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Advanced Physical Models for MOSFETs

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Abstract

A higher order moment model for simulating electrical characteristics for deep submicron MOSFETs is proposed. The model is useful for investigating non-steady state carrier transport effects. These effects are essential factors to predict drain current, when the channel length is less than 0.2μm, while it is important to predict the substrate current even for MOSFETs with longer channel lengths.

Furthermore, a distribution function oriented simulator in k-space is proposed for studying carrier transport properties in detail. Useful information is obtained, including the feasibility of applying an isotropic distribution function to the higher order moment model.

§1 Introduction

Recently, a test vehicle using MOSFETs with 0.1μm channel length has been reported. Ultra short channel CMOS may be the most promising device for realizing high performance ULSIs, because lower supply voltage is acceptable without band gap scaling and because the fabrication process is simpler.

Figure 1 shows the anticipated performance for future CMOS ULSIs[1]. Here, a microprocessor is chosen as an example. Using extremely small MOSFETs

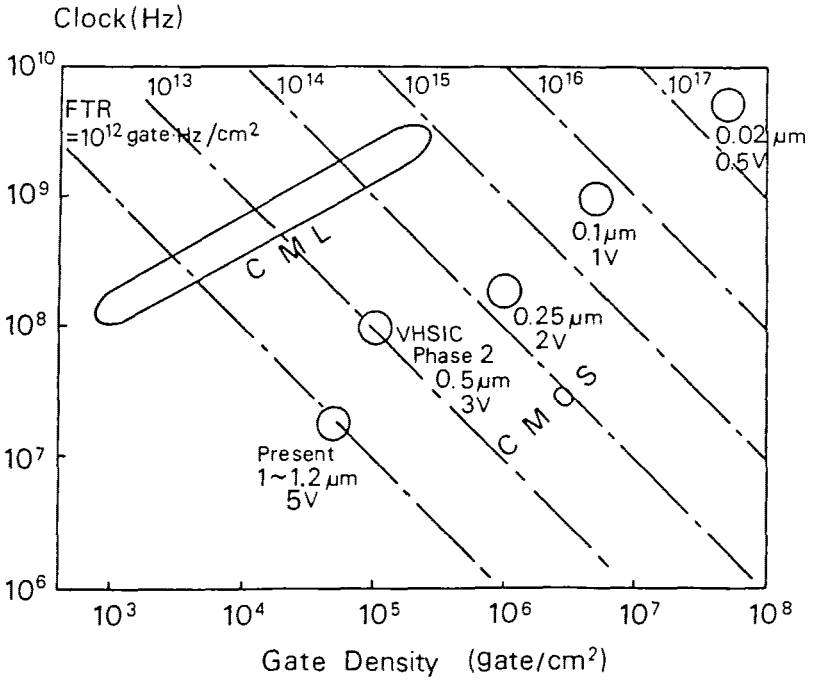

Fig.1 Anticipated performance for CMOS microprocessors [1]

(L=10-20nm), a functional throughput rate of 10^{17} gateHz/cm^2 is expected, which is 10^5 times as high a performance as that for a present microprocessor.

Although a conventional drift-diffusion model is widely used for designing today's MOSFETs, it cannot be applicable to tomorrow's MOSFETs. The reason is that non-steady state carrier transport is becoming essential. For example, when the effective channel length is less than a quarter micron, velocity overshooting phenomena increase drain current. Furthermore, carrier energy is no longer determined by the local electric field. Very careful treatment is necessary for simulating hot carrier related characteristics, such as gate and substrate currents. These currents are important measures for investigating MOSFET long term reliability, which may be one of the limiting factors for miniaturization. In designing future MOSFETs, more accurate models are necessary.

In this paper, a 2D MOSFET simulator is presented, including energy transport, in which

momentum and energy conservation equations are solved as well as Poisson and continuity equations. By using this simulator and an energy dependent impact ionization coefficient, substrate current characteristics were analyzed. Furthermore, a distribution function oriented model is proposed for use in investigating carrier transport properties in detail. Feasibility of applying the isotropic distribution function to the energy transport model is discussed.

