SIMULATION OF SEMICONDUCTOR DEVICES AND PROCESSES Vol. 5
Edited by S. Selberherr, H. Stippel, E. Strasser - September 1993

Inverse Modeling of Impact Ionization Rate Formula Through Comparison Between Simulation and Experimental Results of MOS Device Characteristics

S. Imanaga, K. Hane, and Y. Hayafuji

Yokohama Technology Center, Sony Corporation
134 Goudo, Hodogaya, Yokohama, Kanagawa 240, JAPAN

Abstract

This paper appraises the degree of agreement between simulated and experimental results of drain current versus drain voltage ($I_d - V_d$). It also derives the impact ionization rate formula inversely by compared the simulated and experimental dependence of the substrate current(I_{sub}) on the gate voltage(V_g). We found that : (1) for $I_d - V_d$ characteristics, the agreement in the linear region was off, but overall agreement was fairly good, and (2) the simulated $I_{sub} - V_g$ characteristics were in fairly good agreement with the experimental characteristics when the modified Keldish formula $P_{ii} = P_0((E - 1.12)/1.12)^n$ with n of 7 and P_0 of $2.8 \times 10^{11} s^{-1}$ was used as the formula for the impact ionization rate.

1. Introduction

Rigorous models of the transport characteristics of electrons in bulk Si, such as the real band model [1], have been developped. Direct comparison of device characteristics of MOS device between Monte Carlo simulation results and experimental results, however, is rare. We think that in order to assess the status of the conventional full Monte Carlo simulation, including highly doped regions, it is necessary to compare Monte Carlo simulation results with experimental results even if some of the models are not sufficient rigorous. Our first aim is to appraise the degree of agreement between simulated and experimental results of drain current versus drain voltage ($I_d - V_d$). Our second aim is to determine an impact ionization rate formula inversely through a comparison between simulated and experimental results of the dependence of the substrate current(I_{sub}) on the gate voltage(V_g).

2. Simulation method

As a band model, a spherical band is employed, and nonparabolicity ($\alpha = 0.35eV^{-1}$) is taken into account. The scattering mechanisms included[2] are intervalley scattering, acoustic phonon scattering, ionized impurity scattering (Brooks-Herring formula),

surface roughness scattering, and impact ionization. We employed Park's model[3] of surface roughness scattering. This is a partial diffusive scattering model in which a critical parameter P_s is introduced to identify the boundary between a specular and diffusive scattering event. The value of P_s is taken to be 0.77 by Park. Various formulas have been proposed for the dependence of the impact ionization rate on the electron energy ($P_{ii} - E$ dependence). Among those formulas, those proposed by Fischetti [1] and Thoma [4] base their claim on validity on the close agreement of simulated and experimental results of the impact ionization coefficient for bulk Si. However, Fischetti and Thoma have not compared the simulated and experimentally derived substrate current of MOS devices produced by impact ionization. We attemted, therefore, to determine $P_{ii} - E$ dependence inversely by comparing the simulated and experimentally derived $I_{sub} - V_g$ dependence. We assume that Eq. 1 is the formula for $P_{ii} - E$ dependence,

$$P_{ii} = P_0((E - E_{th})/E_{th})^n, \tag{1}$$

where E_{th} is the threshold energy for impact ionization and is assumed to be 1.12 eV. Then, we attempted to determine the value of n and P_0 to give the best fit to the experimental results. Ohmic contact for source and drain is modeled conventionally, namely, a layer of cells beneath the electrode is heavily doped and is maintained neutral every simulation time step. Electron-electron scattering and the degeneracy effect are not taken into account in the present simulation. The impurity profile of the device is obtained as a result of the process simulation using real process steps. The simulated MOS device has an LDD structure and its effective channel length is 0.6 μm. The maximum carrier concentration of source/drain and LDD are $2.4 \times 10^{20} cm^{-3}$ and $1.5 \times 10^{19} cm^{-3}$, respectively. The maximum doping concentration of p-type substrate is $1.6 \times 10^{17} cm^{-3}$ near the surface.

