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Characterization of generation–recombination noise using a physics-based device noise simulator

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Abstract

The implementation of generation–recombination (g–r) noise in a partial differential equation based device simulator is presented. Derived from the Shockley–Read–Hall model, the strength of each local g–r noise source is calculated based on the carrier transition rates between the conduction band, valence band, and trap states. The perturbations of these local g–r noise sources are then transmitted to the electrodes of the simulated device through scalar Green's functions. g–r noise simulations are compared with existing measurements made on a four trap level, p-type silicon resistor. Good agreement between measured and simulated data is observed. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Partial differential equation (PDE), physics-based device simulators have quickly gained popularity in recent years because of their advantages over other types of device simulators and design tools. They can provide fast and accurate results. For example, they require fewer computations than Monte Carlo simulators. In addition, PDE-based device simulators are easily adapted to device model updates. Add-on software packages, such as, in our case, a noise simulator, can be created and draw on already produced simulator parameters. Furthermore, this type of simulator can be made to extract data directly from a process simulator. This combination is a cost-effective tool for device optimization since the simulators are parameter compatible. This paper presents the implementation of generation–recombination (g–r) noise in Florida object-oriented device simulator (FLOODS), a PDE-based generalized box scheme device simulator. FLOODS is capable of doing two-dimensional dc, ac, and transient simulations. Recently, diffusion and $1/f$ Hooge noise models were implemented in FLOODS by Bosman et al. [1,2] and by Bonani et al. [3] in a similar simulator. The latter noise models based on velocity and mobility fluctuations, respectively, are implemented by adding Langevin noise sources to the electron and hole continuity equations. The effect of each local, distributed noise source at the contact terminals is calculated using vector Green's functions. The total voltage noise spectral density observed at the contact terminals follows from integration over all noise sources. The g–r noise sources representing transition rate fluctuations can effectively be accounted for by adding Langevin noise sources to Poisson's equation [3] as will be shown below. By utilizing the Green's function already calculated by FLOODS, the g–r noise spectral voltage density contact contribution from each local g–r noise source can be calculated.

2. Theory

The formulation of local g–r noise sources is based on the Shockley–Read–Hall model. In addition to the three basic equations,

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$$F_\psi = -\frac{d^2\psi}{dr^2} - \frac{q}{\varepsilon}\left[p - n + N_D^+ - N_A^- - n_t\right] = 0, \quad (1)$$

$$F_n = \frac{dn}{dt} - \frac{1}{q}\nabla \cdot \boldsymbol{J}_n - g_n + r_n - \gamma_n(\boldsymbol{r}, t) = 0, \quad (2)$$

$$F_p = \frac{dp}{dt} + \frac{1}{q}\nabla \cdot \boldsymbol{J}_p - g_p + r_p + \gamma_p(\boldsymbol{r}, t) = 0, \quad (3)$$

the trapped electron continuity equation is used [4]:

$$F_{n_t} = \frac{dn_t}{dt} + g_n - r_n - g_p + r_p - \gamma_t(\boldsymbol{r}, t) = 0, \quad (4)$$

where γ_n, γ_p, and γ_t are the Langevin noise terms describing transition rate fluctuations. Two approaches can be adopted to solve ψ, n, p, and n_t. One approach is to place the four above-listed equations into FLOODS and solve the variables simultaneously. Disadvantages include increased data storage and programming overhead. The other approach is to eliminate the trap electron continuity equation by mapping the trapped electron density n_t and the noise term γ_t from Eq. (4) into Eqs. (1)–(3). This approach is preferred since no additional data storage is needed and little programming overhead is involved since the three basic equations in ψ, n, and p are already implemented in FLOODS.

