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Tail Electron Hydrodynamic Model for Consistent Modeling of Impact Ionization and Gate Injection

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We have implemented tail electron Hydrodynamic equations(TEHD) into two-dimensional simulator and applied them in the simulations of nMOSFET devices. The resulted substrate currents agree to the measured values in the range of drain voltages from $2.5V$ to $5.5V$. Simulations of substrate hot electron injection experiment also give good agreement with the measurement. The good results of TEHD simulations are due to the fact that they can treat tail electrons more detaily than the conventional model with well-calibrated parameters.

1. INTRODUCTION

Hydrodynamic(HD) model has been developed to overcome the limits of the Drift-Diffusion(DD) model in modeling the hot carrier effects. The application of HD model to the real devices, however, has been limited[1) 2)] since hot electron related effects are determined by a small portion of electrons having higher energies, called *tail electrons*, whose behaviours cannot be predicted by the conventional models based on *whole electrons* in nonstatic fields. For example, the *tail electron* density at position C in Fig.1 cannot be predicted by *whole electrons* density(n) and average electron energy(w_n) since the high energy tail electrons are imbedded into the abundant cold electrons. Recently a set of equations, called Tail Electron HydroDynamic equations (TEHD) has been introduced [3) 4)] applying the moment method only to the energy domain of $\varepsilon \geq \varepsilon_{th}$. This paper will demonstrate the power of TEHD model in prediction of both susbtrate current and gate injection in real MOSFET devices.

2. TEHD EQUATIONS

TEHD equations consist of two continuity equations for the density(n_2) and the average energy(w_2) of *tail electrons* with two constitutive equations for the fluxes(*see Table 1*). Newly introduced quantities for TEHD are expressed as functions of w_2 using the results of space-dependent Monte Carlo(SDMC) simulations[4)]. n_{20} in Eq.(1) means the tail electron density predicted from the conventional model obtained by using quantities related with *whole electrons*(such as electron density(n) and average energy(w_n) in HD model[1)] or n and potential(ψ) in Lucky Electron(LE) model[5)]).

3. SIMULATION OF IMPACT IONIZATION

In device simulations, TEHD are solved to obtain the profile of n_2 and w_2 after *whole electron* quantities and n_{20} are calculated. From n_2 and w_2, the impact ionization(I/I) rates are calulated using the model in Table 2 which has been obtained by SDMC[3)]. Good agreement of the I/I rates from TEHD model with those from MC model in an $n^+ - n^- - n^+$ structure can be obtained[3)]. In Fig.2 we show the simulated and measured I_{SUB} vs. V_{GS} with various V_{DS} values for (a) DILDD MOSFET with $L_{eff} = 0.25\mu m$ and $t_{ox} = 80$ Å and (b) LDD MOSFET with $L_{eff} = 0.40\mu m$ and $t_{ox} = 73$ Å. Simulated substrate currents from TEHD model shows good agreement with measured values for a wide range of drain bias conditions from $2.5V$ to $5.5V$. The results from three models(TEHD, HD, and LE) are compared in Fig.2(a). As shown in the figure, HD or LE model predicts the peak of I_{SUB} at $V_{GS} \cong 2.5\ V$ when $V_{DS} = 4.5\ V$, while TEHD predicts the peak at $V_{GS} \cong 2.0\ V$ complying with the measurements. This can be explained by comparing the profiles of both n_2 from TEHD and n_{20} from HD for the two V_{GS} values as shown in Fig. 3. HD model gives higher n_{20} at $V_{GS} = 2.5\ V$ due to the higher density of *whole electrons* than at $V_{GS} = 2.0\ V$, while TEHD gives higher n_2 at $V_{GS} = 2.0\ V$. Besides n_{20}, the rapidly increasing electric field near the drain junction plays an important role in determining n_2 and this is reflected in TEHD model through the $\gamma_0 \vec{E} \cdot \vec{J}_2$ term in Eq.(1).

4. SIMULATION OF GATE INJECTION

We applied TEHD to the substrate hot electron injection experiment performed by T. H. Ning et al.[6)] for the injection probability from Si into SiO_2. We introduced optical generation term in both the electron and hole continuity equations to get optically generated electron-hole pairs. We defined another tail electron density, n_3 as the density of electrons having energy $\geq \phi_b$ where ϕ_b is oxide barrier height obtained by barrier lowering model[6)]. After TEHD are solved, the profile of n_3 in the ***Si***-region can be obtained from the model of

$$n_3 = n_2 \cdot A \exp[-(q\phi_b - \varepsilon_{th}) / (B(w_2 - \varepsilon_{th})), \quad (7)$$

