Solid-State Electronics Vol. 31, No. 3/4, pp. 543–546, 1988
Printed in Great Britain

0038-1101/88 $3.00 + 0.00
Pergamon Journals Ltd

GENERATION-RECOMBINATION NOISE OF HOT CARRIERS IN SEMICONDUCTORS

Lino Reggiani and Paolo Lugli

Dipartimento di Fisica e Centro Interuniversitario di Struttura della Materia
dell'Universita' di Modena, Via Campi 213/A, 41100 Modena, Italy

Vladimir Mitin

Institute of Semiconductors, Academy of Sciences of the Ukrainian SSR, Kiev, USSR

ABSTRACT

We present an original Monte Carlo procedure to account for generation-recombination noise through impurity centers in semiconductors. An exact decomposition procedure of the current spectral density evidences the importance of a cross-correlation contribution coming from velocity and number fluctuations.

KEYWORDS

Electronic transport, semiconductors, noise and fluctuations, scattering mechanisms, Monte Carlo method.

INTRODUCTION

An important source of noise specific for semiconductors comes from the statistical generation and recombination (GR) of charge carriers through impurity centers. This GR noise, being proportional to the square of the current flowing in a two terminal network, generally yields an intrinsic limit to the performances of a device when increasing voltages are applied and/or submicron structures are considered. While several macroscopic approaches to GR noise can be found in the literature (Van der Ziel, 1965; Van Vliet and Fasset, 1965; Nougier, 1981; Pellegrini, 1981), microscopic theories are very scarce. Furthermore, the concomitant presence of non-linear effects in the applied field (hot-electron effects) makes a rigorous analytical approach to the problem very difficult. The aim of this paper is to present an exact decomposition procedure of the spectral density in terms of its elemental noise sources. Then, an original Monte Carlo (MC) code, which accounts for GR noise through impurity centers in semiconductors, is used for the numerical calculations.

THEORY AND RESULTS

We consider a uniform semiconductor sample, of length L small compared to its cross-sectional area A, in which charge transport occurs through a two-level system: the conduction (valence) band and the traps which supply the carriers. By definition the current spectral density S_I at low frequency is given by:

$$S_I(\omega \to 0) = 4 \int_0^\infty \overline{\delta I(0) \delta I(t)} dt \tag{1}$$

where $\delta I(t) = I(t) - I_0$ is the current fluctuation around the steady state value I_0, and the bar denotes a time average (the explicit time dependence will herewith indicate instantaneous quantities). Steady-state conditions, that is invariance with respect to time translation, ensure that S_I is time independent. From the Ramo-Shockley theorem and its generalization (Pellegrini, 1986), the total current $I(t)$, as measured in the outside circuit, can be expressed in the two following equivalent forms:

$$I(t) = \frac{e}{L} N_0 v_d^r(t) = \frac{e}{L} N(t) v_d(t) \tag{2}$$

where e is the electron charge, N_0 the total number of impurity centers, $v_d^r(t)$ the total carrier drift velocity (which

accounts for GR mechanism), $N(t)$ the number of free carriers and $v_d(t)$ their drift velocity (which neglects GR mechanism). The last expression in Eq.(2) allows for an exact decomposition of S_I in terms of different noise sources. Indeed, from Eq. (2) S_I can be given the two following equivalent expressions:

$$S_I = \frac{4e^2}{L^2} N_0^2 \int_0^\infty \overline{\delta v_d^r(0) \delta v_d^r(t)} dt \tag{3a}$$

$$\begin{aligned} S_I = \frac{4e^2}{L^2} \int_0^\infty dt \{ \bar{N}^2 \overline{\delta v_d(0) \delta v_d(t)} + \bar{v}_d^2 \overline{\delta N(0) \delta N(t)} + \bar{N} \bar{v}_d [\overline{\delta N(0) \delta v_d(t)} + \overline{\delta v_d(0) \delta N(t)}] \} \\ = S_{Ivf} + S_{Igr} + S_{Icross} \end{aligned} \tag{3b}$$

where we have isolated the three contributions coming respectively from velocity and number fluctuations and from their cross-correlations. From their definition in terms of correlation function, it appears that S_{Igr} and S_{Icross} are proportional to v_d^2 and v_d , respectively. Therefore they describe excess noise and, as expected, vanish at equilibrium and/or when (for isotropic structure) the noise is measured in a direction perpendicular to the applied electric field. In the absence of intercarrier scattering (Lugli and Reggiani, 1986), the terms $N_0 \int \overline{\delta v_d^r(0) \delta v_d^r(t)} dt$ and $\bar{N} \int \overline{\delta v_d(0) \delta v_d(t)} dt$ give respectively the diffusion coefficients of carriers with and without GR mechanism. Thus, S_I and S_{Ivf} can be calculated from the MC technique in the standard way (Jacoboni and Reggiani, 1983), once the GR processes are included into the simulation. S_{Igr} is also calculated directly using the equation

$$S_{Igr} = \frac{4e^2 N_0}{L^2} \frac{v_d^2}{\gamma} [\frac{u^2(1-u)}{(2-u)^2}]. \tag{4}$$

