Influence of spatial correlations on the analysis of diffusion noise in submicron semiconductor structures

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We present a microscopic analysis of the influence of the spatial correlations between local diffusion noise sources on the noise calculation in a submicron GaAs n^+nn^+ diode under different applied voltages. The simulation is carried out using an ensemble Monte Carlo simulation. We demonstrate that in the case of submicron nonhomogeneous structures the use of the diffusion coefficient to characterize the local noise sources is not correct, specially under far-from-equilibrium conditions. The nonuniformity of the electric field and the nonstationary behavior of the electrons lead to significant changes in the spatial correlations with respect to the case of an homogeneous semiconductor. Therefore, the diffusion noise at the terminals must be calculated in terms of the correlations between the local noise sources.

It has already been demonstrated that noise sources placed at distances of the order of the mean free path of the carriers inside a semiconductor are correlated.[1–4] The importance of these correlations in homogeneous materials depends on the distance, the electric field and the type of semiconductor.[3,5] The correlation length (distance over which the correlation persists) decreases as the electric field increases, and is longer in GaAs than in Si because of the different type of scattering mechanisms predominating.

The diffusion coefficient is usually employed to characterize the local noise sources when calculating diffusion noise in devices,[6] thus assuming that the spatial correlations related to a given point are the same as those present in a homogeneous semiconductor under stationary conditions. However, in the case of nonhomogeneous devices, several factors (nonuniformity of the electric field, nonstationary transport) may change the behavior of the spatial correlations with respect to the case of an homogeneous material. These effects are important on the noise at the terminals when the length of the device is of the order of the correlation length, i.e., in submicron devices.

The purpose of this work is to study the importance of the above-mentioned effects on the diffusion noise in a submicron GaAs n^+nn^+ structure, where the nonhomogeneity is introduced by the n^+-n homojunctions. The analysis is performed by using an ensemble Monte Carlo simulation.[7] This method allows the calculation of the noise without introducing any *ad hoc* supposition about the properties of the noise sources or their correlations.

In the simulation the structure is divided into cells of 100 Å each, and the cross correlations between the mean velocities of the carriers inside each of them are calculated. The spatial correlations are studied by decomposing the noise related to cell n, represented by a magnitude $D_n(f)$, into the contributions coming from the correlations with near cells m, $D_{nm}(f)$, so that

$$D_n(f)=\sum_m D_{nm}(f). \tag{1}$$

The details of the theory underlying this decomposition were described in a previous work.[5]

In Ref. 5 it was shown that $D_n(f)$ corresponds to the longitudinal diffusion coefficient when the field and carrier distributions are homogeneous over distances longer than the correlation length. This is not the case of the structure we are going to analyze, where the values of $D_{nm}(f)$ are expected to be modified by the nonhomogeneity. We study a GaAs n^+nn^+ diode. The impurity density is 10^{17} cm^{-3} in the n^+ regions and 5×10^{15} cm^{-3} in the n region. The dimensions are: 0.3 and 0.4 μm for the source and drain n^+ regions, respectively, and 0.6 μm for the n region. The initial number of particles (to assure charge neutrality) is 29 200. Ohmic boundary conditions are applied at the ends of the structure, where the number of carriers is updated every time step. The carrier kinetics is simulated during 1 ns divided in time steps of 10 fs. The values of $D_{nm}(f)$ are calculated by Fourier transform of the cross-correlation functions of the velocity fluctuations obtained from the simulations. During this study the field profile is fixed to its stationary value, evaluated previously by averaging over 50 ps in which the field is updated at each time step by using a one-dimensional Poisson solver. The material parameters and scattering mechanisms taken into account in the simulations were described in previous works.[5,8]

We have analyzed three situations, one of them corresponding to equilibrium, and the other two to bias voltages of 0.15 and 0.6 V. The stationary profiles of the free-carrier concentration, electric field, velocity, and energy are plotted in Fig. 1. The results obtained for the low-frequency value of D_n in the n region of the structure are presented in Fig. 2, together with the value of the longitudinal diffusion coefficient (for homogeneous GaAs with the impurity concentration of the n region) corresponding to the electric field present at each position. Figure 3 shows the contributions to $D_n(0)$ in certain positions of the sample coming from the correlations with close cells, $D_{nm}(0)$ (for the sake of clear-

