INSTITUTE OF PHYSICS PUBLISHING SEMICONDUCTOR SCIENCE AND TECHNOLOGY
Semicond. Sci. Technol. **19** (2004) S170–S172 PII: S0268-1242(04)72248-8

Dynamical formation of hot-carrier intergroup noise under sub-terahertz cyclostationary conditions

P Shiktorov[1], E Starikov[1], V Gružinskis[1], L Reggiani[2], L Varani[3], J C Vaissière[3], S Pérez[4] and T González[4]

[1] Semiconductor Physics Institute, A Goštauto 11, 2600 Vilnius, Lithuania
[2] INFM–National Nanotechnology Laboratory, Dipartimento di Ingegneria dell' Innovazione, Università di Lecce, Via Arnesano s/n, 73100 Lecce, Italy
[3] Centre d'Electronique et de Micro-optoélectronique de Montpellier (CNRS UMR 5507), Université Montpellier II, 34095 Montpellier Cedex 5, France
[4] Departamento de Física Aplicada, Universidad de Salamanca, Plaza de la Merced s/n, 37008 Salamanca, Spain

Received 28 July 2003
Published 3 March 2004
Online at stacks.iop.org/SST/19/S170 (DOI: 10.1088/0268-1242/19/4/059)

Abstract
We show the existence of an upconversion of low-frequency intergroup noise by means of Monte Carlo simulations in bulk materials and semiconductor structures operating under periodic large-signal regime. The intergroup noise is associated with stochastic transitions in momentum space of carriers between regions characterized by different dynamics originated by the presence of hot-carrier conditions.

1. Introduction

In semiconductors the onset of some scattering mechanism occurring once charge carriers attain a given energy threshold (e.g. optical phonon emission, intervalley transfer, impact ionization, etc) can subdivide the momentum space into regions characterized by substantially different carrier dynamics. The transition to these dynamic regimes is usually indicated by a kink in the static velocity-field characteristic $v_d(E)$. In the presence of carrier heating from a static electric field, the simultaneous coexistence of two (or more) groups of carriers can lead to the appearance of an extra low-frequency component of velocity fluctuations (the so-called intervalley or partition noise) [1, 2]. We expect that under cyclostationary conditions, when carrier heating is driven by a microwave electric field (MWEF), such an extra noise can be transferred from the low- to the high-frequency region of the noise spectrum in full analogy with the upconversion of other low frequency excess noise such as: $1/f$ and generation-recombination noise [3].

The aim of this communication is to investigate this upconversion phenomenon by means of Monte Carlo (MC) simulations for two physical cases of relevant interest, namely: when the kink of the $v_d(E)$ characteristic is originated by the onset of: (i) optical phonon emission and, (ii) scattering between nonequivalent valleys. Details of MC calculations of noise spectra, parameters of bandstructure and scattering mechanisms of GaAs and InN used in MC simulations can be found elsewhere [4, 5].

2. Two groups in momentum space

Let us subdivide the momentum space into two non-overlapping regions Ω_1 and Ω_2 where carriers can be characterized by different dynamic properties. Accordingly, the total carrier velocity, $v_d(t)$, is decomposed into two additive contributions as:

$$v_d(t) = \int_{\Omega_1+\Omega_2} v(\mathbf{k}) f(\mathbf{k}, t)\, d\mathbf{k} = [p_1(t)v_1(t) + p_2(t)v_2(t)], \tag{1}$$

where $v_i(t)$ and $p_i(t)$ are the instantaneous values of the velocity and relative population in the region Ω_i. Since a carrier is always inside one of the momentum space regions, it is $p_1(t) + p_2(t) = 1$, so that the fluctuations of the relative populations of the two regions (groups) are correlated as: $\delta p_1(t) = -\delta p_2(t) = \delta p(t)$. As follows from equation (1), there are two components that determine the fluctuations of the total velocity, $\delta v_d(t) = \delta v^{\mathrm{r}}(t) + \delta v^{\mathrm{ig}}(t)$. The first (regular) component $\delta v^{\mathrm{r}}(t) = \overline{p}_1 \delta v_1(t) + \overline{p}_2 \delta v_2(t)$

describes velocity fluctuations inside the groups, while the second (intergroup) component $\delta v^{\mathrm{ig}}(t) = [\overline{v}_1 - \overline{v}_2]\delta p(t)$ describes the intergroup exchange driven by the random fluctuations of the relative group population $\delta p(t)$. When the fluctuations of velocity inside the ith group, $\delta v_i(t)$, and its relative populations $\delta p(t)$ can be considered to be statistically independent, i.e. $\langle \delta v_i(t)\delta p(t)\rangle = 0$, the total spectral density of velocity fluctuations is subdivided into two independent parts: $S_{\delta v\delta v}(\omega) = S^{\mathrm{reg}}_{\delta v\delta v}(\omega) + S^{\mathrm{ig}}_{\delta v\delta v}(\omega)$, where $S^{\mathrm{reg}}_{\delta v\delta v}(\omega)$ is due to intra-group processes while the inter-group velocity fluctuations are given by [1, 2, 4]

