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NOISE OF GaAs DIODES

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RESUME: L'étude à faible polarisation d'une diode n^+nn^+ GaAs à profil de dopage réel montre, par comparaison entre le bruit expérimental et le bruit modélisé, que la méconnaissance actuelle de la variation précise du coefficient de diffusion $D(E)$, en fonction du champ électrique E , peut conduire à une modélisation erronée, en particulier des caractéristiques de bruit de composants GaAs. Les profils de champ électrique et de densité de porteurs libres, sont étudiés également en mode d'oscillations Gunn.

ABSTRACT: By comparing experimental and modelled noise results of a n^+nn^+ GaAs diode, we show that the lack of precise knowledge on the variation of the diffusion coefficient $D(E)$, versus the electric field E , may lead to erroneous predictions, in particular as concerning the noise behaviour of GaAs devices. The electric field and free carrier density profiles are also studied in Gunn oscillation operating regime.

1. INTRODUCTION:

In spite of numerous studies of hot carriers in GaAs, the variation of the diffusion coefficient $D(E)$, versus the electric field E , is not well known ([1] to [4]). The aim of this paper is to demonstrate that this may lead to erroneous prediction of the behaviour of devices, particularly as concerning noise characteristics. For this purpose, we shall model the simple but realistic case of n^+nn^+ diodes, with a doping profile $N_D(x)$.

2. STEADY STATE CHARACTERISTICS:

The devices modelled are about $10\ \mu\text{m}$ long. Then, the classical transport equations may be used, we do not need using the dynamic equations for submicron devices, but one should of course take into account hot carrier effects). The total current $I(t)$ is then the sum of drift, diffusion, and displacement currents. With obvious standard notations, this writes, with $q = +1.6 \times 10^{-19}\text{ Cb}$, $V(x=0)=0$, $V(x=L)=V_L > 0$, $E(x) < 0$, $v(E(x)) > 0$, $I > 0$:

$$I(t) = q n(x,t) v(E(x,t)) A - q A D(E(x,t)) \frac{\partial n(x,t)}{\partial x} - \epsilon A \frac{\partial E(x,t)}{\partial t} \quad (1)$$

$$\frac{\partial E(x,t)}{\partial x} = \frac{q}{\epsilon} [n(x,t) - N_D(x)] \quad (2)$$

Eliminating $n(x,t)$ gives eq. (3), where v and D stand for $v(E(x,t))$ and $D(E(x,t))$:

$$\frac{\partial E}{\partial t} = -D \frac{\partial^2 E}{\partial x^2} + v \frac{\partial E}{\partial x} + \frac{q}{\epsilon} v N_D(x) - \frac{qD}{\epsilon} \frac{dN_D(x)}{dx} - \frac{I(t)}{\epsilon A} \quad (3)$$

In the present section, we are interested in studying the steady state regime ($\partial E/\partial t = 0$). We drop the diffusion current, we found negligible. From eq. (3), we get then the electric field profile $E_0(x)$ as a solution of:

$$\epsilon A v(E_0(x)) \frac{dE_0(x)}{dx} + q A N_D(x) v(E_0(x)) = I_0 \quad (4)$$

The diode extends from $x=0$ to $x=L$. These points should be chosen far enough inside the n^+ electrodes, so that the conduction is ohmic at $x=0$ and at $x=L$. One should then have, since $N_D(x=0) = N_D(x=L)$:

$$E_0(x=0) = E_0(x=L) = I_0 / [q A N_D(x=0) \mu_0(0)] \quad (5)$$

The first order differential equation (4) was solved, for a given value of the bias current I_0 , using a predictor-corrector method, with the initial condition given by eq. (5). The characteristic field E_c and the saturation drift velocity v_s of the $v(E)$ law [6], were taken as: $E_c = 4\text{ kV/cm}$ and $v_s = 1.1 \times 10^7\text{ cm/s}$. The discretization step Δx was not constant. The commercially available diode presented here, labelled G2, had an active thickness of $10.6\ \mu\text{m}$. The origin $x=0$ and the extremity $x=L$ were taken $2\ \mu\text{m}$ far from the n^+n junction, hence $L=14.6\ \mu\text{m}$. The diameter was $125\ \mu\text{m}$, the ohmic resistance $R_0=11\ \Omega$, the ohmic mobility $\mu_0=4800\text{ cm}^2/\text{Vs}$.

Figure 1 shows the doping profile of the diode G2, so as the electric field profiles obtained at different d.c. current biases. The electric field intensity always exhibits a spike, even at low bias.

As shown figure 2, the agreement, between the experimental and the computed $I_0(V_0)$ characteristics, is excellent at every bias below the Gunn oscillation threshold.

3. GUNN EFFECT:

For bias current higher than 200 mA, oscillations appeared. It was then interesting to model them, since we had the tools, although a lot of work has already been done in that field (see for example [6]).

For modeling the Gunn effect, one should take into account the output circuit, namely a voltage supply $e_g(t)$ in series with a resistor R . The time dependant regime is governed by eqs. (3), where $E = E(x, t)$, and eq. (6):

$$V(t) = - \int_0^L E(x, t) dx \quad \text{and} \quad V(t) = e_g(t) - RI(t) \quad (6)$$

$e_g(t)$ was assumed to be linear with t , from 0 at $t=0$ to E_g at time 100 ps, and then constant. If the electric field profile $E(x_i, t)$ is known, at each point x_i , at a given time t , a numerical integration gives $V(t)$, then $I(t)$ (eq. (6)). A fourth order predictor-corrector method gives then $E(x_i, t+\Delta t)$, since the right hand side of eq. (3) is numerically known.

