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UPCONVERSION OF INTERGROUP HOT-CARRIER NOISE IN SEMICONDUCTORS OPERATING UNDER PERIODIC LARGE-SIGNAL CONDITIONS

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By means of Monte Carlo simulations of carrier transport in bulk semiconductors operating under periodic large-signal regime, we show the existence of upconversion of low-frequency hot-carrier noise associated with velocity fluctuations into a high-frequency region centered around the fundamental frequency of the large-signal. It is found that the upconverted noise corresponds to long-time fluctuations of relative populations of two groups of carriers characterized by different dynamical properties in momentum space. The appearance of the upconversion process is related to kinks of the static velocity-field characteristic when the dynamics of carrier motion in momentum space undergoes drastic changes.

Keywords: Monte Carlo simulation; hot-carrier noise; noise upconversion.

1. Introduction

The phenomenon of noise upconversion consists in the transfer of an excess noise component from the proper low-frequency region to a high-frequency region of the spectrum under the presence of a periodic signal of given amplitude. Typical examples are the transfer of 1/f or generation recombination noise, inherent to the sample under static conditions, from the low-frequency to the GHz region in voltage controlled oscillators [1] and systems driven by periodic large-amplitude excitations [2–4]. Usually, upconversion processes are related with the existence of two groups of carriers and the stochastic carrier exchange between them (e.g. generation-recombination noise, etc.). One can expect that under a drastic change of the dynamics of carrier motion in momentum space such a scenario of upconversion based on two or more groups of hot carriers also can take place.

The aim of this paper is to announce the existence of an upconversion of a noise source that appears only as a result of strong carrier heating in the presence of periodic large-signal conditions.

2. Mathematical Model of Upconversion

Here we are concerned with a random process $\{x(t)\}$ whose spectrum contains the contribution of a noise upconversion phenomenon consisting in the amplitude modulation of a periodic signal with frequency f by some stationary random process $\{u(t)\}$. The simplest mathematical model to describe the fluctuations of such a random process is $\{x(t)\} = x_0 cos(2\pi ft)\{u(t)\}$ [5]. It is assumed that the random process $\{u(t)\}$ has zero average value and is characterized by the correlation function $C_{uu}(\tau) = \langle u(t-\tau/2)u(t+\tau/2)\rangle$, with the corresponding low-frequency spectral density $S_{uu}(\nu)$. The two-time symmetric correlation function of the random process $\{x(t)\}$, $C_{xx}(t,\tau) = \langle x(t-\tau/2)x(t+\tau/2)\rangle$, can then be expressed as

$$C_{xx}(t,\tau) = \frac{x_0^2}{2}[cos(2\pi f\tau) + cos(4\pi ft)]C_{uu}(\tau)\,. \tag{1}$$

According to Eq. (1), the instantaneous spectral density of $x(t)$ is decomposed into two terms, $S_{xx}(t,\nu) = \overline{S}_{xx}(\nu) + S'_{xx}(t,\nu)$, corresponding, respectively, to the stationary component

$$\overline{S}_{xx}(\nu) = \frac{x_0^2}{4}[S_{uu}(\nu+f) + S_{uu}(\nu-f)] \tag{2}$$

and to the nonstationary component

$$S'_{xx}(t,\nu) = \frac{x_0^2}{2}cos(4\pi ft)S_{uu}(\nu)\,. \tag{3}$$

Due to the stochastic amplitude modulation of the harmonic signal, the noise spectrum of the stationary random process $\{u(t)\}$ given in Eq. (2) is shifted (i.e. is upconverted) to the high-frequency region centered around the excitation frequency f. As a signature of the upconversion process, Eq. (3) indicates that the low-frequency nonstationary component of the instantaneous spectral density, $S'_{xx}(t,\nu)$, should exhibit an harmonic behavior with frequency $2f$.