3. Simulation results and discussion

Figure 1 shows the impurity profile of the simulated device. Figure 2 shows the simulated and experimental results of $I_d - V_d$ characteristics. The agreement in the linear region and that in saturation region with V_g of 5 V are off, but overall agreement is fairly good. Figure 3 compares the experimental and simulated $I_{sub} - V_g$ characteristics. Here, we assume that the substrate current is the electron charge times the simulated number of electrons produced by impact ionization divided by simulation time after the system reaches the steady state. The squares in Fig.3 show $I_{sub} - V_g$ characteristics when Eq. 1, with n of 2 (the standard Keldish formula) and P_0 of 7.5×10^{12}, which is Tang and Hess's model [5], is employed as the formula for the impact ionization rate. In this case, the dependence of I_{sub} on V_g is not in agreement with the experimental results. Moreover, the absolute values of I_{sub} are two orders larger than the experimental values. The crosses in Fig.3 show $I_{sub} - V_g$ characteristics when Eq. 1 with n of 7 and P_0 of 2.8×10^{11} is used as the formula for the impact ionization rate. In this case, it is found that the simulated dependences of I_{sub} on V_g for both V_d of 4 V and V_d of 5 V are in fairly good agreement with the experimental results. The functional form of $I_{sub} - V_g$ characteristics is determined by the subtle balance between the increase of drain current and the decrease of the ratio of the number of high energy electrons in the channel which have enough energy to create electron-hole pairs by impact ionization, as the gate voltage increases. Figure 4 shows the dependence of the impact ionization rate on the electron energy proposed by various groups. Among those shown in Fig.4, the present result is most closely related to that of Taniguchi et.al [6] . Figure 5 shows the distribution of averaged electron

energy in the device. We can see that the peak of the electron energy increases and becomes sharper as the gate voltage decreases. Figure 6 shows the comparison of energy distributions between (a) at the drain-LDD edge and (b) at the source-LDD edge in the channel. At the position (b), the energy distribution is sharp and the peak of the distribution is about 0.15 eV. At position (a), the energy distribution broadens a great deal and is tailing towards higher energy. The peak of the distribution is about 1.14 eV. Figure 7 compares the energy distributions under the conditions of V_g of 1 V and V_g of 5 V. Figure 8 shows the distribution of electron positions in the device. It shows the increase of electron number in the channel as the gate voltage increases. We can see that at low gate voltages, pinch off occurs, and the depleted region with a high electric field near the LDD edge of the drain broadens gradually as the gate voltage decreases.

4. Conclusion

We simulated the device characteristics of a real MOS device by the self consistent full Monte Carlo method including high doping regions and compared the simulation results with the experimental results. We found that (1) as for $I_d - V_d$ characteristics, the agreement in the linear region was off, but overall agreement was fairly good. (2) The simulated $I_{sub} - V_g$ characteristics were in fairly good agreement with the experimental characteristics when Eq. 1 with n of 7 and P_0 of $2.8 \times 10^{11}\ s^{-1}$ was used as the formula for the impact ionization rate.

References

[1] M. V. Fischetti and S. E. Laux Phys. Rev. B, vol.30, no. 14, 9721(1988).

[2] C. Jacoboni, R. Minder, and G. Majni, J. Phys. Chem. Solids 36, 1129(1975).

[3] Y. -J. Park, T. -W. Tang, and D. H. Havon, IEEE Trans. Electron Devices, ED-30, no.9, 1110(1983).

[4] R. Thoma, H. J. Peifer, W. L. Engl, W. Q. Brunetti, and C. Jacoboni, J. Appl. Phys. 69(4), 2300(1991).

[5] J. Y. Tang and K. Hess, J.Appl.Phys. 54, 5139(1983).

[6] T. Kunikiyo, Y. Kamakura, M. Yamaji, H. Mizuno, M. Takenaka, K. Taniguchi and C. Hamaguchi, VPAD, 40(1993).

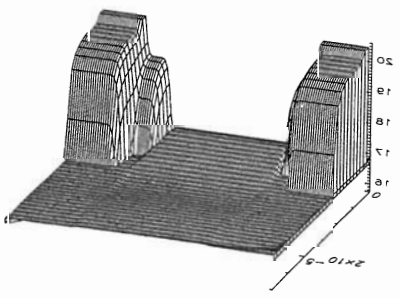

Fig.1 Impurity profile of the simulated MOS device

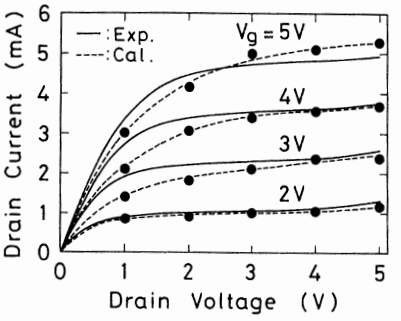

Fig.2 Comparison of Id-Vd characteristics between simulation and experimental results