The full ac noise matrix equation is defined as $[\tilde{J}][\tilde{x}] = [\tilde{b}]$, where $[\tilde{J}]$ is the small-signal, frequency domain, Jacobian matrix defined as

$$[\tilde{J}] = \begin{bmatrix} \frac{dF_\psi}{d\psi} & \frac{dF_\psi}{dn} & \frac{dF_\psi}{dp} & \frac{dF_\psi}{dn_t} \\ \frac{dF_n}{d\psi} & \frac{dF_n}{dn} + j\omega & \frac{dF_n}{dp} & \frac{dF_n}{dn_t} \\ \frac{dF_p}{d\psi} & \frac{dF_p}{dn} & \frac{dF_p}{dp} + j\omega & \frac{dF_p}{dn_t} \\ \frac{dF_{n_t}}{d\psi} & \frac{dF_{n_t}}{dn} & \frac{dF_{n_t}}{dp} & \frac{dF_{n_t}}{dn_t} + j\omega \end{bmatrix} \quad (5)$$

with

$$[\tilde{x}] = \begin{bmatrix} \tilde{\psi} \\ \tilde{n} \\ \tilde{p} \\ \tilde{n}_t \end{bmatrix}, \quad [\tilde{b}] = \begin{bmatrix} 0 \\ \tilde{\gamma}_n \\ \tilde{\gamma}_p \\ \tilde{\gamma}_{n_t} \end{bmatrix}. \quad (6)$$

Knowing the terms dF_ψ/dn_t, dF_n/dn_t, dF_p/dn_t, $dF_{n_t}/d\psi$, dF_{n_t}/dn, dF_{n_t}/dp, and dF_{n_t}/dn_t allows $\tilde{n}_t$ to be back-substituted into the first three equations to get

$$\begin{bmatrix} \frac{dF'_\psi}{d\psi} & \frac{dF'_\psi}{dn} & \frac{dF'_\psi}{dp} \\ \frac{dF'_n}{d\psi} & \frac{dF'_n}{dn} + j\omega & \frac{dF'_n}{dp} \\ \frac{dF'_p}{d\psi} & \frac{dF'_p}{dn} & \frac{dF'_p}{dp} + j\omega \end{bmatrix} \begin{bmatrix} \tilde{\psi} \\ \tilde{n} \\ \tilde{p} \end{bmatrix} = \begin{bmatrix} \tilde{B}_\psi \\ \tilde{B}_n \\ \tilde{B}_p \end{bmatrix}, \quad (7)$$

where $\tilde{B}_\psi$, $\tilde{B}_n$, and $\tilde{B}_p$ are the noise terms in the modified Poisson's, electron, and hole continuity equations, respectively. These terms are functions of γ_t, γ_n, and γ_p, and are equal to

$$\tilde{B}_\psi = \frac{\tau_t}{1 + j\omega\tau_t}\tilde{\gamma}_t, \quad (8)$$

$$\tilde{B}_n = \tilde{\gamma}_n + \frac{c_n(n + n_1)\tau_t}{1 + j\omega\tau_t}\tilde{\gamma}_t, \quad (9)$$

$$\tilde{B}_p = -\tilde{\gamma}_p - \frac{c_p(p + p_1)\tau_t}{1 + j\omega\tau_t}\tilde{\gamma}_t, \quad (10)$$

where the trap time constant τ_t is defined as

$$\tau_t = \left[c_n(n + n_1) + c_p(p + p_1)\right]^{-1}, \quad (11)$$

where c_n and c_p are the electron and hole capture coefficients, and n_1 and p_1 are the Shockley parameters. The strength of the modified noise sources for GR becomes

$$K_{\gamma'_t,\gamma'_t} = \frac{\tau_t^2}{1 + \omega^2\tau_t^2}K_{\gamma_t,\gamma_t}, \quad (12)$$

$$K_{\gamma'_n,\gamma'_n} = K_{\gamma_n,\gamma_n} - 2X_n K_{\gamma_n,\gamma_t} + \left(X_n^2 + Y_n^2\right)K_{\gamma_t,\gamma_t}, \quad (13)$$

$$K_{\gamma'_p,\gamma'_p} = K_{\gamma_p,\gamma_p} - 2X_p K_{\gamma_p,\gamma_t} + (X_p^2 + Y_p^2)K_{\gamma_t,\gamma_t}, \quad (14)$$

where

$$X_n = \frac{-c_n(n + n_1)\tau_t}{1 + \omega^2\tau_t^2}, \qquad Y_n = -\omega\tau_t X_n, \quad (15)$$

$$X_p = \frac{c_p(p + p_1)\tau_t}{1 + \omega^2\tau_t^2}, \qquad Y_p = -\omega\tau_t X_p. \quad (16)$$

