Ensemble Monte Carlo with Poisson solver for the study of current fluctuations in homogeneous GaAs structures

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An analysis of current fluctuations in homogeneous $N$-type GaAs structures of different lengths and doping concentrations is presented. The study is performed coupling self-consistently a Poisson solver to a many-particle Monte Carlo simulation. The autocorrelation functions and the spectral density of current fluctuations are calculated, dividing them into different contributions that allow one to analyze several sources of noise. A qualitative analysis of shot noise is made. Different behaviors of current fluctuations are found among the different structures; these are interpreted in terms of the microscopic processes occurring inside them. For high values of impurity concentration ($10^{17}$ cm$^{-3}$), the coupling between fluctuations in the electric field and in carrier velocity is found to be an important source of noise.

I. INTRODUCTION

When one wishes to optimize the performance of electronic devices it is extremely important to have detailed knowledge of the transport processes responsible for the noise in the output current. Accordingly, the analysis of the fluctuations in velocity, current, electric field, carrier number, etc. is of great interest. The progressive decrease in the size of electronic devices down to submicrometer dimensions implies that the study of fluctuations should be based on techniques such as the Monte Carlo method, which allows one to take into account all the processes (scattering mechanisms, variations in the electric field, etc.) affecting the appearance of fluctuations, instead of phenomenological approximations that do not integrate in detail all the mechanisms responsible for the appearance of noise.

The Monte Carlo method has been used to analyze, under stationary conditions and with constant electric field, the fluctuations in current and in carrier velocity for different situations and models in the semiconductor most frequently used, using both single-particle and multiparticle simulations. Studies have also been made of velocity fluctuations in transients between two different constant-field situations. Some works have also dealt with the calculation of current fluctuations in simple devices, such as $n^+nn^+$ and homogeneous structures. Some of these works include the self-consistent calculation of the electric field, thereby enabling the analysis of the correlation between fluctuations in the current and in the field. The difficulties encountered when fluctuations are studied using multiparticle Monte Carlo simulations including Poisson solver are manifold: lengthy computation times, “noisy” autocorrelation functions, sensitivity to contact models, influence of the number of simulated particles, etc. Thus, there have been relatively few works attempting to deal with noise in which this kind of simulation has been used. However, it is only the ensemble Monte Carlo method that provides access to all the information required for a correct characterization of the fluctuations occurring in submicrometer structures. In view of this, in the present work we employ it to analyze current fluctuations in homogeneous GaAs structures.

In previous works we have analyzed the fluctuations in carrier velocity in $N$-type GaAs (considered as a homogeneous and limitless material) when the carriers are subjected to the action of a constant electric field, and also in transient conditions when the electric field changes. However, when the material considered is limited and a voltage is applied to its ends, the current circulating through it will depend not only on carrier velocity but also on the number of carriers present in the structure. Additionally, the dynamics of the charge inside the device leads to the electric field being nonhomogeneous; rather, there are oscillations which in turn contribute to modifying carrier velocity and, through this, the current. This velocity-field coupling, according to its magnitude, may also be the origin of current fluctuations.

In the present article we analyze current noise in homogeneous GaAs structures of different lengths and dopings. To do so we employ a one-dimensional Poisson solver coupled to a three-dimensional multiparticle Monte Carlo simulation, which allows us to study the effect of field fluctuations on those of the current. We also report on the static characteristics of the structures, which are a first and very important step in understanding the fluctuations, since they provide information concerning the processes occurring inside the structures that are the origin of the behavior of the fluctuations.

The article is organized as follows: Section II details the Monte Carlo simulation developed for this study, and the physical model used for GaAs. In Sec. III we present the theoretical analysis of the magnitudes calculated, together with the decomposition of the autocorrelation function and of the spectral density of current fluctuations that has been performed. Section IV deals with the results concerning the static characteristics of the structures analyzed. The results obtained for the autocorrelation function and the spectral density of current fluctuations are given in Sec. V. Finally, in Sec. VI we offer the main conclusions.
II. MONTE CARLO SIMULATION

A. Physical model

We consider homogeneous structures of N-type GaAs and length L at 300 K, with two contacts at their ends between which a constant voltage is applied, studying the fluctuations of the output current. Throughout the structure the cross section is homogeneous, such that the device can be analyzed as one dimensional.