§2 Higher order moment model for MOSFETs[2]

2-1)Model

Basic equations for momentum and energy conservation for electrons are derived from the Boltzmann's transport equations.

$$\vec{v} = \frac{\tau_p}{m}\left(q\vec{E} - \frac{2}{3}\nabla w - \frac{2w}{3n}\nabla n\right) \quad \text{---- (1)}$$

$$\vec{v}\cdot\nabla w = q\vec{v}\cdot\vec{E} - \frac{2}{3}\vec{v}\cdot\nabla w - \frac{w - w_0}{\tau_w} \quad \text{---- (2)}$$

Here, τ_p and τ_w are momentum and energy relaxation times. w is average energy for electrons and other notations have normal meanings.

To derive Eqs. 1 and 2, several assumptions are introduced [3,4]. They are:

1)Displaced Maxwellian distribution function
2)Parabolic energy band
3)Negligibly small drift kinetic energy compared with thermal energy
4)Collision terms expressed by relaxation times
5)Only electrons contribute to drain current
6)$\tau_p(w) = mv(E_0(w))/qE_0(w)$
7)τ_w=5E-13sec

To obtain energy dependent momentum relaxation time (Assumption 6), a w-E_0 relationship, obtained by the Monte Carlo method in steady state and the v-E_0 relationship by Scharfetter and Gummel, are utilized.

A two-dimensional energy transport oriented simulator, METRO, has been developed, in which Eqs.1 and 2 are solved as well as Poisson and electron continuity equations.

2-2)Results

Deep submicron n-channel MOSFETs were analyzed by using METRO.

Figure 2 shows energy distribution in a quarter micron n-channel MOSFET. The highest energy region appears in the channel near the drain edge.

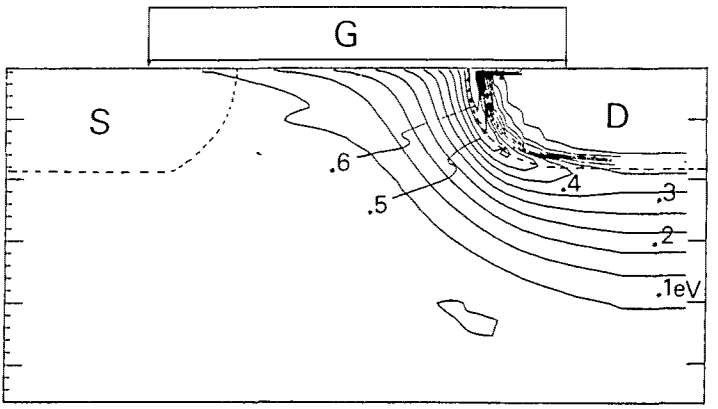

Fig.2 Electron energy distribution in nMOSFET
L_{eff}=0.25μm, T_{ox}=10nm, V_D=V_G=2V

Figure 3 shows I_D-V_D characteristics for a quarter micron nMOSFET, calculated by the present model and a conventional drift-diffusion model. Drain current predicted by the present model is 15% as large as that predicted by a drift-diffusion model. This increase is due to the velocity overshooting phenomena near the source. Although the velocity overshooting near the drain is more enhanced, as shown in Fig.4, its contribution to the drain current increase is smaller. As far as drain current is concerned, transport characteristics near the source are important. Non-steady-state carrier transport near the source is essential, when the channel length is less than a quarter micron.

On the other hand, hot carrier related characteristics, such as gate and substrate currents, are strongly dependent on the transport properties near the drain. Therefore, a non-steady-state effect is more essential for these characteristics, even in longer channel MOSFETs.