The g–r noise source strengths defined in Ref. [4] are

$$K_{\gamma_n,\gamma_n} = 2g_n + 2r_n = -K_{\gamma_n,\gamma_t}, \quad (17)$$

$$K_{\gamma_p,\gamma_p} = 2g_p + 2r_p = -K_{\gamma_p,\gamma_t}, \quad (18)$$

$$K_{\gamma_t,\gamma_t} = K_{\gamma_n,\gamma_n} + K_{\gamma_p,\gamma_p}. \quad (19)$$

Implementation of the above equations into FLOODS enables the program to calculate the g–r noise voltage spectral density at an external contact from

$$S_{V,g\text{–}r} = \sum_{i=1}^{N_{trap}} \sum_{\alpha=\psi,n,p} \tilde{G}_\alpha K_{\gamma_{\alpha i},\gamma_{\alpha i}} \tilde{G}_\beta^* dr, \quad (20)$$

where N_{trap} is the number of trap levels in the device and $\tilde{G}$ is the modified Green's function which accounts for the correlation between trap transition rates.

As mentioned previously, to reduce the overhead of adding the trapped electron continuity equation as the fourth equation to the system, the dc value of n_t can be analytically calculated and back substituted into the first three equations. Under dc condition, $g_n - r_n = g_p - r_p$. The dc value of n_t can be obtained from this equality:

$$n_t = \frac{(c_n n + c_p p_1) N_t}{c_n(n + n_1) + c_p(p + p_1)}. \quad (21)$$

By substituting this into Poisson's, electron, and hole continuity equations, the changes in the device dc characteristics due to the effect of traps are accounted for.

3. Simulation results

Measurements on a multi-trap p^+–p–p^+ silicon resistor bar were made by one of the authors and the results were documented in Ref. [5]. The voltage noise spectral density and the characteristic time τ_t of each g–r trap state were measured as a function of temperature. The purpose for varying the temperature was to shift the Fermi level, as shown in Fig. 1. As the Fermi level crosses a trap state, the low frequency g–r noise plateau value due to that trap will reach a maximum as shown in Fig. 2. In this figure, the open circles and the solid curves represent the measured and simulated data, respectively. This representation will be used for the subsequent figures unless specified otherwise. The four maxima suggest that there are four trap states that are electrically active. By varying the energy position of each trap state and matching the noise simulation results with the measured data, the energy position of each trap can be found. By adjusting the trap density, the magnitude of the simulated noise level can be matched to the measurement data. At each temperature, the characteristic time τ_t of each g–r trap was determined. The results are shown in Fig. 3. By adjusting the values of the hole capture coefficients, the simulation could match the measured data. Since the noise spectral density of each g–r trap is affected by its energy level position, hole capture coefficient c_p, and trap concentration N_t, the FLOODS simulations and procedures of adjusting these parameters need to be done iteratively. The results are shown in Table 1.

