Noise and impedance of submicron InP diodes

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Abstract

The noise power spectral density of submicron n^+nn^+ InP diode loaded by a resistor R is investigated making use of a Monte Carlo particle technique and a closed hydrodynamic approach. We observe a peak in the spectrum which is caused by the spontaneous formation of electron accumulation layers. Furthermore, the drift of these layers through the n-region is monitored for biasing conditions above threshold for microwave generation. The frequency of the noise peak is shown to correspond to the highest generation frequency at the given R.

Introduction

The determination of hot-carrier noise in the high-frequency region (above GHz) is one of the most important figure of merit for submicron semiconductor devices. From one side, the time and frequency behavior of the fluctuations reflects both the dynamic and chaotic features of the hot carrier system and, as such, can be used for a detailed investigation of the physical processes responsible for the device performance [1,2]. From another side, noise characteristics are of great practical importance since they determine the lower limit of a device sensitivity, indicate the onset of generation processes, etc. [3,4]. The aim of this work is to provide a theoretical investigation of the hot-carrier noise in submicron n^+nn^+ InP diodes under biasing conditions for which the microwave power generation associated with velocity overshoot and electron valley-transfer is possible.

Procedure

The Monte Carlo Particle (MCP) method is the most appropriate technique for hot-carrier noise investigations since it allows the appropriate correlation functions to be calculated in a natural way, by using a time-averaging over a multi-particle history simulated during a sufficiently long time interval. As a rule, MCP is used to calculate either current or voltage noise spectral densities [2,5]. These noise operations correspond to idealized conditions when either the voltage U_d applied to the diode or the total current j flowing through the diode are kept constant in time. The current noise operation is realized when the diode resistance R_d is much greater than the external load resistance R. The conditions for the voltage noise operation are fulfilled in the opposite case. To consider the diode noise in intermediate cases we propose to study the voltage fluctuations on a load resistance R connected in series with the diode. To this purpose the correlation function of the fluctuations of the voltage drop U_R on the load resistance is calculated as:

$$K_U(\tau)=\frac{1}{T}\int_0^T \delta U_R(t)\delta U_R(t+\tau)dt \qquad (1)$$

where T is the averaging time, $\delta U_R(t)$ the fluctuation of U_R, τ is delay time. Then the noise power spectral density

$P_n(f)$ extracted from the load resistance at the frequency f is calculated in the standard way as:

$$P_n(f) = \frac{4}{R}\int_0^{\infty} K_U(\tau)\cos(2\pi f\tau)d\tau \qquad (2)$$

The advantage of this procedure is that by varying R and keeping constant the average voltage U_d applied to the diode one can make a continuous investigation of the diode performance from the current to voltage noise operations. To clarify the physical origin of the hot carrier noise for the same diodes we have also calculated the frequency dependence of the small-signal impedance Z(f). To this end, we employ a closed hydrodynamic (HD) approach. The details of the MCP and HD techniques used in our calculations can be found elsewhere [6].

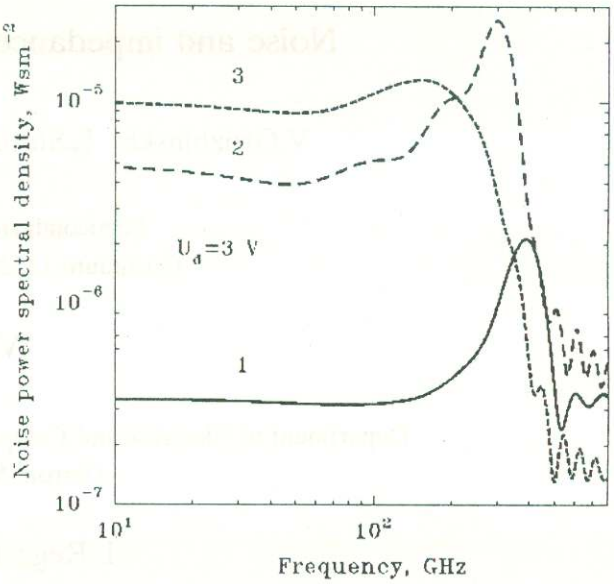

Fig. 1. Noise power spectral densities $P_n(f)$ versus frequency f at different R values.

