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Hot-Carrier Energy Distribution Model and Its Application to the MOSFET Substrate Current

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Abstract - **The lack of information for carrier energy distributions in the continuum drift-diffusion (DD) or hydro-dynamic (HD) device simulation has been a major obstacle in simulating the physical phenomena related to hot carriers. In this study, a practical construction method of the hot-carrier energy distribution is proposed. Results from Monte-Carlo (MC) simulation in the uniform field distribution are utilized to construct the electron energy distributions (EED) for arbitrary device structures and field distributions in the continuum simulation. For the NIN structure, the electron-hole pair generation rate by impact ionization using the HD simulation employing the proposed method agrees well with that from the MC simulation. We have calculated the substrate currents of nMOSFETs without using any fitting parameters which agree very well with measurements.**

I. INTRODUCTION

One of the major reliability problems in the current CMOS technology is the degradation of the gate dielectric materials due to hot electrons. In order to gain a better insight into damage mechanisms and associated reliability problems, it is highly desirable to have information about the spatial and energy distribution of hot electrons above the damage threshold. Semi-classical Monte-Carlo (MC) device simulation is the most physically accurate vehicle demonstrated until now to probe complex phenomena related to the hot carrier [1]. Because of the large computational cost of MC simulation, in engineering environment, continuum device simulators are still most popular. The lack of information for carrier energy distributions in the continuum DD or HD device simulation has been a major obstacle in simulating the physical phenomena related to hot carriers, such as an impact ionization (II), the hot-carrier injection into the oxide of MOSFET and the MOSFET substrate current, etc. Work to get the information about the electron energy distribution in the continuum simulation has been conducted using the various methods. In the analytical model of the energy distribution of hot electrons [2], the average energy was related to the parameters for the distribution function. Momentum expansion and two-population macroscopic equations were more accurate models and successfully applied to the calculation of the impact ionization [3]. This model attempted to relate EED to the high-order momentum of the electron energy. A non-local impact ionization model [4] can be considered as another simple model for EED. In this model, EED is represented using a constant mean free path and the spatial distribution of the potential and the electric field. However, this model is insufficient for all energies and fields as shown in Fig.1.

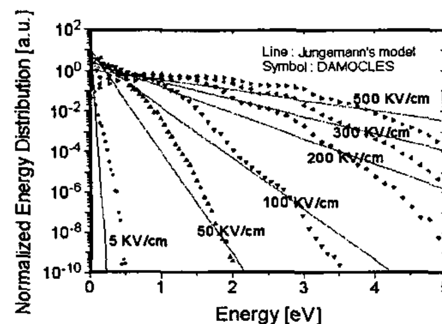


Fig. 1. Electron energy distributions of the constant mean free path model [3] and MC simulation (DAMOCLES) in uniform electric fields.

In this paper, a practical construction method of the hot-carrier energy distribution in the conventional continuum device simulation is proposed. Normalized EEDs using MC simulation (DAMOCLES) in the homogeneous field are utilized as probability coefficients to construct EED for arbitrary device structures and field distributions in the continuum simulation without further calibration process.

II. PROPOSED MODEL

For a non-local model of impact ionization, the information for non-locality of the carrier can be interpreted as EED [4]. Therefore, such a model can adopt a microscopic impact ionization rate (IIR) usually used in MC simulation and the accuracy of the model fully depends on the accuracy of the utilized EED. Fig.1 shows EEDs for the electron assuming a constant mean free path [5] and EEDs obtained from MC simulation (DAMOCLES) in the uniform electric field. In this figure, we can find out easily that a constant mean free path is not adequate for all the energy levels and electric fields.

We utilized MC simulation results in the uniform electric field in Fig.1 more directly into the course of model formulation for EED construction. To illustrate

how to calculate EED, a simple 1-D potential profile is shown in Fig.2. At x_0, we estimate the number of electrons from x_i whose kinetic energies are over ε_p.

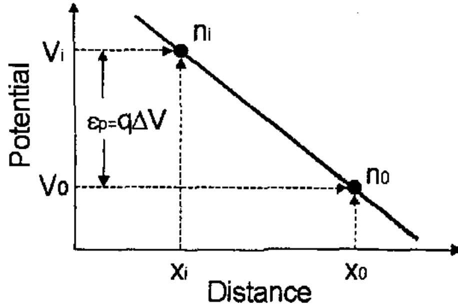


Fig. 2. Potential distribution in a uniform field.