To obtain the physical magnitudes to be studied, we have coupled self-consistently a one-dimensional Poisson solver with a multiparticle Monte Carlo simulation, three-dimensional in momentum space and one dimensional in real space.

We consider the conduction band of GaAs formed of three nonparabolic spherical valleys: Γ, L, and X. The electric fields attained in the different structures are not excessively high, such that this conduction band model is valid for the analysis performed. The scattering mechanisms considered are: intervalley (equivalent and non-equivalent), acoustic, piezoelectric, polar optical, non-polar optical, and interaction with ionized impurities. The physical parameters of GaAs employed in the simulation are the same as those used for the three valleys of the first conduction band in previous works, and used by other authors.

Structures of different lengths and doping levels have been simulated to observe the effect that such magnitudes have on the noise occurring in the output current. The doping concentrations analyzed are: 10^{14}, 10^{15}, 10^{16}, and 10^{17} cm^{-3}, and the lengths range from 0.6 to 2 μm. In each, the static characteristics were calculated, together with the autocorrelation function and the spectral density of current fluctuations for different applied voltages.

B. Simulation parameters

The number of simulated particles varies as a function of the doping concentration of each of the structures, searching for a compromise between a reduction in computation time and obtaining a reliable solution of the electric field. This number varies between 300 and 13 000 particles. As mentioned, the simulation is one-dimensional in real space, such that each simulated particle is equivalent to Q electrons m^{-2}. The value of Q, the simulated particle-electron equivalent, varies according to the doping density of the structures between 1.25 \times 10^{11} and 10^{13} electrons m^{-2}. Q corresponds to the inverse of the value of the cross-sectional area that gives with the number of carriers initially simulated a free-carrier density equal to the impurity concentration of the structure. The values of the output current are therefore given as current density in the electrodes through a cross-sectional area perpendicular to the field-resolution direction.

The Monte Carlo simulation, incorporating the Poisson solver, is performed following the usual method. All the structures are divided into equal cells of 100 Å each. It has been confirmed that by reducing the length of the cells the results obtained are the same. The same time step is used for all the simulations, 10 fs, which is appropriate in all cases for obtaining a correct solution for the electric field. Simulations have been made reducing this time step; similar results were obtained. Current values are recorded under steady-state conditions every 10 fs over 2 ns to calculate, from these values, the autocorrelation function of current fluctuations. Despite the long time interval simulated with a view to obtaining sufficient precision in the calculation of the autocorrelation functions, these show a fair amount of noise. This gives some idea of the calculation difficulties encountered when studying fluctuations.

In some cases, the values of the electric field are also recorded in order to analyze the spectrum of its fluctuations.

C. Contact models

One important factor involved in analyzing the output current of these structures is the model employed for simulating the electrodes; that is, the boundary condition (BC) in the contacts. In the case of one-dimensional structures, several alternatives exist, as follows.

(a) Periodic boundary condition (PBC): The carriers that reach a contact are reinjected into the opposite end with the same energy and wave vector.

(b) Thermal periodic boundary condition (TPBC): The carriers that reach an electrode are reinjected into the opposite end thermalized; that is, with a wave vector calculated randomly from a thermal distribution.

(c) Ohmic boundary condition (OBC): The electrodes are modeled as ideal ohmic contacts; that is, as a region of the device that is in thermal equilibrium even when a current is flowing through it. For this, one imposes the condition that the free-carrier concentration of a small region close to each contact should remain constant and equal to the doping density. To do so, the number of thermal carriers necessary for neutrality to be maintained in this regions is introduced in each time step.

