Hydrodynamic Modeling of the Hot Electron Effect in Submicron MOSFET's Using a Simplified Energy Balance Equation

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Abstract - This paper describes a newly-developed approach for simulating the hot electron effect of submicron LDD n-MOS devices. The conventional drift-diffusion (DD) method tends to overestimate the impact ionization rate by comparing with experimental data. In particular, divergency is frequently incurred while calculating the continuity equations inclusive of impact ionization terms. To cope with this difficulty, a new simplified Hydrodynamic (HD) model, incorporating an analytical energy balance equation solutions, will be proposed. In the present method, a simple and efficient approach to obtain the effective electric field distribution is used so that accurate impact ionization rate can be determined. With the calculated impact ionization rate, substrate current can be accurately predicted. Excellent agreement has been achieved for a wide range of bias conditions and channel lengths.

1. Introduction

The substrate current has long been used as an indicator for monitoring the hot carrier effect. Although the simulation of the substrate current in short channel MOS devices has been extensively investigated [1], so far most of the reported methods, their results cannot be easily matched well with those from experiments. The key factor which causes such a deviation is the difficulties in calculating the impact ionization rate. Basically, there are two typical approaches which are classified as isothermal [2] and non-isothermal [3] theory. Nevertheless, as device dimensions are shrunk to submicron range, the isothermal approximation using DD method is no longer valid. In contrast, conventional MC [4] or fully self-consistent HD [5] approachs are rather time-consuming.

In order to resolve the abovementioned shortcoming, we propose in this paper for the first time an efficient calculation of the impact ionization rate for submicrometer MOSFET's based on a simplified hydrodynamic approach in which an analytical energy balance equation is incorporated in the DD solution and implemented as a post-processor. A modified energy-dependent lucky electron model for the impact ionization rate has been introduced in the analytical expression by considering the non-equilibrium effects of high electric field. The analytical model has been incorporated in a modified Minimos version [6] and predicts the substrate currents that compare fairly well with experimental results.

An integrated simulation system, shown in Fig.1, from process simulation (SUPREM IV) to device simulation (MINIMOS 4.2) is established for hot carrier analysis. First, the system has been calibrated based on a 0.8 µm LDD CMOS process and devices. Good matches of the simulated drain current characteristics with experiment can be achieved as shown in Fig.2 and the set of these parameters is suitable for a wide range of different channel length devices.

2. A Simplified 2-D Hydrodynamic Model

A physical set of hydrodynamic equations, which comprises the Poisson equation, momentum balance equations, and a simplified energy balance equation shown in Table 1, are used to investigate the nonisothermal characteristics of submicron devices. Here, an analytical energy balance equation, (3), is derived and implemented as a post-processor to determine an effective electric field distribution in the whole device bulk region. In this equation, T and T_0 are carrier and lattice temperatures respectvely. E is local electric field from DD solution, and τ_s is the energy relaxation time. v is non-equlibrium velocity, which is inadequately regarded as saturation velocity as ever been reported [7]. First, we will decide the value of v for each grid on a simulation mesh. If we make the assumption that the behavior of v acts in accordance with exponential change, v_1 and v_2 the equilibrium velocities at grid 1 and grid 2 respectively, d the distance between these two grids, and t_l the drift time needed for carriers traversing from grid 1 to grid 2. From above, one can obtain the non-equilibrium velocity v by combining eqs. (4) and (5) without difficulty. Usually, the magnitude by observing from Figs. 3 and 4 that the lateral current density is much larger than that of transversal current density in submicron MOSFET's, the transversal components play a minor role and the characteristics of impact ionization rate is overwhelmingly predominated by the lateral electric field and current density. Consequently, the transversal component can be neglected. No doubt, not only will the assumption greatly reduce the complexity of numerical simulation and CPU time, but also increase the probability of convergence. Carrier temperature and energy can be calculated with accuracy from the above simplified energy balance equation.