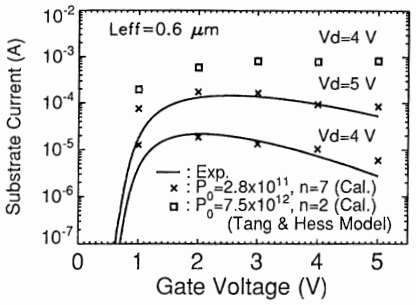

Fig.3 Comparison of Isub-Vg characteristics between simulation and experimental results

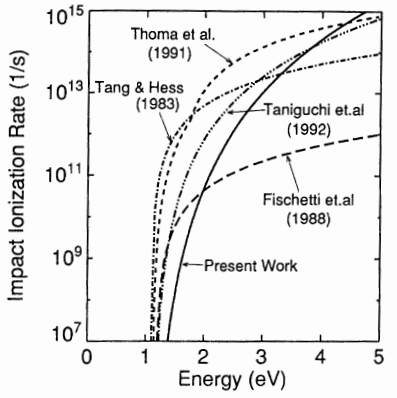

Fig.4 Dependence of the impact ionization rate on the electron energy proposed by various groups.

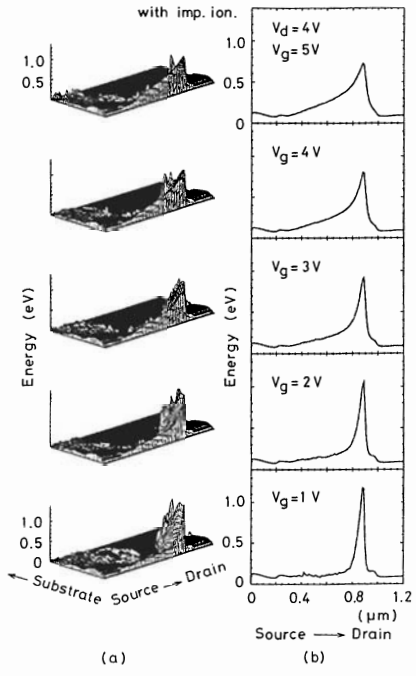

Fig.5 Distribution of averaged electron energy in the device

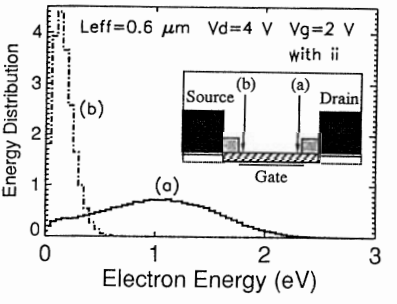

Fig.6 Energy distributions (a) in the channel near the drain-LDD edge and (b) in the channel near the source-LDD edge

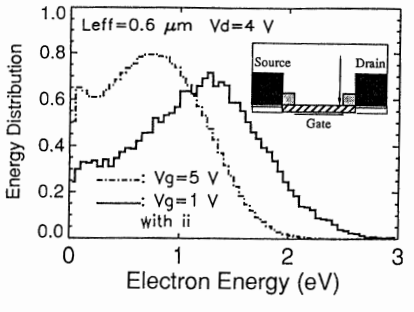

Fig.7 Comparison of the energy distriburions under the conditions of Vg of 1 V and Vg of 5 V.

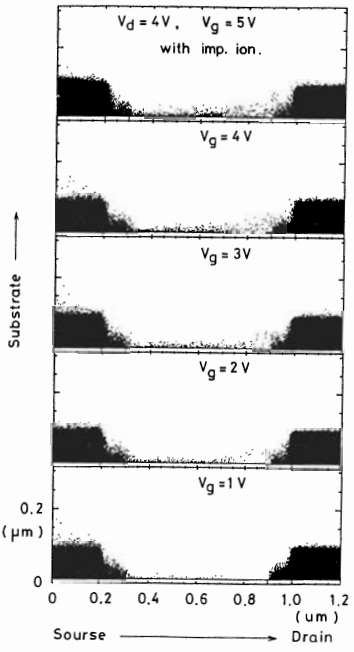

Fig.8 Distribution of electron positions in the device