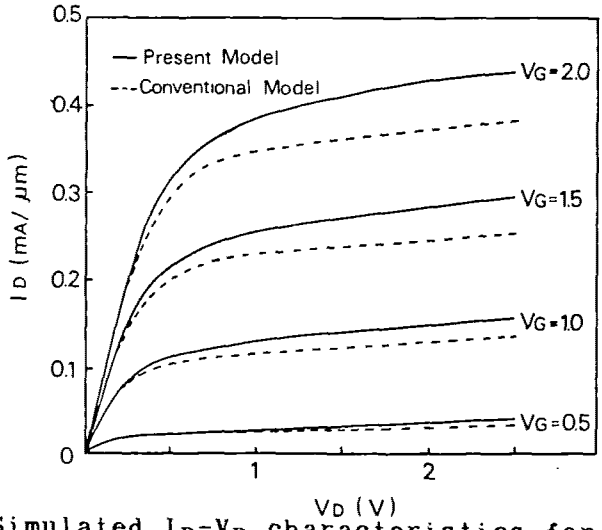

Fig.3 Simulated I_D-V_D characteristics for nMOSFET L_{eff}=0.25μm, T_{ox}=10nm

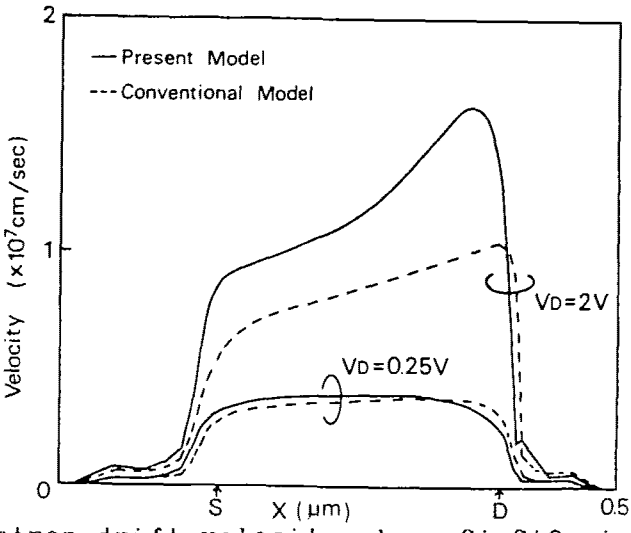

Fig.4 Electron drift velocity along Si-SiO_2 interface L_{eff}=0.25μm, T_{ox}=10nm, V_G=2V

§3 Substrate current model[5]

Hot carrier related problems, such as threshold voltage shift and transconductance degradation, are serious for submicron MOSFETs. Substrate current, I_{sub}, is one of the good measures for predicting long term reliability in MOSFETs[6]. For accurate I_{sub} prediction, non-steady-state effects on impact ionization coefficient should be modeled appropriately.

3-1)Model

Impact ionization coefficient, α, is expressed by

$$\alpha=\frac{\int_{p_i}^{\infty} f/\tau_i \, d^3p}{\int_0^{\infty} v \cdot f \, d^3p} \equiv \frac{\beta}{v} \qquad ----(3)$$

where f is the distribution function, and τ_i is the mean free time for impact ionization. Since the threshold energy for impact ionization, w_i, and average carrier energy are large enough, compared with the drift kinetic energy, α may be expressed by

$$\alpha=\frac{\beta_0(w)}{v}. \qquad ----(4)$$

Here, $\beta_0(w)$ is the numerator of Eq.3 in steady state, derived from electric field dependencies of α, v and w in steady state. As a result, no explicit formulation for τ_i for estimating α is necessary.

If the substrate current is negligibly small, compared with the drain current, a post processing technique can be applied for calculating the substrate current. By using METRO, two-dimensional distributions for potential, electron density, group velocity and average energy are calculated. Therefore, α at any position can be determined by using Eq.4. Substrate current is calculated by

$$I_{sub}=\Sigma q n v \alpha \Delta h \Delta l. \qquad ----(5)$$

3-2)Results

Figures 5(a) and (b) show I_{sub}-V_G characteristics for n-channel MOSFETs with L=1.05μm and 0.45μm, respectively. Curve A corresponds to the calculation results obtained from the present model and curve B corresponds to those obtained from the conventional model, ie., a drift-diffusion model with a local field dependent ionization coefficient. Experimental data are represented by curve C. As can be seen, the present model offers better agreement with the experimental data for both MOSFETs.

There are three factors to explain the difference between the present model and the conventional model.

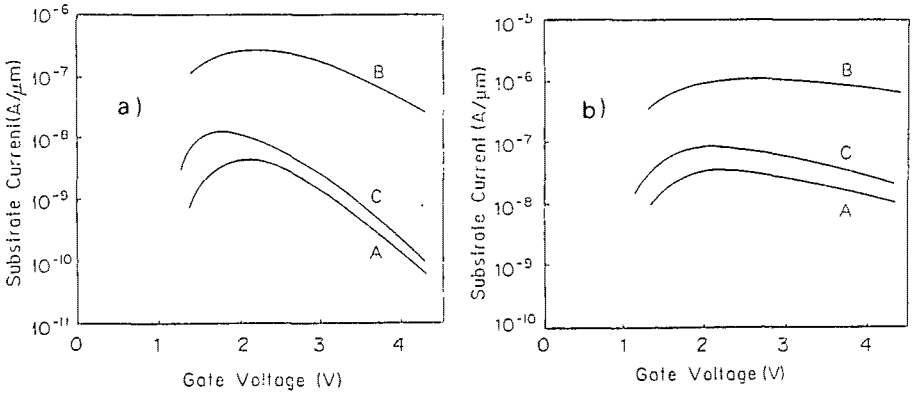

Fig.5 I_{sub}-V_G characteristics: a)L_{eff}=1.05μm and b)L_{eff}=0.45μm T_{ox}=19.3nm, V_D=3V
A:Present model B:Conventional model
C:Experimental Data

