Noise and impedance of n^+-n-n^+ InP microwave generators

V. Gruzinskis and V. Mitin
Department of Electrical and Computer Engineering, Wayne State University, Detroit, Michigan 48202

E. Starikov and P. Shiktorov
Semiconductor Physics Institute, Vilnius 2600, Lithuania

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The noise power spectral density P_n in a submicron InP diode loaded by resistor R is calculated using the Monte Carlo particle technique. It is shown that at biases above the generation threshold the P_n has a peak at the frequency f_{peak} which corresponds to the highest generation frequency at the given R. The excess noise is the shot noise of electrons accumulated into the layers. Measuring the frequency of the peak f_{peak} as the function of R one can obtain the negative values of the real part of impedance at the high-frequency side of the negative impedance spectrum.

One of the most reliable and direct theoretical methods for noise investigation is the Monte Carlo particle (MCP) method. This method is widely used for the noise simulations in bulk semiconductors and gives a good agreement with available experimental data. The MCP method for noise simulation in n^+-n-n^+ structures was proposed by Zimmerman and Constant.[1] In this method the current and voltage fluctuations are calculated straightforwardly. Unfortunately, this method accounts only for the conduction current fluctuations which are the result of velocity fluctuations. The origin of total current fluctuations is the velocity and concentration fluctuations. The concentration fluctuations manifest themselves through the displacement current. To account for the displacement current we propose to simulate directly the voltage or current (in principal the same) fluctuations in a resistor connected in series with an n^+-n-n^+ structure. Because the current through the resistor is the sum of the conduction and displacement currents, the displacement current fluctuations in the device are naturally accounted for. The noise power calculated in this way can be directly measured by experiment.

In this communication we present the results of noise investigations in submicron InP diodes by the MCP method.[2] The diode impedance is calculated by a modified hydrodynamic method.[2,3]

The following parameters of n^+-n-n^+ InP are chosen in our simulation: the length of the n region is 0.6 μm, and the doping concentration in the n and n^+ regions is 3×10^{16} and 10^{18} cm^{-3}, respectively. Current-voltage relations of this structure have no region with the static negative differential resistivity (NDR); however, there exists dynamic NDR in the frequency region 160–400 GHz. The voltage threshold for NDR is about 1.3 V.[2]

The noise power spectral density $P_n(f)$ calculations showed that in a wide range of applied voltages (0.04–3.0 V) the noise power has a plateau from $f=0$ up to $f=20$ GHz. The value of the $P_n(f)$ in this frequency region we call the low-frequency noise $P_n(0)$ value. The $P_n(0)$ dependence on diode bias U_d is shown in Fig. 1 by solid circles. The zero frequency impedance $Z(0)$ is shown in the same figure by a solid line. The $P_n(0)$ and $Z(0)$ are normalized to the values at U_d=0.04 V. As one can see from Fig. 1, $P_n(0)$ and $Z(0)$ exhibit the same behavior up to the threshold voltage, which is shown in the figure by an arrow. The $Z(0)$ continues the growth after the threshold while $P_n(0)$ somewhat decreases. The decrease of $P_n(0)$ after the threshold can be explained by the onset of microwave generation in the diode. The generation leads to the considerable noise power density enhancement in the frequency region where the real part of impedance Re Z has negative values. The noise power density redistribution in the frequency domain results in a low-frequency noise decrease. The total noise power P_n integrated over the entire frequency range (see Fig. 1, open circles) monotonically increases with the bias increasing. The dependence dP_n/dU_d on U_d (see Fig. 1, dashed line) has a maximum at the threshold voltage.

It was found by MCP simulation that the noise power spectral density $P_n(f)$ has a peak in the frequency range where the Re Z is negative. The position of the peak f_{peak} in frequency domain depends on the value of the load resistance R at the fixed value of U_d (see Fig. 2). To examine in more detail this dependence, the noise power spectral densities are calculated as a function of load resistance. The parameters of the structure were the same as mentioned above. The voltage on the diode was fixed at the value U_d=3 V. This voltage is considerably above the generation threshold. The frequency dependence of the real part of impedance Re Z (impedance spectrum) is shown in Fig. 3. If we have the noise spectra at different values of R we can construct the $-R$ dependence on the noise power maximum frequency f_{peak}. The relation $-R(f_{\text{peak}})$ is shown in Fig. 3 (solid circles). One can see that the solid circles are close to the high-frequency side of the impedance spectrum (see Fig. 3). Therefore, it is evident that the $P_n(f)$ maximum at frequency f_{peak} is the consequence of microwave power generation in near linear regime.