The original lucky electron (LE) concept [6] can be reiterated as follows; the number of electrons whose kinetic energy is more than ε_p at x_0 is estimated using a certain probability and the number of electrons at x_i where the potential energy is higher than that at x_0 by ε_p [6]. In the conventional LE model, the probability is obtained based on the scattering escape probability and several other assumptions. In our model, instead of invoking these arguments, the probability is obtained from the homogeneous-field EED generated by MC simulation. Normalized EED can be interpreted as the probability that electron energy is over ε_p at x_0. The probability is given as

$$P[\varepsilon > \varepsilon_p; x_0] = \frac{1}{n}\int_{\varepsilon_p}^{\infty} f_u(\varepsilon'; F))d\varepsilon' \qquad (1)$$

where $f_u(\varepsilon; F)$ is EED from MC simulation in a uniform electric field F. The number of electrons between ε_p-δ/2 and ε_p+δ/2 is interpolated by the following equation.

$$\begin{aligned} n(\varepsilon_p - \delta/2 < \varepsilon < \varepsilon_p + \delta/2; x_0) \\ = \delta \cdot f_u(\varepsilon_p; x_0) \\ = n \cdot P[E > \varepsilon_p + \delta/2; F] \\ - n \cdot P[E > \varepsilon_p - \delta/2; F] \end{aligned} \qquad (2)$$

In a non-uniform electric field (Fig.3), the above calculation method is applied in the same way using a mean value theorem [7] and the equation is given by

$$\begin{aligned} n(\varepsilon_p - \delta/2 < \varepsilon < \varepsilon_p + \delta/2; x_0) \\ = \delta \cdot f(\varepsilon_p; x_0) \\ = n(x_i^-) \cdot P[\varepsilon > \varepsilon_p + \delta/2; F^-] \\ - n(x_i^+) \cdot P[\varepsilon > \varepsilon_p - \delta/2; F^+] \end{aligned} \qquad (3)$$

where $n(x_i^-)$ and $n(x_i^+)$ are carrier concentrations at x_i^- and x_i^+, respectively. The potential difference between x_0 and x_i^- is $(\varepsilon+\delta/2)/q$ and that between x_0 and x_i^+ is $(\varepsilon-\delta/2)$. The average electric fields F^- and F^+ are $(\varepsilon+\delta/2)/q(x_0-x_i^-)$ and $(\varepsilon+\delta/2)/q(x_0-x_i^+)$.

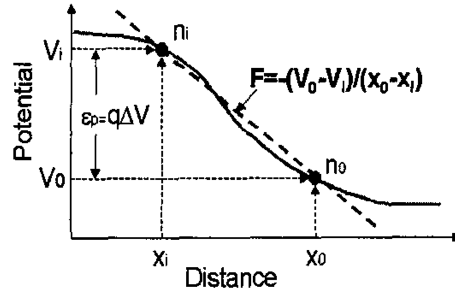


Fig. 3. Potential distribution in a non-uniform field.

In the 2 or 3-D case, x_i is determined by the maximum probability instead of conventional forward or backward electric field lines. Using the obtained EED, the electron-hole-pair (EHP) generation rate by impact ionization per unit time can be calculated by the following equation

$$G_{II}(x_0) = \int_0^{\infty} S_{II}(\varepsilon) f(\varepsilon; x_0) d\varepsilon \qquad (4)$$

where $S_{II}(\varepsilon)$ is a microscopic IIR. We used IIR in Fig.4 [8], which is extended for impact ionization at the SiO_2/Si interface using the surface impact ionization model [1].

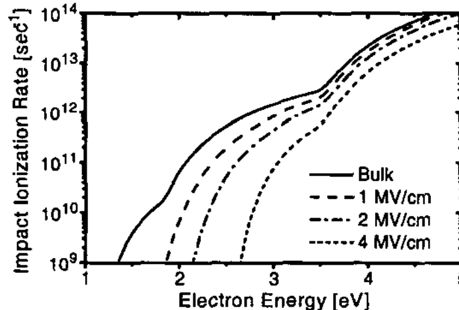
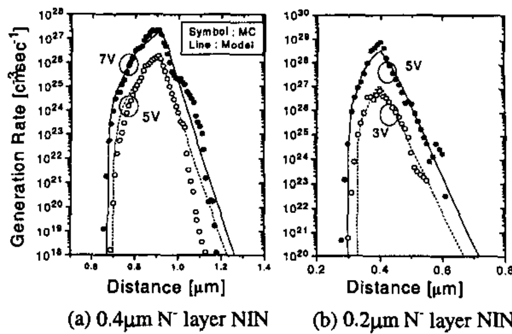


Fig. 4. Cartier's model [6] for an IIR and surface IIRs according to Fischetii's work [1].

III. SIMULATION RESULTS

We have applied this model to 1-D NIN and 2-D nMOSFET. First, two NIN structures are tried. The first NIN has N^+(0.5μm, 5×10^{17}/cm^3), N^-(0.4μm, 2×10^{16}/cm^3) and N^+(0.5μm, 5×10^{17}/cm^3) and the second NIN has N^+(0.2μm, 5×10^{19}/cm^3), N^-(0.2μm, 1×10^{17}/cm^3) and N^+(0.4μm, 5×10^{19}/cm^3). Fig.5 shows the EHP generation profiles obtained from our model and MC simulation (DAMOCLES) for the previously described NINs. It can be seen that the new model accurately reproduces the EHP generation rates of MC without any adjusting parameters.