3. Physical Model of Upconversion

From a physical point of view, the stochastic amplitude modulation required by the mathematical model can appear in bulk semiconductors subject to large-amplitude microwave electric fields (MWEF) due to random transitions of carriers between two or more physically distinct groups of states located in momentum (or wavevector) space [6–8]. In the case of two groups, the average value of carrier velocity, $v_d(t)$, obtained by integration over the carrier distribution function in momentum space, $f(\mathbf{k},t)$, can be decomposed into two contributions as

$$v_d(t) = \int v(\mathbf{k}) f(\mathbf{k},t) d\mathbf{k} = \left[p_1(t) v_1(t) + p_2(t) v_2(t) \right], \tag{4}$$

where $v_i(t)$ and $p_i(t)$ are the instantaneous values of the average velocity and relative population of the i-th group. Since $\int f(\mathbf{k},t)d\mathbf{k} = 1$, i.e. a carrier always is inside one of the momentum space regions, it follows that $p_1(t)+p_2(t) = 1$, so that fluctuations of the relative populations of the groups are correlated as: $\delta p_1(t) = -\delta p_2(t) = \delta p(t)$. As follows from Eq. (4), there are two components that determine fluctuations of the total velocity, $\delta v_d(t) = \delta v^r(t) + \delta v^{ig}(t)$. The first (regular) component is given by

$$\delta v^r(t) = \left[\langle p_1 \rangle \delta v_1(t) + \langle p_2 \rangle \delta v_2(t) \right], \tag{5}$$

and describes velocity fluctuations inside the groups (here brackets $\langle \cdots \rangle$ mean statistical averaging). The second component is given by

$$\delta v^{ig}(t) = \left[\langle v_1(t) \rangle - \langle v_2(t) \rangle \right] \delta p(t) \tag{6}$$

and describes the intergroup exchange, which corresponds to an amplitude modulation of the harmonic response $(\langle v_1(t) \rangle - \langle v_2(t) \rangle)$ driven by the random fluctuations of the relative group population $\delta p(t)$. For such a decomposition into groups to take place, the characteristic time of carrier exchange between groups, τ_g, must be much longer than all other times, so that velocity fluctuations inside each group, $\delta v_i(t)$, and fluctuations of the relative populations $\delta p(t)$ can be considered to be statistically independent, that is $\langle \delta v_i(t) \delta p(t) \rangle = 0$. In this case, due to the stochastic intergroup exchange, the low-frequency spectrum of fluctuations of the relative population of one of the two groups is described by the usual Lorentzian expression

$$S_{\delta p \delta p}(\nu) = 4 \langle p_1 \rangle \langle p_2 \rangle \frac{\tau_g}{1 + (2\pi \nu \tau_g)^2} \, . \tag{7}$$

Within the two-group model, the random process $\{x(t)\}$ corresponds to instantaneous fluctuations of the electron velocity $\delta v^{ig}(t)$, which are caused by the stochastic intergroup exchange ($\{u(t)\} \equiv \{\delta p(t)\}$ process) when groups of carriers characterized by different dynamics appear in momentum space in the presence of a MWEF. In this case, the high-frequency modulating factor $x_0 cos(2\pi f t)$ is described by the difference between the amplitudes of the average drift velocity in the two groups, i.e. $x_0 \sim (v_1 - v_2)$. As follows from Eq. (3), the low-frequency spectrum $S^{ig}_{\delta v \delta v}(\nu) = \frac{1}{2} x_0^2 S_{uu}(\nu)$ corresponds to the amplitude of the nonstationary component $S'_{\delta v \delta v}(t,\nu)$ of the instantaneous spectrum of fluctuations and, in accordance with Eq. (2), it is the spectrum that is upconverted to the high-frequency range multiplied by a factor of $\frac{1}{2}$.

Below we will investigate two cases of relevant physical interest pertaining to bulk semiconductors subject to high-frequency large-amplitude MWEFs, when the appearance of two groups of carriers is caused by a drastic change of the carrier dynamics due to the threshold character of some scattering mechanism (e.g. carrier transitions to upper valleys, optical phonon emission, etc.). Usually such a change is accompanied by kinks of the static velocity-field characteristic.

