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A microscopic interpretation of hot-electron noise in Schottky barrier diodes

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Abstract. We present a microscopic analysis of current and voltage fluctuations in GaAs Schottky barrier diodes under forward-bias conditions in the absence of $1/f$ contributions. Calculations are performed by coupling self-consistently an ensemble Monte Carlo simulator with a one-dimensional Poisson solver. By using current and voltage operation modes we provide the microscopic origin and the spatial location of the noise sources respectively. The coupling between fluctuations in carrier velocity and self-consistent field is found to be essential in determining the noise spectra. Different types of noise (shot, thermal and excess) are exhibited by the device at different voltages. In particular excess noise due to hot carriers and intervalley transfer is detected for the highest voltages.

1. Introduction

Several applications of Schottky barrier diodes (SBDs), such as mixing and detection, extend up to frequencies of several hundred gigahertz. The quality factor of these applications is limited by the noise characteristics of the diodes [1]. Hence, a detailed characterization of the noise performances in these devices remains necessary. In particular, the noise temperature is one of the most important parameters to be determined. In recent years this subject has received special attention [2–5]. However, the phenomenological approaches which are usually employed make an unambiguous identification of the noise sources responsible for fluctuations difficult. Therefore, to our knowledge, a microscopic interpretation of the processes causing noise is still lacking. In the present work we employ a Monte Carlo simulator coupled with a one-dimensional Poisson solver (PS) to study the noise characteristics (both of current and voltage) of a GaAs SBD under forward-bias conditions. The application of this method avoids any *ad hoc* assumptions about the properties of the noise sources, and thus provides a unifying microscopic analysis of the processes responsible for the fluctuations.

2. Physical model

The simulated structure is shown schematically in figure 1. It is modelled as a one-dimensional GaAs n^+–n–metal structure. The n^+ region is 0.35 μm long and its doping is 10^{17} cm^{-3}. At its left side, where the carriers are injected into the device, an ohmic contact is simulated, and the number of electrons considered is updated. The n region is 0.35 μm long and its doping is 10^{16} cm^{-3}. At its end is the Schottky barrier with the metal contact acting as a perfect absorbing boundary. The barrier height considered in the simulation is 0.735 V, which leads to an effective built-in voltage at equilibrium of 0.640 V between the n region of the semiconductor and the metal. The GaAs conduction band consists of three non-parabolic spherical valleys (Γ, L and X). The material parameters and the scattering mechanisms are the same as in [6]. The Monte Carlo simulation follows the standard scheme [7]. The device is divided into equal cells of 100 Å each, and the electric field is updated each 2.5 fs by employing a one-dimensional PS. The cross-

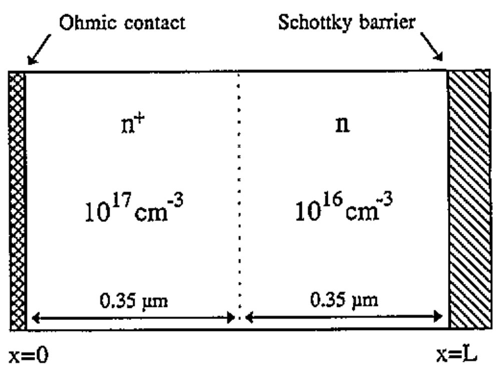

Figure 1. Schematic drawing of the Schottky barrier diode under study.

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sectional area adopted for the device is $2 \times 10^{-13}\ m^2$, which means an average number of simulated carriers of around 7600 depending on the bias. The simulation is performed at 300 K.

3. Operation modes

In a one-dimensional structure of length L with a single type of carrier (electrons), the total current, $I(t)$, is given by [8]:

$$I(t) = I_c(t) - \frac{\varepsilon_0 \varepsilon_r A}{L} \frac{d}{dt} \Delta V(L, t) \quad (1)$$

where ε_0 is the free space permittivity, ε_r the relative static dielectric constant of the material, A the cross-sectional area, $\Delta V(L, t)$ the instantaneous voltage drop between the terminals, and $I_c(t)$ the conduction current defined by

$$I_c(t) = -\frac{q}{L} \sum_{i=1}^{N_T(t)} v_i(t)$$

with q the absolute value of the electron charge, $N_T(t)$ the total number of carriers inside the device, and $v_i(t)$ the instantaneous velocity along the field direction of the ith particle.

Starting from equation (1), two complementary operation modes [8, 9] are used to analyse the noise properties of the SBD:

(i) Current-noise operation (Norton generator), in which the applied voltage is kept constant in time and the current fluctuations are analysed. In this case from equation (1) we obtain $I(t) = I_c(t)$. With this operation mode we investigate the effect of the coupling between fluctuations in carrier velocity and self-consistent electric field.

