Numerical Langevine-like method for modelling the noise currents in semiconductors

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Abstract **This paper presents a numerical method for determining the spectral density of noise current in semiconductor structures. Based on P. Handel's theory we have considered a wide range of sources of 1/ f noise caused both by generation-recombination (g-r) and scattering processes. In addition to the shot g-r noise caused by different mechanism, the diffusion noise and temperature fluctuations are also included. Moreover, we have found in HgCdTe nBn long wavelength detectors the place where the noise current is mainly generated.**

I INTRODUCTION

Infrared photon detectors must be cryogenically cooled to achieve high sensitivity and reduction of noise and leakage currents. Significant research effort is now directed towards innovative solutions to obtain new types of detectors operating in high temperatures with a much better detection performance and lower manufacturing costs. One of the promising solutions is the HgCdTe nBn device operating in a long wavelength infrared radiation (LWIR) range. Photoelectric characteristics of this type of detector are relatively easy to estimate theoretically. The key to this is the numerical solution of transport equations by using iterative methods. For this purpose we use our own computer programmes. You can also take advantage of the many commercial programmes. However, analysis of the fluctuation phenomena is still an open problem. The possibility of numerical modelling of spectral density of current noise in semiconductor devices gives a lot of information about g-r mechanisms and scattering mechanisms. Knowing the principal place of generation of noise currents in the semiconductor structure and the participation of different mechanisms of generation, we can find the optimal design solutions limiting the noise current . In this work we present a numerical method which gives those possibilities. We show the result of our calculations for cylindrical HgCdTe LWIR nBn detector working at room temperature.

II. NUMERICAL METHOD

The key to modeling the fluctuation phenomena in semiconductors is the solution of set of transport equations for fluctuations (TEFF), derived by the author for the first time in 2001 [1]. These equations were modified and developed in subsequent works , taking the form below:

$$\nabla^2(\delta\Psi) = -\frac{e}{\varepsilon\varepsilon_0}\left(\frac{\partial N_D^+}{\partial\Psi}\delta\Psi + \frac{\partial N_D^+}{\partial\Phi_n}\delta\Phi_n + \frac{\partial N_D^+}{\partial T}\delta T - \frac{\partial N_A^-}{\partial\Psi}\delta\Psi - \frac{\partial N_A^-}{\partial\Phi_p}\delta\Phi_p - \frac{\partial N_A^-}{\partial T}\delta T + \frac{\partial p}{\partial\Psi}\delta\Psi + \frac{\partial p}{\partial\Phi_p}\delta\Phi_p + \frac{\partial p}{\partial T}\delta T - \frac{\partial n}{\partial\Psi}\delta\Psi - \frac{\partial n}{\partial\Phi_n}\delta\Phi_n - \frac{\partial n}{\partial T}\delta T\right) - \frac{1}{\varepsilon}\nabla(\delta\Psi)\nabla\varepsilon \quad (1)$$

$$\frac{\partial n}{\partial\Psi}\frac{\partial\Psi}{\partial t} + \frac{\partial n}{\partial\Phi_n}\frac{\partial\Phi_n}{\partial t} + \frac{\partial n}{\partial T}\frac{\partial T}{\partial t} = \nabla\left[\left(\frac{\partial\mu_n}{\partial\Psi}\delta\Psi + \frac{\partial\mu_n}{\partial\Phi_n}\delta\Phi_n + \frac{\partial\mu_n}{\partial\Phi_p}\delta\Phi_p + \frac{\partial\mu_n}{\partial T}\delta T + \frac{\partial\mu_n}{\partial\tau_{rel}^{e}}\boldsymbol{\delta\tau_{rel}^{e}}\right)n\nabla\Phi_n + \mu_n\left(\frac{\partial n}{\partial\Psi}\delta\Psi + \frac{\partial n}{\partial\Phi_n}\delta\Phi_n + \frac{\partial n}{\partial T}\delta T\right)\nabla\Phi_n + \mu_n n\nabla(\delta\Phi_n)\right] + \boldsymbol{\delta(G-R)_{SHOT}} + \boldsymbol{\delta(G-R)_{1/f}} + \frac{\partial(G-R)}{\partial n}\left[\frac{\partial n}{\partial\Psi}\delta\Psi + \frac{\partial n}{\partial\Phi_n}\delta\Phi_n + \frac{\partial n}{\partial T}\delta T\right] + \frac{\partial(G-R)}{\partial p}\left[\frac{\partial p}{\partial\Psi}\delta\Psi + \frac{\partial p}{\partial\Phi_p}\delta\Phi_p + \frac{\partial p}{\partial T}\delta T\right] + \boldsymbol{F_n(t)} \quad (2)$$

