectral density of current fluctuations per unit surface in a GaAs $n^+ n$-metal SBD with: $l_+=l_-=0.1 \mu$m and $N_- = 5 \times 10^{16}$ cm$^{-3}$. Curve 1: homogeneous material ($N_+ = N_-$) and $l_d = 0$; curve 2: diode with $l_d=0$ and $N_+ = 10 N_-; \text{ curve 3: } N_+ = N_- \text{ and } \text{depletion region } l_d = 0.01 \mu$m and \text{ curve 4: } \text{diode with } l_d = 0.01 \mu$m and $N_+ = 10 N_-$. For the case of a complete SBD (curve 4 in Fig.2), the spectral density exhibits an initial growth proportional to $\omega^2$ followed by two resonant peaks in the low and high frequency regions corresponding respectively to the carriers reflected by the SBD barrier and to the hybrid plasma resonance frequency.

**Figure 3.** Spectral density of current fluctuations in a GaAs $n^+ n$-metal SBD with: $l_+ = 0.05 \mu$m, $l_- = 0.15 \mu$m, $N_- = 5 \times 10^{16}$ cm$^{-3}$. Curve 1: applied voltage is $U = 0.7$ V; Curve 2: $U = 0.75$ V; Curve 3: $U = 0.8$ V; Curve 4: $U = 0.85$ V; Curve 5: $U = 0.9$ V; Curve 6: $U = 0.95$ V and Curve 7: $U = 1$ V.

In Fig. 3 the absence and presence of the depletion region is controlled by the applied voltage $U$. We observe a red-shift of the low-frequency resonance peak by increasing the applied voltage. The HBV spectral density is similar to the spectrum of the SBD with a difference in the position of the resonance peaks. For a complete HBV structure (curve 4 of Fig.4) the two resonance peaks appear near 1 and 20 THz compared to the SBD structure (curve 4 of Fig.2) where the peaks appear at 0.3 and 3 THz. Therefore the resonance frequency position increases significantly.
4. Conclusion

We have proposed an analytical model of the intrinsic noise in HBV structures which describes the high-frequency part of the noise spectrum. The low-frequency shot noise is not considered in the model. The model proposed for the HBV can calculate the intrinsic noise of $i$ regions of any structure and the results can be useful for optimizing the device parameters for the extraction of the high-order harmonics.

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References