Results

The following parameters for the n^+nn^+ InP diode are chosen in the present simulation: the length of the n-region is 0.6 μm, and the doping concentration in the n- and n^+-regions is $3{\cdot}10^{16}$ cm^{-3} and 10^{18} cm^{-3}, respectively. The current-voltage characteristic of this structure does not exhibit any region with a static negative differential resistivity (NDR). However, there exists a dynamic NDR in the frequency region 160÷400 GHz where the real part of the small-signal impedance, ReZ(f), is negative. The voltage threshold, U_{th}, for the presence of a dynamic NDR is of about 1.3 V.

Quite different behavior of the noise power spectral density $P_n(f)$ is obtained for values of the applied voltages below and above the NDR threshold U_{th}. Below the threshold, when ReZ(f) is positive at all frequencies, $P_n(f)$ exhibits the expected Lorentzian shape with two additional peaks at the frequencies which correspond to the plasma oscillations in the n and n^+ regions. Above the threshold for the dynamic NDR, $P_n(f)$ exhibits a huge peak whose amplitude and position depend on R.

Fig. 1 shows the noise power spectral densities $P_n(f)$ versus frequency calculated at different values of the load resistance R: 1 - 10^{-10}, 2 - $2{\cdot}10^{-9}$ and 3 - 10^{-8} Ωm^2. Here the applied voltage U_d=3 V is the same for all the curves and is considerably above the threshold value. The variation of $P_n(f)$ with R reflects a continuous transition from the current to voltage noise operation. Indeed, the most pronounced peak of $P_n(f)$ is observed when R is relatively small, i.e. under the conditions close to the current noise operation. Such a peak is similar to that of the spectral density of conduction current fluctuations as obtained for an unloaded diode under constant applied voltage operation [7]. This peak is caused by the spontaneous formation of electron accumulation layers and their subsequent drift through the n-region. The layers formation is related to the spatial overshoot of the drift velocity due to electron transfer to upper valleys and it usually takes place in the region where the local drift velocity exhibits the maximum negative slope. The peak frequency f_0 is determined by the average transit-time of the layer. Under the conditions close to the voltage noise operation all current oscillations are effectively damped due to influence of very high external resistance. Therefore, the peak of $P_n(f)$ practically disappears at large R (see curve 3), and the shape of the frequency dependence of $P_n(f)$ becomes very similar to the spectral behavior of the voltage fluctuations of the unloaded diode calculated under the constant total current operation [7].

As it follows from Fig. 1, by increasing R the peak frequency f_0 shifts to lower values. To explain such a shift Fig. 2 shows the frequency dependence of the real part of the small-signal impedance, ReZ(f), calculated for the same diode at U_d=3 V (solid curve). In general, to obtain amplification of a small-signal, ReZ(f) must be negative. For the case considered here, this condition is fulfilled in the range of frequencies f=160÷400 GHz. For values of the U_d which are above the threshold, i.e. when ReZ(f)<0 within a certain frequency range, due to spontaneous formation of the accumulation layers the generation process is always present in the structure even in the absence of a resonant circuit. A stable regime of microwave power generation is achieved when the total resistance of the circuit, R+ReZ(f), is equal to zero. Thus, the generation frequency f_0 must satisfy the condition ReZ(f_0)=-R. To verify this expectation, the dependence of the peak frequency f_0 on R, as obtained from the results of the MC calculations is presented in Fig. 2 by full circles with coordinates (f_0,-R). One can see that the full circles are close to the high frequency side of the impedance spectrum. Therefore, it is evident that the situation of a P_n(f) maximum at frequency f_0 is the consequence of microwave power generation in near linear regime.

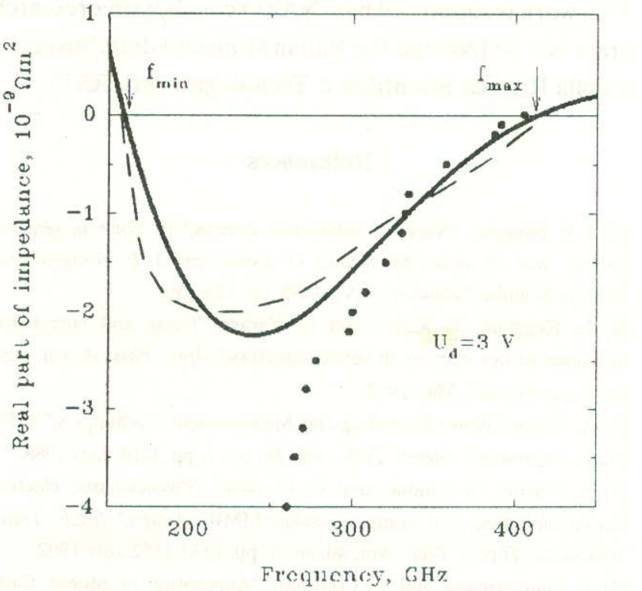

Fig. 2 Real part of the impedance spectrum calculated by the HD approach and by the MC method using eq. (3) (solid and dashed lines, respectively).