4. Numerical Results

The procedure for the noise analysis is based on the Monte Carlo (MC) calculation of the two-time symmetric correlation functions and it is similar to that described in [9]. In accordance with this procedure, the stationary and periodic parts of the instantaneous spectral density of velocity fluctuations, $\overline{S}_{\delta v \delta v}(\nu)$ and $S'_{\delta v \delta v}(t,\nu)$, respectively, are calculated by Fourier transform of the two-time symmetric correlation function directly obtained from the MC simulations [9], while the upconverted spectrum $S^{ig}_{\delta v \delta v}(\nu)$ is calculated as the second harmonic of $S'_{\delta v \delta v}(t,\nu)$ with respect to time t.

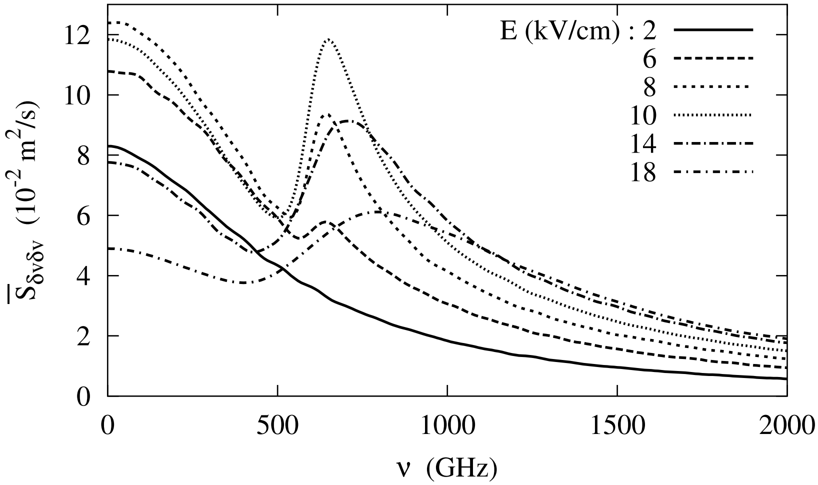

Fig. 1. Stationary spectral density of velocity fluctuations calculated when a MWEF of frequency $f = 600$ GHz and different amplitudes E is applied to a bulk GaAs with donor concentration $N_D = 10^{16}$ cm^{-3} at $T_0 = 300$ K.

As first application, we consider the standard case of the so called intervalley noise in compound semiconductors [6–8] when the amplitude of the MWEF is high enough for intervalley transitions from the lowest (Γ) into upper (X, L) valleys to take place. Here, electrons placed in the lowest and upper valleys can be naturally considered as belonging to two groups characterized by different ac mobility due to the strong difference in the effective mass and scattering time. To illustrate the appearance of the upconversion process with the onset of the intervalley transfer, Fig. 1 shows the stationary spectral density of velocity fluctuations calculated by MC simulations in bulk GaAs at $T_0 = 300$ K for a MWEF of $f = 600$ GHz at increasing amplitude of the field, i.e. at increasing values of the carrier average energy. The parameters of the band structure and scattering mechanisms used in MC simulations are those of the strong intervalley coupling model [10]. When the field amplitude becomes higher than the threshold field for intervalley transfer (i.e. $E > 5$ kV/cm), the spectrum exhibits a peak at the MWEF frequency. With a further increase of E, and hence of carrier heating, the peak increases, reaches the maximum value at $E \approx 10$ kV/cm, and then gradually disappears by showing a slight shift to higher frequencies. Numerical calculations performed for a constant amplitude E show an analogous behavior of the peak with the increase of the MWEF frequency f which is associated with the decrease of carrier heating. Such a behavior agrees with the predictions of the two-group model given by Eq. (7). Indeed, the peak is found to vanish when all the carriers are inside one of the two groups, and to reach the maximum value when the relative populations of the groups are the same, i.e. $\langle p_1 \rangle = \langle p_2 \rangle = 0.5$.