3. Calculation of the Substrate Current and Comparison with Experiments

At steady state, the effective electric field can be determined by eq.(4). After performing this operation for each space grid, an effective electric field distribution can thus be found. The impact ionization rate can be modified as

$$\alpha(x,y,T)=A\cdot\exp(-B/E_{eff}(x,y,T)) \qquad (7)$$

where $E_{eff}(x,y,T)$ is the spatial effective electric field distribution obtained from eq. (6). Once $\alpha(x,y,T)$ is known, I_{sub} can be directly obtained by integrating over the whole device.

The resulting impact ionization rate distribution is shown in Fig.5. Comparison of the electric field distribution along channel interface for HD and conventional DD models and the corresponding carrier temperature distribution is shown in Fig.6, from which the maximum value of the local electric fields is larger than that of effective electric fields. This is why one usually overestimates the impact ionization rate with conventional DD model. Fig. 7 shows the simulated substrate current, I_{sub}, for devices with effective channel lengths of 0.56 µm to 0.86 µm respectively at high drain-source bias. Fig. 8 shows the simulated substrate current, I_{sub}, for device with effective channel length of 0.66 µm under various bias conditions. Calculated results are compared with experimental data and excellent agreement can be achieved. The results derived from the DD and HD models have also been compared in the same diagram. The comparison shows that the DD model significantly overestimates the substrate current, while our HD model predicts more accurate results by comparing with experimental data.

In summary, this paper describes a new approach, from a simplified analytical energy balance equation, for calculating the device substrate characteristics in submicron MOS devices. Two different approaches have also been employed to calculate the substrate current and for comparison, i.e., the local theory based on the conventional DD solution and the nonlocal theory based on the simplified hydrodynamic approach. Results show that the simplified hydrodynamic approach gives much better results while the DD approach will overestimate the substrate current. Moreover, the divergency problem in fully-HD method can be prevented while keeping good accuracy in the newly developed method.

Acknowledgements The authors would like to thank Mr. M.-C. Chang and C.-N. Chen of ERSO, ITRI, Taiwan, ROC, for providing testing samples and other technical support. Financial support by the National Science Council under contract No. NSC81-0404-E009-112 and in part by the ERSO, ITRI, R.O.C. under the contract E80003, are also gratefully acknowledged.

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$$\nabla^2\psi = -\frac{\rho}{\varepsilon_S} \qquad (1)$$

$$0 = \frac{1}{q}\nabla\cdot\vec{J_{n}} \qquad (2)$$

$$\frac{\partial T}{\partial x} + \frac{3}{5}\frac{1}{v\tau_s}(T-T_0) = -\frac{2}{5}\frac{q}{k}E \qquad (3)$$

where $v = v_2 + (v_1 - v_2)\cdot\exp(-\frac{t_1}{\tau_s})$ (4)

$$d = v_2 t_1 - \tau_s\cdot(v_1 - v_2)\cdot(\exp(-\frac{t_1}{\tau_s}) - 1). \qquad (5)$$

$$E_{eff}(T) = \frac{3}{2}\frac{1}{v\tau_s}\frac{k}{q}(T - T_0). \qquad (6)$$

Table 1 The set of hydrodynamic equations for simulating the non-isothermal hot carrier characteristics.

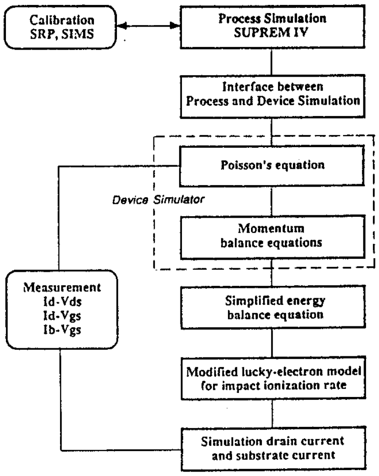

Fig. 1 Flowchart of the present HD model, in which the device simulator uses the DD solutions.