We remark that, by assuming a linear regime of generation one can express the noise power P_n(f) in the form:

$$P_n(f)=S_V(f)\frac{R}{|Z(f)+R|^2} \qquad (3)$$

where S_V(f) is the spectral density of voltage fluctuations of the unloaded diode under the constant current operation. By using the P_n(f) calculated from the MCP method at three different values of R one can obtain from (3) the frequency dependence of S_V(f), ReZ(f) and ImZ(f) of the unloaded diode. ReZ(f) as obtained by this procedure is presented in Fig. 2 by the dashed curve. We find a good agreement with the HD approach. Thus, the proposed procedure can be used for an indirect calculations of the small-signal impedance, provided the P_n(f) spectra are calculated with a sufficiently high accuracy.

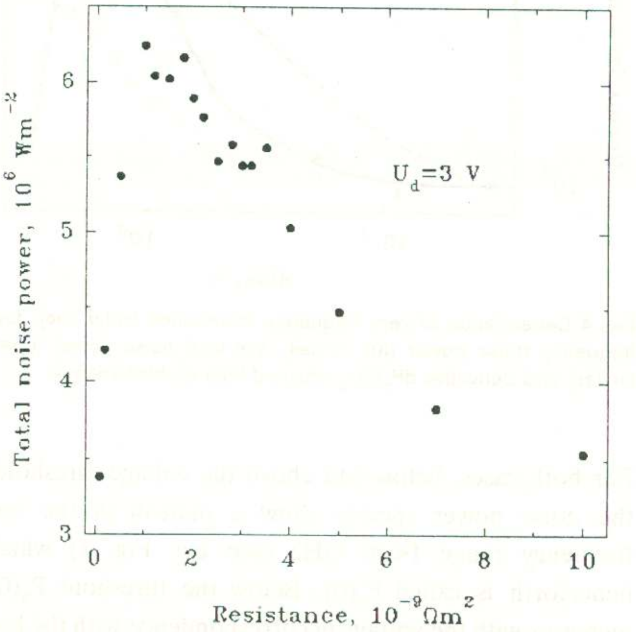

Fig. 3 Total noise power integrated over entire frequency range versus load resistance R.

From the above analysis we conclude that the peak in the noise spectra found for applied voltages above threshold comes from the noise of electrons accumulated into the layers due to the NDR. This process is similar to the nonlinear process of the microwave power generation when the diode is placed into an external resonant circuit. This similarity can be proven by the dependence of the total noise power integrated over the whole frequency range, P_n, on the load resistance R (see Fig. 3). Such a picture is typical of microwave generators operating in the resonant circuit. As one can see from Fig. 3, the maximum of P_n can be achieved when R ranges from 10^{-9} to $2\cdot10^{-9}$ Ωm^2. This coincides well with the impedance spectrum (see Fig. 2) and with the results obtained from a microwave generation simulation, which are not presented here. The decreasing of P_n at high values of R can be explained by the damping of the high frequency oscillations due to the load resistance, as it is clearly seen in the noise spectrum (see Fig. 1 curve 3).

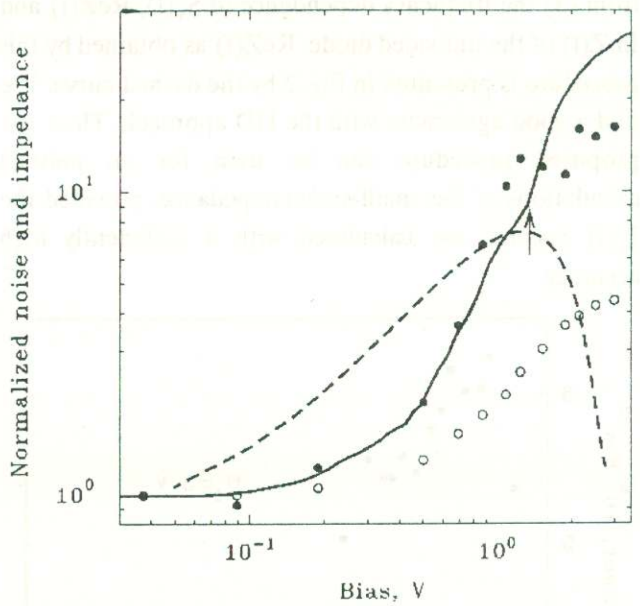

Fig. 4 Dependence of zero frequency impedance (solid line), low frequency noise power (full circles), the total noise power (open circles) and derivative dP_n/dU_d (dashed line) on bias voltage.