(ii) Voltage-noise operation (Thevenin generator), in which the total current is kept constant in time and the voltage fluctuations are analysed. By imposing the condition that the total current is constant in time, $I(t) = I_0$, from equation (1) we obtain

$$\frac{d}{dt} \Delta V(L, t) = \frac{L}{\varepsilon_0 \varepsilon_r A} (I_c(t) - I_0). \quad (2)$$

By employing a finite-differences scheme, equation (2) allows us to calculate $\Delta V(L, t)$ in each time step during the simulation. Moreover, by solving the Poisson equation one can get $\Delta V(x, t)$ as a function of different positions x inside the device as measured from one of the terminals. With this operation mode we provide a spatial analysis of the noise sources by calculating the spectral density of voltage fluctuations $S_V(x, f)$.

In both modes the fluctuations are studied through the calculation of the respective autocorrelation functions which, after Fourier transform, provide the spectral densities.

The equivalent noise temperature $T_N(f)$ (experimentally measurable) is a very important parameter for the characterization of the noise properties of SBDs. In our case we calculate its low-frequency value $T_N(0)$ from

$$T_N(0) = \frac{S_I(0)}{4K_B G(0)} \quad (3)$$

when current-noise operation is employed (here $S_I(0)$ is the low-frequency value of the current spectral density, K_B the Boltzmann constant and $G(0)$ the low-frequency differential conductance), and from

$$T_N(0) = \frac{S_V(0)}{4K_B R(0)} \quad (4)$$

when voltage-noise operation is employed (here $S_V(0)$ is the low-frequency value of the voltage spectral density and $R(0)$ the low-frequency differential resistance). Both $G(0)$ and $R(0)$ are obtained from the slope of the I–V characteristics [9].

4. Results and discussion

Figure 2 shows the I–V characteristic of the SBD under forward-bias conditions. Two different regions can be clearly observed: a first exponential region where the current is determined by the thermionic emission of carriers over the barrier, and a second one where the current tends to assume a linear behaviour due to the disappearance of the barrier, and it is the series resistance which controls the current in the device.

Figure 3 reports the results for the low-frequency value of the voltage spectral density at several points inside the device, $S_V(x, 0)$. Here, the spectral density is found to increase in going from the ohmic to the Schottky contact, thus providing a spatial resolution of the noise sources. For low voltages (in fact lower than the built-in potential at equilibrium, 0.640 V) shot noise is dominant, and most of the noise arises in the depletion region close to the barrier. At increasing voltages, when flat-band conditions are reached, the noise becomes spatially more distributed. It mainly originates from the n region of the device and corresponds to the thermal noise associated

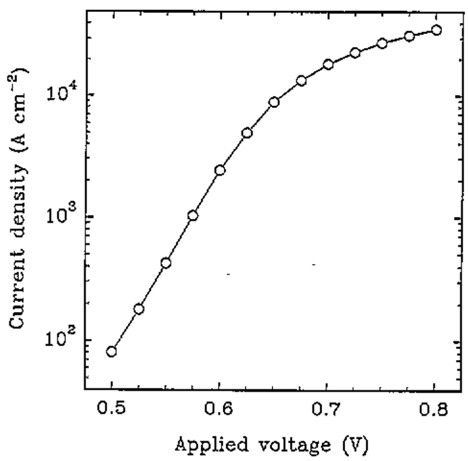

Figure 2. Current–voltage characteristic of the Schottky barrier diode under study. Circles refer to Monte Carlo calculations.

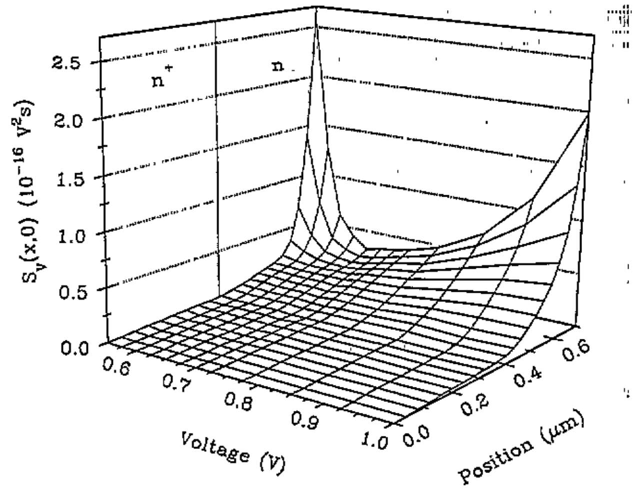

Figure 3. Low-frequency value of the spectral density of voltage fluctuations as a function of position and mean voltage in the Schottky diode under study.