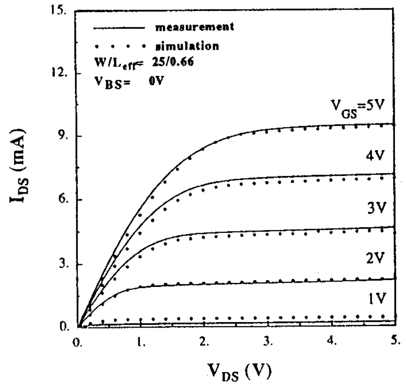

Fig. 2 Comparison of the drain currents between experiment and simulation for L_{eff}= 0.66μm device.

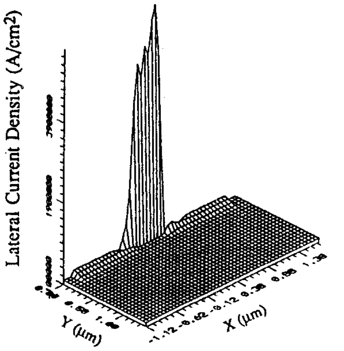

Fig. 3 The lateral component of electron current density for W/L_{mask}=25/0.6,V_{DS}=5V,V_{GS}=2V,V_{BS}= 0V.

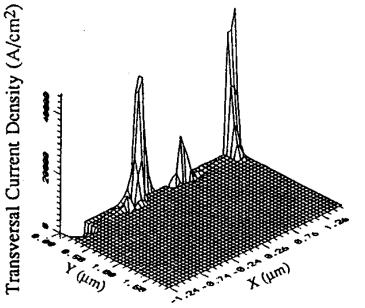

Fig. 4 The transversal component of electron current density for W/L_{mask}=25/0.6,V_{DS}=5V,V_{GS}=2V,V_{BS}= 0V.

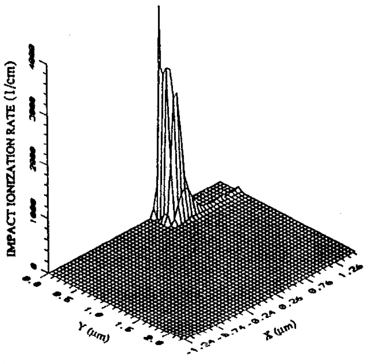

Fig. 5 Spatial distribution of the impact ionization rate for W/L_{mask}=25/0.6, V_{DS}=5V,V_{GS}=2V.

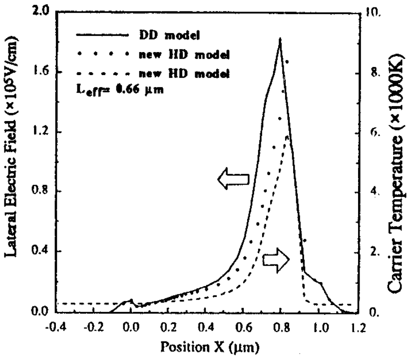

Fig. 6 Comparison of the surface electric field distribution between HD and DD models. Temperature distribution is also shown.

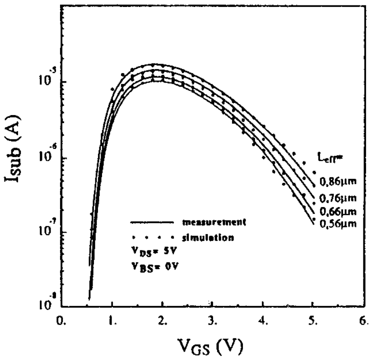

Fig. 7 Comparison of the substrate currents between simulation and experiment for various channel length devices.

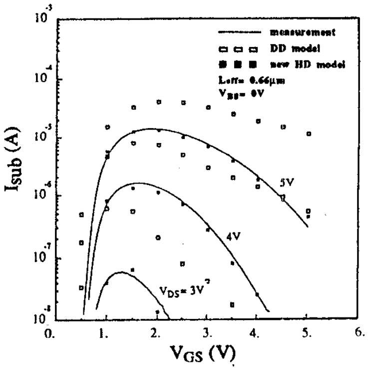

Fig. 8 Comparison of the substrate currents among experiment, HD and DD simulations at various biases.