For both cases, below and above the voltage threshold, the noise power spectra show a plateau in the low frequency range f<20 GHz (see e.g. Fig. 1) which henceforth is called $P_n(0)$. Below the threshold $P_n(0)$ increases with the voltage in correspondence with the low frequency impedance ReZ(0). This is illustrated in Fig. 4 where the dependencies of $P_n(0)$ and ReZ(0) upon the diode bias are shown by full circles and solid line, respectively. The $P_n(0)$ and ReZ(0) are normalized to their values at U_d=0.04 V. Just above the threshold, $P_n(0)$ decreases while ReZ(0) continues to increase. This can be explained by a redistribution in frequency domain of the noise power density which is associated with the onset of the microwave power generation in the high frequency range. Indeed, the generation leads to a considerable enhancement of the noise power density in the frequency region where the real part of impedance ReZ(f) exhibits negative values. This yields a low frequency noise reduction, if we assume that P_n has no significant variations near the threshold voltage. Such an explanation is in good agreement with the monotonical increase of P_n with U_d, as reported in Fig. 4 by the open circles. Nevertheless, above threshold the appearance of generation influences the dependence of P_n on U_d too. Indeed, the behavior of dP_n/dU_d, as reported in Fig. 4 by the dashed line, has a maximum at the threshold voltage.

Conclusions

By performing a theoretical analysis of the noise spectral density of submicron n^+nn^+ InP diodes, we have proven that the calculation of the noise spectra provides useful information. In particular we determine the dynamic impedance and the upper frequency limit for microwave generation. From the calculation of the frequency of the noise peak as function the load resistance one can obtain the negative values of the real part of the small-signal impedance in the high frequency range of the spectrum. The full spectrum of the small-signal impedance can be recalculated from (3) using $P_n(f)$ as calculated at three different values of the load resistance. The threshold voltage U_{th} can be determined by evaluating the low frequency noise power $P_n(0)$ as a function of the diode bias U_d.

Acknowledgments

This work is supported by a NATO collaborative research grant No. 931360 and the Italian Ministero dell'Universita' e della Ricerca Scientifica e Tecnologica (MURST).

References

[1] J. P. Nougier, "Noise of submicron devices," in *Noise in physical systems and 1/f noise*, M. Savelli, G. Lecoy and J. P. Nougier eds., Elsevier Science Publishers B.V., 1983, pp. 153-159.

[2] L. Reggiani, T. Kuhn, and L. Varani, "Noise and correlation functions of hot carriers in semiconductors," *Appl. Phys. A*, vol. A54, no. 5, pp. 411-427, May 1992.

[3] A. Cappy, "Noise Modelling and Measurement Techniques," *IEEE Trans. Microwave Theory Tech.*, vol. 36, no. 1, pp. 1-10, Jan. 1988.

[4] F. Filicori, G. Ghione, and C. U. Naldi, "Physics-based electron device modelling and computer-aided MMIC design," *IEEE Trans. Microwave Theory Tech.*, vol. 40, no. 7, pp. 1333-1352, July 1992.

[5] J. Zimmermann and E. Constant, "Application of Monte Carlo techniques to hot carrier diffusion noise calculation in unipolar semiconducting components," *Solid-St. Electron.*, vol. 23, no. 9, pp. 915-925, 1980.

[6] V. Mitin, V. Gruzinskis, E. Starikov, and P. Shiktorov, "Submillimeter wave generation and noise in InP diodes," *J. Appl. Phys.*, vol. 75, no. 2, pp. 935-941, Jan. 1994.

[7] V. Gruzinskis, E. Starikov, P. Shiktorov, L. Reggiani, M. Saraniti, and L. Varani, "Small-signal and noise characteristics of submillimeter diode generators," in *Noise in physical systems and 1/f fluctuations*, P. H. Handel and A. L. Chung eds., AIP Press, New York, 1993, pp. 312-315.