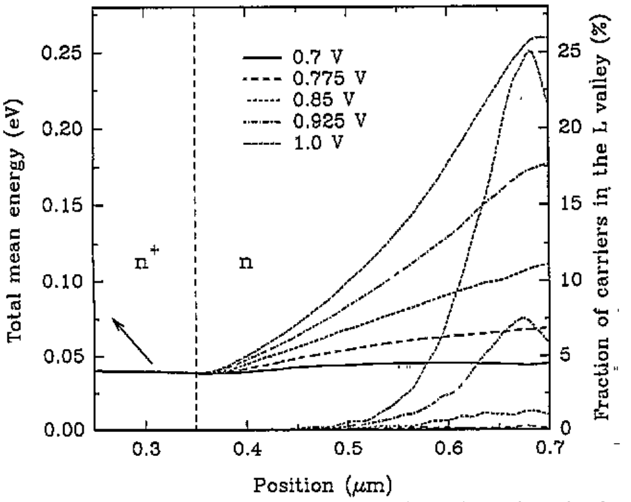

Figure 4. Total mean energy and fraction of carriers in the L valley for several voltages as a function of position in the *n* region of the diode.

with the series resistance. Finally, at the highest voltages, the presence of hot carriers and intervalley mechanisms in the n region is responsible for an excess noise contribution which leads $S_V(x, 0)$ to increase significantly.

To illustrate this hot-carrier effect, in figure 4 we show both the total mean energy and the fraction of carriers in the L valley at the highest voltages, when there is no barrier and most of the voltage drop occurs in the n region of the device. The increase of the voltage is responsible for high values of the electric field in the n region, where the carriers become hot. For voltages higher than 0.775 V the electrons get enough energy to transfer to the L valleys near the end of the n region. In these valleys the electrons have a larger effective mass, making this region highly resistive and thus an important source of noise. This is the reason why $S_V(x, 0)$ takes higher values and increases mainly near the barrier.

Finally, in figure 5 we show the equivalent noise temperature at low frequency calculated in different ways

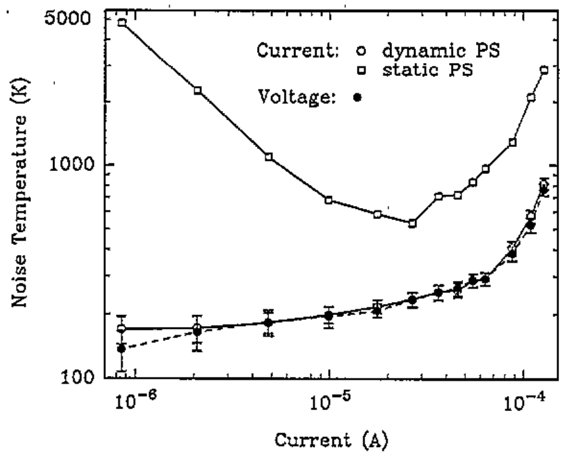

Figure 5. Equivalent noise temperature at low frequency as a function of current. Circles correspond to calculations performed considering the dynamic Poisson solver in the simulations and employing current-noise operation (open circles) and voltage-noise operation (full circles). Squares correspond to calculations considering a static Poisson solver and making use of current-noise operation.

as a function of the current flowing through the diode. $T_N(0)$ is evaluated from equations (3) and (4) by employing current and voltage noise operation modes. Moreover, we get the value of $T_N(0)$ within current-noise operation when the time fluctuations of the self-consistent field (dynamic PS) are neglected, thus considering only the stationary field profile (static PS). For the case in which the dynamic PS is employed, the results obtained for $T_N(0)$ from both operation modes are found to coincide satisfactorily. For low currents, corresponding to the exponential region of the I–V characteristic, the noise temperature is close to half of the lattice temperature. This reveals a full shot noise behaviour, $S_I(0) = 2qI$. As the current increases, the effect of the thermal noise in the series resistance becomes important and the noise temperature increases towards the lattice temperature, which is clearly crossed over for the highest currents because of the onset of the hot-carrier effects described before. This behaviour of $T_N(0)$ agrees favourably with that found by different experimental measurements [2, 4, 5]. While the I–V characteristic is checked to remain the same, the results obtained with a static PS for $S_I(0)$, and thus for $T_N(0)$, differ considerably (being systematically higher) with respect to those obtained with a dynamic PS. We remark on the great influence of the coupling between fluctuations in carrier velocity and self-consistent electric field in determining the noise properties of these devices. This is especially clear for low currents, where the noise suppression due to the presence of the space charge near the barrier [10] is only detected when the dynamic PS is employed.

5. Conclusions

An original Monte Carlo analysis of current and voltage fluctuations in a GaAs Schottky barrier diode has been reported. The presence of shot, thermal and excess noise has been observed according to the value of the voltage. The spatial location of these noise sources has been determined. Excess noise due to the onset of hot carriers and intervalley transfer has been found at the highest voltages. The coupling between fluctuations in carrier velocity and self-consistent field has been proved to be essential for a microscopic interpretation of the noise characteristics.

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