$$S^{\mathrm{ig}}_{\delta v\delta v}(\omega) = \frac{4(\overline{v}_1 - \overline{v}_2)^2 \overline{p}_1 \overline{p}_2 \tau_{\mathrm{g}}}{1 + \omega^2 \tau_{\mathrm{g}}^2}, \tag{2}$$

where τ_{g} is the characteristic time of carrier exchange between the groups. Under stationary conditions, the source of intergroup noise is proportional to the square of the group velocity difference and manifests itself as an additional low-frequency noise at $\omega < \tau_{\mathrm{g}}^{-1}$.

Under cyclostationary conditions, when carriers are heated by a strong monochromatic MWEF of frequency f, the statistical independence of velocity fluctuations inside and between the groups will take place when $f > \tau_{\mathrm{g}}^{-1}$. In this case, only the average statistical value of the group velocities, $\overline{v}_i(t) = \overline{v}_i \cos(2\pi f t + \phi_i)$, will keep the dependence on time during a MWEF period. Thus, the instantaneous spectral density, which depends on the phase time t, will take the form [4]

$$S_{\delta v\delta v}(t,\omega) = S^{\mathrm{reg}}_{\delta v\delta v}(t,\omega) + \tfrac{1}{4}\big[S^{\mathrm{ig}}_{\delta v\delta v}(\omega - 2\pi f) + S^{\mathrm{ig}}_{\delta v\delta v}(\omega + 2\pi f)\big] + \tfrac{1}{2} S^{\mathrm{ig}}_{\delta v\delta v}(\omega)\cos(4\pi f t), \tag{3}$$

where $S^{\mathrm{ig}}_{\delta v\delta v}(\omega)$ is the intergroup noise contribution given by equation (2). As follows from equation (3), under cyclostationary conditions only half of the low-frequency intergroup noise $S^{\mathrm{ig}}_{\delta v\delta v}(\omega)$ is shifted (upconverted) to the high-frequency region contributing into the stationary (i.e. independent of the phase time t) component $\overline{S}_{\delta v\delta v}(\omega)$ of the total spectral density of velocity fluctuations. The remaining half (last term in equation (3)) remains in the low-frequency region, but it is transferred to the nonstationary part of the spectrum, $S'_{\delta v\delta v}(t,\omega) = S_{\delta v\delta v}(t,\omega) - \overline{S}_{\delta v\delta v}(\omega)$, which is a periodic function of the phase time t with the double MWEF frequency $2f$.

3. Numerical results and conclusions

It is well known that at low lattice temperatures the static velocity-field characteristic $v_d(E)$ exhibits a kink related to the threshold onset of the optical phonon emission process. In this case, the formation of two groups under carrier heating by MWEF is illustrated in figure 1, which reports the time behaviour of the distribution function along the field direction $f(k_x, t)$ during half a period of the MWEF applied to a bulk InN at $T_0 = 80$ K. Here, the peak of the distribution corresponds to the group of carriers that cannot reach the optical phonon energy $\varepsilon(\mathbf{k}) = \hbar\omega_0$, and the lower plateau corresponds to the group of carriers that emit an optical phonon twice per period (see also [6]).

The appearance in the noise spectrum of a peak caused by upconversion processes is illustrated in figure 2. At the lowest value $E = 2$ kV cm^{-1} (dashed line), carrier heating is insufficient for the electron energy ε to reach the optical phonon value. As a consequence, the spectrum of velocity fluctuations is found to take the usual Lorentzian shape with the cutoff frequency being the value of the scattering rate in the passive region $\varepsilon(\mathbf{k}) < \hbar\omega_0$. At the highest value $E = 15$ kV cm^{-1} (dotted line) the field amplitude is sufficient to enable all the carriers to reach the active region $\varepsilon(\mathbf{k}) > \hbar\omega_0$ and then to emit an optical phonon at least several times during every half a period of the MWEF. As a consequence, the noise spectrum is found to take a near-Lorentzian shape determined by optical phonon emission in the active region and quasielastic scattering in the passive region. At the intermediate MWEF amplitude of $E = 9$ kV cm^{-1} (solid line) corresponding to the coexistence of the two groups (see figure 1), the spectrum is found to exhibit a significant peak at the MWEF frequency, $\nu = f$, originated by the intergroup noise upconversion.