Within PBC and TPBC the number of carriers inside the structure remains constant in time (thus ensuring charge neutrality), which implies that the electric field is the same in both terminals; however, within OBC the number of carriers inside the device fluctuates over time, becoming adapted to the requirements of the electron dynamics inside the structure. This type of model allows one to calculate the noise in the output current caused by carrier number fluctuations, which is not possible with the other BCs. The first two models are adequate for cases in which the carriers reach the electrodes in a situation close to thermal equilibrium; i.e., the active zone of the device is distant from the terminals. In the structures simulated in the present work this situation is very uncommon, and hence OBC has been adopted for modeling the electrodes, keeping charge neutrality in each time step in the cell adjacent to each contact. In any case, in order to observe the effect of the contact models on the spectral density of current fluctuations, the same structure was simulated with the three BCs under identical bias conditions. In Ref. 18 PBC and OBC are considered, together with their effects on current fluctuations.

One important aspect that should be analyzed is the possible effect on the results of modifications in the length...
of the region close to the ohmic electrodes in which charge neutrality is imposed. In the present case, the length of this region is that of a 100 Å cell. Owing to the large increase in computation time that this would involve, we have not performed this analysis; however, it is a question that should receive attention in future studies.

III. THEORETICAL ANALYSIS

Considering that the length of the structures is much smaller than the lateral dimensions, which implies that the current density \( I(t) \) through any cross-sectional area of the device will be the same, and taking into account that the voltage applied to the electrodes remains constant, with which the overall contribution of the displacement current is null, the current density is given by

\[
I(t) = \frac{qQ}{L} \sum_{i=1}^{N(t)} v_i(t),
\]

where \( q \) is the absolute value of the electron charge, \( Q \) is the simulated particle-electron equivalent, \( L \) is the length of the structure, \( N(t) \) is the instantaneous number of particles inside the structure, and \( v_i(t) \) is the instantaneous longitudinal velocity of the \( i \)th particle.

\( I(t) \) can also be expressed as

\[
I(t) = (qQ/L) \bar{v}(t) N(t),
\]

where \( \bar{v}(t) \) is the mean instantaneous velocity of the carriers in the device; that is,

\[
\bar{v}(t) = \frac{1}{N(t)} \sum_{i=1}^{N(t)} v_i(t).
\]

From Eq. (2), the current-density fluctuations \( \delta I(t) \) are given by

\[
\delta I(t) = I(t) - \langle I \rangle = \langle qQ/L \rangle [N(t) \bar{v}(t) - \langle N(t) \bar{v}(t) \rangle],
\]

where the angular brackets indicate time average. If one takes into account that

\[
N(t) = \langle N \rangle + \delta N(t),
\]

\[
\bar{v}(t) = \langle \bar{v} \rangle + \delta \bar{v}(t),
\]

one has for \( \delta I(t) \) the approximate expression

\[
\delta I(t) \approx (qQ/L) [\langle N \rangle \delta \bar{v}(t) + \langle \bar{v} \rangle \delta N(t)],
\]

where second-order terms in fluctuations have been neglected.

The autocorrelation function of current-density fluctuations is given by

\[
C_I(t) = \langle \delta I(t') \delta I(t'+t) \rangle = C_V(t) + C_N(t) + C_{VN}(t),
\]

where

\[
C_V(t) = \langle q^2 Q^2/L^2 \rangle \langle N \rangle^2 \langle \delta \bar{v}(t') \delta \bar{v}(t'+t) \rangle,
\]

\[
C_N(t) = \langle q^2 Q^2/L^2 \rangle \langle \bar{v} \rangle^2 \langle \delta N(t') \delta N(t'+t) \rangle,
\]

\[
C_{VN}(t) = \langle q^4 Q^4/L^4 \rangle \langle N \rangle \langle \delta \bar{v}(t') \delta N(t'+t) \rangle + \langle \delta N(t') \delta \bar{v}(t'+t) \rangle
\]

are the terms associated with different contributions to the autocorrelation function. \( C_V \) is associated with the fluctuations in the mean velocity of the electrons in the structure, \( C_N \) with the fluctuations in carrier number, and \( C_{VN} \) with the correlation between both magnitudes.