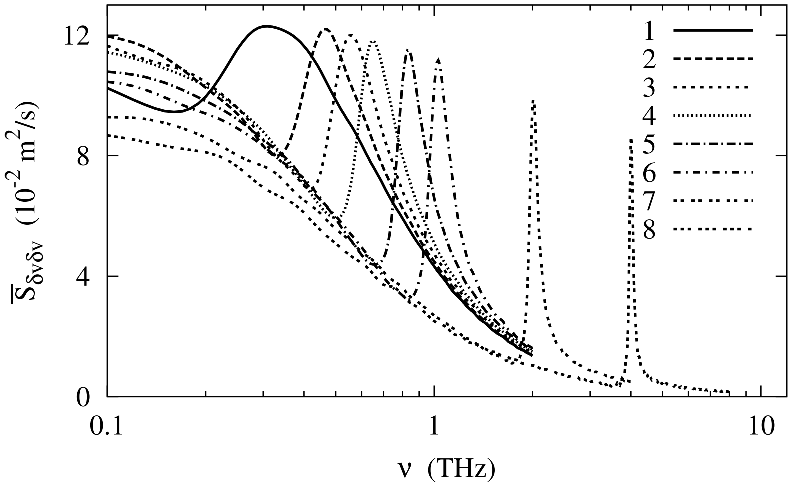

Fig. 2. Stationary spectral density of velocity fluctuations calculated for the same semiconductor of Fig. 1 under the application of MWEFs with frequency, f = 200, 400, 500, 600, 800, 1000, 2000, 4000 GHz and amplitude E = 7, 8, 9, 10, 12, 14, 24, 45 kV/cm (curves 1 to 8), respectively.

Figure 2 illustrates the modifications of the spectrum with the increase of the frequency when the value of the ratio E/f is kept at the optimum level of about 15 kVcm^{-1}THz^{-1} which corresponds to the maximum value of the peak. In this case, carrier heating remains nearly the same, as well as the relative populations, i.e. $\langle p_1 \rangle \approx \langle p_2 \rangle$. Here, the usual static hot-carrier peak [9] (curve 1) evolves into a resonant-like peak around f, thus shifting with f for $f \geq 500$ GHz (curves 3 to 7). As evident from Fig. 2, the resonant-like peak is superimposed to the Lorentzian part of the spectrum caused by velocity fluctuations inside the groups. This peak is the consequence of an upconversion process, as confirmed by the results reported in the inset of Fig. 3, corresponding to the case of $f = 600$ GHz. Here, the zero-frequency value of the nonstationary part of the instantaneous spectral density $S'_{\delta v \delta v}(t, 0)$ is shown to exhibit a pure harmonic behavior with frequency $2f$, the double of the MWEF frequency f. (The same behavior is generally confirmed for $f \geq 500$ GHz.) Moreover, in full agreement with the mathematical model of Eqs. (2) and (3), the amplitude of $S'_{\delta v \delta v}(t, 0)$ is found to be twice higher than the amplitude of the peak, considering the latter as an extra noise superimposed to the Lorentzian part of the spectrum. For $f < 500$ GHz this harmonic behavior of $S'_{\delta v \delta v}(t, 0)$ is found to vanish, and thus no clear upconversion peak is observed in $\overline{S}_{\delta v \delta v}(\nu)$.

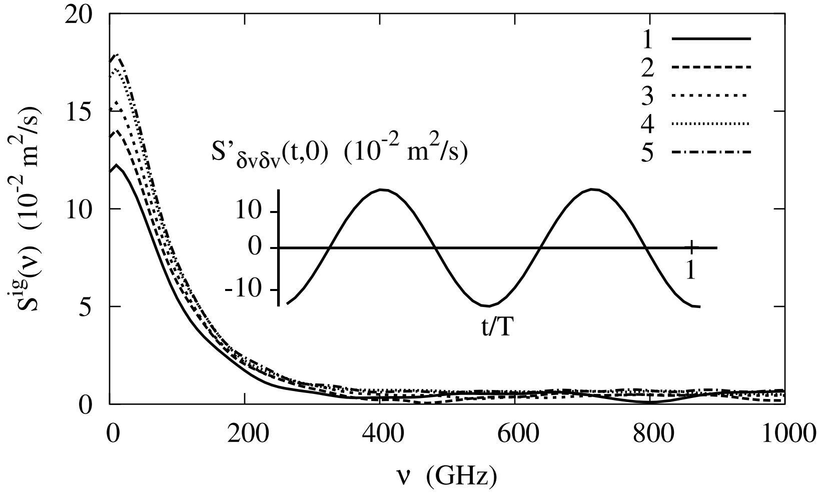

Fig. 3. Upconverted low-frequency intergroup spectral density $S^{ig}(\nu)$ calculated for the same conditions of Fig. 2 for f = 400, 500, 600, 800, 1000 GHz (curves 1 to 5, respectively). The inset shows the time dependence of $S'_{\delta v\delta v}(t, 0)$ for the case of curve 3 (f = 600 GHz) during one period of the MWEF.