First is a non-steady state effect, which is represented by the term on the left hand side in Eq.2. It requires a distance greater than 50nm for electrons to settle down to steady state. However, even for a MOSFET with L=1.05μm, high electric field region length near the drain is less than 50nm, as shown in Fig.6. Electron energy never reaches the steady state value. Thus, the lower α value is obtained by the present model, which results in smaller substrate current.

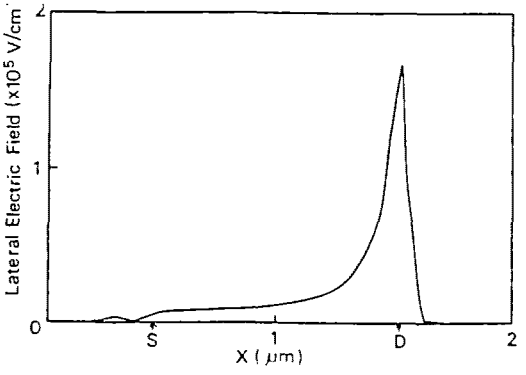

Fig.6 Lateral electric field along Si-SiO_2 interface L_{eff}=1.05μm, T_{ox}=19.3nm, V_D=V_G=3V

Second is the work accomplished by electron pressure, which appears in the second term on the right hand side in Eq.2. As shown in Fig.7, energy

gradient increases towards the drain. Due to the force expressed as this energy gradient, energy gain by the electric field is partially suppressed, which leads to a lower α value.

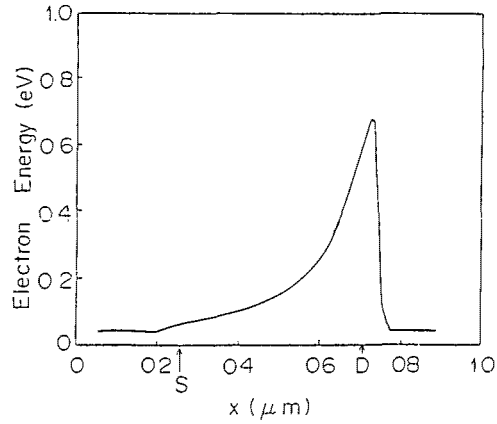

Fig.7 Electron energy distribution along $Si-SiO_2$ interface
$L_{eff}=0.45\mu m$, $T_{ox}=19.3nm$, $V_D=V_G=3V$

Third is electron distribution modification by electron pressure. Since electron energy is high near the drain, electron diffusion is enhanced. Therefore, the current path by the present model is wider and surface electron concentration near the drain is lower, as shown in Fig.8. Lateral electric field near the drain depends on the surface electron concentration when it exceeds the acceptor concentration; this is the case for high gate bias. Thus, the lower electric field is expected by the present model at higher gate bias, as shown in Fig.9. As a result, a lower value is predicted. This is the reason why the present model shows a steeper slope in $I_{sub}-V_G$ characteristics in the higher gate bias region and shows better agreement with experimental data.

As discussed, for investigating hot carrier related characteristics such as the substrate current, a conventional drift-diffusion model with local field dependent α is no longer useful. The energy transport oriented simulator presented is preferable.

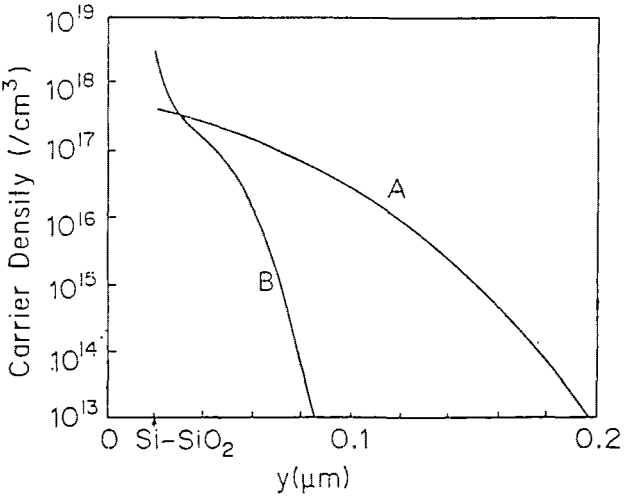

Fig.8 Electron distribution in depth direction at the drain edge
A:Present model B:Conventional model
L_{eff}=0.45μm, T_{ox}=19.3nm, V_D=V_G=3V