As follows from impedance spectrum shape (see Fig. 3), the condition for generation $R+\text{Re}\,Z=0$ at a certain R can be fulfilled for two frequencies $f_{\min}$ and $f_{\max}$. Above the generation threshold the generation process is always present in the structure even in the absence of a resonant circuit. This process is related with the accumulation layer formation and travelling along the diode. The generation frequency in this case can be expressed by the simple formula $f=v_d/l_d$, where v_d and l_d are the accumulation layer drift velocity and drift length, respectively. At high electric fields v_d is practically

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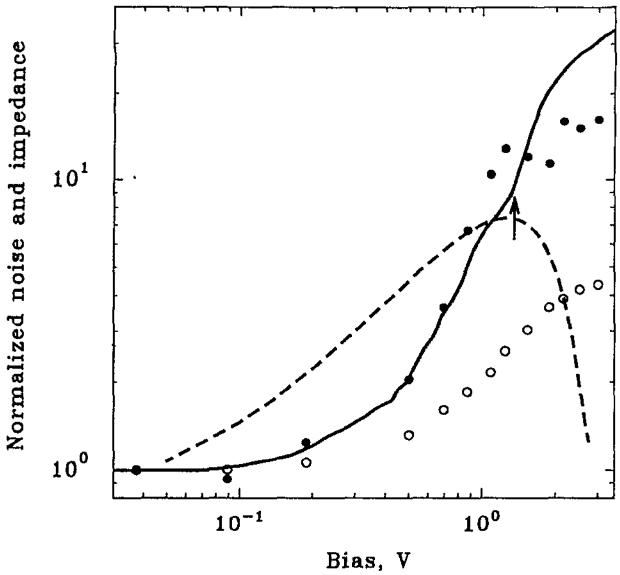

FIG. 1. Dependence of zero frequency impedance (solid line), low-frequency noise power (●), the total noise power P_n (○), and derivative of P_n (dP_n/dU_d) (dashed line) on bias voltage U_d. The n^+-n-n^+ InP structure parameters are: the length of the n region is 0.6 μm, and the doping concentrations in the n and n^+ regions are 3×10^{-16} cm^{-3} and 3×10^{18} cm^{-3}, respectively. The value of load resistance is $R=10^{-9}$ Ω m^2. The arrow indicates the generation threshold.

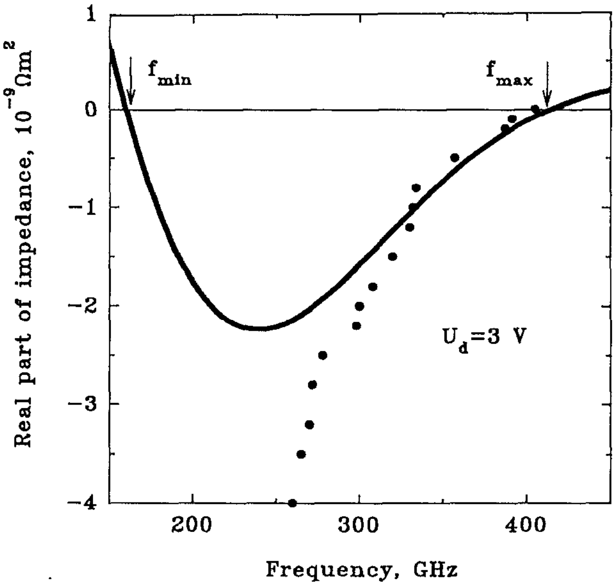

FIG. 3. Real part of the impedance spectrum (solid line) and function $-R(f_{peak})$ (●). The structure parameters are the same as in Fig. 1.

independent of field and is approximately equal to 10^5 m/s. Therefore, the generation frequency at high electric field depends only on the accumulation layer drift length l_d. The values of l_d evaluated from f_{max} and f_{min} (see Fig. 3) can vary in the range from 0.25 to 0.6 μm. The highest value of l_d coincides with the diode n-region length. The formation probability of an accumulation layer with the drift length 0.6 μm, which corresponds to the frequency f_{min}, is negligible. This is the main reason why the peak, corresponding to the f_{min}, does not appear in the noise spectrum (see Fig. 2).