According to the Wiener-Kintchine theorem, the spectral density of current-density fluctuations is obtained from the autocorrelation function as its Fourier transform,

\[
S_I(f) = 2 \int_{-\infty}^{\infty} C_I(t) e^{i2\pi ft} dt = S_V(f) + S_N(f) + S_{VN}(f),
\]
TABLE I. Characteristic parameters (L, N, and Q) of the simulated structures, and mean values obtained for several magnitudes at the bias voltages for which S1 has been calculated.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Length (µm)</th>
<th>Doping (cm⁻²)</th>
<th>Q (10¹² electrons m⁻²)</th>
<th>Voltage (V)</th>
<th>&lt;(I)&gt; (10⁵ A m⁻²)</th>
<th>&lt;(V)&gt; (10⁷ cm/s)</th>
<th>&lt;(N)&gt; (particles)</th>
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<tr>
<td>A</td>
<td>1.0</td>
<td>10¹⁴</td>
<td>0.125</td>
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<td>0.0</td>
<td>631</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td>0.219</td>
<td>2.25</td>
<td>487</td>
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<td>1.0</td>
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<td>1.66</td>
<td>867</td>
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<td>0.335</td>
<td>1.29</td>
<td>1295</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0 (PBC)</td>
<td>0.194</td>
<td>1.21</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0 (TPBC)</td>
<td>0.268</td>
<td>1.67</td>
<td>800</td>
</tr>
<tr>
<td>B</td>
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<td>0.125</td>
<td>0.5</td>
<td>0.219</td>
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<td>1286</td>
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<tr>
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<td>0.0</td>
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<td>2.49</td>
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<td></td>
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<td>402.0</td>
<td>2.44</td>
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<td>10¹⁷</td>
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<td>1.2</td>
<td>358.0</td>
<td>2.12</td>
<td>9504</td>
</tr>
<tr>
<td>H</td>
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<td>10¹⁷</td>
<td>10.0</td>
<td>1.6</td>
<td>332.0</td>
<td>1.95</td>
<td>12765</td>
</tr>
</tbody>
</table>

where

\[ S_N(f) = 2 \int_{-\infty}^{\infty} C_N(t) e^{2\pi f t} dt, \]  

\[ S_{VN}(f) = 2 \int_{-\infty}^{\infty} C_{VN}(t) e^{2\pi f t} dt. \]  

By separating in these terms both the autocorrelation function and the spectral density, one obtains information about the contribution of several sources to the noise in the current, such as fluctuations in carrier velocity and in the number of electrons present in the structure. \( S_N \) will reflect, for example, shot noise due to the injection through the ohmic electrodes. Of course, \( S_N \) and \( S_{VN} \) will be zero in the case of considering PBC or TPBC; in this case the only contribution to the noise is that of \( S_F \).

Since \( I(t) \) is obtained directly from the carrier velocities, the value of \( \delta I(t) \) will depend on the number of particles contributing with their velocity in Eq. (1), \( N(t) \). This dependence is of the type \( N(t)^{-1/2} \).

On simulating the same structure under identical bias conditions with different values of \( Q \), and hence with different values of \( \langle N \rangle \), and calculating the time-average values \( \langle \delta I \rangle \) and \( \langle \delta I^2 \rangle \), one finds that they show a dependence on \( \langle N \rangle \) of the type \( \langle N \rangle^{-1/2} \) and \( \langle N \rangle^{-1} \), respectively. This is shown in Fig. 1. One has

\[ \langle \delta I \rangle \langle N \rangle^{1/2} = A \langle \delta I \rangle \langle N \rangle^{1/2}, \]  

where \( A \) is a constant, and \( \delta I \) and \( N \) are the real values in a structure of unitary cross-sectional area of the current density fluctuations and the number of carriers inside it, respectively. Accordingly, a suitable estimation of \( \delta I(t) \) will be given by

\[ \delta I(t) = \frac{\delta I(t)}{\langle N(t) \rangle^{1/2} Q^{1/2}}. \]  

As mentioned above, the value of \( Q \) employed in each simulation varies from one structure to another according to their doping concentration, in order to obtain a valid solution for the electric field. Following Eq. (17), in our simulations all the \( \delta I(t) \) values recorded were divided by \( Q^{1/2} \). In this way it is possible to compare the results obtained both for \( C(f) \) and for \( S_f(f) \) among different structures (and within the same structure among different bias situations), regardless of the number of particles present inside them in each of the situations, as well as of their doping level and length.