The upconverted spectra presented in Fig. 3 are well described by the usual Lorentzian expression [see Eq. (7)] with a characteristic time for the intergroup exchange $\tau_g \approx 1.9$ ps common to all the curves. The increase of the spectrum amplitude at increasing f is mainly caused by the simultaneous increasing of the difference between the dynamics of the groups. Since the characteristic time τ_g of intergroup exchange is in this case of about 2 ps, the low frequency limit $f \geq$ 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 $f \geq 1/\tau_g$.

By comparing the value of the characteristic intergroup time $\tau_g \approx 1.9$ ps extracted from the spectra of Fig. 3 with the carrier lifetimes in the lowest and upper valleys $\tau_\Gamma = 1.27$ ps and $\tau_{LX} = 0.44$ ps, respectively, as well as with the characteristic intervalley time $\tau_{inter} = 0.33$ ps (these values refer to the case of $E = 10$ kV/cm and $f = 600$ GHz) we notice that τ_g is significantly longer than the characteristic time of intervalley transfer, $\tau_{inter} = 0.33$ ps. Therefore, in this case the intergroup exchange does not represent the simple intervalley exchange. The long intergroup time allows us to conclude that the first group of carriers consists of Γ-valley electrons with energy below the value necessary for intervalley transfer to take place, and the second group consists of all other high-energy electrons, which undergo very quick randomizing intervalley scatterings. In some sense, the transfer of electrons from the lowest to upper valleys is quite similar to the generation-recombination processes from shallow impurity centers into the conduction band leading to trapping-detrapping noise [6, 7]. As follows from Fig. 2, the relative contribution of the upconverted fluctuations to the total value of the spectral density of velocity fluctuations in the region $\nu \approx f$ increases at increasing the MWEF frequency f and finally dominates. Such a dominant contribution is caused by the large difference in the value of the high-frequency mobility pertaining to each group.

The situation considered above is associated with the static kink of the velocity-field characteristic which is caused by the onset of the intervalley transfer. It is well known, that at low lattice temperatures an additional kink related to the threshold onset of optical phonon emission processes appears at intermediate field values considerably lower than the threshold value for intervalley transfer. Under these conditions, most of the carriers are inside the optical phonon sphere in momentum space where the carrier energy $\varepsilon(\mathbf{k})$ is less than the optical phonon energy $\hbar\omega_0$ (the so called *passive region*). As shown in Refs. [11-13], in such a case the carriers placed in the passive region can be subdivided into two (or even more) groups, so that one can expect the appearance of the intergroup noise upconversion under proper conditions. The second application presented in the following considers this possibility for the case of bulk n-InN at the lattice temperature $T_0 = 80$ K when the optical phonon energy $\hbar\omega_0 = 89$ meV $\gg kT_0 = 6.9$ MeV. The parameters of the band structure and scattering mechanisms used in MC simulations are taken from [14].

