Simulations of Schottky Barrier Diodes and Tunnel Transistors

K. Matsuzawa, K. Uchida, and A. Nishiyama

Advanced Semiconductor Devices Research Laboratories, Toshiba Corporation
8, Shinsugita-cho, Isogo-ku, Yokohama 235-8522, Japan
Phone: +81-45-770-3693, Fax: +81-45-770-3578,
E-mail: matsuzawa@amc.toshiba.co.jp

We present the implementation and simulated results of a practical model to cover Schottky and Ohmic contacts. The model considers thermionic emission and the spatially distributed tunneling. Simulations using the present model reproduce characteristics of Schottky barrier diodes and show the transition from Schottky to ohmic as the doping level is increased. As an application example, the immunity of Schottky barrier tunnel transistor to the short channel effect is demonstrated.

1. Introduction

The Schottky barrier has been utilized for the SBD (Schottky barrier diode), the HSBD (hybrid SBD) and the SBTT (Schottky barrier tunnel transistor). In order to examine the performance of these structures by simulations, an appropriate Schottky contact model with the tunneling is indispensable. The numerical techniques have been proposed for SBD [1]-[7], the HSBD [8] and the SBTT [9]-[11]. However, the tunneling is not considered [2]-[5], or the tunneling current is concentrated at the metal/semiconductor interface [6][10][11], or the boundary to distinguish the tunneling region and the drift-diffusion region is necessary in the semiconductor region [7][8]. In this work, we have implemented the Schottky contact model of the spatially dependent tunneling in the device simulator DIAMOND without any special boundary in the semiconductor region, verified the validity of the model by comparisons with SBD measurements, showed the transition from Schottky to Ohmic contacts in reverse bias characteristics of SBDs, and examined the immunity to the SCE (short channel effect) of SBTTs.

2. Schottky Contact Model

We have calculated the thermionic emission current J_{TE} and the tunneling current J_{TL}:

$$J_{TE} = AT^2 \frac{n - n_0}{N_C} exp\left(\frac{q\Delta\phi_B}{k_B T}\right), \tag{1}$$

$$J_{TL} = AT^2 T_{TL}(\xi)(f_S - f_M)\frac{\Delta\xi}{k_B T}, \tag{2}$$

where A [Acm^{-2}K^{-2}] is the Richardson constant (112 for electrons, 32 for holes [4]), T the carrier temperature, n the carrier concentration, n_0 the carrier concentration at equilibrium, N_C the effective density of state, $T_{TL}(\xi)$ the tunneling probability, ξ the carrier energy, $\Delta\xi$ the energy difference in the control volume, k_B Boltzmann's constant, f_S and f_M the energy distribution functions in the semiconductor and in the metal, and $\Delta\phi_B$ the barrier lowering by the image force. $T_{TL}(\xi)$ is calculated under the approximations of the WKB and the triangular potential [5]. J_{TE} is calculated at the interface between the semiconductor and the metal, and J_{TL} is calculated at each grid in the semiconductor. The calculation of the spatially distributed tunneling current allows us to unify the field emission and the thermionic-field emission in the J_{TL}. Namely, the field emission occurs around the Fermi-energy in the metal and the thermionic-field emission occurs in the energy region higher than the Fermi energy. J_{TL} can be calculated at the position where the potential corresponds to the each energy level in the metal. It should be noted that the validity of the WKB approximation for simulations of actual devices has to be checked by the comparison with the solution of the Schrödinger equation [9], however has not been evaluated in this work.