Thus, Eqs. (4) and (7) should be divided by \( Q^{1/2} \) and Eqs. (9)-(11) by \( Q \), to obtain the final form used in the calculations. Moreover this originates that the units employed for \( C(f) \) should be \( A^2 \text{m}^{-2} \) instead of \( A^2 \text{m}^{-4} \), and for \( S_f(f) \) should be \( A^2 \text{s}^{-2} \) instead of \( A^2 \text{s}^{-4} \). With this normalization if one wants to obtain the value of the spectral density of current fluctuations in a real structure, it is only necessary to multiply the calculated value of \( S_f(f) \) by its cross-sectional area.

IV. STATIC CHARACTERISTICS

In this section we present some of the results corresponding to the static characteristics of the simulated structures that we consider of great importance for revealing the processes causing noise. Table I shows the charac-
Figure 2 shows the I-V characteristics of structures A and F, which can be considered as extreme cases among those analyzed. In both cases it can be observed that after a small linear region, another saturation region appears, which is much more pronounced in structure F. In these curves no negative differential resistance region typical of GaAs velocity-field characteristics appears. This is due to the fact that, with the BC applied, when the carriers pass to the higher valleys the number of them present inside the structure increases to keep the current constant along the device. This makes the current rise in spite of the decrease in the velocity. These characteristics allow these devices to be used as current limiters.\textsuperscript{27,28}

The stationary mean values of free-carrier density, electric field, and drift velocity at different bias voltages in some of the structures are shown in Figs. 3–5. It can be seen that, owing to the different doping levels, the same relative charge unbalances give rise to very different electric-field distributions inside the structures. Thus, in the structure with the lowest doping concentration the electric field remains practically constant, while, as doping increases, the field distribution becomes progressively less uniform, until it acquires very high values in the neighborhood of the electrodes in structure F for applied voltages of 0.6 and 0.8 V.

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The high values of the electric field reached at the ends of this structure when high voltages are applied are due to different processes, which in turn they feed back. At the cathode it is caused by an overshoot in the velocity of the
FIG. 4. Profiles of (a) free-carrier density, (b) electric field, and (c) drift velocity as a function of the distance from the cathode in structure C ($L=1\, \mu m$ and $N_D=10^{15}\, \text{cm}^{-3}$) for several bias voltages.

carriers, which are shot into the structure in the $\Gamma$ valley. In the neighborhood of the anode, it is caused by the appearance of a narrow region of strong accumulation of free carriers, which is due to a massive transfer of these to the higher $L$ and $X$ valleys (with a greater effective mass), as shown in Fig. 6. As the doping density decreases, the space-charge effects decrease and the transference of carriers to higher valleys becomes increasingly softer, and their occupation becomes more uniform in a larger region of the structure; the distribution of the field is therefore more homogeneous.

For low doping (Figs. 3 and 4), when space-charge effects are not very important, the BC adopted is not able to keep the carrier concentration inside the structures at low applied voltages, when most of the carriers are in the $\Gamma$ valley, and a charge depletion appears. When the voltage is higher, so that the electric field is far beyond the threshold value for the carriers to pass to the upper valleys, the concentration is strongly nonuniform in order to keep the current constant along the structure. Thus, near the cathode, where the carriers are very fast because they are injected thermalized, the concentration is low, while in the region where they become slower due to their transference to the $L$ and $X$ valleys, the concentration increases.