$$\frac{\partial p}{\partial\Psi}\frac{\partial\Psi}{\partial t} + \frac{\partial p}{\partial\Phi_p}\frac{\partial\Phi_p}{\partial t} + \frac{\partial p}{\partial T}\frac{\partial T}{\partial t} = -\nabla\left[\left(\frac{\partial\mu_p}{\partial\Psi}\delta\Psi + \frac{\partial\mu_p}{\partial\Phi_n}\delta\Phi_n + \frac{\partial\mu_p}{\partial\Phi_p}\delta\Phi_p + \frac{\partial\mu_p}{\partial T}\delta T + \frac{\partial\mu_p}{\partial\tau_{rel}^{h}}\boldsymbol{\delta\tau_{rel}^{h}}\right)p\nabla\Phi_p + \mu_p\left(\frac{\partial p}{\partial\Psi}\delta\Psi + \frac{\partial p}{\partial\Phi_p}\delta\Phi_p + \frac{\partial p}{\partial T}\delta T\right)\nabla\Phi_p + \mu_p p\nabla(\delta\Phi_p)\right] + \boldsymbol{\delta(G-R)_{SHOT}} + \boldsymbol{\delta(G-R)_{1/f}} + \frac{\partial(G-R)}{\partial n}\left[\frac{\partial n}{\partial\Psi}\delta\Psi + \frac{\partial n}{\partial\Phi_n}\delta\Phi_n + \frac{\partial n}{\partial T}\delta T\right] + \frac{\partial(G-R)}{\partial p}\left[\frac{\partial p}{\partial\Psi}\delta\Psi + \frac{\partial p}{\partial\Phi_p}\delta\Phi_p + \frac{\partial p}{\partial T}\delta T\right] + \boldsymbol{F_p(t)} \quad (3)$$

$$c_V \frac{\partial(\delta T)}{\partial t} - \nabla[\chi \nabla(\delta T)] = \mathbf{F_C(t)} + \mathbf{G_C(t)} \qquad (4)$$

The equations contain standard phrases; the index n refers to electron h, to the holes respectively. δ denotes fluctuation, $(\boldsymbol{G}-\boldsymbol{R})$ -g-r rate, Ψ electrical potential, Φ quasi-Fermi energy, T temperature. Other symbols are explained in our last paper [2].As the set of Eqs. (1)-(4) is linear one can express all random variables by means of the Fourier series and separately consider any Fourier coefficient at any frequency. In this way TEFF now becomes the set of Langevine-like equations in which we can determine the random source terms i.e. $\boldsymbol{\delta\tau^{e}_{rel}}$, $\boldsymbol{\delta\tau^{h}_{rel}}$, $\boldsymbol{\delta(G-R)_{SHOT}}$, $\boldsymbol{\delta(G-R)_{1/f}}$, $\mathbf{F_C(t)}$, $\mathbf{G_C(t)}$. $\boldsymbol{F_n(t)}$ and $\boldsymbol{F_p(t)}$. Knowing the SD of random sources one may determine the complex amplitude a_f of their Fourier coefficients defined as follows:

$$\delta a(\vec{r}, t) = \int_0^{\infty} \frac{1}{\sqrt{2}} c_f exp(i\varphi_f) exp(i2\pi f t)\, df$$

$$a_f = \frac{1}{\sqrt{2}} c_f exp(i\varphi_f); \quad S_a(f)\Delta f = a_f a_f^* \qquad (5)$$

Here $S_a(f)$ denotes the SD of fluctuation quantity, $\Delta f = 1Hz$, $c_f exp(i\varphi_f)$ is the complex Fourier coefficient for frequency f. The numerical method for solving TEFF equations is described in Refs [1,2]. To solve the set of equations (1)-(4) one has to know the SD of mobility fluctuations (this was shown in Ref. [3]) as well as the SD of fluctuations of G-R processes. Similar to ref. [2], the influence of dislocations on noise current was taken into account.