3. SBD Simulation

In order to examine the validity of the present Schottky contact model, we have compared simulated results of SBDs characteristics with measurements. Figures 1 and 2 show SBD characteristics of ZrSi$_2$/Si [4] and Ti/Si [7]. The simulated results show good agreement with measurements. The difference between simulations and measurements are considered to result from uncertainty of the effective density of state and the thermal velocity assumed implicitly in the Richardson constant, as studied by J. Adams et al. [2]. Figure 3 shows the influences of the impurity concentration N_D on the SBD characteris-

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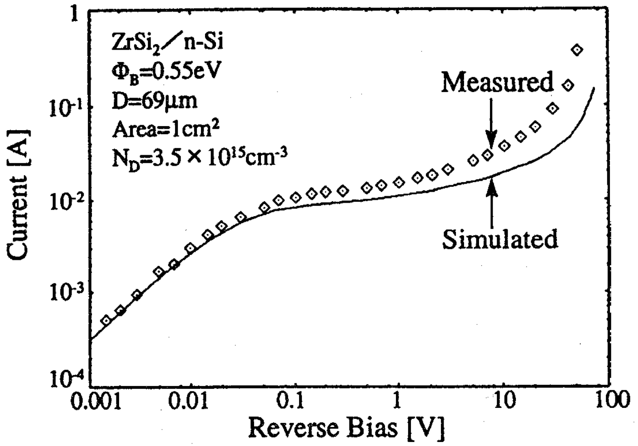

Figure 1: ZrSi$_2$ / Si diode characteristics.

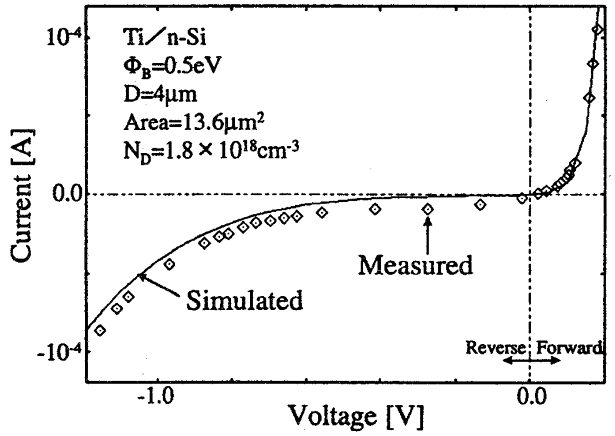

Figure 2: Ti / Si diode characteristics.

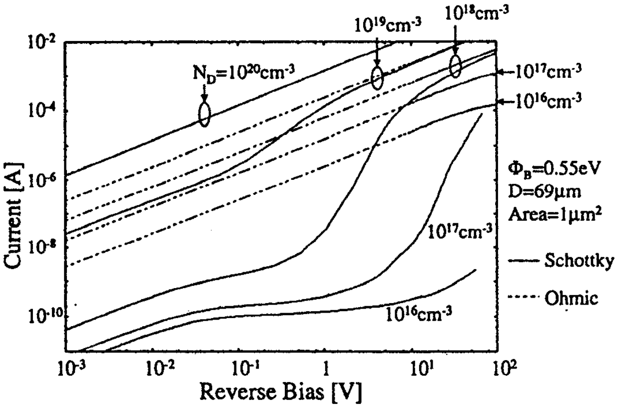

Figure 3: SBD characteristics with the impurity concentration as a parameter.

tics under the reverse bias. As N_D increases, the SBD characteristics become close to those of the ideal Ohmic contacts. Under such conditions, the tunneling probability becomes extremely high and f_S gets pinned to f_M. In this work, f_M is assumed to be in equilibrium. Therefore, the carrier concentration calculated by $n = N_C f_S$ is almost fixed on the equilibrium value, that is, $n \sim N_D$, which corresponds to the fixed boundary condition of the Ohmic contact. Consequently, the present Schottky contact model permits the unified simulation of the Schottky and Ohmic contacts.

4. SBTT Simulation

The SBTT has been studied as a candidate to realize ultra-short channel devices due to the immunity to the SCE [9]-[11]. We have examined the SCE for SBTTs and compared with results of conventional nMOSFETs. Figure 4 is the schematic structure of the SBTT simulated in this work. Figure 5 shows the gate bias dependence of the drain currents for the two gate lengths. The SBTTs show the high immunity to the SCE compared with the conventional MOSFETs. It should be noted that the "ON" state drain currents of SBTTs are lower than those of the conventional nMOSFETs. This is because the tunneling probability of electrons from the source electrode to the channel limits the drain currents. One could increase the drain currents by reducing the barrier height of the source electrode, but would cause the problem of the electron leak current from the source electrode to the drain electrode in the subthreshold region.