FIG. 5. Profiles of (a) free-carrier density, (b) electric field, and (c) drift velocity as a function of the distance from the cathode in structure F ($L=0.6\, \mu m$ and $N_D=10^{17}\, \text{cm}^{-3}$) for several bias voltages.
It should be stressed that, whereas in the structures with the lowest doping levels the saturation of the $I-V$ characteristics is mainly due to the decrease of the velocity of the carriers when they are transferred to the higher valleys, as the doping concentration increases the space-charge effects and the carrier accumulation region are much more important, and are the main cause of current saturation, which becomes increasingly more pronounced. The different origins of the current-limiting effects also lead to different kinds of behavior in current fluctuations, and hence in the noise characteristics in these structures.

V. AUTOCORRELATION FUNCTIONS AND SPECTRAL DENSITY

In this section we present the results obtained concerning the autocorrelation functions and the spectral density of current fluctuations, as well as the different terms into which these have been divided, as explained in Sec. III.

The noise sources that can be registered in the structures analyzed are diverse: thermal noise, diffusion noise, shot noise, noise due to electric field fluctuations, etc. The BC adopted, OBC, allows one to analyze the noise due to the fluctuations in the number of carriers inside the structure, and therefore to account for shot noise. The time scale of shot noise is considerably higher than that of the other noise sources analyzed. It appears at very low frequencies as compared with the range of them that the method employed allows one to analyze with an acceptable degree of accuracy. Certain difficulties were found in reliably calculating the autocorrelation functions that record shot noise, in some cases obtaining results that present a rather "noisy" shape. To calculate them correctly, many more carriers should be simulated over a longer time interval, which would require excessive computation time. However, the calculations performed do permit a qualitative analysis of shot noise, which we consider of great interest, above all taking into account the broad range of doping levels analyzed.

Figure 7 shows the results obtained for $S_f$ and $S_v$ [Eqs. (12) and (13)] in structure A for different applied voltages. Two different contributions can be seen in $S_f$; these appear in very different frequency ranges. One arises from carrier shot noise, reflected in $S_N$ and $S_{VN}$, appearing at low frequency. The other is associated with the diffusion noise caused by velocity fluctuations, recorded in $S_v$, and dominant at higher frequencies. For a null bias, when there is no current, $S_f$ coincides with $S_P$, since in this case there is only thermal noise. When the sample is biased, shot noise appears, and it is present at lower frequencies as the applied voltage increases.

Accordingly, when the structures are biased, the noise present at low frequencies is dominated by the fluctuations in the number of carriers inside them. At higher frequencies, the main term corresponds to fluctuations in the velocity of the electrons. As may be seen in Fig. 3, the electric field in structure A is almost uniform, and there is a broad region in which velocity is also uniform. This occasions that the shape of the $S_v$ curves coincides with that of the spectral density of velocity fluctuations calculated under constant electric-field conditions in limitless material.513
FIG. 8. Decomposition of the spectral density of current fluctuations vs frequency in structure A \((L=1 \, \mu m \text{ and } N_D=10^{14} \, \text{cm}^{-3})\) for an applied voltage of 1.5 V.

and that the maximum is at the same frequency. The differences in the relative amplitude between both calculations are due to the different number of carriers inside the structures for each voltage (Table I).

Figure 8 shows the decomposition of \(S_f\) for an applied voltage of 1.5 V in structure A. The foregoing statements are clearly appreciable in it. It should be noted that the crossed term \(S_{VN}\) has a significant value; the effect of the correlation between fluctuations in velocity and in carrier number thus being important.

To highlight the importance of the BC in the results, \(S_f\) has been calculated in structure A for a voltage of 1 V with the three BCs proposed in Sec. II C (Fig. 9). As was explained, within PBC and TPBC the total number of carriers inside the structure remains constant in time. Thus, \(S_f\) coincides with \(S_V\) and shot noise is not accounted for. Whereas within PBC all the magnitudes (electric field, valley occupation, velocity, free-carrier concentration) are uniform throughout the structure, in the case of TPBC there is an initial region close to the cathode where these magnitudes are different because the carriers are injected thermalized. This gives rise to the differences between \(S_f\) for both BCs. It seems clear that the most appropriate model of BC is OBC, since in these structures the carriers do not reach the anode in thermal equilibrium and, also, because it is the only model that takes into account the effect of carrier number fluctuations on the output current.