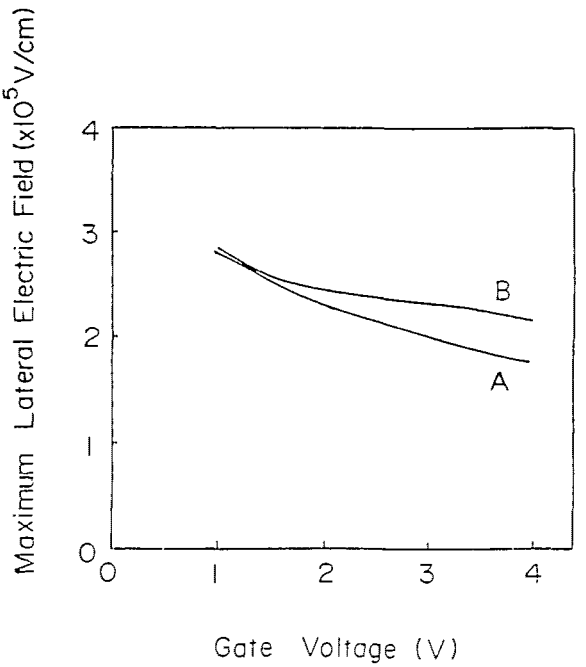

Fig.9 V_G dependencies of lateral electric field at the drain edge
A:Present model B:Conventional model
L_{eff}=0.45μm, T_{ox}=19.3nm, V_D=3V

§4 Carrier transport model based on the distribution function[7]

In the higher order moment model proposed in § 1 assumptions regarding the distribution function and the band structure are introduced, which are responsible for simplifying momentum and energy conservation equations. However, the validity for these assumptions becomes questionable under some conditions. Furthermore, for accurately calculating I_{sub} and I_G, information on the distribution function, such as energy distribution, is necessary. To investigate transport properties in detail, a distribution function oriented simulator in k-space has been developed.

4-1) Model

The direct method used to solve the Boltzmann's transport equation is similar to the method for ion implantation simulation[8].

The momentum space is discretized by equi-energy surfaces and equi-directional cosine planes, with respect to the external field. The distribution function is updated at each time step through carrier transactions among discretized states. Scattering processes are described as transitions among states. Drift motion by the electric field is described by the longitudinal momentum increase for carriers in any state. Transport properties, such as drift velocity and mean average energy, are calculated from the distribution function. The method is called "Population Transaction (PT)".

4-2)Results

The PT method is applied to analyze electron transport properties in bulk silicon. As scattering mechanisms, f_2(500K), f_3(630K) and g_2(700K) scatterings are considered. Carrier-carrier scatterings and impurity scatterings are excluded this time.

Figure 10 shows transient characteristics for velocity and average energy. Compared with the Monte Carlo (MC) method, the PT method offers smoother results.

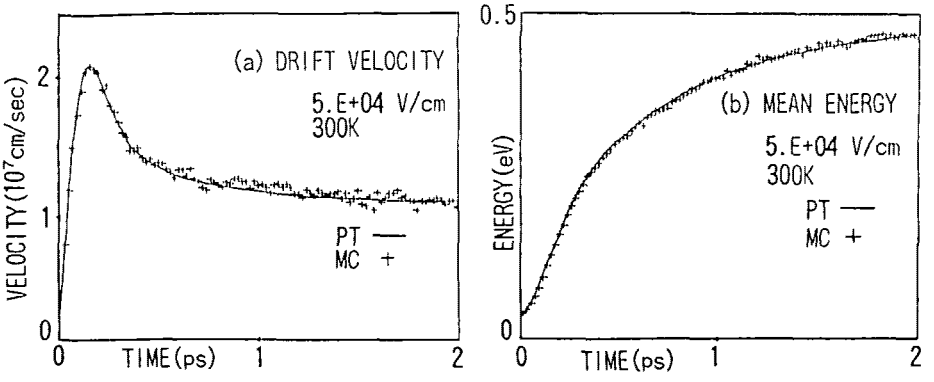

Fig.10 Transient characteristics for electrons
a)Drift velocity b)Average energy

Figures 11 (a),(b) and (c) show contour maps for carrier distribution at t=0, 0.16psec and 2psec, respectively. In quasi-steady state (t=2psec), distribution seems to be symmetrical, although carrier-carrier scattering is not taken into account.