From the above analysis it can be concluded that the excess noise above the generation threshold is the result of the shot noise of electrons accumulated into the layers due to the NDR. This process is similar to the microwave generation process. This similarity can be demonstrated by the total noise power P_n dependence on the load resistance R (see Fig. 4). This figure is typical for the microwave generators

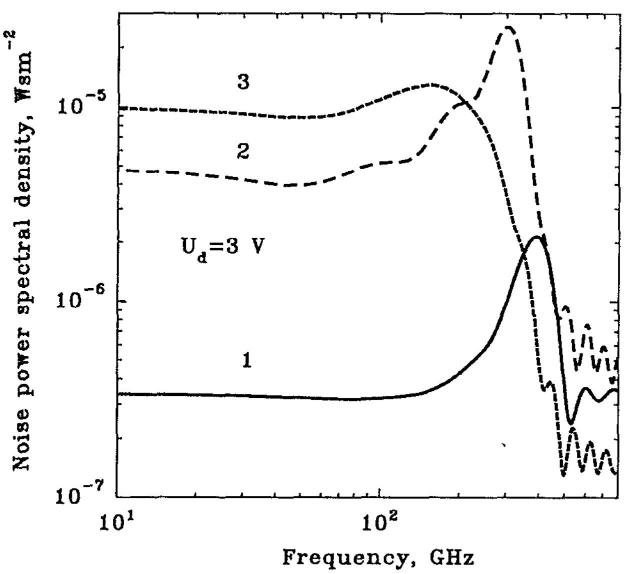

FIG. 2. Noise power spectral density vs frequency at different R values: 1–10^{-10} Ω m^2, 2–2×10^{-9}, and 3–10^{-8}. The structure parameters are the same as in Fig. 1.

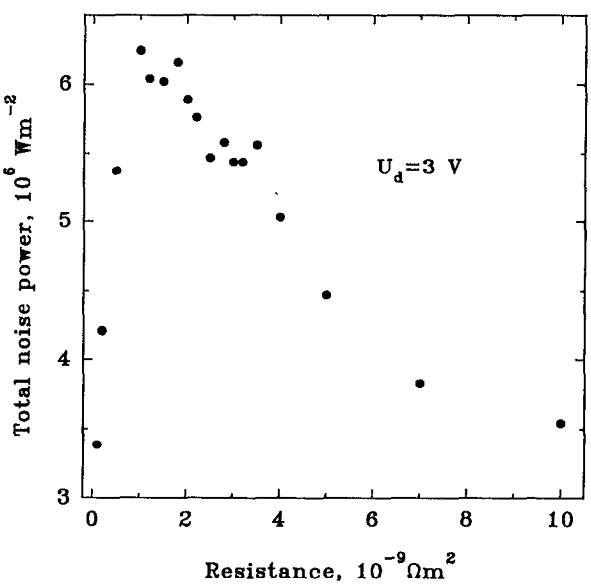

FIG. 4. Total noise power integrated over entire frequency range vs load resistance R. The structure parameters are the same as in Fig. 1.

operating in the resonant circuit. As once can see from Fig. 4, the maximum P_n can be achieved when the R is in the range from 10^{-9} to 2×10^{-9} Ω m^2. This coincides well with the impedance spectrum (see Fig. 3) and with the microwave generation simulation results, which are not presented here. The P_n decreasing at high values of R can be explained by damping of high-frequency oscillations by the load resistor. It is clearly seen in the noise spectrum at $R=10^{-8}$ Ω m^2 (see Fig. 2, curve 3).

Therefore, the noise measurements above the generation threshold $U_{\rm th}$ can be used to determine the negative impedance and upper-frequency limit of n^+-n-n^+ microwave generators. Measuring the frequency of the peak $f_{\rm peak}$ as the function of R one can obtain the negative values of the real part of impedance at the high-frequency side of the negative impedance spectrum. The $U_{\rm th}$ can be determined by measuring the low-frequency noise power $P_n(0)$ as a function of diode bias U_d.

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