INSTITUTE OF PHYSICS PUBLISHING SEMICONDUCTOR SCIENCE AND TECHNOLOGY

Semicond. Sci. Technol. **16** (2001) L8–L11 www.iop.org/Journals/ss PII: S0268-1242(01)19328-4

LETTER TO THE EDITOR

Monte Carlo analysis of the influence of dc conditions on the upconversion of generation-recombination noise in semiconductors

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Received 23 November 2000, accepted for publication 18 December 2000

Abstract

We present a study of the influence of nonlinear velocity-field characteristics of semiconductors on the upconversion of low-frequency generation-recombination noise to high frequencies. An ensemble Monte Carlo simulation is used for the calculations. When a periodic electric field of large amplitude is applied to the semiconductor we observe the generation of harmonics in the current response, and the upconversion of generation-recombination noise as sidebands around these harmonics. By varying the dc value of the applied electric field we obtain the main result of this work: upconverted noise is dramatically reduced when the sample is biased in the quasi-saturation region.

The sensitivity of communication systems is strongly affected by the presence of noise, which sets the lower limit for signal detection in electronic circuits. The direct noise contributions at high frequencies play an important role but, in addition, the low-frequency noise present in electronic devices can affect the high-frequency performance. As examples, the microwave phase noise in oscillators is a result of the carrier phase modulated by the low-frequency noise [1] and can limit the channel frequency spacing in communication systems [2]. Also, the low-frequency noise can be upconverted to affect the high-frequency performance of mixers [3]. Thus, achieving low $1/f$ and generation-recombination (GR) noise levels is critical for sensitive circuit applications.

In a previous work it was shown that GR noise of a linear semiconductor is transferred to high frequencies by means of the amplitude modulation of the semiconductor response to ac or time-varying electric fields due to trapping–detrapping processes [4]. The semiconductor was modelled as a linear system; the energy-independent scattering time and trapping–detrapping probabilities were considered.

However real materials and devices exhibit strong nonlinearities, such as the appearance of saturation in their characteristics. Therefore new effects have to be considered (as the excitation of harmonics [5]) and nonlinear analysis of noise must be performed [6, 7]. In general, the noise characteristics are significantly different when devices work in a linear regime with respect to nonlinear conditions. As a direct consequence of this fact, the upconversion of GR noise is expected to change with respect to that observed in linear systems.

In this letter we analyse the upconversion of GR noise in a semiconductor exhibiting a nonlinear velocity–field characteristic when it is driven by periodic signals of large amplitude. In particular, we focus on the influence of the dc conditions on the high-frequency noise. As a main result we found that the transfer of the baseband noise to high frequencies is minimized when the semiconductor works under near-saturation conditions. This fact may be considered as an important result to be borne in mind by circuit designers when the optimization of noise properties is one of the key issues of an application.

For the calculations we make use of an ensemble Monte Carlo (MC) simulation. We consider an n-type homogeneous semiconductor of length L and cross sectional area A at temperature $T = 300$ K with a single type of electron trap. The microscopic model is the same as that reported in [4], except that now the characteristic time of inelastic (thermalizing) scattering here becomes dependent on energy $\tau_s(\varepsilon)$. For a given energy $\tau_s(\varepsilon)$ is considered to be inversely proportional to $\varepsilon^{1/2}$. This constitutes the origin of the nonlinearity in the semiconductor response. The noise analysis is performed by means of the calculation of $S_I(f)$ and the spectral density of the current $I(t)$ directly obtained from the simulations, by squaring its Fourier transform [8].

When a time-varying field of the type $E(t) = E_{dc} + E_{ac}\sin(2\pi f_{ac}t)$ is applied to the semiconductor, according to its nonlinear behaviour and depending on the amplitudes of E_{dc} and E_{ac}, some harmonics of f_{ac} may be excited in the current response. Thus, a deterministic time-dependent response $I_d(t)$ given by $I_d(t) = (q/L)\langle N_f\rangle v_d(t)$ is expected, where q is the electron charge, $\langle N_f\rangle$ is the average number of free carriers and $v_d(t)$ is the deterministic velocity response. Within our model $\langle N_f\rangle = N\tau_r/(\tau_r + \tau_g)$, where N is the total number of carriers (free plus trapped electrons) and τ_r and τ_g are the recombination and generation characteristic times, respectively (both are considered to be energy independent). The deterministic velocity response is $v_d(t) = v_{dc} + \sum_{m=1}^{\infty} v_{dm}\sin(2\pi m f_{ac}t)$ where v_{dc} is the dc component of the velocity and v_{dm} is the amplitude of the mth harmonic. By defining $\delta v'(t) = v(t) - v_d(t)$ as the fluctuation of the instantaneous velocity $v(t)$ over the average deterministic value and $\delta N_f = N_f(t) - \langle N_f\rangle$ as the fluctuation of free carriers, $N_f(t)$, over its mean value, the instantaneous current can be written as [4]

$$I(t)=\frac{q}{L}[\langle N_f\rangle v_d(t)+\langle N_f\rangle\delta v'(t)+v_d(t)\delta N_f(t)+\delta N_f(t)\delta v'(t)]. \qquad (1)$$