In structure C, the behavior found for the current fluctuations (Fig. 10) is similar to that observed in structure A. For this doping concentration \((10^{15} \, \text{cm}^{-3})\) the electric field in the structure is less uniform (Fig. 4), such that \(S_V\) becomes more distant from that calculated with constant field in limitless material. Figure 11 shows the components of \(S_f\) for an applied voltage of 1 V. As may be seen, this decomposition is similar to the case of \(N_D=10^{14} \, \text{cm}^{-3}\).

The values obtained for \(S_f\) in structures A and C with an applied voltage of 1 V are compared (Fig. 12) with

FIG. 9. Spectral density of current fluctuations vs frequency in structure A \((L=1 \, \mu m \text{ and } N_D=10^{14} \, \text{cm}^{-3})\) for a bias voltage of 1 V employing different boundary conditions for modeling the contacts.

FIG. 10. Spectral density of current fluctuations vs frequency in structure C \((L=1 \, \mu m \text{ and } N_D=10^{15} \, \text{cm}^{-3})\) for several bias voltages.

FIG. 11. Decomposition of the spectral density of current fluctuations vs frequency in structure C \((L=1 \, \mu m \text{ and } N_D=10^{15} \, \text{cm}^{-3})\) for an applied voltage of 1 V.
FIG. 12. Comparison between the values of the spectral density of current fluctuations in structures of different length: (a) structures A ($L = 1 \mu m$ and $N_D = 10^{14} \text{cm}^{-3}$) and B ($L = 2 \mu m$ and $N_D = 10^{14} \text{cm}^{-3}$); (b) structures C ($L = 1 \mu m$ and $N_D = 10^{15} \text{cm}^{-3}$) and D ($L = 2 \mu m$ and $N_D = 10^{15} \text{cm}^{-3}$).

those corresponding to an increase in length up to 2 \mu m (structures B and D). The applied voltage in the longer devices has been increased proportionally to maintain the mean field inside them equal to that of the shorter ones. The behavior of both doping levels ($10^{14}$ and $10^{15} \text{cm}^{-3}$) is the same. On increasing length, shot noise increases considerably, whereas $S_N$ is reduced (keeping the same shape), as corresponds to the increase in the number of particles inside the structure.

Figure 13 shows the values of $S_I$ obtained for structure E. No results are offered for voltages higher than 0.5 V because above this voltage Gunn oscillations$^{25}$ are detected. With this doping level ($10^{16} \text{cm}^{-3}$) an important difference appears with respect to the previous ones. The $S_N$ term takes much lower values as a result of the fact that the current starts to be controlled by space-charge effects, which in turn regulate the behavior of the number of carriers in the device. Now $S_V$ is the dominant component of $S_I$ even at low frequencies, as may be seen in Fig. 14 for a voltage of 0.5 V.

When the impurity concentration is increased up to $10^{17} \text{cm}^{-3}$ (structure F) the behavior of $S_I$ changes (Fig. 15). For low voltages, when the carriers do not pass to the higher valleys, $S_I$ is dominated by $S_V$. $S_V$ has a shape similar to that observed in the structures with lower doping levels, and it is mainly determined by the value of the field, which is fairly uniform (Fig. 5). The influence of $S_N$ in this case is minimal, like that of $S_{VN}$.

For higher voltages, when the carriers do pass to the higher valleys, a region of strong space-charge accumulation is formed in the neighborhood of the anode which, as has been explained, is what regulates the current in the structure. Its effect causes the value reached by $S_I$ to become far higher than in the previous cases, and the frequency of its maximum to remain constant despite modifications in the bias voltage. As seen in Fig. 16, corresponding to 0.8 V, the most important contribution in $S_I$ is $S_V$. $S_{VN}$ also takes a significant value. $S_N$ is almost negligible due to the controlling effect of the space-charge.