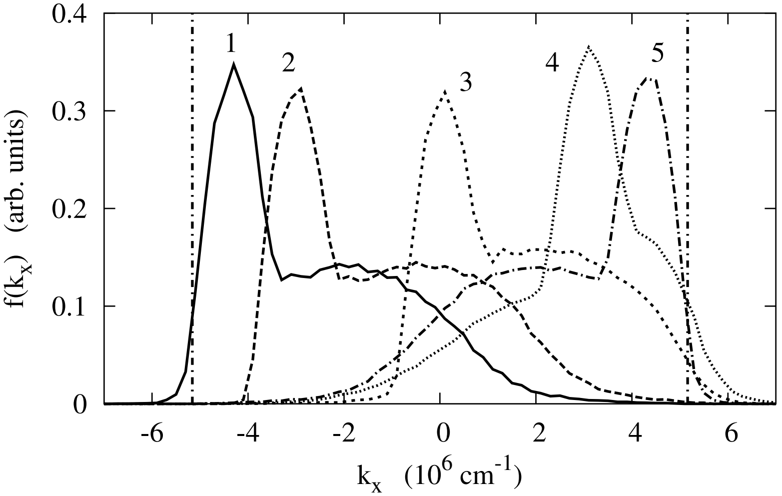

Fig. 4. Hot-electron distribution function as a function of wavevector along the field direction, $f(k_x, t)$, calculated at different time moments corresponding to different phases (0, $\pi/4$, $\pi/2$, $3\pi/4$, π, curves 1 to 5, respectively) of the MWEF $Esin(2\pi ft)$, with $E = 9$ kV/cm and $f = 500$ GHz, applied to InN at $T_0 = 80$ K. Vertical lines at $k = 5.16 \times 10^6$ cm^{-1} refer to the boundaries of the passive region.

The formation and evolution of two groups of carriers under carrier heating by a MWEF of proper amplitude is illustrated in Fig. 4, which reports the time behavior of the distribution function along the field direction $f(k_x, t)$ during half a period of the MWEF. Here, the peak of the distribution corresponds to the group of carriers that cannot reach the active region boundary $\varepsilon(\mathbf{k}) = \hbar\omega_0$, and the lower plateau corresponds to the group of carriers that emit an optical phonon twice per period. As follows from Fig. 4, the average velocities of each group ($\langle v_1(t)\rangle$ and $\langle v_2(t)\rangle$, respectively), both exhibiting the periodicity of the MWEF, have amplitudes which are significantly different, higher for carriers belonging to the peak.

The appearance in the noise spectrum of a peak caused by upconversion processes is illustrated in Fig. 5, which reports the stationary component of the spectral density of velocity fluctuations, $\overline{S}_{\delta v \delta v}(\nu)$, calculated for three values of the amplitude of a MWEF of frequency $f = 500$ GHz applied to a bulk InN at $T_0 = 80$ K.

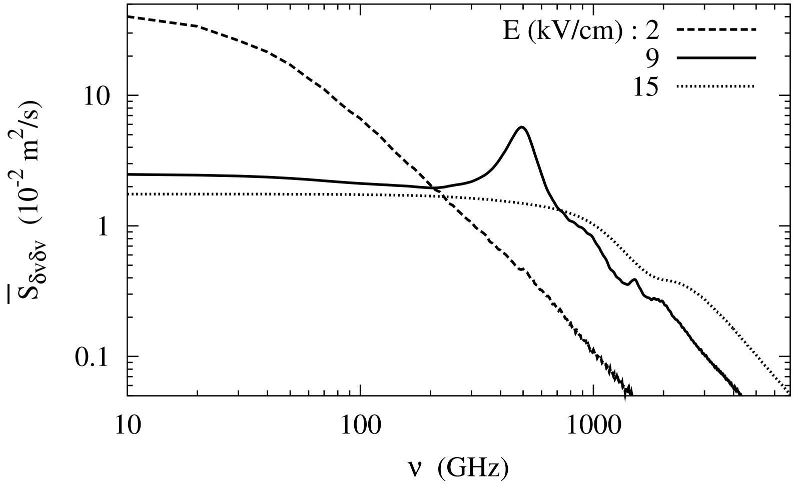

Fig. 5. Stationary spectral density of velocity fluctuations calculated by the MC method when a MWEF of frequency $f = 500$ GHz and different amplitudes E is applied to a bulk InN with a donor concentration $N_D = 10^{16}$ cm^{-3} at $T_0 = 80$ K.

At the lowest value $E = 2$ kV/cm (dashed line), carrier heating is insufficient for the electron energy ε to reach the optical phonon value. Accordingly, all the carriers are in the passive region $\varepsilon(\mathbf{k}) < \hbar\omega_0$ where, because of the low lattice temperature, the main sources of scattering are acoustic phonons and ionized impurities. 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. At the highest value $E = 15$ kV/cm (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 double-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 (solid line), the spectrum is found to exhibit a significant peak at the MWEF frequency, $\nu = f$, and minor peaks at higher harmonics.