Due to the number fluctuations originated by the trapping–detrapping processes, a term of the form $(q/L)v_d(t)\delta N_f(t)$ appears in $I(t)$, which corresponds to an amplitude modulation of the current response by number fluctuations. This term should lead to the upconversion of the low-frequency GR spectrum, contributing with sidebands centred around f_{ac} and its harmonics. Based on this analysis, our objective is the study of the influence of GR mechanisms on the current response of nonlinear semiconductors in the presence of small and large amplitude periodic electric fields for different dc biases.

We used the following set of parameters in the simulations: $m = 0.25m_0$ (m_0 is the mass of a free electron), $N = 1000$, $\tau_r = 2\times10^{-12}$ s and $\tau_g = 18\times10^{-12}$ s. Since τ_r and τ_g are energy independent, the carrier lifetime $\tau_l = \tau_r\tau_g/(\tau_r + \tau_g) = 1.8\times10^{-12}$ s is always the same for all of the electric field amplitudes considered. For the same reasons $\langle N_f\rangle$ always takes a value of 100. The inelastic scattering time, τ_s, is given by (with ε in electronvolts)

$$\tau_s(\varepsilon) = \begin{cases} 4\times10^{-13}\ \text{s} & \varepsilon \leqslant 0.04\ \text{eV} \\ 1.4436\times10^{-13}\varepsilon^{-1/2} - 3.2180\times10^{-13}\ \text{s} & \\ \qquad 0.04\ \text{eV} < \varepsilon < 0.2\ \text{eV} & \\ 4.472\times10^{-16}\varepsilon^{-1/2}\ \text{s} & \varepsilon > 0.2\ \text{eV}. \end{cases}$$

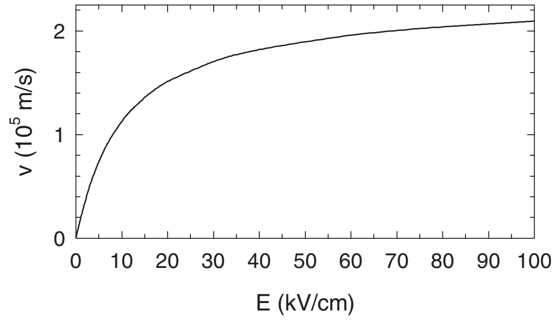

Figure 1. The average electron velocity as a function of the electric field amplitude obtained with the energy-dependent scattering time used in the model.

This model for τ_s is adopted to have significant variation (more than two orders of magnitude) of the scattering probability in the energy range of interest with a standard dependence of the type $\varepsilon^{1/2}$. Moreover, this model provides a velocity–field characteristic that resembles nicely that of a typical semiconductor, as shown in figure 1. Here the nonlinear response is clearly observed. For low electric fields ($\leqslant$5 kV cm^{-1}) only, the velocity increases linearly with E. For higher field values, as the electron energy increases the probability of carriers to suffer scattering increases; as a consequence a tendency to saturation is observed. The values of velocity in the quasi-saturation region obtained with our ideal model are somewhat high as compared to those found in conventional semiconductors. This is due, on the one hand, to the fact that we consider a single-valley semiconductor with no energy dependence of the effective mass (parabolic band) and, on the other hand, to the low values of the scattering rate considered in the simulation as compared to typical semiconductors, in order to save computer time [4]. In any case, the main conclusions of our work are related to the nonlinearity of the v–E curve and not to the actual values of velocity. For the same reasons, this is to avoid simulation times that are too long, a high frequency f_{ac} of 500 GHz is taken for the periodic time-varying electric fields in the following.

