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Accurate Modeling of the Energy-Dependent Hot Electron Effects in Submicron MOSFET's

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Calculation of the hot electron induced substrate currents in submicron and even deep-submicron n-MOS devices using the conventional drift-diffusion numerical simulation method tends to overestimate the results by comparing with experimental data. A newly-developed approach which uses a Hydrodynamic model by incorporating the 2-D energy balance equations can accurately predict substrate currents in submicron and even deep-submicron LDD and LATID n-MOSFET's. In the present method, a simple and efficient approach to obtain the non-local electric field distribution was used so that accurate impact ionization rate can be determined first. Using the calculated impact ionization rate, substrate currents can be predicted with excellent accuracy by comparing with experimental data for a wide range of bias conditions and device channel length down to 0.36μm.

1. Introduction

Hot carrier effects and the induced substrate current in short channel MOS devices have been extensively studied [1] due to its impact on the submicron VLSI and ULSI design. Accurate modeling of the substrate current is becoming increasingly important since it has long been used as an indicator for monitoring the generated hot carriers. In the simulation approach, so far most of the reported methods, their results can not 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 diffenent approaches which are classified as local [2] and non-local [3] theories. The local theory uses the solution of the semiconductor drift-diffusion (DD) equations, in which the distribution function is uniquely specified by the local electric field based on the assumption of thermal equilibrium approximation (TEA). Nevertheless, as device dimensions are shrunk to submicron range, in particular with fast varying electric field in the near drain region of MOS devices, this approximation is no longer valid. In contrast, the non-local theory uses either the Monte-Carlo (MC) [4] approach or the so called Hydrodynamic (HD) approach [5] by taking the non-equilibrium effects of high electric field into account and characterizing the carrier phenomena as function of the energy distribution instead of the electric field and thus a physical meaningful impact ionization rate can be obtained. However, conventional MC and fully HD approaches are rather time-consuming and inefficient.

In order to overcome the above mentioned weakness, we propose in this paper for the first time an efficient calculation of the impact ionization rate for submicrometer MOSFET's based on the Hydrodynamic approach in which simplified 2-D energy balance equations are incorporated in the conventional Drift-Diffusion solutions. A *non-local electric-field 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 device simulator [6] and predicts the substrate currents that compare fairly well with experimental results for submicron and deep-submicron LDD and LATID structures with effective lengths ranging from 0.36 to 0.86μm.

2. An Efficient 2-D Hydrodynamic Model

The physical model used in this paper, which is the so called Hydrodynamic (HD) model, comprises the following set of fundamental semiconductor equations : (1) Poisson equation, (2) momentum balance equations, and (3) energy balance equation. The three partial differential equations can be used to calculate electrostatic potential, ψ, electron and hole concentrations, n and p, and carrier temperature T_n, respectively. So far the above mentioned equations, solved self-consistently, have been implemented in the commercial PISCES simulator [7]. However, some factors such as demanding very much computer time, divergence especially including generation-recombination and impact ionization terms in momentum balance equations, have significantly degraded the performance of the device simulator. Usually, the number of iteration for convergence is the critical bottleneck for consistently solving all the Hydrodynamic model equations. To save the huge CPU time while preserving the accuracy, we developed an analytical energy balance equation for implementating as a post-processor (Fig.1) to determine the non-local electric field distribution in the whole device bulk region. In the architecture of the integrated simulation system, the input files of SUPREM IV were written according to an actual process flow so that the entire dopant distribution within the devices can be obtained. The 2-D doping profile should be thus

transformed into the input file of the device simulator through an interface. After the convergence of the first two equations being achieved, the Drift-Diffusion solutions of electrostatic potential and carrier current density distribution are put into the simplified 2-D energy balance equation, which can be solved for carrier temperatures as a device-simulating post-processor. By observing from Figs. 2 and 3 that the magnitude of the lateral current density is much larger than that of the transversal current density in submicron MOSFET's, the transversal components play a minor role in contrast to the lateral ones during device simulation procedure and the characteristics of impact ionization rate are overwhelmingly predominated by the lateral electric fields and current densities. Consequently, the transversal components can be neglected for convenience without the sacrifice of computing accuracy. No doubt, not only will the assumption greatly reduce the complexity of numerical simulation and CPU time, but also increase the probability of convergence. However, when the applied gate voltage becomes larger, the transversal electric field is correspondingly increased and the effects due to the inner product of the transversal electric fields and current densities should not be omitted in this case. The developed 2-D energy balance equation is given by :

$$\frac{\partial E_{eff}}{\partial x} + CE_{eff} = C\frac{\partial \psi}{\partial x} + \kappa C\frac{J_{ny}}{J_{nx}}\frac{\partial \psi}{\partial y} \qquad (1)$$