The upconversion origin of the peak is demonstrated by the results reported in Figs. 6 and 7 which are analogous to Figs. 2 and 3 of the previous application. Accordingly, Fig. 6 shows the stationary part of the fluctuation spectrum $\overline{S}_{\delta v \delta v}(\nu)$ calculated by keeping the ratio E/f nearly constant to provide similar trajectories of carrier free motion in the passive region at different frequencies f. By excluding the frequency regions near $2f$, the upconverted spectrum $S^{ig}(\nu)$ presented in Fig. 7

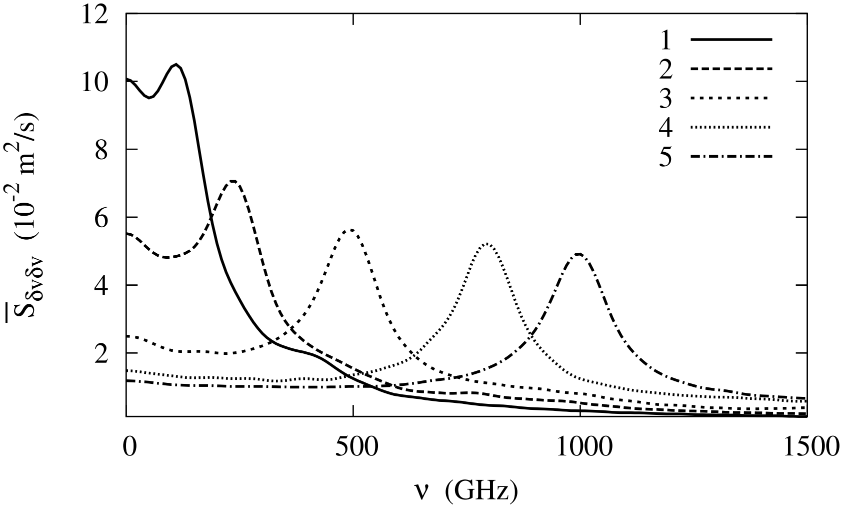

Fig. 6. Stationary spectral density of velocity fluctuations calculated for the same semiconductor of Fig. 5 under the application of MWEFs with frequency, f = 133, 250, 500, 800, 1000 GHz and amplitude E = 2, 5.5, 9, 15, 19 kV/cm (curves 1 to 5), respectively.

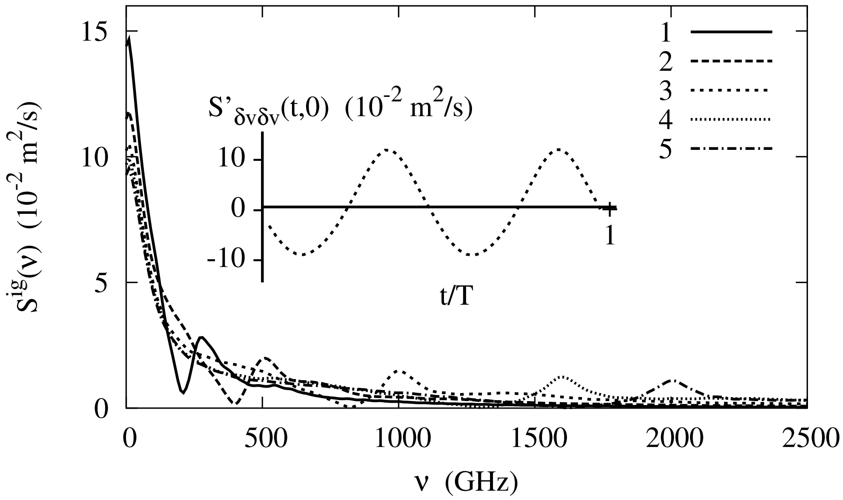

Fig. 7. Upconverted spectral density of intergroup exchange $S^{ig}(\nu)$ calculated for the same conditions of Fig. 6 (curves 1 to 5). The inset shows the time dependence of $S'_{\delta v \delta v}(t, 0)$ for case 3 (f =500 GHz) during one period of the MWEF.

is again well described by a Lorentzian shape with a characteristic intergroup time $\tau_g \approx 1 \sim 2$ ps. The additional peaks at the double frequency $2f$ in $S^{ig}(\nu)$ are attributed to the strong nonlinearity present in the system due to the coherent-in-time emission of two optical phonons at every MWEF period.