In order to compare the nonlinear case with previous results under a linear response [4], we will report the current spectral density for similar physical conditions. First we consider the situation when only a periodic electric field of large amplitude is applied to the semiconductor (no dc field). The evolution of $S_I(f)$ with increasing values of E_{ac} is reported in figure 2. In all cases only one plateau related to thermal noise is distinguished. In contrast with the linear case, the low-frequency value of the thermal noise decreases and its corner frequency is displaced to higher frequencies as the field increases; as a consequence of the reduction of τ_s with the energy increase. In the absence of a dc current the GR noise does not appear as a plateau at low frequencies, however it is upconverted as two sidebands around the oscillation frequency and its harmonics. The amplitude of these sidebands is directly dependent on the magnitude of the electric field, as happens in the linear case. Thus, for very low fields the sidebands are very difficult to detect, as noticed in figure 2(*a*); when the electric field increases they become more evident (figures 2(*b*) and 2(*c*)), even extending its influence to the low-frequency region, where the lower sideband around the fundamental

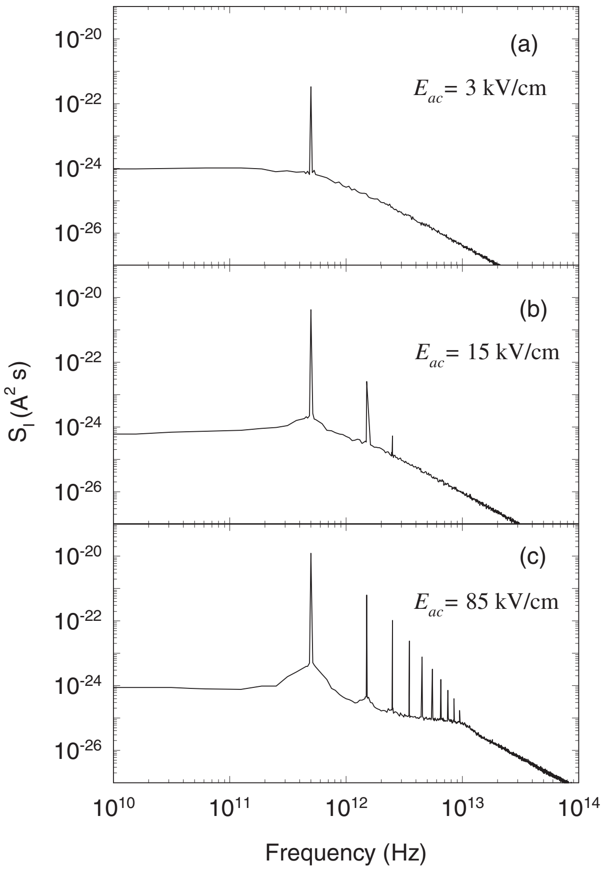

Figure 2. Current spectral density for different amplitudes of the time-varying electric field in the absence of a dc field: (*a*) 3, (*b*) 15 and (*c*) 85 kV cm^{-1}.

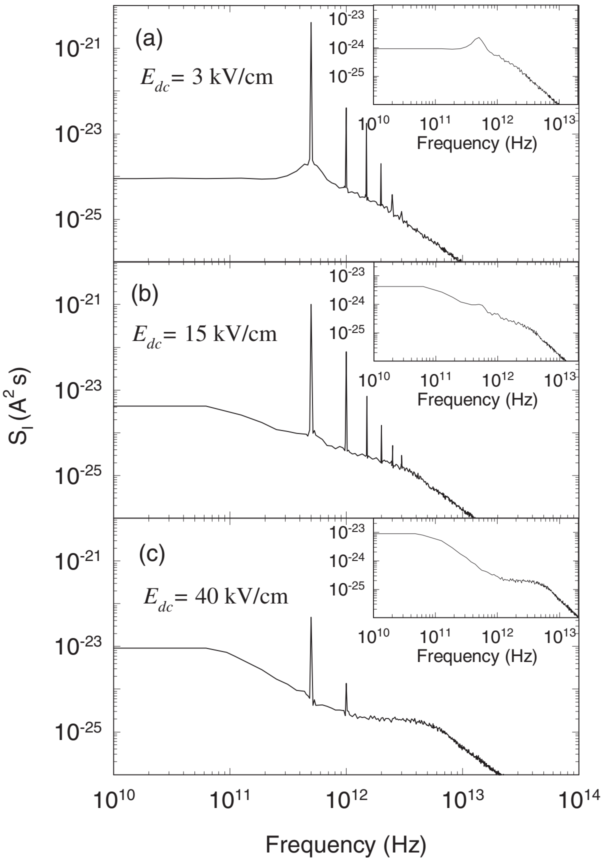

Figure 3. Current spectral density for an amplitude of the time-varying electric field of 15 kV cm^{-1} and different values the dc field: (*a*) 3, (*b*) 15 and (*c*) 40 kV cm^{-1}. The insets show the same results when the deterministic component of the current is suppressed.