The leak currents by the majority carriers between the drain and the substrate could be a serious problem in the SBTT. Figure 6 shows the gate bias dependence of the leak currents by holes. The reason why the leak current decreases as the gate bias increases is that the tunneling probability decreases as the potential difference between the drain and the channel decreases. In the subthreshold region, the leak currents for the both gate lengths are relatively high. These substrate leak currents could be suppressed by using higher barrier for holes, which would, however, make the drain leak current higher in the subthreshold region.

There must be the trade-off between the drive capability and the subthreshold leak currents to apply the SBTT.

5. Conclusions

The Schottky contact model has been implemented in the device simulator DIAMOND, which reproduces measurements of SBD characteristics well and makes the unified simulation of Schottky and Ohmic contacts possible. By using this model, the immunity of SBTTs to the short channel effect has been demonstrated.

Acknowledgment

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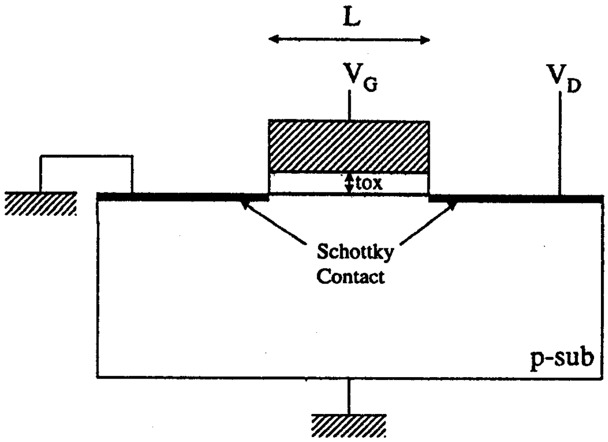

Figure 4: Schematic of SBTT structure.

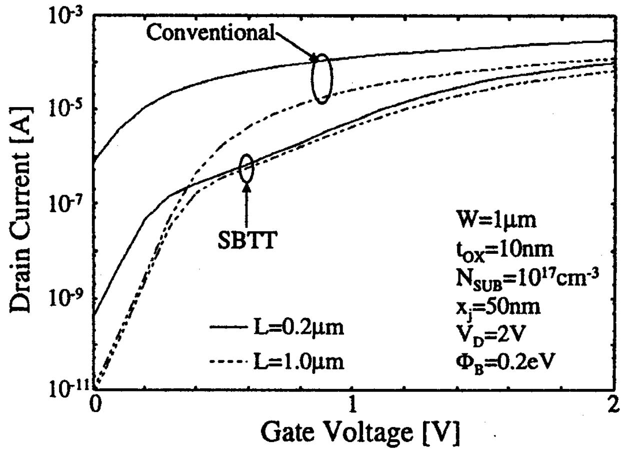

Figure 5: Gate bias dependence of drain currents of a conventional nMOSFET and SBTT.

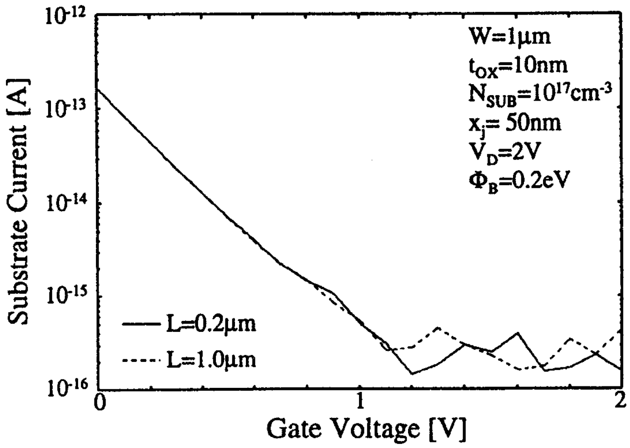

Figure 6: Leak currents between drain and substrate.

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