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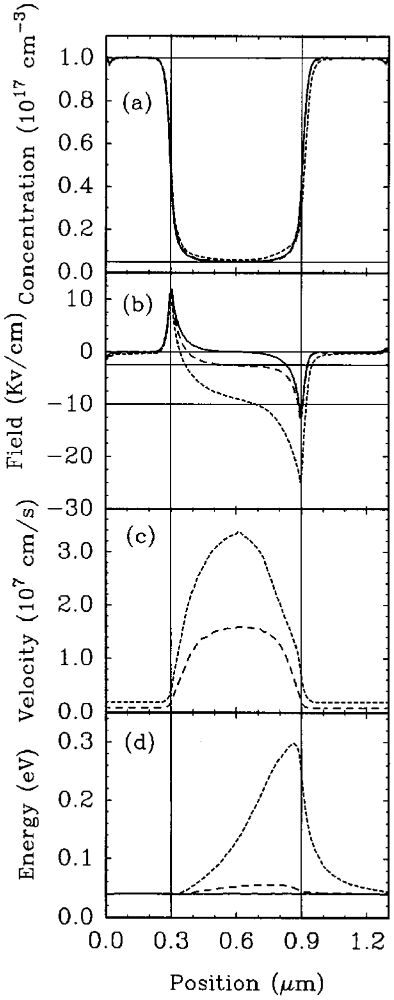

FIG. 1. Profiles of (a) free-carrier concentration, (b) electric field, (c) velocity, and (d) energy, as a function of the position in the structure. The applied voltage is: 0 V (solid line), 0.15 V (long dash), 0.6 V (short dash).

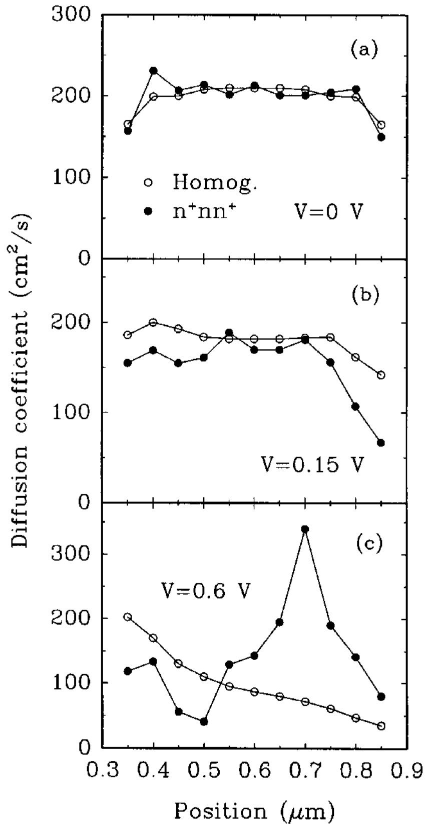

FIG. 2. Low-frequency value of D_n as a function of the position in the n^+nn^+ structure (full circles) obtained by adding the contributions from the cross-correlations D_{nm}. Open circles correspond to the values obtained for the longitudinal diffusion coefficient in bulk GaAs (homogeneous, with the doping of the n region) for the electric field present in that point of the n^+nn^+ structure. The bias voltages are (a) equilibrium, (b) 0.15 V, and (c) 0.6 V.

ness we do not represent them when they become negligible).

At equilibrium Fig. 2(a), both sets of values (D_n and the longitudinal diffusion coefficient) are similar within the uncertainty of the calculations, which we estimate to be 15%. This agreement can be explained taking into account how the cross-correlations behave inside the sample. Figure 3(a) shows the decomposition of $D_n(0)$, at the positions 0.35, 0.6, and 0.85 μm, into the spatial contributions $D_{nm}(0)$, as well as the values obtained in homogeneous material at equilibrium.[5] The exactness in the curves of the n^+nn^+ structure is lower because the number of particles simulated in each cell is lower than in the homogeneous case. In fact, spurious spikes and spatial fluctuations are observed when the correlation vanishes. The behavior of the spatial correlations in the n^+nn^+ diode is quite similar to that in the homogeneous sample, specially for positions inside the n region where the electric field [Fig. 1(b)], velocity and carrier concentration are uniform (Fig. 1). Only slight deviations appear near the n-n^+ homojunctions (due to the electric field associated with the built-in potential) and inside the n^+ regions (due to the higher efficiency of impurity scattering, which reduces the correlations).[5] We can conclude that in this case the diffusion coefficient can be used to characterize the noise associated with each position.

Figure 2(b) presents the results obtained for a bias voltage of 0.15 V. In this case, both sets of values only agree in the central part of the sample. The differences can be explained by comparing the decomposition of $D_n(0)$ into the spatial correlations $D_{nm}(0)$ with the homogeneous case (for an electric field of 2.5 kV/cm, which corresponds to the mean field in the n region of the diode) [Fig. 3(b)]. Only in the center of the n region the spatial dependence of the correlations is similar to the bulk case. When the electrons enter the n region (coming from the source) they are practically thermal, and must cover some distance before their energy and velocity take the values corresponding to the electric field present in the n region [Figs. 1(c) and 1(d)]. Near the second homojunction the velocity and energy decrease due to the thermalizing effect of the drain n^+ region. Thus, the electrons only reach the steady state corresponding to the electric field along a zone of 0.3 μm in the center of the n region, and it is there where the spatial correlations are similar to the homogeneous case and $D_n(0)$ corresponds to the diffusion coefficient. Elsewhere, inside the n^+nn^+ structure the correlations show a different behavior, leading to values of $D_n(0)$ lower than the diffusion coefficient corresponding to the local electric field. The differences are stronger in the