where E_{eff} is the non-local effective electric field in the lateral direction, J_{nx} and J_{ny} are the lateral and transversal current densities respectively, and ψ the electrostatic potential. The last term on the right-hand side represents the effects under higher gate biases. All the current densities and potential distribution can be obtained from the solutions of conventional device simulator, in which only Poisson equation and momentum balance equations are solved consistently, then substituting all the required parameters into (1). The fitting parameter κ can be straightforwardly determined through experiments and the optimized κ is 0.3, which is suitable for a wide range of device channel length. When κ is 0, the equaton is reduced to 1-D formula. Although, solving such a 1-D equation is a piece of cake, the simulated results could not be satisfied at very high gate biases. The coefficient C can be obtained over some energy range from Frey 8) , from which we can approximate the field-energy relation curve with three first-order lines, please refer to Fig. 4, where

$$\begin{array}{ll} C = 366.5 & 0 < E_{eff} < 170 \ (KV/cm) \\ C = 464.1 & 170 < E_{eff} < 260 \ (KV/cm) \\ C = 618.8 & 260 < E_{eff} \ (KV/cm). \end{array} \qquad (2)$$

The above analytical 2-D model including the transversal electric field perturbation can be implemented into the 2-D conventional drift-diffusion simulator as a post-processor to calculate the impact ionization rates for the whole device region.

3. Results and the Comparison with Experiments

At steady state, the effective electric field can be determined by (1). After performing this operation for each space grid, an effective electric field distribution can thus be found. The non-isothermal model for the impact ionization rate can be modified as $\alpha(x,y,T) = A \cdot \exp(-B/E_{eff}(x,y,T))$, where $E_{eff}(x,y,T)$ is the spatial effec- tive electric field distribution obtained from (1). Once $\alpha(x,y,T)$ is known, I_{sub} can be directly obtained by integrating over all the device bulk region.

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 and 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, V_{DS}= 5V. Fig. 8 shows the simulated and the experimental substrate current for device with effective channel length of 0.46 μm under V_{DS}= 3,4,5 V. and the corresponding drain current on the same graph. Fig.9 gives the verification of the presented model against the measured data for a LATID n-MOSFET with effective channel length L_{eff}= 0.36 μm under the conditions of V_{DS}= 4,5 V and various gate biases. Calculated results are compared with experimental data and excellent agreement can be achieved. The results derived from the conventional and simplified hydrodynamic approaches have also been compared in the same diagram. The comparison shows that the conventional 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 an analytical energy balance equation, for calculating the device substrate current characteristics. The newly-developed method provides a simple and efficient algorithm for simulating hot carrier effects. In this paper, two different approaches have also been employed to calculate the substrate current and for comparison, i.e., the *local theory* based on the DD solution and the *nonlocal theory* based on the proposed HD approach. Results show that the new hydrodynamic approach gives much better results while the DD approach tends to overestimate the substrate current. The simulated non-isothermal hot carrier effect is rather important to the scaling study of future deep-submicron technology applications.

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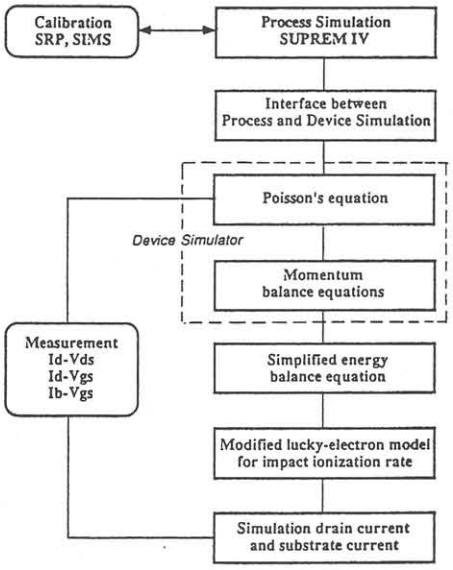

Fig. 1 Flowchart of the present HD model, in which the device simulator uses the DD solutions.

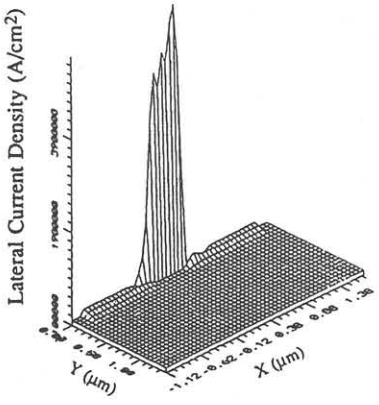

Fig. 2 The lateral component of electron current density for W/L_{mask}=25/0.6, V_{DS}=5V, V_{GS}=2V, V_{BS}= 0V.

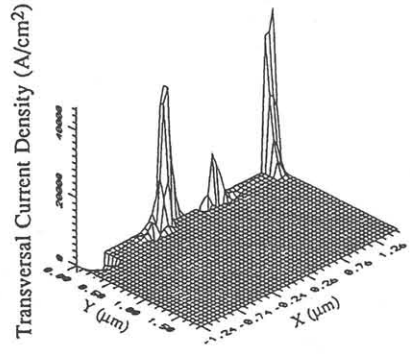

Fig. 3 The transversal component of electron current density for W/L_{mask}=25/0.6, V_{DS}=5V, V_{GS}=2V, V_{BS}= 0V.