which has been obtained by SDMC simulations. Parameter B is calibrated to be 0.66 from SDMC, and A is an adjusting parameter to be 0.58. The profile of n_3 in the *oxide*-region is obtained by solving the electron continuity equation in simple drift-diffusion model, with the boundary condition, $J_{inj} = qn_3 v_{th}$, applied to the oxide-silicon interface, where v_{th} is thermal electron velocity set to $1.0 \times 10^7\ cm/\sec$. By doing so, we can simulate the electrons returning back to the Si-region. By above procedures, gate current(I_{GATE}) and substrate current(I_{SUB}) are calculated at the terminals and P_{em}(emission probability) ($\equiv I_{GATE} / I_{SUB}$) values are obtained at each V_{BS} and V_{GS} values. The results are shown in Fig.4 and Fig. 5, and show good agreement with the measurements. When P_{em}'s are plotted vs. d which is defined as the distance between a point P and the surface such that $\psi(P) - \psi(surface) = \phi_b$, all the data are shown on a single line for various V_{BS} and V_{GS} values as shown in Fig.6. The single line for various V_{GS} values could not be obtained by LE model suggested in [5].

5. CONCLUSIONS

The good results of TEHD in both I/I and gate injection are possible because TEHD treats *tail electrons* more detaily than the conventional models and because all the parameters are calibrated well by the SDMC. Since TEHD model gives us the detailed profile of *tail electrons*, it is expected to be used in the simulation of MOSFET degradation by hot-carrier effect.

References

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3) J. G. Ahn et al., *IEEE EDL*, pp. 348-350, 1994.
4) C. S. Yao et al., *IEEE EDL*, pp. 26-29, 1995.
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6) T. H. Ning et al., *J. of Appl. Phys.*, pp. 286-293, 1977.

$$-\gamma_0 \vec{E} \cdot \vec{J}_2 - \frac{1}{q} \vec{\nabla} \cdot \vec{J}_2 = \frac{n_{20}}{\tau_{12}} - \frac{n_2}{\tau_{21}} \tag{1}$$

$$-\vec{E} \cdot \vec{J}_2 + \vec{\nabla} \cdot (\vec{S}_2 + \frac{\varepsilon_{\rm th}}{q} \vec{J}_2) = -\frac{n_2 (w_2 - w_{20})}{\tau_{w_{22}}} \tag{2}$$

$$\vec{J}_2 = q\mu_2 (\gamma_1 + < \frac{m}{m^*} >_2) n_2 \vec{E} + \mu_2 k_B T_2 \vec{\nabla} n_2 \tag{3}$$

$$\vec{S}_2 = -\mu_2 [\varepsilon_{\rm th} \gamma_1 + k_B T_2 + w_2 < \frac{m}{m^*} >_2] n_2 \vec{E} - \mu_2 \frac{k_B T_2}{q} \vec{\nabla} (n_2 w_2) \tag{4}$$

Table 1. TEHD equations. The quantities with subscript 2 correspond to *tail electrons*.

$$G_{II} = \alpha_2 n_2 |\vec{v}_2| \tag{5}$$

$$\alpha_2 = 3.6 \times 10^7 \cdot \exp(-12.5 / w_2) \tag{6}$$

Table 2. I/I modeling in TEHD. w_2 is in eV and α_2 is in $1/cm$.

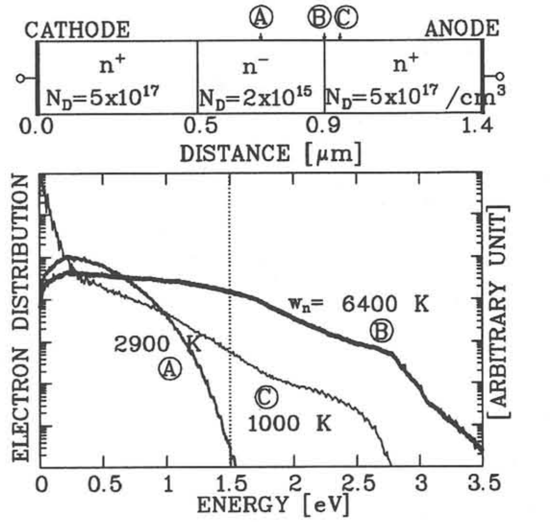


Fig.1. Electron energy distribution at three positions in an $n^+ - n^- - n^+$ structure. At position C, the density of *tail electrons*(n_2) can not be predicted by n and w_n due to the abundant cold electrons.