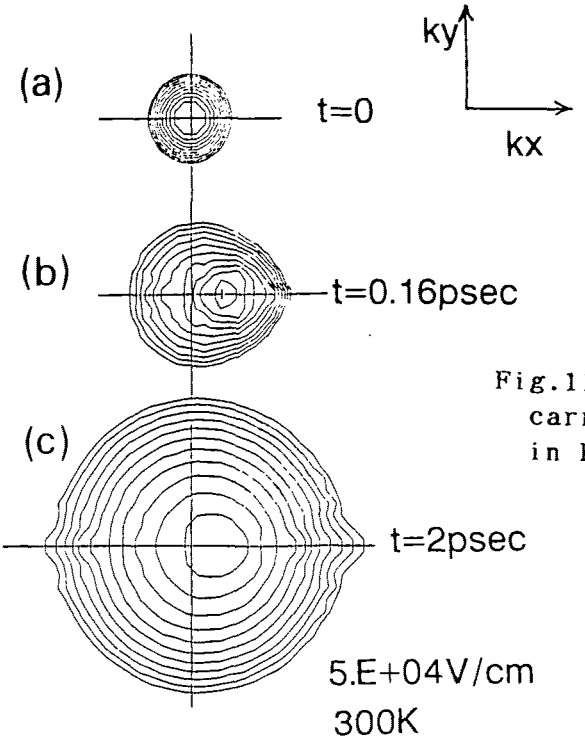

Fig.11 Contour maps of carrier distribution in k-space

The reason is considered to be that lucky electrons contributes to the extension in x direction and random scattering by intervalley phonons contributes to the extension in y and -y directions. On the other hand, at t=0.16psec, ie., when velocity overshooting occurs as shown in Fig.10, distribution is asymmetric.

As is well known, carrier-carrier scatterings make distribution symmetrical, when carrier density is sufficiently high. In typical submicron MOSFETs, carrier density near the drain is on the order of $10^{18}/cm^3$ in the pentode region. Therefore, an assumption on symmetricity in the higher order moment model might be questionable, when velocity overshooting occurs. Influence of carrier-carrier scatterings on the distribution function should be investigated in detail.

In Fig.12, energy dependency of electron population is shown. Due to the non-parabolic band, population in the high energy region is quite different from that calculated from the displaced Maxwellian distribution function, although both distributions give the same value of drift velocity and of average energy. This information may be useful for next advanced models for hot carrier related characteristics.

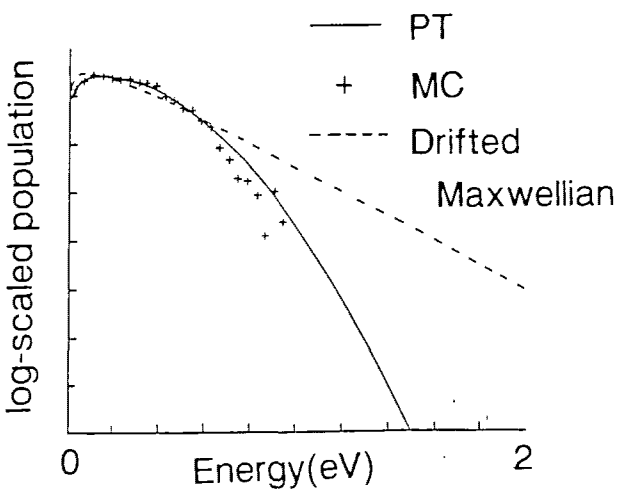

Fig.12 Energy dependency of electron population
E=5x10^{4}V/cm t=2psec

§5 Conclusion

The higher order moment model is practical and accurate for use in investigating electrical characteristics for deep submicron MOSFETs. Both drain and substrate currents are well predicted within reasonable calculation time and computer memory capacities. However, more sophisticated treatment regarding the distribution function is necessary to improve the model.

The population transaction method exceeds the Monte Carlo method in precision and accuracy. It offers useful information for distribution function as well as transport properties such as drift velocity and average energy.

Acknowledgment

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