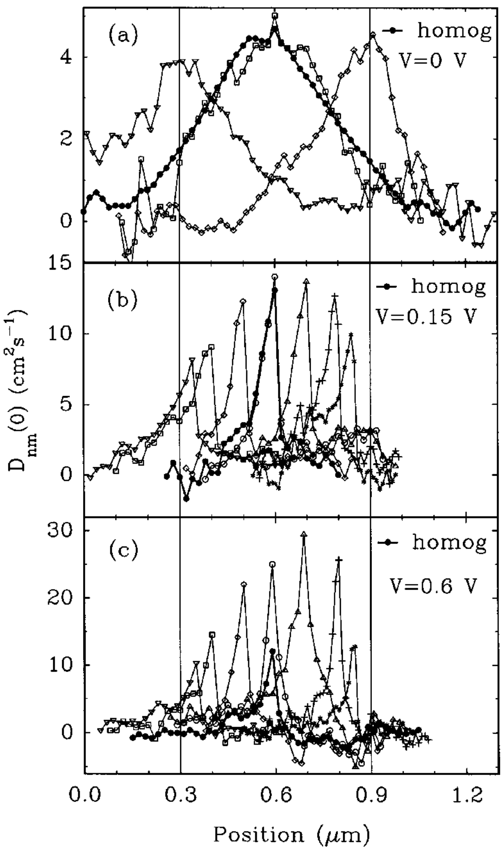

FIG. 3. Contribution to the low-frequency value of D_n in cells located at (▽) 0.35 μm, (□) 0.4 μm, (◇) 0.5 μm, (○) 0.6 μm, (△) 0.7 μm, (+) 0.8 μm, and (*) 0.85 μm from the source contact [only at (▽) 0.35 μm, (□) 0.6 μm, and (◇) 0.85 μm at equilibrium], coming from the correlation with cells at different distances D_{nm}. The full circles correspond to the value of D_{nm} obtained for a sample of homogeneous GaAs (with the doping of the n region) and an electric field equal to the mean field in the n region of the n^+nn^+ structure. The bias voltages are (a) equilibrium, (b) 0.15 V, and (c) 0.6 V.

vicinity of the drain homojunction, where an important number of randomizing scattering mechanisms takes place due to the high energy of the electrons. These mechanisms make the correlation disappear for very short distances inside the drain. However, near the source n^+ region the carriers are practically at equilibrium, and the only effect modifying the correlation is the presence of the field due to the built-in potential. Thus, the correlation extends over a longer distance, mainly in the source direction.

The effects related to the nonstationary motion of the electrons are higher as the applied voltage is increased, as can be observed in Fig. 1 for a bias voltage of 0.6 V. The electrons do not exhibit the velocity and the energy corresponding to the field. There is an overshoot in the velocity and the steady state is not reached at any position inside the n region. Moreover, while for the previous bias points the electric field was uniform along an important part of the n region, for 0.6 V it is strongly nonuniform (as compared with the correlation length). All these factors increase the disagreement between $D_n(0)$ and the diffusion coefficient associated with the local electric field [Fig. 2(c)]. Nowhere inside the structure do the spatial correlations coincide with those in the homogeneous sample (for an electric field of 10 kV/cm, corresponding to the mean field in the n region of the diode) [Fig. 3(c)]. Near the source, similar effects to the previous applied voltage take place. As the carriers advance along the n region the free paths increase, and as a result the velocity correlations persist over a longer time and distance, leading to very high values of $D_{nm}(0)$ [and consequently of $D_n(0)$]. Near the drain junction the intervalley scattering mechanisms (isotropic) between the Γ and the upper valleys are dominant. This fact produces negative values in the cross-correlation functions which lower $D_{nm}(0)$ and $D_n(0)$,[5,9,10] and the correlation practically disappears inside the drain. Therefore, in view of the results obtained under far-from-equilibrium conditions, we must remark that the use of the diffusion coefficient to characterize the noise associated with each position in the n^+nn^+ structure is not correct, and the different spatial correlations must be taken into account.

In conclusion, we have presented a microscopic analysis of spatial correlations between local diffusion noise sources in a GaAs n^+nn^+ diode in order to investigate the effect of the nonhomogeneity. By using an ensemble Monte Carlo simulation we have avoided any *a priori* assumption about the behavior of the noise sources. The results show that the diffusion coefficient cannot be used to describe the local noise sources when calculating diffusion noise in short (as compared with the correlation length) nonhomogeneous devices, specially far from equilibrium. The nonstationary transport and the nonuniformity of the electric field are responsible for a behavior of the spatial correlations different to the case of an homogeneous semiconductor. Thus, in such devices, the noise must be analyzed by taking into accoiunt all the individual cross correlations, instead of describing it through the diffusioin coefficient corresponding to the local electric field.

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