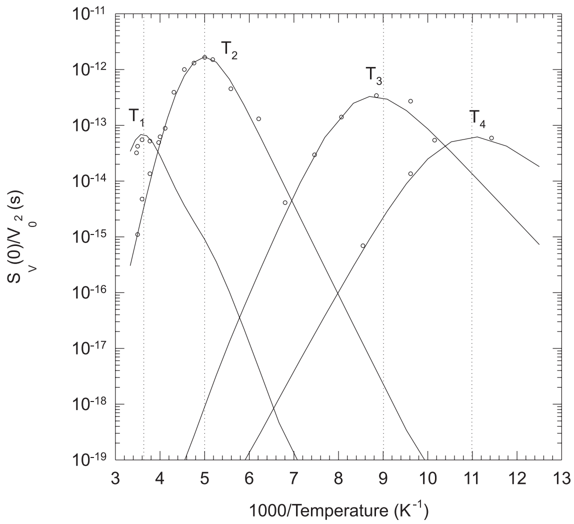

Fig. 2. The low frequency g–r noise plateau $S_v(0)/V_0^2$ versus $1000/T$.

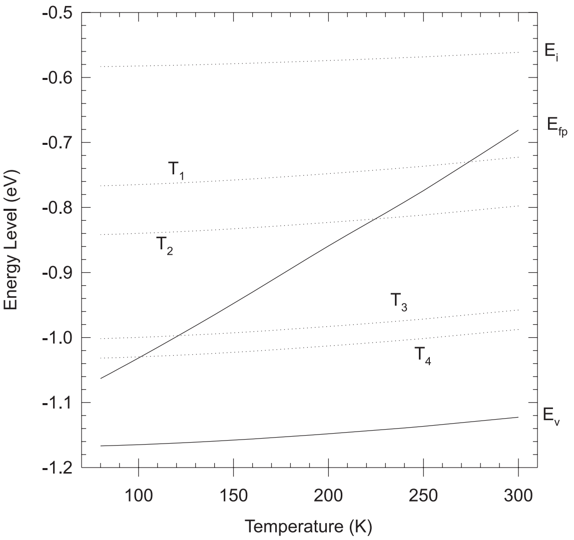

Fig. 1. The energy levels of g–r traps are represented by the dotted lines. The position of the Fermi level is shown by the solid line.

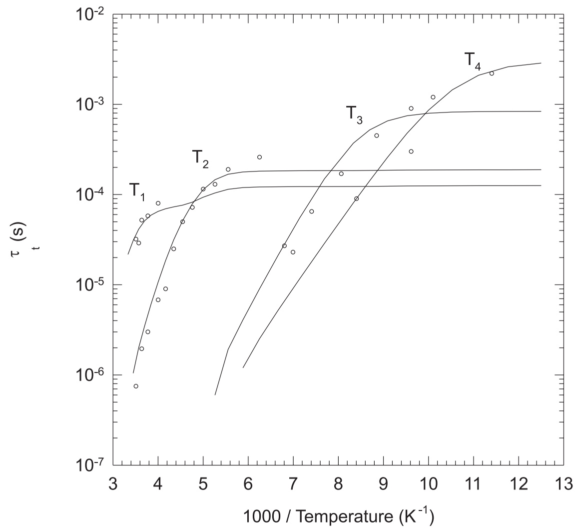

Fig. 3. The characteristic time τ_t of different traps versus $1000/T$.

Table 1
Information on each g–r trap

	Energy position (eV)	Hole capture coefficient ($cm^3 s^{-1}$)	Concentration (cm^{-3})
T_1	$E_v + 0.405$	6.0×10^{-9}	2.0×10^{11}
T_2	$E_v + 0.300$	4.0×10^{-9}	1.1×10^{12}
T_3	$E_v + 0.155$	9.0×10^{-10}	2.0×10^{10}
T_4	$E_v + 0.120$	2.5×10^{-10}	1.0×10^{9}

4. Conclusion

Noise simulations were carried out for a multi-trap silicon resistor and the data was compared with the measured results. The combination of noise measurement and simulation reveal detailed information for each electrically active g–r trap state. This is useful tool to analyze and predict the electrical and noise characteristics of traps in semiconductor devices. Noise measurements and simulations for p–n diodes and bipolar junction devices are currently underway. Preliminary results have shown that the observed 1/*f*-like noise in these devices is due to the defects in the space charge region.

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