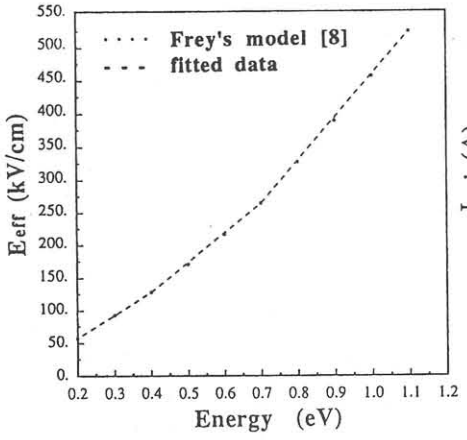

Fig. 4 Effective electric field versus average energy generated by the MC simulation [8].

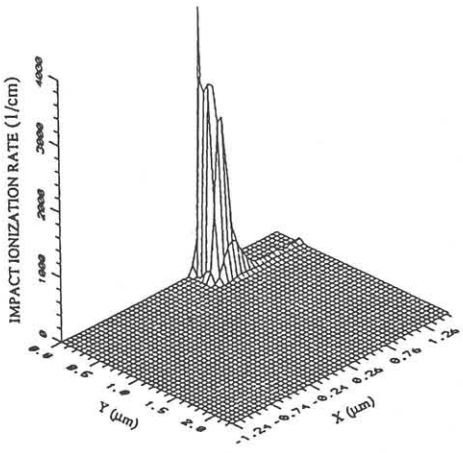

Fig. 5 Spatial distribution of the impact ionization rate for W/L_{mask}=25/0.6, V_{DS}=5V, V_{GS}=2V.

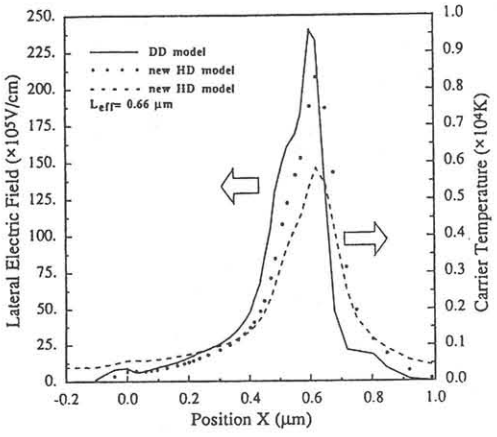

Fig. 6 Comparison of the surface electric field distribution between HD and DD models. Temperature distribution is also shown.

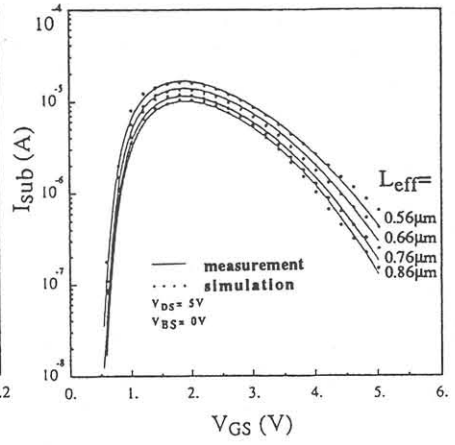

Fig. 7 Comparison of the substrate currents between simulation and experiment for various channel length devices.

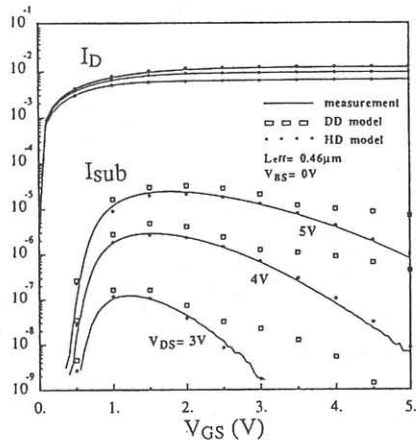

Fig. 8 Comparison of the substrate currents among experiment, HD and DD simulations at various biases.

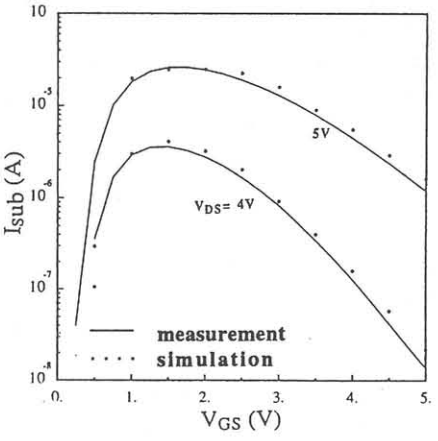

Fig. 9 Comparison of the substrate currents between new model and experiment for LATID MOS devices with L_{eff}= 0.36μm.