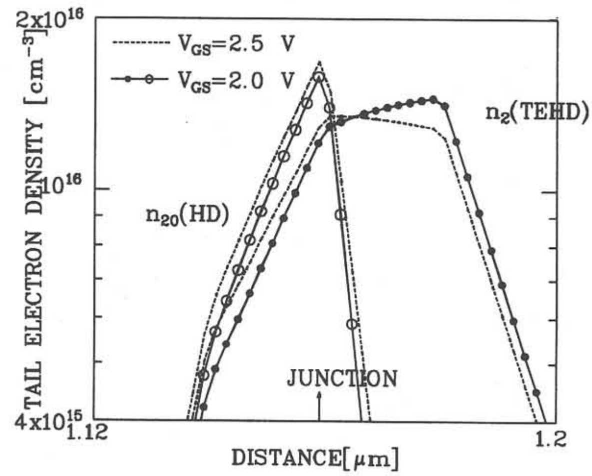
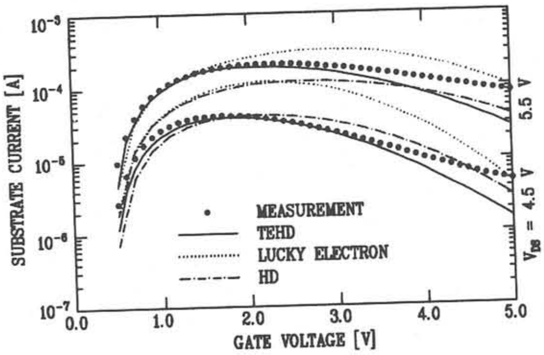
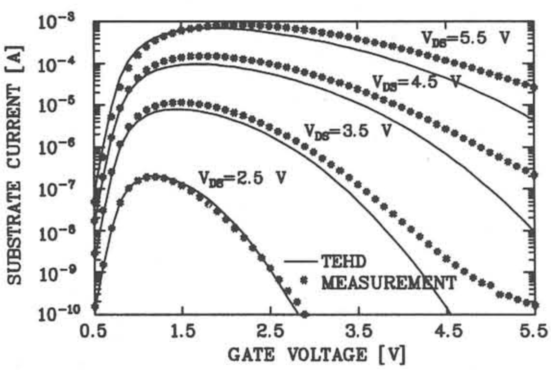


Fig.3. The profile of n_2 from TEHD and n_{20} from HD model along the main current path in the device of Fig.2(a).



(a)



(b)

Fig.2. The simulated I_{SUB} vs. V_{GS} for various V_{DS}'s for (a) DILDD n-MOSFET with $L_{eff} = 0.25\mu m$ and $t_{ox} = 80$ Å and (b) LDD n-MOSFET with $L_{eff} = 0.40\mu m$ and $t_{ox} = 73$ Å .

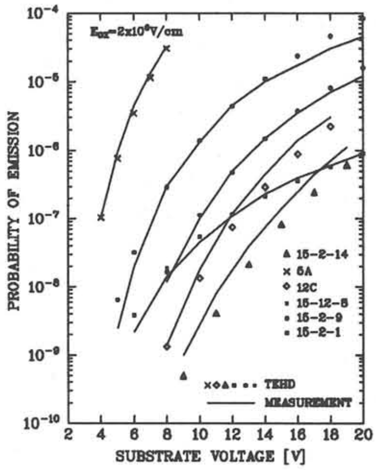


Fig.4. Emission probabilities P_{em} vs. V_{BS} for various devices with $E_{ox} = 2\times10^6 V/cm$.

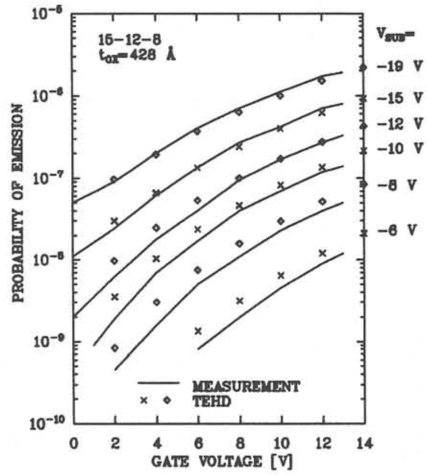


Fig.5. P_{em} vs. V_{GS} with various V_{BS}'s for device 15-12-8[6].

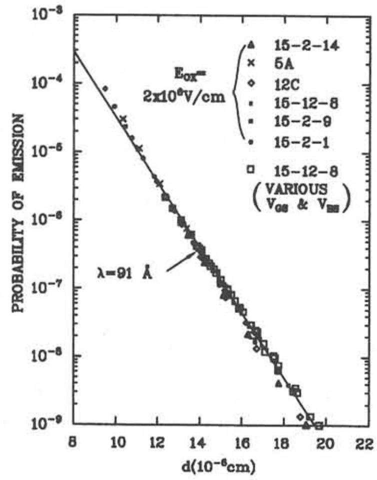


Fig.6. P_{em} vs. d with various V_{GS}'s and V_{BS}'s. All the data are shown on a single line.