(a) 0.4μm N⁻ layer NIN (b) 0.2μm N⁻ layer NIN

Fig. 5. The comparison of II generation profiles of the proposed model and MC simulation (DAMOCLES) for 1-D NINs.

For 2-D nMOSFETs, the gate oxide thickness is 92Å and the gate lengths are 0.35, 0.5, 0.65, 1.0 and 10.0μm. We have used TSUPREM4 to calculate geometries and doping profiles, and MEDICI to obtain the potential and electron distribution. Fig.6 shows that drain current vs. gate voltage characteristics of simulations agree well with measurements. Fig.7 shows EEDs of the proposed model and MC simulation (DEGAS) for (1.18, 0.01)μm of 0.35μm nMOSFET. Fig.8 is the EHP generation profiles of 0.35μm nMOSFET at Vd = Vg = 3.3V. In Fig.9, the substrate currents of the proposed model and measurements agree well for a wide range of channel lengths. All the calculations have used the proposed EED model using MC simulation data in the uniform field and surface impact ionization rate without further calibration.

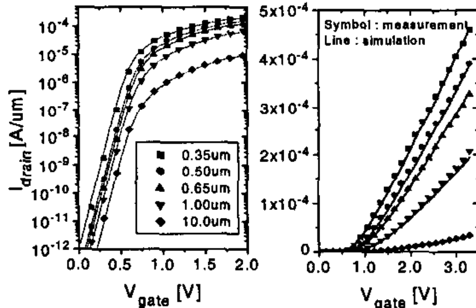


Fig. 6. Drain currents of nMOSFETs, of which gate lengths are 0.35, 0.5, 0.65, 1 and 10μm, at Vd = 3.3V.

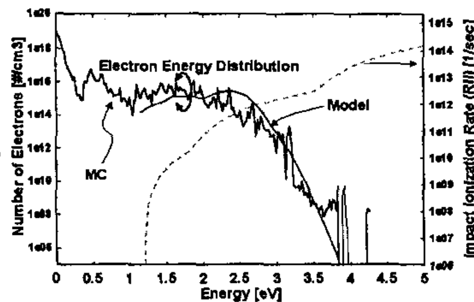


Fig. 7. Electron energy distributions at (1.18, 0.01)μm of 0.35μm nMOSFET. MC result is calculated using DEGAS of ISE.

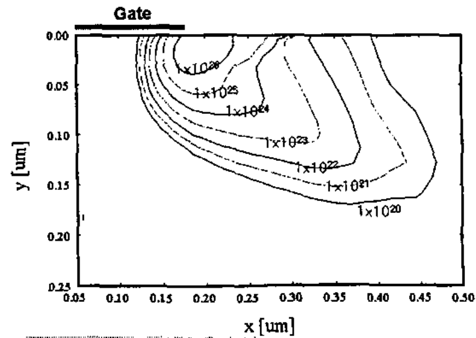


Fig. 8. EHP generation rates by impact ionization for 0.35μm nMOSFET at Vd = Vg = 3.3V.

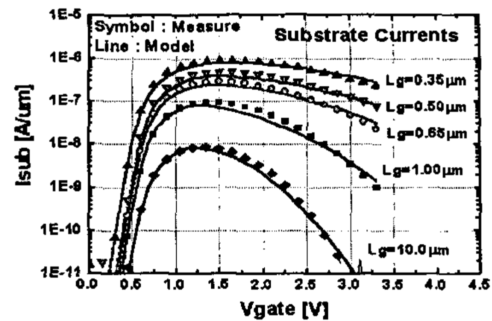


Fig. 9. The comparison of substrate currents of nMOSFETs at Vd = 3.3V. Symbol and line indicate measurement and simulation results, respectively.

IV. CONCLUSIONS

We have shown that the proposed method reproduced the result from MC simulation in the one-dimensional case. For experimental validation, we have calculated the substrate currents of nMOSFETs without any calibration process for the proposed model. The calculated values agree well with measurements. Therefore, our new model can predict the hot-carrier energy distribution for next generation devices.

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REFERENCES

[1] M. V. Fischetti *et al*, *J. Appl. Phys.*, vol.78, no.2, p.1058 (1995)
[2] D. Cassi *et al.*, *IEEE Trans. Electron Devices*, vol.37, no.6, p.1514 (1990)
[3] T. Grasser *et al.*, *SISPAD*, p.46 (2001)
[4] C. Jungemann *et al.*, *Solid-State Elec.*, vol.39, no.7, p.1079 (1996)
[5] B. Meinerzhagen *et al.*, *Symp. VLSI Tech.*, p.233 (1997)
[6] W. Shockley, *Solid-State Elec.*, vol.2, no.1, p.35 (1961)
[7] E. C. Kan *et al.*, *Proceedings of ISSDT* (1995)
[8] Cartier *et al.*, *Appl. Phys. Lett.*, vol.62, no.25, p.3339 (1993)