The electric field profile at $t=0$ is solution of eq. (3), where $I(t=0) = 0$ and $\partial E/\partial t = 0$, with the boundary conditions given by eqs. (5) and (6). This system can be easily solved using a double sweep iterative method.

As an example, results obtained in the Gunn oscillation regime are displayed figure 3. The free carrier density profiles, drawn every 10 ps on fig. 3a, show the formation and the propagation of domains, and fig. 3b shows the time evolution of current through the diode.

As a comparison, we show figure 4 the same quantities for a diode with a uniform doping profile in the active n region: the domains form in that case in a much more regular way than in the real diode (compare fig. 4a and fig. 3a). As a consequence, the current in the diode with a uniform doping (see fig. 4b) is much more sinusoidal, with a period better defined.

4. NOISE MODELING AT LOW BIAS:

We are interested in modeling the "low frequency" noise, i.e. at frequency lower than 100 GHz, corresponding to time constants much larger than the dielectric relaxation time, below the Gunn oscillation threshold: then we start again from eq. (3), and we apply the impedance field method [7]. First, eq. (3) writes, when neglecting the diffusion and the displacement currents:

$$\epsilon A v[E(x, t)] \frac{\partial E(x, t)}{\partial x} + q A N_D(x) v[E(x, t)] = I(t) \quad (7)$$

One then sets: $I(t) = I_0 + \delta I \exp(i\omega t)$ and $E(x, t) = E_0(x) + \delta E(x) \exp(i\omega t)$. These expressions are carried into eq. (9). The zero order terms give back eq. (4). The first order terms give:

$$a(x) \frac{d\delta E(x)}{dx} + b(x) \delta E(x) = \delta I(x) \quad \text{with} \quad a(x) = \epsilon A v_0 \quad \text{and} \quad b(x) = \frac{I_0}{v_0} \frac{dv_0}{dE_0} \quad (8)$$

The quantities $a(x)$ and $b(x)$ are known, numerically, from section 2 above. The Green function of eq. (9) can then be found, leading to the impedance field $\nabla Z(x')$, given as:

$$\nabla Z(x') = - \frac{1}{a(x')} \int_{x'}^L K(x, x') dx \quad \text{with} \quad K(x, x') = \exp \int_{x'}^x \frac{b(u)}{a(u)} du \quad (9)$$

The differential impedance Z , the noise voltage S_V and the noise current S_I for diffusion noise, are then given by:

$$Z = \int_0^L \nabla Z(x') dx', \quad S_V = 4 q^2 A \int_0^L |\nabla Z(x')|^2 n_0(x') D_0(x') dx' \quad \text{and} \quad S_I = S_V / |Z|^2 \quad (10)$$

The variation of the differential impedance Z , versus the bias current I_0 , computed using eq.(10), is shown fig. 5, so as the differential impedance obtained by computing the derivative of the $I_0(V_0)$ characteristic. Both quantities are in excellent agreement with the experimental differential impedance.

As can be seen from eqs. (10), the determination of the diffusion noise implies the knowledge of the variation of the diffusion coefficient versus the electric field. Unfortunately, very few results have been published in the literature till now, as concerning GaAs ([1], [8] to [10]), and the results available differ quite significantly. Theoretical models also exhibit quite different variations of $D(E)$ versus E , according to the values chosen for the coupling constants ([4], [11] to [13]): the results obtained are quite similar at low field, but differ by a considerable amount at fields higher than 2 kV/cm.

Figure 6 shows the experimental noise of the diode G2, measured using a pulse technique in order to avoid thermal heating. We verified that the noise was white in the range 220 MHz - 10 GHz, so that we actually deal with diffusion noise. Also are shown fig. 6 the theoretical noise computed through eq. (10), using the variations [4][12]

of $D(E)$ available in the literature. As can clearly be seen on fig 6, the experimental and the computed results are in good agreement at low bias, but none of the two theoretical models is able to account for experimental results at higher bias. This figure clearly shows that the noise predictions strongly depend on the variation law of $D(E)$, and can be quite erroneous according to the law chosen: this demonstrates the usefulness of a precise knowledge of $D(E)$, and also exhibits a lack of available data in the literature as concerning GaAs.

Obviously, not enough precise data $D(E)$ are now available, this determination needs both theoretical and mostly experimental efforts. Of course, this effect, pointed out in the present paper in the case of diodes, also remains valid in the case of any GaAs device exhibiting diffusion noise.

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Fig. 1: n^+nn^+ GaAs diode G2 at 300 K: doping profile $N_D(x)$, and electric field profiles at different d.c. current bias

Fig. 2: Static characteristics $I_0(V_0)$ of diode G2.

Fig. 3: Diode G2 at 300 K, in Gunn oscillation mode. $R=25 \Omega$, $E_g=10$ V. Time evolution of:
(a) The free carrier density profile.
(b) The current through the diode.

Fig. 4: n^+nn^+ GaAs diode at 300 K, uniformly doped in the active region. $R=20 \Omega$, $E_g=25$ V. Time evolution of
(a) The free carrier density profile.
(b) The bias current.

Fig. 5: Differential impedance Z of diode G2 at 300 K, versus the d.c. current bias I_0 .

Fig. 6: Noise current spectral density S_I of diode G2 at 300 K, versus the d.c. current bias I_0 .