The fraction of ionized impurities u is estimated from the ratio between the time spent by the carriers in the conduction band and the time of simulation, while the generation rate γ is estimated from the ratio between the number of generations and the time spent by the carrier into the traps. S_{Icross} can then be evaluated by difference. Calculations are specialized for the case of holes in Si where recent experiments on GR noise performed by the Montpellier group (Vaissiere, 1986) are available. The microscopic model follows from Reggiani and others (1986). It uses a single valence band (the heavy one) warped with non-parabolic effects accounted for and includes acoustic, nonpolar optical and ionized impurity scattering mechanisms. A non-radiative GR mechanism is introduced as an additional scattering mechanism in the line previously reported in the literature (Abakumov and others, 1978; Mitin and others, 1986). Fig. 1 shows the energy dependence of the scattering rates due to the different mechanisms which are used in the MC calculation. The results at 77 K for an acceptor concentration (Boron) of 3 x $10^{15} cm^{-3}$ and with an electric field applied along the $< 100 >$ direction are shown in Fig. 2. Here the different contribution to the current spectral density of Eq. (3b) are reported as a function of the applied electric field. (Without loosing in accuracy but saving computer time, S_{Ivf} has been calculated from the transverse in place of the longitudinal diffusion coefficient). At the lowest electric fields only the velocity-fluctuations contribution is present, in agreement with the Nyquist-Einstein relationship. As shown in Fig. 2, the three components of the noise spectral density exhibit a quite different field dependence. While S_{Ivf} varies very slowly, S_{Igr} and S_{Icross} have respectively a linear and quadratic field dependence up to about 10^3 V/cm. S_{Igr} becomes predominant at 10^4 V/cm. Then, by further increasing the field, both S_{Icross} and S_{Igr} are found to reach a maximum and then decrease. This behavior should be attributed to the instauration of hot-electron conditions. As known, under these conditions the energy distribution function deviates from its equilibrium Maxwell-Boltzmann shape, and the average carrier energy increases with the electric field. As a consequence, v_d tends to saturate and u becomes unit, yielding the high-field dependence of S_{Igr} shown in Fig. 2. In the field region where S_{Icross} dominates over S_{Igr}, we ascribe its larger value to the strong coupling between velocity and number fluctuations of carriers. This coupling occurs in the low energy region of the carrier distribution function where the scattering rates for GR are comparable or larger than those for interaction with the lattice, as can be seen in Fig. 1. However, carrier heating by decreasing the number of carriers in the low energy region of the distribution function weakens the velocity-number correlation. As a result, S_{Icross} is found to decrease at the highest fields. Similar results are found for a lower acceptor concentration of 4 x $10^{14} cm^{-3}$, see Fig. 3. Owing to the small concentration, the importance of the cross-correlation contribution is significantly diminished and it becomes negligible above 2000 V/cm. For both cases, available experiments (Vaissier, 1986) compare favourably with present calculations.

In summary, an analysis of the excess noise in semiconductors in presence of two sources, namely velocity and number fluctuations of charge carriers has been reported. The current spectral density has been decomposed into three terms which correspond to fluctuations associated with velocity (Johnson noise), number (generation-recombination) and their cross-correlation. An original Monte Carlo procedure to evaluate each contribution has been devised. At vanishing electric field, the equilibrium Nyquist-Einstein relation is recovered. At intermediate fields, results show a dominant contribution of the cross-correlation term, which is usually neglected in theoretical analysis. At the highest fields, the noise spectral density reaches a maximum and then decreases as a result of hot-electron effects.

ACKNOWLEDGMENT

This work has been performed on the basis of a scientific cooperation agreement between the Academy of Sciences of the USSR and the National Research Council of Italy. Partial support has been provided by the Ministero della Pubblica Istruzione (MPI) and the Centro di Calcolo dell'Universita' di Modena (CICAIA).

REFERENCES

Abakumov, V.V. , Perel, V.I. and Yanievich, I.N. (1978). Sov. Phys. Sem., **12**, 1-18.

Jacoboni, C. and Reggiani, L. (1983). Rev. Mod. Phys., **55** , 645-705.

Lugli, P. and Reggiani, L. (1986). In A. D'Amico and P. Mazzetti (Eds.), Proc. 8th Int. Conf. on Noise in Physical Systems, North Holland, Amsterdam, pp. 235-238.

Mitin, V.V. , Asche, M. and Kostial, H. (1986). Phys. Rev., **B33**, 4100-4107.

Nougier, J.P. (1981). In P.H.E. Mijer, R.D. Mountain and R.J. Souklen Jr. (Eds.) , Proc. 6th Int. Conf. on Noise in Physical Systems, NBS, Washington , pp. 397-405.

Pellegrini, B. (1981). Phys. Rev., **B24**, 7071-7083.

Pellegrini, B. (1986). Phys. Rev., **B34**, 5921-5924.

Reggiani, L. , Brunetti, R. and Normantas, E. (1986). J. Appl. Phys., **59**, 1212-1215.