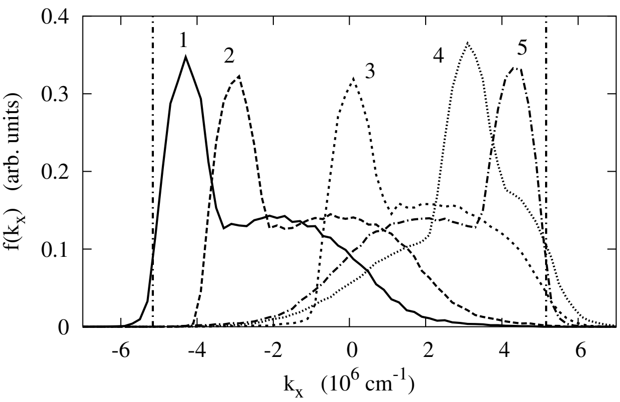

Figure 1. Hot-electron distribution function as a function of wavevector along the field direction, $f(k_x, t)$, calculated at different time moments corresponding to different phases (0, $\pi/4$, $\pi/2$, $3\pi/4$, π, curves 1 to 5, respectively) of the MWEF $E\sin(2\pi f t)$, with $E = 9$ kV cm^{-1} and $f = 500$ GHz.

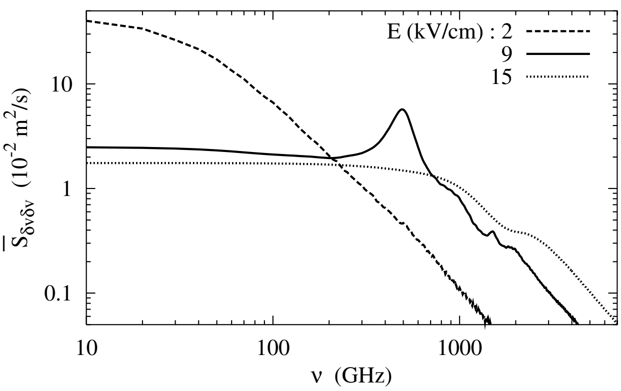

Figure 2. Stationary spectral density of velocity fluctuations calculated by the MC method when a MWEF of frequency $f = 500$ GHz and different amplitudes E is applied to a bulk InN with a donor concentration $N_D = 10^{16}$ cm^{-3} at $T_0 = 80$ K.

As the next application, we consider the upconversion of intervalley noise in GaAs. This noise is related to the second kink of the static $v_d(E)$, when electrons placed in the lowest and upper valleys can be naturally considered as belonging to two groups characterized by different ac mobility. Figure 3

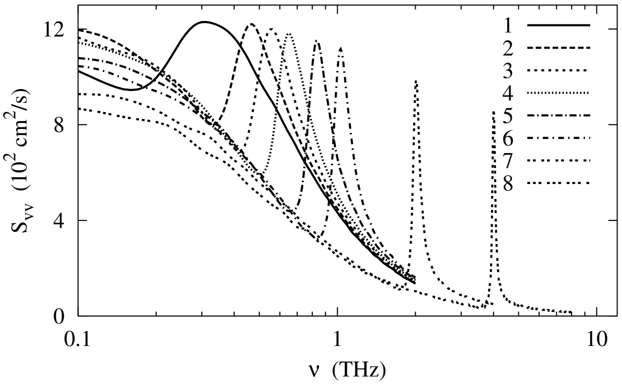

Figure 3. Stationary spectral density of velocity fluctuations calculated for GaAs at 300 K under the application of MWEFs with frequency $f = 200, 400, 500, 600, 800, 1000, 2000, 4000$ GHz and amplitude $E = 7, 8, 9, 10, 12, 14, 24, 45$ kV cm^{-1} (curves 1 to 8), respectively.

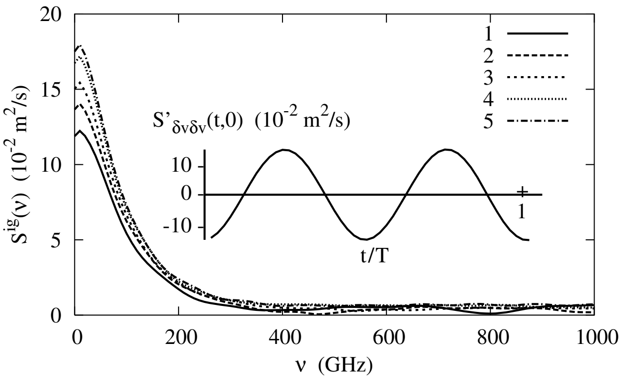

Figure 4. Upconverted low-frequency intergroup spectral density $S^{\mathrm{ig}}(\nu)$ calculated for the same conditions as figure 3 for $f = 400, 500, 600, 800, 1000$ GHz (curves 1 to 5, respectively). The inset shows the time dependence of $S'_{\delta v \delta v}(t, 0)$ for the case of curve 3 ($f = 600$ GHz) during one period of the MWEF.