FIG. 13. Spectral density of current fluctuations vs frequency in structure E ($L = 1 \mu m$ and $N_D = 10^{16} \text{cm}^{-3}$) for several bias voltages.

FIG. 14. Decomposition of the spectral density of current fluctuations vs frequency in structure E ($L = 1 \mu m$ and $N_D = 10^{16} \text{cm}^{-3}$) for an applied voltage of 0.5 V.
accumulation. It should be stressed that the three contributions display their extreme value at the same frequency.

The origin of this change lies in the behavior of the final accumulation layer. The intervalley transitions occurring in this region lead to important modifications in the charge density which give rise to strong variations in the electric field throughout the structure; this significantly affects the velocity of the carriers. This coupling between the fluctuations in the electric field and in carrier velocity is the reason underlying the very high values of $S_V$. To illustrate this effect, in Fig. 17 we show the spectral density of electric-field fluctuations in the cells situated at 0.015 μm from the cathode and the anode in structure F, for a voltage of 0.8 V. As can be seen, their shape is similar to that of $S_V$ and their value is fairly high as compared with that calculated for other biases and dopings, for which electric-field oscillations are not so clear. The appreciable value of the crossed term $S_{VN}$ (Fig. 16) shows that there is also a relationship between the behavior of the accumulation region and the fluctuations in the number of carriers inside the structure.

When the length of the structures is increased (G and H) and the applied voltage is increased proportionally in order to maintain the mean electric field, it can be seen that the maximum present in $S_F$, in the presence of the accumulation layer, is displaced to lower frequencies (Fig. 18). The frequency corresponding to the maximum of $S_F$ is related with the time taken by the carriers shot into the cathode to reach the accumulation region, feeding back the process that causes the electric-field fluctuations, and thus determining the characteristic time of the field oscillation. In this way, the longer the structures, the larger the region that the carriers have to cross, and the smaller the frequency of the maximum of $S_F$.

VI. CONCLUSIONS

Using a one-dimensional Poisson solver for the calculation of the electric field coupled to a three-dimensional many-particle Monte Carlo simulation, we have analyzed both the static characteristics and the current fluctuations in homogeneous $N$-type GaAs structures with dimensions...
The static $I$-$V$ characteristics reach a different degree of saturation depending on the doping level of the structures, since the processes leading to it differ. Current fluctuations have been analyzed through their autocorrelation function and their spectral density, dividing these into several terms associated with the fluctuations in the mean carrier velocity and in the number of carriers present inside the structure. In this way, different noise sources have been studied: thermal noise, diffusion noise, noise due to field oscillations, shot noise, etc. Shot noise has only been analyzed qualitatively.

The following was found.

(i) The choice of a suitable BC is very important for obtaining results that will reliably reflect the physical processes occurring at the contacts. It is for this reason that OBC has been chosen, which also allows one to consider the fluctuations in carrier number.

(ii) Shot noise appears at low frequencies and is more important for low doping levels ($10^{14}, 10^{15}$ cm$^{-3}$), when the current in the structure is only limited by the decrease in the velocity of the carriers when passing to the higher valleys. This type of noise increases when the length of the structures increases. The appearance of space-charge effects, which limit the current in the structures, makes the fluctuations in carrier number decrease.

(iii) For high frequencies, the noise associated with fluctuations in carrier velocity predominates; up to $10^{16}$ cm$^{-3}$ this coincides with that corresponding to homogeneous and limitless material with constant field.

(iv) In the structures with $N_d=10^{17}$ cm$^{-3}$, a region of free-carrier accumulation is seen to appear for high bias voltages, leading to a coupling between the fluctuations in the electric field and in carrier velocity. This gives rise to a very high value of the spectral density of current fluctuations, above all in a frequency range that depends on the length of the structure.

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