5. Conclusions

In this paper we have proven the existence of an upconversion of the low-frequency hot-carrier noise in bulk semiconductors operating under periodic and large-signal conditions. The upconversion is a consequence of the coexistence of two groups of carriers characterized by different dynamics in momentum space, so that the transition of carriers from one type of dynamics (one group) to the other type (second group) leads to the appearance of an extra noise, in full analogy with what occurs in phase transitions. In semiconductor materials, where some scattering mechanisms have a threshold character (low-temperature optical phonon emission, intervalley scattering, etc.) changes of carrier dynamics in momentum space usually takes place with the increase of the electric field strength when the carrier energy begins to exceed some threshold value. Because of the short time scale associated with the intergroup exchange considered here, the upconversion takes place mostly around the THz frequency range.

Finally, we notice that one can expect the appearance of upconversion phenomena related also to other kinds of hot-carrier kink appearing in the static velocity-field characteristic, as for instance that caused by impact ionization and occurring at sufficiently high electric fields. However, in such a situation the upconversion is caused mostly by fluctuations of the total carrier concentration, as is typical in the case of the generation-recombination noise [15].

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References

[1] A. Hajimiri and T. H. Lee, *IEEE J. Solid-State Circuits* **33** (1998) 179.

[2] S. Pérez, T. González, S. L. Delage and J. Obregon, *Microscopic analysis of generation-recombination noise in semiconductors under dc and time-varying electric fields, J. Appl. Phys.* **88** (2000) 800–807.

[3] S. Pérez, T. González, S. L. Delage and J. Obregon, *Monte Carlo analysis of the influence of dc conditions on the upconversion of generation-recombination noise in semiconductors, Sem. Sci. Technol.* **16** (2001) L8–L11.

[4] F. Bonani and G. Ghione, *Noise in Semiconductor Devices, Modeling and Simulation*, Springer, Berlin (2001).

[5] J. S. Bendat and A. G. Piersol, *Random Data*, John Wiley and Sons (1986).

[6] P. J. Price, *Intervalley noise, J. Appl. Phys.* **31** (1960) 949–953.

[7] W. Shockley, J. A. Copeland and R. P. James, *The impedance field method of noise calculation in active semiconductor device*, in: *Quantum theory of atoms, molecules and the solid state*, ed. P. O. Löwdin, Academic Press, New York (1966) 537–563.

[8] J. P. Nougier, *Fluctuations and noise of hot carriers in semiconductor materials and devices, IEEE Trans. Electron Devices* **41** (1994) 2034–2049.

[9] P. Shiktorov, E. Starikov, V. Gružinskis, L. Reggiani, L. Varani and J. C. Vaissière, *Monte Carlo calculation of electronic noise under high-order harmonic generation, Appl. Phys. Lett.* **80** (2002) 4759–4761.

[10] K. Brennan and K. Hess, *High field transport in GaAs, InP and InAs, Solid-State Electron.* **27** (1984) 347–357.

[11] R. S. Brazis, E. V. Starikov and P. N. Shiktorov, *Hall factor and evolution of the distribution function of hot electrons, Sov. Phys. Semicond.* **17** (1983) 25–28.

[12] P. N. Shiktorov, *The bunching and negative dynamic conductance in semiconductors with strongly inelastic scattering of carriers, Sov. Phys.-Collect.* **25** (1985) 59–66.

[13] N. Ishida and T. Kurosawa, *Carrier accumulation in momentum space and related phenomena under intense microwave fields in semiconductors, Jap. J. Appl. Phys.* **64** (1995) 2994–3006.

[14] B. E. Foutz, S. K. O'Leary, M. S. Shur and L. F. Eastman, *Transient electron transport in wurtzite GaN, InN, and AlN, J. Appl. Phys.* **85** (1999) 7727–7734.

[15] V. Mitin, L. Reggiani and L. Varani, in *Noise and fluctuations control in electronic devices*, ed. A. A. Balandin, ASP, Stevenson Ranch (2002).