illustrates the modifications of the spectrum with increasing MWEF frequency when the value of the ratio E/f is kept at the optimum level corresponding to the maximum value of the peak. In this case, carrier heating remains nearly the same, as well as the relative populations, i.e. $\overline{p}_1 \approx \overline{p}_2$. Here, the usual static hot-carrier peak [7] (curve 1) evolves into a resonant-like peak around f, thus shifting with f for $f \geqslant 500$ GHz (curves 3 to 8). As evident from figure 3, the resonant-like peak is superimposed onto the Lorentzian part of the spectrum, caused by the velocity fluctuations inside the groups, and it can exceed considerably the regular noise contribution. This peak is the consequence of an upconversion process, as confirmed by the harmonic behaviour of $S'_{\delta v \delta v}(t, 0)$ at frequency $2f$ reported in the inset of figure 4, corresponding to the case of $f = 600$ GHz. The upconverted spectra presented in figure 4 are well described by the usual Lorentzian expression (see equation (2)) with a characteristic time for the intergroup exchange $\tau_{\mathrm{g}} \approx 1.9$ ps common to all the curves.

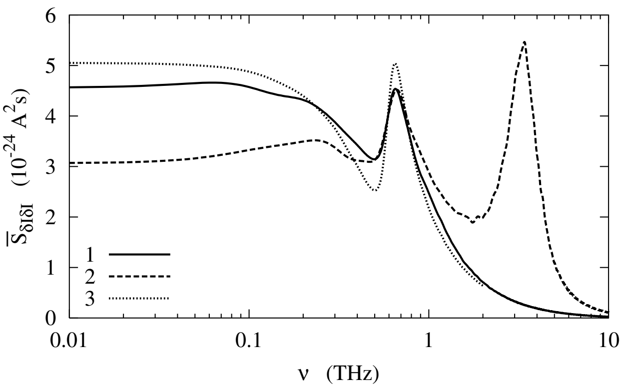

Figure 5. Spectral density of current fluctuations for a homogeneous 0.6 μm n-GaAs resistor (curve 1) and a submicron 0.2–0.6–0.2 μm n^+nn^+ GaAs diode (curve 2) subject to an applied voltage $U_{\mathrm{a}} \cos(2\pi f t)$ with $U_{\mathrm{a}} = 0.6$ and 0.62 V, respectively, and $f = 0.6$ THz. Curve 3 refers to $S_{\delta I \delta I}(\omega)$ for the same resistor as in curve 1 calculated in accordance with the standard relation $S_{\delta I \delta I}(\nu) = e^2 n S_{\delta v \delta v}(\nu) A/L$ by using $S_{\delta v \delta v}(\omega)$ obtained for a bulk GaAs at $E = 10$ kV cm^{-1}.

Since the characteristic time τ_{g} of intergroup exchange is in this case about 2 ps, the low frequency limit $f \geqslant 500$ GHz necessary to observe upconversion simply means that the frequency of the applied signal must be higher than the characteristic rate of intergroup exchange, that is $f \geqslant 1/\tau_{\mathrm{g}}$.

The spectral density of velocity fluctuations in bulk materials calculated here constitutes, in turn, the noise source that enters into the impedance field method, used to evaluate electronic noise in semiconductor devices. Thus, under the conditions for which the noise source exhibits the upconversion peak, a similar behaviour could be expected in devices. This is illustrated by figure 5 which presents the spectral density of current fluctuations calculated by MC simulations coupled with the Poisson solver for an n-GaAs homogeneous resistor (curve 1) and a submicron n^+nn^+ diode (curve 2). Despite some modifications of the current noise spectra in the diodes, the upconversion phenomenon is confirmed in all cases as an output measurable quantity.

References

[1] Price P J 1960 *J. Appl. Phys.* **31** 949

[2] Gupta M S 1978 *J. Appl. Phys.* **49** 2837

[3] Pérez S, González T, Delage S L and Obregon J 2001 *Semicond. Sci. Technol.* **16** L8

[4] Shiktorov P, Starikov E, Gružinskis V, Pérez S, González T, Reggiani L, Varani L and Vaissière J C 2003 *Phys. Rev.* B **67** 165201

[5] Shiktorov P, Starikov E, Gružinskis V, Pérez S, González T, Reggiani L, Varani L and Vaissière J C 2003 *IEEE Trans. Electron Devices* **50** 1171–8

[6] Ishida N and Kurosawa T 1995 *Japan. J. Appl. Phys.* **64** 2994

[7] Varani L, Vaissiere J C, Nougier J P, Houlet P, Reggiani L, Starikov E, Shiktorov P, Gružinskis V and Hlou L 1995 *J. Appl. Phys.* **77** 665