Shockley, W. , Copeland, J.A. and James, R.P. (1960). In P.O. Loewdin (Ed.), **Quantum Theory of Atom, Molecules and the Solid State** , Academic Press, New York.

Vaissiere, J.C. (1986). Dissertation, University of Montpellier, unpublished.

Van der Ziel, A. (1970). **Noise Source, Characterization, Measurement**, Prentice Hall , New Jersey.

Van Vliet, K.M. and Fassett, J.R. (1965). In R. E. Burgess (Ed.). **Fluctuation Phenomena in Solids** , Academic Press , New York. pp. 267-354.

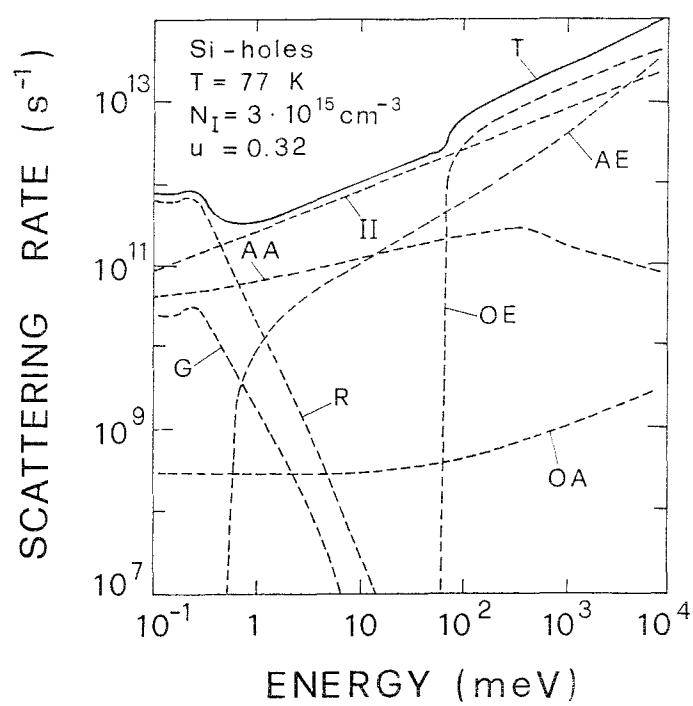

Fig. 1 - Scattering rate as a function of energy for holes in Si at 77K. Symbols have the following meaning: AA (Acoustic Absorption), AE (Acoustic Emission), OA (Optical Absorption), OE (Optical Emission), II (Ionized Impurities), G (Generation), R (Recombination), T (Total).

Fig. 2 - Total (continuous curve) and individual (broken curves) current spectral densities as a function of the electric field for the case of holes in Si at 77 K with $N_I = 3 \times 10^{15}\ cm^{-3}$, $L = 1.5 \times 10^{-2} cm$, and $A = 3.6 \times 10^{-3} cm^2$. Curves report Monte Carlo calculations with bars indicating uncertainties. The point represents the only experimental result available at present (Vaissiere, 1986).

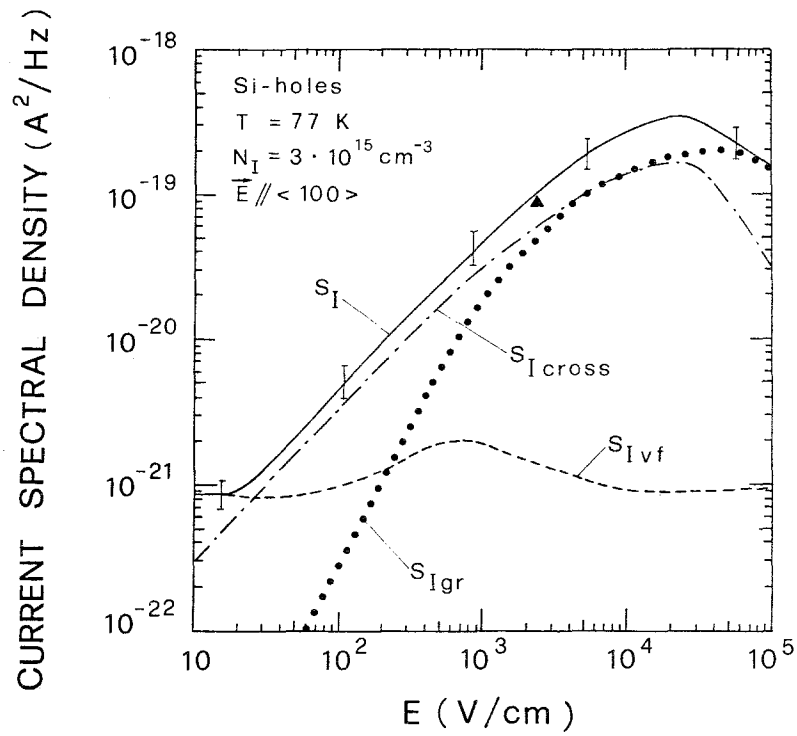

Fig. 3 - The same as in the previous figure with $N_I = 4 \times 10^{14}\ cm^{-3}$, $L = 3.55 \times 10^{-2}\ cm$, and $A = 7 \times 10^{-3} cm^2$.