II. NUMERICAL RESULTS

From the following update these selected results of calculations of physical parameters of the cylindrical $Hg_{1-x}Cd_xTe$ nBn MESA detector with a diameter of 60 micrometers at 296 K. Spatial distributions of mole fraction and donod and acceptor concentrations are shown along the axis of symmetry of the structure in Fig.1. The spatial distribution of electric field and noise power density for 1 Hz frequency and -800 mV revere bias are shown in Fig.2. Fig. 3 shows the noise current at Δf=1Hz as a function of frequency. Noise current is caused mainly by g-r shot noise and temperature noise

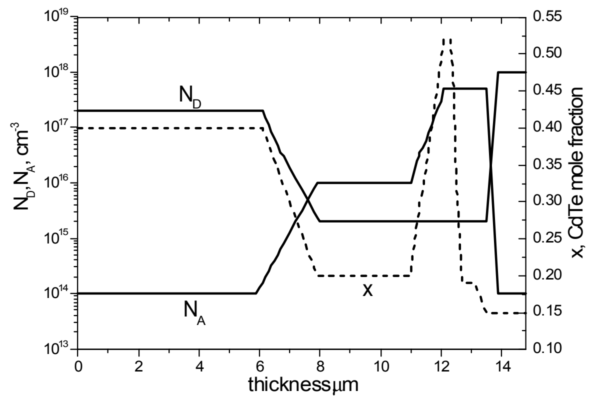

Fig. 1. Spatial distribution of mole fraction x donor concentration N_D and acceptor concentration N_A

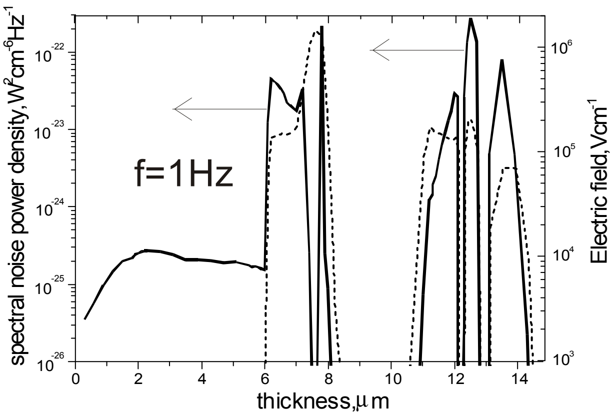

Fig. 2. Calculated spatial distribution of electric field and noise power density in nBn detector operating at room temperature for 1Hz frequency, biased with -800mV. The noise power density is caused by shot g-r noise and temperature noise

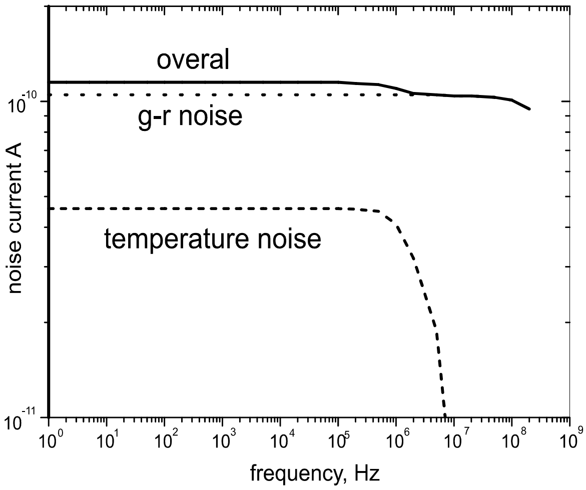

Fig.3.Noise current at Δf=1Hz as a function of frequency caused mainly by g-r shot noise and temperature noise

III. CONCLUSIONS

Theoretical analysis reported in this paper shows, that the noise current in a LWIR nBn non-cooled structure is mainly generate by shot g-r mechanisms connected with Auger processes. The presence of misfit dislocations in the depletion regions results in the increase of the dark current and consequently the noise current which is always proportional to the total dark current. 1/f noise caused by fluctuations of mobility have a marginal meaning. Cooling of the structure reduces the dark current and the noise current. At lower temperatures, 1 / f noise dominates the g -r noise especially in the area of low frequency. Noise current is mainly generated in regions where there is a strong built-in electric fields.

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