frequency provides a significant contribution that adds to the thermal noise level [4]. At high amplitudes of the electric field, nonlinearity and saturation effects become important, and new features appear with respect to the linear behaviour, such as the generation of harmonics. Only odd harmonics are excited in this case, due to the symmetrical current response around zero in the absence of a dc field. The number of excited harmonics grows with the strength of the field (stronger nonlinearity of the system). It is interesting to remark that in the case of $E_{ac} = 85$ kV cm^{-1} the GR noise is noticeable around all harmonics, even at very high frequencies; for example, the sidebands around 1.5×10^{12} Hz are clearly observed. This noise upconversion can limit the use of semiconductors as wave generators at very high frequencies [5].

In typical applications, devices are biased with a dc voltage and time-varying signals are applied over the stationary conditions. So they work under the influence of dc as well as time-varying electric fields. Let us analyse how the dc electric field influences the upconversion of the GR noise. In figure 3 we show $S_I(f)$ for three values of E_{dc} corresponding to different regimes of semiconductor response: figure 3(*a*) $E_{dc} = 3$ kV cm^{-1}, linear region; figure 3(*b*) $E_{dc} = 15$ kV cm^{-1}, close-to-saturation region; and figure 3(*c*) $E_{dc} = 40$ kV cm^{-1}, quasi-saturation region. For all cases we chose a value of $E_{ac} = 15$ kV cm^{-1}. In these figures the insets correspond to $S_{\delta I}(f)$, the spectral density of the current fluctuations over the deterministic response $\delta I_{ac}(t) = I(t) - I_d(t)$. By removing from the spectrum the peaks at f_{ac} and their harmonics (associated with $I_d(t)$) this quantity allows a better examination of the upconverted GR noise [4]. A similar procedure is necessary in some experimental measurements [9, 10]. We remark that the spectra in figure 3 are reported in a range well above the lowest frequencies where a peak related to the dc response would be present.

For $E_{dc} = 3$ kV cm^{-1}, in spite of the presence of a dc voltage, no substantial contribution of the GR noise at low frequencies is detected due to the low dc current level. As expected because of the low value of E_{dc}, the upconverted GR noise is quite similar to that observed in figure 2(*b*), where the same E_{ac} was applied, but in the absence of E_{dc}. However, now, due to the non-symmetrical current response around the dc value (associated with the presence of E_{dc}), even harmonics also appear. When $E_{dc} = 15$ kV cm^{-1} the dc current increases and, consequently, the low-frequency plateau associated with the GR noise becomes more pronounced (even more for $E_{dc} = 40$ kV cm^{-1} in figure 3(*c*)). The cut-off frequency of this contribution is independent of the electric field conditions, since τ_r and τ_g are energy independent. In the case of figure 3(*b*) the total electric field changes periodically from 0 to 30 kV cm^{-1}; so that the semiconductor behaviour is strongly nonlinear (see figure 1): changing from a linear to a quasi-saturation response. As a consequence the number of excited harmonics increases with respect to the previous case (figure 3(*a*)), but the value of the upconverted GR noise is significantly lower, only slightly distinguishable around the fundamental frequency. When the semiconductor is biased in the quasi-saturation region ($E_{dc} = 40$ kV cm^{-1}, figure 3(*c*)) the velocity response becomes more linear, thus exciting only the second harmonic, and more important, the sidebands around the fundamental frequency and the second harmonic become very small, nearly undetectable, even if the semiconductor's deterministic response is still clearly noticeable. Therefore, these bias conditions enable us to minimize the influence of the GR noise at high frequencies around f_{ac}. For this high value of the dc field, due to the higher carrier energy, the velocity relaxation time becomes short enough to separate clearly the GR and thermal noise plateaus in the spectrum, which were very close for the lower fields.

In summary, by means of an ensemble MC simulation we have analysed the upconversion of low-frequency GR noise in bulk semiconductors under a nonlinear response. As the main result we have provided, for the first time, microscopic evidence of the reduction of the influence of GR noise at high frequencies when working under near-saturation conditions. The results presented here must be considered as a first step towards a full simulation of the noise performance of semiconductor devices including low-frequency GR noise sources and working under radiofrequency (time-varying) electric fields.

This work was partially supported by the projects PB97-1331 from the Dirección General de Enseñanza Superior e Investigación Científica and SA44/99 from the Consejería de Educación y Cultura de la Junta de Castilla y León.

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